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The Effect of Carbon Taxes on Directed Technological Innovation: A Case Study of Sweden

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Abstract

A carbon tax is widely seen as an effective climate policy instrument for discouraging the emission of greenhouse gases that cause climate change. According to the economic theory of the Porter hypothesis, a carbon tax can induce directed technological change toward innovation in clean technologies. Nevertheless, empirical research on the effects of a carbon tax on clean innovation, especially concerning recent periods, is sparse. This paper uses a quasi-experimental approach, in the form of the synthetic control method, to estimate the effect of carbon taxes on climate change mitigating technologies. I conduct a case study of the introduction of the carbon tax in 1990/1991 in Sweden and its effect on clean technology in the transportation sector. Sweden is chosen as it was the first country, next to Finland, to implement a carbon tax, and that at a significant price. I find that the introduction of the carbon tax in 1990/1991 has a positive effect with an economically meaningful magnitude on driving innovation in climate change mitigating technologies. The significant and strong effect of the carbon tax on clean innovation can provide important policy insights for other governments, which did not yet introduce a carbon tax or did not do so at an insignificant rate.

Keywords: carbon taxation; clean technology innovation; Sweden; synthetic control method; transportation sector

1. An Introduction to the Role of Carbon Taxes in Carbon Pricing

Since the middle of the previous century, human activity has caused large amounts of greenhouse gas (GHG) emissions to be emitted into the atmosphere, which caused climate change (Azam et al., 2021; Khan et al., 2021). This anthropogenic climate change is one of the imperative issues of our time (United Nations, 2021). Carbon pricing, in the form of a carbon tax or an emissions trading system (ETS), is regarded by many as the policy of choice to achieve the goal of limiting global warming to below 2°C, preferably even to 1.5°C, which was set forth in the Paris Agreement in 2015 (Commission, 2017).

Some scientists advocate using an ETS over a carbon tax because of its better dynamical performance as a cap-and-trade system. The mechanism underlying an ETS is the following: An ETS puts a cap on the total amount of GHG emissions emitted annually. The entities covered by the system receive, buy, or trade allowances to emit GHG emissions with other market participants. This is done to the degree that the regulated entities obtain enough allowances to cover their emissions. Hence, the price of the ETS allowances is determined market-based through supply and demand. The cap ensures that the required emissions reductions occur and emitters stay within their carbon budgets (European Commission, 2022a; World Bank, 2022).

Other scientists advocate a carbon tax over an ETS-based approach (Metcalf & Weisbach, 2009; Weitzman, 1974). Under a carbon tax, the price per ton of GHG emissions is fixed and set by the government implementing it. Proponents of

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a carbon tax argue that a carbon tax allows for fast and precise price control to ensure that carbon is priced at a sufficiently high level. This allows the carbon price to interact more harmoniously with other government policies (Goulder & Schein, 2013).

There is empirical evidence that the ETS drives eco-innovation (Dechezleprêtre & Sato, 2017). Moreover, there exists comparative literature on the advantages and disadvantages of both carbon pricing options (Chen et al., 2020). However, there is less research on whether the carbon tax is a policy instrument that should be used in those sectors that the EU ETS does not cover. More specifically, there is a lack of research regarding the effectiveness of implementing a carbon tax to increase eco-innovation and thus achieve long-term GHG emission reduction. I use the implementation of a carbon tax in Sweden as a case study and subsequently explain to which degree my findings may serve as a recommendation for other countries.

On a global scale, ETSs can predominantly be found in the European Union (EU), China, and parts of the US. The EU ETS is currently the second largest ETS in the world, next to the Chinese ETS, which was launched in 2021 (IISD, 2021). It currently encompasses 30 countries and about 40% of the EU's GHG emissions (European Commission, 2022b). The EU ETS has successfully reduced the emissions of energy-intensive industries, such as the manufacturing, power, and aviation sectors (Borghesi & Montini, 2016; Dechezleprêtre & Sato, 2017; Venmans, 2012). According to the Effort Sharing Regulation (ESR), each EU member state has binding annual GHG emission targets for 2021-2030 regarding those sectors that the EU ETS does not cover (European Commission, 2022a). These sectors are transportation, buildings, agriculture, small industry (non-ETS), and waste. They account for around 60% of GHG emissions. ETS member states principally use national ETSs or a carbon tax to reduce emissions in the sectors not covered by the EU ETS (Life Unify, 2022).

The preeminent argument for using carbon pricing as a mitigation instrument is that polluters are economically incentivized to reduce emissions because the previously unpriced negative externalities, GHG emissions, are now priced. This price signal then triggers the development, innovation, and deployment of technologies that emit lower levels or even zero GHGs. These technologies are coined as clean technologies. The underlying dynamics are discussed more extensively in Chapter 2.1. Another argument for carbon pricing is that the technological transition to ecotechnologies can be accelerated through state intervention. Research on technological transition shows that there are other factors next to the pricing of negative externalities that influence the pace of innovation. Some countries may face carbon lock-in, meaning they prefer to use and develop technologies that emit high levels of carbon, so-called dirty technologies. This is the case because there are both decreasing marginal costs in improving already existing technologies and increasing returns through network effects. Therefore, innovation in new clean technologies is competitively disadvantageous in terms of marginal costs and returns (Unruh, 2000). Intervention through policies like a carbon tax can break up the lock-in and subsequently increase the pace of innovation (Arthur, 1989).

Carbon pricing can trigger short-term and longer-term effects. Short-term effects are characterized by operational changes to existing assets, like switching coal to gas as an input source for power-producing plants (Vogt-Schilb et al., 2018). These short-term carbon reduction techniques reduce emissions immediately but do not foster the necessary transformational change toward long-term or full decarbonization. Longer-term effects of carbon pricing on emission reduction are achieved through innovation in clean technology. Many researchers, for instance, study the long-term effects of carbon pricing by analyzing the directed technological innovation in clean technology rather than the shorter-term emission reduction level (Vogt-Schilb et al., 2018). Hence, in this paper, I investigate the effect of carbon pricing, in terms of a carbon tax, on directed technological change toward clean technology innovation. *My research question is: What is the impact of introducing a carbon tax on clean innovation?*

In order to answer my research question, I choose to conduct a case study of Sweden and the transportation sector and then discuss to which degree these findings can be applied to other countries and sectors. The main reason Sweden is chosen is that Sweden was one of the first countries globally to introduce a carbon tax and that at a high rate. The transport sector in Sweden is especially well suited as the ETS does not cover it, and it has a large carbon tax coverage. I construct my counterfactual by creating a synthetic version of Sweden through synthetic control method. Since the carbon tax pertains to the entire transportation sector, I do not have an easily obtainable counterfactor for a differences-in-differences (DiD) regression. In simple terms, the synthetic control method allows me to weigh other EU countries that do not have a carbon tax to create synthetic Sweden.

The remainder of this paper is structured as follows. In section two, I explain the theoretical anchoring behind carbon pricing and its effect on innovation, which role carbon taxes play concerning the ESR. I explain why Sweden and the transport sector are especially well suited to investigate the effect of carbon taxes on innovation. I also provide a critical synthesis and develop the main hypothesis. Section three explains why I chose the synthetic control method as my analysis method of choice and provides the synthetic control method's formal specifications. Moreover, I present my data sources and the steps conducted to arrive at the final dataset that I used for the analysis. Section four comprises a description of my results and robustness checks. Section five thoroughly discusses the results, deducts relevant political implications, links the results back to the economic theory, and explains that the results are generalizable to other countries outside Sweden. Finally, chapter six summarizes the advancements and points out future research opportunities.

2. Carbon Pricing and Innovation

The internalization of negative externalities, like carbon, leads companies to innovate to reduce the per unit cost of the externality they face (Acemoglu et al., 2012; Hicks, 1932; Pigou, 1920; Porter, 1991). In Europe, the Effort Sharing Regulation (ESR) sets binding annual GHG emission targets for its member states. A carbon tax can be used by these states to reduce GHG emissions through innovation in clean technology. Sweden plays a special role in carbon pricing as it was one of the first countries globally to implement a carbon tax at a high rate (Appendix 1). In this chapter, I will thoroughly examine each of the aforementioned components, explain their interconnectedness, embed them in the existing literature, and derive my hypothesis.

2.1. Economic theory on Carbon Pricing and Innovation

In a theoretically perfect market, sellers and buyers communicate effortlessly, and the market equilibrium equates to the producer's marginal cost and the consumer's willingness to pay. In reality, however, market failures, which are characterized by the inefficient distribution of products on the free market, often arise due to externalities. Externalities cause market failure as these are discommodities that a rational agent is incentivized to disown and avoid. Hence, the rules of market operations apply to discommodities but in reverse (Tybout, 1972). An environmental externality arises when the environmental damage of a good is not priced in the product. Hence, market outcomes are inefficient when consumers or companies are not exposed to the actual social cost attributed to their behavior (Knittel & Sandler, 2018). One solution to correct the distortion caused by negative externalities is introducing a Pigouvian tax so that the agents internalize the cost of their behavior (Pigou, 1920). Through the internalization of externalities, the value of the damage is factored into the actions that companies and consumers take. Hence, an efficient price level of the commodity and, importantly, an efficient level of emissions are reached (Lilliestam et al., 2020). The Pigouvian tax is often not applied to the actual externality but rather to the product most closely correlated with the externality. In the transportation sector, for instance, the carbon tax is applied to the average fossil carbon content of fuels because it is practically infeasible to tax the actual carbon emitted during usage.

An optimal Pigouvian tax incentivizes lower-cost abatement options to the level that matches the costs induced by the tax itself. In the automotive industry for example, abatement options can come in different forms, such as switching the fuel type of a vehicle, improving the fuel usage of internal combustion engines (ICEs), using a hybrid system, or entirely replacing the ICE with an electric motor (OECD Environment Directorate & International Energy Agency, 2001). The CO_2 abatement options that are patented fall under the Y02T category. The Y02T category refers to clean technologies related to transportation and is used as a critical variable for the analysis conducted in this paper.

Next to cost-minimization, a carbon tax generates incentives for developing and disseminating technologies that are less emitting than the prevailing standard. The assumption is that companies are motivated to innovate because they face a larger price for their emissions, increasing their production costs. Hence, companies are incentivized to invest strategically to reduce the ratio of emissions per production unit. Hicks (1932) was the first to make this assumption, which he coined the microeconomic-induced innovation hypothesis (IIH). He states that an increase in the price of input factors of production motivates invention. Porter (1991) and Acemoglu et al. (2012) expand on Hicks' microeconomic hypothesis and apply it to environmental policy. They hypothesize that a significant part of investments will flow to the development and commercialization of clean technologies as this is more economical than the cost incurred through continuing business as usual (Jaffe et al., 2003; Stavins, 2007). From a strategic point of view, companies that innovate early, so-called first movers, can take advantage of learning curve effects and patenting to attain a sustained competitive advantage compared to companies that do so later. In general terms, the "weak" Porter hypothesis (PH) asserts that stricter environmental policy regulations[1] stimulate innovation. It has to be differentiated from the "strong" Porter hypothesis, which argues that stricter regulations positively impact business performance. In this paper, I follow the rationale of the weak PH as a considerable strand of literature supports the first PH, while there is mixed empirical evidence concerning the second PH (Ambec et al., 2013; Palmer et al., 1995).

Carbon pricing, in the form of a carbon tax, can positively impact eco-innovation through the higher costs exerted on companies, government revenue allocated to carbon mitigation technology development, and a credible policy commitment. Carbon pricing is widely considered to be an economically viable option to inducing clean innovation as well as reducing GHG from a theoretical perspective (Baumol & Oates, 1988; Stavins, 2007), which is corroborated by empirical studies (Andersson, 2019; Elgie & McClay, 2013; Rivers & Schaufele, 2015).

2.2. The Effort Sharing Regulation and Carbon Taxes

According to the ESR, each EU member state has binding annual GHG emission targets for 2021-2030 regarding those sectors that the EU ETS does not cover. These sectors are transportation, buildings, agriculture, small industry (non-ETS), and waste. They account for around 60% of GHG emissions. Member states have different capacities to take action to reduce GHG emissions. Therefore, differentiating targets are allocated across the members according to the gross domestic product (GDP) per capita. Slight adjustments are made for countries with extraordinarily high

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[1] This paper uses a credible carbon tax as a proxy for strict policy regulation. Although there is no clearcut definition for a credible carbon tax, I refer to a carbon tax that is implemented at a rate similar to Nordic European countries (Appendix 1).

GDP per capita so that these do not face excessive mitigation costs. Country-specific targets for 2030 range from 0% to 40% emission reduction compared to 2005 levels, while the legislation currently in place aims to reduce emissions by 30% across the entire EU (European Commission, 2022a). Although Iceland and Norway are not EU members, they committed themselves to being part of the ESR. According to the Unify Program (2022), which is funded by the LIFE program of the European Union, the ESR targets should be further increased if the EU wants to comply with the obligations under the Paris Agreement. Emissions should be reduced by at least 50% instead of the current 30% compared to 2005 (European Environment Agency, 2021).

In order to achieve current or even more ambitious targets while maintaining economic competitiveness, the green growth strategy is a common policy approach chosen. The aim of the green growth strategy, as laid out by the European Union's Green Deal, is to foster economic growth and development while decreasing GHG emissions. This decoupling of economic growth and environmental pollution is envisaged to be achieved through the development of clean technologies. According to Howard and Sylvan (2015) and Commission (2017), the most economical way to decrease the risks of climate change and foster innovation is to implement a carbon tax or an ETS. However, public support outside of academia is lower. Many politicians for instance believe that the effect on innovation and the environment are limited. Support increases when evidence is presented that carbon taxes indeed foster innovation and GHG mitigation (Andersson, 2019; Murray & Rivers, 2015). To date, only 17 out of the 30 EU ETS member states have implemented a carbon tax. Out of these 17 countries, predominantly Nordic countries implemented carbon taxes with a significant price level (Appendix 1). Correct empirical estimations of the effect of carbon taxes on eco-innovation and related GHG mitigation potential are crucial to foster political support and to ensure credible policy commitments.

The first wave of countries that implemented a carbon tax predominantly did so because of green governments and comprises of the countries Finland (1990), Norway (1990), Sweden (1990), Denmark (1992), Slovenia (1996), Estonia (2000), and Latvia (2004), and Liechtenstein (2008).

In order to mitigate GHG emissions not explicitly covered by the EU ETS and comply with the ESR, several other EU countries introduced carbon taxation after the introduction of the Effort Sharing Decision in 2008. This second wave of countries comprises Iceland (2010), Ireland (2010), Ukraine (2011), France (2014), Spain (2014), Portugal (2015), Luxembourg (2021), Netherlands (2021), and Germany (2021). The Effort Sharing Decision was introduced in 2008 and set national emission targets for 2013 to 2020. The Effort Sharing Decision then transitioned into the Effort Sharing Regulation, which sets targets for 2021 until 2030. The national carbon taxes vary in GHG emission coverage, rate, and percentage of GHG emissions overlapping with the EU ETS (World Bank, 2022).

The transport sector accounted for around 36% of ESR emissions in 2019. Among all the ESR sectors, transport has the highest intended reduction until 2030. Nevertheless, between 2005 and 2019, the total reductions of the transport sector comprised only 5% of the reductions achieved in the total ESR, corresponding to 13 Mt CO_{2e} (Unify Program, 2022). As emission abatement in the transportation sector poses a significant challenge, an increasing number of countries have implemented a carbon taxation system, particularly for this sector. On the EU level, the European Commission proposed the "Fit for 55" legislative package in July 2021. This package proposes an ETS that also covers road transport, which would make it the largest ETS to apply to road transport. It is intended to exist separate from the EU ETS and regulated fuel suppliers, which will be responsible for incorporating the carbon cost. Applying carbon pricing to the road transport sector increases the price level of fuel, which according to Hicks (1932) and Porter (1991) and Acemoglu et al. (2012), increases innovation in clean technologies. There is an incentive to reduce the CO_{2e} content per liter of fuel to face lower taxation. CO_{2e} reduction might be accomplished by increasing vehicles' fuel efficiency or substituting conventional fuels with alternative fuels or energy sources such as electric batteries. The increase in the fuel price is ultimately passed to the consumer, who will strive to save fuel by buying increasingly environmentally friendly vehicles. Producers can capitalize on this trend by investing in the development of vehicles with low carbon emissions, which customers prefer (Aghion et al., 2016).

In contrast to an ETS, the carbon tax price is less volatile, which allows the risk-averse investor to make more confident investment decisions. Thus, firms can make significant clean technology-related investments (International Energy Agency, 2007). Analyzing the Swedish carbon tax's effect on innovation in the transportation sector may provide insights that can be used to fine-tune the implementation of the "Fit for 55" legislative package. Moreover, Sweden, as a pioneer in the early and credible introduction of a carbon tax, has a vital role in showing other countries that carbon taxes characterized by high price levels allow for innovation and GHG mitigation in harmony with economic growth. This paper fills the gap in ex-post empirical studies on the causal effect of carbon taxes on eco-innovation. I provide an empirical analysis of the effect of introducing a carbon tax in Sweden on eco-innovation. Eco-innovation allows for long-term GHG mitigation. Given the lack of available ex-post studies on the effect of carbon taxes on eco-innovation, the findings of this paper aim to corroborate confidence in implementing carbon taxes. Politicians implementing less efficient long-term mitigation measures will face challenges in reaching current targets set under the Paris Climate Agreement.

2.3. Sweden and Carbon Taxes

In Sweden, the Social Democrats were the first to recognize the threat of climate change and suggest a tax. In 1990[2]

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[2] I use 1990 as the year of my policy intervention. Other empirical studies on the carbon tax in Sweden use either 1990 or 1991 as the year of policy

this tax was promulgated by the Social Democratic government (Collier & Löfstedt, 1997). Sweden has a long history of taxing energy products to raise tax revenue and has been taxing petrol since 1924, diesel since 1937, and coal, oil, and electricity for heating purposes since the 1950s. This preexisting infrastructure for taxing energy products paved the way for implementing a carbon tax in Sweden (Jonsson et al., 2020). The carbon tax remains the fundament of Swedish climate policy today (Ministry of Finance, 2021). Hammar and Åkerfeldt (2011) describe the significant tax reform in 1990–1991 as "grön skatteväxling" translating to a "green tax shift" as other taxes, such as labor taxes, and energy taxes were reduced simultaneously to encourage green growth (Regeringskansliet, 2014). The marginal personal income tax rate was reduced from the highest rate of 80% to 50%, and the corporate tax rate from 57% to 30% (Jonsson et al., 2020). Nevertheless, Sweden also broadened the coverage of its value-added tax (VAT) in 1990 to pertain to gasoline and diesel. A VAT of 25% is applied to transport fuel, exercise taxes, and producer margin (Andersson, 2019). Since implementing the carbon tax more than 30 years ago, Sweden has achieved green growth because it reduced GHG emissions while maintaining GDP growth. GDP per capita increased by over 50% between 1990 and 2021 in real terms (OECD, 2022).

Swedish carbon tax revenues comprise around 1% of the government's total tax revenues, corresponding to SEK 22.2 billion ($2.3 billion) (Natur Vårds Verket, 2019). Although Sweden does not use the carbon tax revenues for direct green spending, which is revenue earmarked for climate protection, they use 50% of the revenues as general funds, which go to the government budget, and the other 50% for revenue recycling. Revenue recycling refers to income redistribution to firms and consumers through tax reductions or subsidies (Lilliestam et al., 2020). From 1990 until 2004, the revenue increased, stabilized until 2010, and decreased slightly over the last decade. As fewer fuels or fuels with lower GHG emissions are used, fewer tax revenues are collected, which is intended by the system's design. The carbon tax revenue collected now comprises 95% of taxes on motor fuels. However, heating fuels made up a large percentage of the collected tax revenue when first implemented. Since 1990 fossil heating fuels have been phased out, and their usage has decreased by 85% and now represents only 2% of Sweden's total GHG emissions. Sweden replaced fossil fuel heating with district heating and heat pumps, a more sustainable and holistic system (Ministry of Finance, 2021).

Although combating climate change had extensive political support in the period from 1980 until 2000, concerns about carbon leakage and competitiveness in a global economy led to the industry paying only 25% of the full rate and exemptions for the electricity industry. Between 1993 and 2015, the tax rate for the Swedish industry varied between 21% and 50% of the full rate and was gradually phased out with the introduction of the EU ETS (OECD, 2016) (Appendix 2). Therefore, the carbon tax had a relatively low impact on the industry (Johansson, 2000). Nevertheless, because tax rates differ across energy products and users, other sectors, such as residential, commercial, or road transport, are affected more significantly (Appendix 3). The current carbon tax in Sweden, with a rate of SEK 1200 per metric ton of CO_2, is the highest in the world (International Energy Agency, 2022).

The introduction of the carbon tax resulted in a low administration as the tax is levied on importers, distributors, and large consumers rather than large numbers of final consumers. Gasoline, for example, is already taxed at the point of import or wholesale, meaning that neither the gas station operator nor the final customer is taxed directly. The legal incidences differ from the economic ones as the tax is administered to importers, distributors, and large consumers, but the economic costs are passed down to the final consumer.

Next to the industry sector, which emits 60,176 t CO_2, road transportation is the second largest emitting sector of CO_2 in Sweden with 21,241 t CO_2 (OECD, 2016). Carbon taxes pertain to 91% of the emissions emitted by the road transportation sector (OECD, 2016). Sweden has a material interest in reducing CO_2 emissions in the transport sector as the automotive industry is its largest export sector with a value of around € 11B annually and employs the highest number of people of all industries in absolute numbers (OEC, 2022). Although Sweden is a relatively small EU country, with a population of only 10.35 m as of 2022, it houses the headquarter of the large truck manufacturers Scania CV AB and the Volvo Group, and the personal vehicle manufacturer Volvo Car AB. Sweden's strong economic position is based on its export-oriented industry. Foreign international competition constantly induces pressure for change, promoting innovation in Swedish firms.

Sweden is particularly well suited to study the effects of carbon taxation on innovation as Swedish companies have a strong focus on achieving growth in line with the government's policies. This is mainly done through product improvement and innovation by investing in R&D (Johansson, 2000). Sweden has the second largest Business R&D intensity of all countries in the Organization for Economic Cooperation and Development (OECD) (Figure 1). Figure 1 shows the Business enterprise expenditure on R&D (BERD) adjusted for industrial structure, which measures a country's business R&D intensity assuming it had an OECD average industrial structure. BERD represents the components of the Government expenditure on R&D (GERD) incurred by units belonging to the Business enterprise sector. The unit of measurement is the BERD as a percentage of gross value added (GVA) in industry (OECD, 2020).

According to the European Innovation Scoreboard (2022b), Sweden is an innovation leader with a performance of 135.7% of the EU average. Sweden scores especially high in public-private co-publications (381.4%), international scientific co-publications (241.1%), intellectual assets such as PCT

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intervention. The actual tax affected consumers in 1991. However, antecedent effects due to press coverage on the promulgation might already exist in 1990.

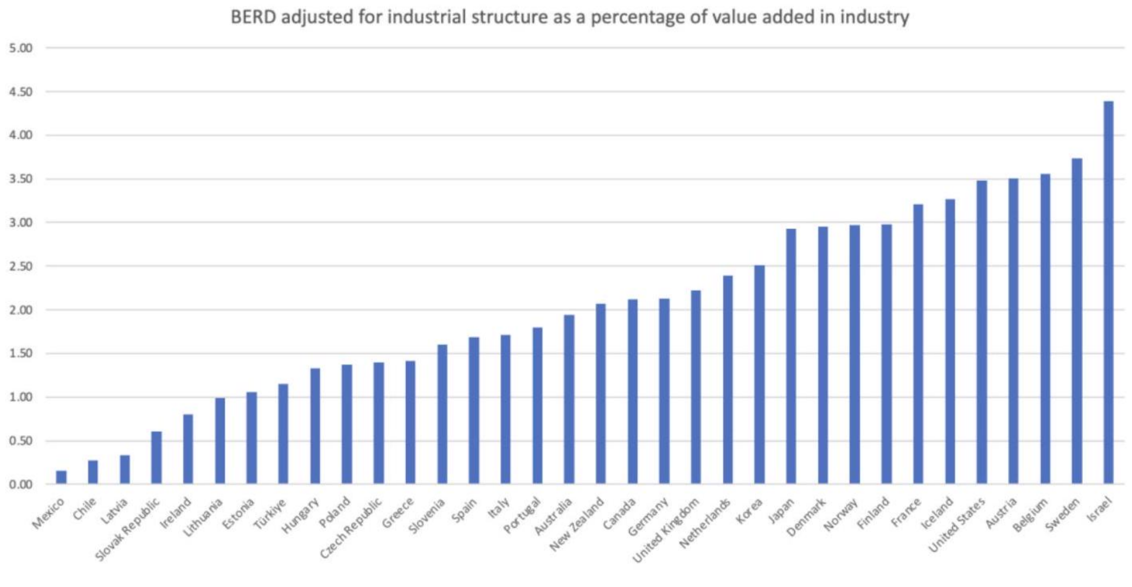

Figure 1: BERD as a percentage of value added in industry (OECD, 2020)

patent applications (150.6%), and eco-innovations (123%). Sweden is among the countries that most significantly invest in R&D in relation to their GDP. Sweden's total R&D investments - an important input for innovation - amount to around 4% of GDP in 2020 (SCB, 2020). The Swedish innovation system comprises an integrated public and business sector, whereby the business sector contributes to nearly 72% of all expenditures.

The configuration of business and public innovation structures is especially pronounced in the automotive industry. The "Fordonsstrategisk forskning och Innovation" (FFI), which translates to Strategic Vehicle Research and Innovation Programme, is the largest collaboration between the Swedish state and the automotive industry. Vinnova, the government's innovation agency, collaborates with the automotive industry (Scania CV AB, AB Volvo, Volvo Car Group, and FKG). From 2009 until 2020, the FFI conducted around 900 research projects with over 500 Ph.D. researchers worth € 100 million annually, with half of the funding coming from the government (VINNOVA SE, 2022). Many of those projects concern reducing energy use per vehicle, linked to clean innovation.

While the Swedish government does not have a mandate to spend the revenues earned from the carbon tax on green *R&D* projects, it still uses some of this revenue to fund research projects concerning clean innovation in transportation. This may be because the Swedish government deems environmentally friendlier vehicles important for the sector's international competitiveness. In Sweden, the automotive industry comprises 14% of its economy. It is not uncommon for governments to participate in the research of climate-friendly technologies after introducing a carbon tax. In Sweden, the government started to invest in the research of clean transportation technologies in the early 2000s and increased funding with the introduction of the FFI (VINNOVA SE, 2022). In my study, I treat the government's research projects as part of the effects of a carbon tax on innovation.

The implementation of the carbon tax was especially successful in reducing GHG emissions in the transport and heating sector (Natur Vårds Verket, 2022a). According to the Swedish environmental protection agency, GHG emissions have been reduced by 32% since 1990, especially during the last 20 years (Natur Vårds Verket, 2022b). Although GHG emissions have been reduced, Sweden's carbon tax is subject to criticism. Experts from the Stockholm School of Economics criticize the carbon tax because it is likely that the effect on emissions reduction is below the effect that could have achieved (Jonsson et al., 2020). While many small companies cut their emissions significantly, the largest polluters, manufacturers of steel and concrete, increased emissions. The failure in nudging large polluters to emit less GHG emissions is due to the cap, which imposes a maximum tax a company must pay. The government's idea was to limit the competitive threat a carbon tax might pose to large steel and cement producers on an international stage, as these sectors were considered of national interest due to extensive lobbying (Karakaya et al., 2018). While their competitiveness was preserved, large polluters were exempt from paying for marginal emissions beyond the cap until they were covered by the EU ETS (Lundberg, 2014).

2.4. Critical Synthesis

In my literature review, I focus on those studies that evaluate the primary aim of green policies, especially the carbon tax policy, under the Paris Climate Agreement in 2015. The Paris Climate Agreement aims to limit GHG emissions to well below 2°C compared to pre-industrial levels and to pursue efforts to limit global warming even further to 1.5°C. In contrast to the Kyoto Protocol, which focuses rather on ephemeral emission reduction, the Paris Agreement is about complete decarbonization and takes a long-term perspective. I emphasize the dissimilarity between emission reduction and entire elimination as differing analysis methods are deployed for policy evaluation (Patt & Lilliestam, 2018). My paper focuses on the carbon tax's long-term effects, which aligns with the efforts under the Paris Climate Agreement. I am interested in the effects of a carbon tax on a shift towards clean innovation and take a dynamic perspective assessing effects over decades, which is the time horizon carbon taxes are designed to operate over (Fuss et al., 2018). I review those ex-post studies that take the cost-effectiveness framework, focusing on deep technological innovation in long-lived carbon-emitting capital stocks such as transportation.

Moreover, I mainly examine peer-reviewed papers, except for Moore et al.'s (2021) paper, which is a working paper but is the only other research I could find which also studies the introduction of the carbon tax in Sweden and its effect on the transportation sector. I perform my search analysis by using the academic search engines ScienceDirect and Google Scholar and searching for terms such as ("carbon pricing", "carbon tax Sweden", "carbon tax") for my research domain. I use more general search terms for literature on carbon pricing theory.

Concerning my theory section in chapter 2.1, an extensive number of macro as well as microeconomic studies exist concerning the IIH (Newell et al., 1999; Popp, 2002). Regarding carbon pricing and innovation, most empirical evidence supports the first Porter hypothesis. In an environmental context, Goulder and Schneider (1999), Gerlagh (2008), and Acemoglu et al. (2012) find empirical support for the innovation effect, namely that strict environmental regulations trigger the introduction of clean technologies, which makes production more efficient. Brunnermeier and Cohen (2003) and Lee et al. (2011) explicitly focus their research on the weak Porter hypothesis and find that environmental policies positively affect clean innovation in the auto industry.

Most of the research on carbon taxes focuses on Nordic countries, as these are among the world's oldest and highest-priced carbon taxes (Lilliestam et al., 2020). Nevertheless, there are also some studies concerning the carbon tax in British Columbia, which was implemented in 2008 and is one of the few examples of a high carbon tax outside of Europe.

Bohlin (1998) investigates the effect of the carbon tax in Sweden on CO_2 emissions in different sectors from 1990 until 1995. He finds a significant effect of carbon taxes on CO_2 savings in the district heating sector and no effect in the transportation sector. Bohlin's study only covers the first five years since the carbon tax's introduction and cannot observe the long-run effects of the policy implementation.

More than ten years later, Lin and Li (2011) investigate the effects of carbon taxes on GHG emissions in Sweden, Denmark, Finland, the Netherlands, and Norway between 1981 and 2008, while the period from 1981 until 1989 is the pre-treatment period. They use a DiD model and only find a significant effect for Finland. They estimate a 1.7% reduction in emission increase compared to the hypothetical scenario without a carbon tax implementation. Lin and Li (2011) point out that tax exemptions for energy-intensive and manufacturing industries are likely the reason they found no emissions growth reduction for the other countries analyzed.

The most prominent paper regarding carbon taxes in British Columbia concerns the impact on gasoline demand (Rivers & Schaufele, 2015). They analyze the period from 2007 until 2011 and find that the carbon tax has a larger negative effect on gasoline consumption than other taxes. They conclude that this can be attributed to the salience of carbon taxes in public disputation and the press.

Shmelev and Speck (2018) analyze the effect of the introduction of the carbon tax in Sweden on CO_2 emissions from 1961 until 2012. The years before 1990 are again used as a pre-treatment period. They find that the carbon tax lowered the CO_2 emissions from the use of petrol, but not so for other energy sources studied. They find several coefficients for the effect on petrol as they implement a multitude of econometric models.

Recent developments concerning econometric policy evaluation tools have made it possible to overcome common issues related to the DiD method. Andersson (2019) applied the synthetic control method to analyze the effect of introducing a carbon tax on emissions from the transport sector from 1990 until 2005, with a pre-treatment period starting in 1960. His donor pool consists of a group of OECD countries that did not implement a carbon tax during the period studied. He finds that the carbon tax reduced emissions in the transport sector by 6% compared to synthetic

Sweden's scenario without introducing a carbon tax. Not only do his findings oppose Lin and Li's (2011), but he also scrutinizes their research design. He mentions two main points of criticism. First, Lin and Li (2011) use total CO_2 emissions as the dependent variable. Therefore, they combine treated and untreated sectors, although all the countries they analyze have sectors of the economy that are exempt from carbon taxes. Second, they include covariates in their DiD model that are related to their outcome variable. While this is allowed in the synthetic control method, it biases results when the DiD method is used.

The only peer-reviewed article that is an ex-post empirical assessment of a carbon tax and innovation is the study by Cheng et al. (2021). They study the dynamics between carbon tax revenue and energy innovation in Sweden from 1990 until 2019. They deploy the recently developed Quantile-on-Quantile Regression framework to observe whether there is a linear relationship between tax revenue and innovation. They observe that when there is a low carbon tax revenue, a higher penetration of energy innovation is desired. They state that this might be because a low carbon tax burden might be less costly for a firm compared to the costs of implementing energy innovation. This effect disappears for larger carbon tax revenues.

Even though Moore et al.'s (2021) paper is a working paper, I choose to include it in this peer review because it has a similar research domain to my paper, as it also investigates the carbon tax and Sweden's transport sector. They use the synthetic control method and find a positive effect of carbon taxes on clean innovation, with an average increase in clean patents of 7.37 per year from 1990 until 1999. Sweden started to finance R&D programs to boost clean innovation beginning in 1999. They see the government's financing of R&D programs as policy interventions unconnected to the carbon tax and hence as a confounding variable they cannot control. Therefore, they decide not to investigate the period after 1999 further. In my study, I take a similar approach to Cheng et al. (2021) and Andersson (2019) and do not regard those government initiatives as separate from the carbon tax. Like Andersson (2019), they construct synthetic Sweden using OECD countries as their donor pool. Using a donor pool that comprises OECD countries is a sensible approach for Andersson's (2019) study, which has GHG emissions as a dependent variable. Using the same donor pool when having patents as a dependent variable might introduce some issues. Using countries like the United States or Japan in the donor pool to construct a counterfactual might bias results as those countries' innovation infrastructure is significantly larger than that of European countries. I provide a more detailed review of Moore et al.'s (2021) study and a comparison of results in the discussion section.

Although Calel and Dechezleprêtre's (2016) study does not concern carbon taxes but the ETS, I chose to include it in this literature review as it is considered one of the most prominent studies on carbon pricing and innovation. It analyzes the EU ETS' effect on directed technological change by using patent count as a proxy for innovation, which is regarded as one of the most robust indicators of innovation (Hagedoorn & Cloodt, 2003). Furthermore, causal claims are made using the DiD approach that allows for a precise interpretation of the estimated results (Teixidó et al., 2019). Calel and Dechezleprêtre (2016) find that the share of lowcarbon patents among the companies regulated by the EU ETS rises significantly during the first five years after the launch of the EU ETS. Notably, they find no such phenomenon concerning non-regulated firms. They estimate that the share of low-carbon technology patents increases by 36.2% compared to a scenario without the EU ETS, while regulated firms continue their patenting behavior for other technologies. One limitation is that the effect could have also been driven by confounding variables such as a rapidly rising oil price, which has not been investigated closer.

Regarding the transport sector, empirical studies find that there is a positive effect of fuel prices on innovation in clean technologies concerning automotives such as improvements in the fuel efficiency of ICE, alternative fuels for the ICE, hybrid vehicles, or electric vehicles (Aghion et al., 2016; Crabb & Johnson, 2010; Hascic et al., 2009). These studies estimate the potential effect of carbon taxation on innovation in the transport sector. A fuel tax is similar to a carbon tax levied on fuel, but the GHG emissions of the fuel are not explicitly accounted for in a general fuel tax. Moreover, the carbon tax levied in Sweden is larger than the fuel tax levied in many other countries (Andersson, 2019; Rivers & Schaufele, 2015).

The literature on carbon taxes and innovation remains scarce. Previous literature predominantly focuses on the environmental effects of introducing a carbon tax. Advancements in econometric models in recent years allowed researchers to apply new methods to investigate the effect of the carbon tax on innovation (Cheng et al., 2021; Moore et al., 2021). It has not yet been sufficiently clarified what the effect of the introduction of a carbon tax is on innovation, particularly regarding recent terms. Although Cheng et al. (2021) do investigate the relationship between a carbon tax and innovation until 2019, their findings lack sufficient interpretation and contextualization as they use complex econometric models for their research which are challenging to interpret. Moreover, their research rather concerns the relationship between carbon taxes and innovation rather than causal dependencies.

2.5. Hypothesis Development

I now develop my main hypothesis by combining my findings on the theory and literature review on carbon pricing. Pigou (1920) suggests that introducing a Pigouvian tax, such as the carbon tax, leads agents to internalize the cost of their behavior. Once the negative externalities are priced in the cost of the product, companies are incentivized to innovate their production methods to reduce the per unit cost of the negative externality they are now facing (Hicks, 1932). More applicable to carbon taxes, Porter (1991) and Acemoglu et al. (2012) apply Hick's (1932) hypothesis to climate policy. They hypothesize that climate policies lead to clean technology development as this is economically more attractive than the cost associated with abatement. Previous literature on carbon taxes and innovation indeed explores the economic relationship between the cost of abatement and the cost to innovate (Cheng et al., 2021). However, it lacks the identification of the overall effect of clean innovation. The only other study on carbon taxation and clean innovation merely investigates a period of roughly ten years and finds a moderate but positive effect on innovation (Moore et al., 2021).

In my paper, I investigate the effect of the introduction of a carbon tax on clean innovation over a prolonged period. It is unfeasible to study the effect of a carbon tax across several countries, given different sector coverages and introduction periods. Therefore, I study the effect in Sweden and discuss to which degree my findings are generalizable to other countries.

Based on this, I hypothesize that a positive relationship exists between introducing a carbon tax and clean innovation in the long run.

I test this hypothesis by looking at Sweden's transport sector and a treatment period that stretches from 1990 until 2018. I chose to focus on Sweden as it was not only one of the first countries to introduce a carbon tax but also has the largest policy tax rate (Appendix 1). The transport sector in Sweden is well suited as the carbon tax covers 91% of its emissions, while the EU ETS covers 0% (Appendix 2). Sweden has a sizeable automotive industry compared to other Nordic countries, so implementing innovation to reduce GHG in this sector has exceptionally high materiality for Sweden (Atradius, 2019). I use the synthetic control method to measure the effect of the carbon tax on clean innovation. To construct my synthetic Sweden, I use the EU ETS member states which do not have a carbon tax as my donor pool.

3. A Methodological Approach to Estimate the Effect of a Policy Introduction on Innovation at the Country Level

To overcome issues concerning the DiD method, I use the synthetic control method to determine the effect of the carbon tax implementation on clean innovation. This chapter explains why the synthetic control method is well-suited to answer my hypothesis. Next, the formal aspects of the synthetic control method are presented. Finally, I explain the data I use to construct my synthetic control and where it originates.

3.1. The Empirical Analysis Method

Previous studies evaluating the effect of a policy on innovation at the company level have mainly used methods such as the DiD method to compute a causal effect (see e.g., the study of Calel and Dechezleprêtre (2016)). The DID method is applied to longitudinal data for which a treatment and control group exist. The effect of an intervention is estimated by measuring the changes in outcomes over time between the treatment and control group. In the case of Calel and Dechezleprêtre (2016) the units exposed are the ETS-regulated companies, and those not covered by the system form the control group. Contrary to the ETS system, which does not affect all firms in a country's sector, the carbon tax usually affects all companies in the same sector. Hence, no set of units can be easily chosen to form the counterfactual. By deploying the synthetic control method, I can create a counterfactual by using other countries in the EU that do not have a carbon tax. In the synthetic control method, the untreated units are weighted so that they mimic the behavior of the treatment unit as precisely as possible without actually being treated themselves. The weighting of the comparison units, which form the donor pool, is done by matching their pre-exposure trends based on predictor variables to estimate the counterfactual optimally. The then-created counterfactual is called the synthetic control unit.

The difference between the evolution of the treatment unit, Sweden, and the synthetic control unit is the gap that represents the effect of the policy intervention. The large portion of existing literature on carbon pricing and innovation does not use a quasi-experimental design because of the lack of a counterfactual. Through the deployment of the synthetic control method, comparative case studies, which were previously not feasible, it has now become possible at the country level. This method was introduced in 2003 and is regarded as one of the most significant innovations in policy evaluation (Abadie & Gardeazabal, 2003). More recent advancements (Abadie et al., 2010, 2014) allow it to be a powerful generalize of the DID approach (Cunningham, 2021). The gap between the scenario in which the government policy would not have been introduced and the current scenario, which is the introduction of the policy, can be estimated through the synthetic control method. The synthetic control method is increasingly used in academia and the industry, especially the tech industry, as it is easy to interpret and can deal with large-scale settings. Recently Andersson (2019) used the synthetic control method to determine the impact of carbon taxes and (VAT) on transport fuel on GHG emissions in Sweden.

Abadie (2021) argues that the synthetic control method poses advantages over common applied econometric regression-based methods. Abadie (2021) points out that a regression-based approach can be useful for studying the short-term effects of a policy introduction where it is estimated that the effect has a significant magnitude. Nevertheless, time-series techniques lose explanatory power for estimating medium and long-term effects due to the presence of confounding variables that pose a shock to the outcome of interest.

In conducting a DID regression, the researcher must make a parallel trends assumption before the intervention to control for selection effects by accounting for time-fixed and unit-fixed effects. In analyzing a policy for a specific country like Sweden, the synthetic control method has the advantage that no parallel trends assumption is needed. The underlying idea of the synthetic control method is to exploit the temporal variation in the data in contrast to the cross-sectional one. Abadie (2021) explores the technical advantages of the synthetic control method over regression-based methods in detail. His three main arguments are that no extrapolation is conducted, there is transparency to the fit, and transparency to the counterfactual.

Given the advantages the synthetic control method poses, I apply the synthetic control method to estimate the effect of the introduction of the carbon tax in Sweden in 1990 on clean technology innovation in the transport sector.

3.2. Formal Aspects of the Synthetic Control Method

I follow a similar approach to Abadie (2021) to construct synthetic Sweden. Abadie (2021) provides an exhaustive explanation of the formal aspects of the synthetic control method. In this section, I delineate the key aspects that are needed to understand how to synthetic control method works. Hence, I retrieved data for J+1 units: $\mathrm{j} = 1, 2, \ldots, \mathrm{J}J + 1$. My first unit, $\mathrm{j} = 1$, represents the treatment unit Sweden, which is affected by the carbon tax introduction. The other units represent the donor pool, $\mathrm{j} = 2, \ldots, \mathrm{J} + 1$, which are the units unaffected by the carbon tax. The entire data span, 1985 to 2018, are T periods. T_0 represents the periods before the intervention. For each time period, t, and unit, j, the outcome Y_{jt} is observed. For every unit, j, I have a set of k predictors of the outcome, $\mathrm{X}_{1\mathrm{j}}, \ldots, \mathrm{X}_{\mathrm{kj}}$. A common approach is to include the outcome variable itself as one of the predictors. I follow this approach and include the outcome variable in the set of k predictors. The outcome variable itself is not affected by the treatment before the intervention. For the treatment unit, $\mathrm{j} = 1$, during the period, $\mathrm{t} > \mathrm{T}_0, Y_{jt}^{I}$ denotes the outcome variable with the policy intervention. The outcome variable without the policy intervention is denoted as Y_{jt}^{N}. The effect of the policy intervention on the treatment unit in the period, $t > T_0$, is:

$$\tau_{1t} = Y_{jt}^{I} - Y_{jt}^{N} \tag{1}$$

The synthetic control unit is the weighted average of the units in the donor pool that most closely match the treatment unit. Hence, the synthetic control unit is a $J \times 1$ vector of the weights, $W = (w_2, \ldots, w_{J+1})'$. The synthetic control estimator of the outcome variable is:

$$\hat{Y}_{lt}^{N} = \sum_{j=2}^{J+1} w_j Y_{jt} \tag{2}$$

To avoid extrapolation, Abadie (2021) uses the approach to restrict the weights to be positive and the sum being one. Restricting the weights to be nonnegative has the advantage of not having to use regression-based methods to extrapolate. This makes the result more transparent and easier to interpret.

I follow Abadie and Gardezabal's (2003) and Abadie et al.'s (2010) proposal to choose the weights that result in the synthetic control unit being the closest resemblance to the pre-intervention values concerning the treated unit of predictors of the outcome variable. The $k \times 1$ vectors $X_1, \ldots, X_{J+1}$ represent the values of the predictors for the units $j = 1, \ldots, J+1$. The $k \times J$ matrix, $X_0 = [X_2 \cdots X_{J+1}]$, represents the values of predictors for the untreated units, J. Hence, I chose the weights such that equation 3 is minimized while the weights are non-negative and sum up to one.

$$\|X_1 - X_0 W\| \tag{3}$$

In simple terms, the resulting synthetic control unit is a weighted average of untreated units that minimize the difference to the control unit concerning key predictors of the outcome variable. W(V) are the weights that are assigned to the untreated units. W is a function $V = (v_1, \ldots, v_k)$, representing the vector of predictor weights of k predictors. To solve equation 3 and choose the optimal values of V, I again follow Abadie and Gardezabal's (2003) and Abadie et al.'s (2010) approach and choose V so that W(V) minimizes the mean squared prediction error (MSPE) of the synthetic control unit.

Finally, the estimated effect of the intervention for the treated unit in period $t = T_0 + 1, \ldots, T$ is defined as

$$\hat{\tau}_{1t} = Y_{1t} - \sum_{j=2}^{J+1} w_j * Y_{jt} \tag{4}$$

3.3. Data

I use patent data from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT) as a proxy of innovation. Using patent data allows me to conduct a detailed analysis of innovation activity induced by the policy intervention. While there is consensus in academic research that patent data is one of the best proxies to measure innovation, there are certain limitations. One limitation is that not all inventions are ultimately patented. Some inventions, which for example, may have a relatively sizeable environmental impact, do not have enough economic possibilities. Hence, those innovations may not justify the cost of patenting (OECD, 2009). According to Pavitt (1988), Strategic considerations may lead the inventor to keep the invention secret to receive an alternative form of protection, such as protection under a trade secret, which results in the patent not appearing in the patent data. Another limitation is that the value distribution of patents is highly skewed (Harhoff et al., 1999). Thus, the number of patents issued does not directly translate into the actual value of the underlying patent. Some patents have considerable economic importance for corporations, while others have limited economic value.

Moreover, there are differences in patent law and practices from country to country, which limits the comparability of patent statistics across countries to some extent. To overcome this issue, I chose to use homogeneous patent data originating from the largest patent offices, such as the EPO and Patent Cooperation Treaty (PCT), rather than smaller national patent offices. If an inventor, for instance, files an international patent application under the PCT, the applicant simultaneously receives protection for the invention in a large number of countries. Using data from these large patent offices controls home bias, which refers to inventors being more probable to file a patent application at their local patent offices. According to Frietsch and Schmoch (2009), the home bias can be overcome by only analyzing patent families with one or more multinational filing at the EPO or PCT. By only including patent applications filed to the EPO or PCT, I overcome the limitation that some patent applications have a higher worth than others. When applying for patent applications at the major patent offices, inventors must pay substantially higher fees than when applying to domestic offices. Hence, selecting only those applications filed at the EPO or PCT discards those with a low expected commercial value.

I am able to distinguish clean technologies by sector by using the Y02 classification system, which was created by the EPO, the International Centre on Trade and Sustainable Development (ICTSD), and the United Nations Environmental Program (UNEP). The Y02 classification system is considered the most accurate representation of patents relating to climate change mitigation technologies available today (Calel & Dechezleprêtre, 2016). Calel and Dechezleprêtre (2016) conclude that it is becoming the international standard for studies on clean innovation. The Y02 scheme is a cross-scheme that overcomes the bias of finding multidisciplinary patents when searching for patent publications using technology fields. The Y02 scheme allows for retrieving patents belonging to several Cooperative Patent Classification (CPC) technology fields (Angelucci et al., 2018). Hence, I focus my analysis on counting the annual Y02 patent frequency as a proxy for directed technological change toward clean technology.

I use the most recent version of PATSTAT, the 2022 version

(European Patent Office, 2022), and retrieved Y02T patents. Y02T patents are Y02 patents concerning the transportation sector. In my PATSTAT query, I joined multiple tables to extract a final data frame that contains the application id of each patent, the inventor's country code, the inpadoc family id[3], the Y02T subclass, and earliest filing date. To record the invention's date, I use the earliest patent application date as it has been shown that this date closest resembles the actual innovation activity. My timeframe concerns all patent applications from 1958 until 2018. As the EPO and PCT were initiated in 1978, data stretches back earliest to 1978. However, for my synthetic control method, I can only use Y02T data from 1985 onwards as the predictors I retrieve from the OECD statistics database only date back to the earliest 1985.

To measure innovation in the transport sector, I use a similar methodological approach as Moore et al. (2021). First, I exclude all Y02T subcategories concerning aeronautics or air transport (Y02T 50/00) and Maritime or waterways transport (Y02T 70/00). An overview of the remaining Y02T subclasses and their respective frequency can be found in Appendix 4. The final data frame I retrieved from PATSTAT concerns all patent applications worldwide for my timeframe and applications of interest. It consists out of 526,456 observations and the variables *appln_id*, *person_id*, *person_ctry_code*, *indpadoc_family_id*, *cpc_class_symbol*, *and earliest_filing_date*.

Instead of counting every application id, I count patent families according to the inpadoc family id. The number of patent families in Sweden translates to the actual count of new technologies invented rather than the number of patent applications. Patent applications can have strongly differing values and might represent rather incremental improvements in the same technology rather than actual innovation. According to Harhoff et al. (2003), the size of the patent family is a good proxy for the value of the underlying technological invention. Therefore, I group all the observations which belong to one Y02T subclass while taking the sum of the number of family applications to get the size of the patent family. Many patent families have multiple inventors, which may be from differing countries. Hence, I weigh the inventor's country location within each family and finally compute a matrix that contains the weighted number of Y02T family applications for each country in the donor pool per year. It is important to note that the inventor must not be a natural person, and the inventor often is represented as a company's office in a certain location. Therefore, the location used is either the natural person's country of residence or the location where the company conducted the research. Each column of this matrix represents my outcome variable for each country, which I use for the synthetic control method.

Figure 2 illustrates the development of the number of Y02T patent families annually for Sweden from 1978 until 2014.

The last step I conduct before I can use the data frame for the synthetic control method is that I exclude countries affected by a similar policy as the carbon tax. My initial set of EU ETS member states consists of the 27 EU countries plus Iceland, Liechtenstein, and Norway. First, I exclude those countries that introduced a carbon tax: Denmark, Estonia, Finland, France, Iceland, Ireland, Latvia, Liechtenstein, Netherlands, Norway, Portugal, Slovenia, and Spain. Second, I exclude Germany and Italy because these countries implemented changes to their fuel tax. Albeit the United Kingdom currently is not a member state of the EU ETS, it was so during my period analyzed. I also exclude the United Kingdom as it also implemented a change to the fuel tax. Hence, my final dataset representing the donor countries consists of the 14 countries: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Greece, Hungary, Lithuania, Luxembourg, Malta, Poland, Romania, and Slovakia.

To predict my outcome variable, Y02T patents, I use the predictors listed in Table 1.

Total climate change mitigation patents refer to the total fraction of climate change mitigation-related patents by the investor's country of residence. This variable includes patents from every sector of the economy. Total triadic patents are those filed at every one of the three largest patent offices, namely the USPTO, JPO, and EPO. Transport (WIPO) IP5 patents are defined as patent families concerning transportation by the Word Intellectual Property Office (WIPO). They are filed in at least 2 of the five largest intellectual property offices. The five largest are the EPO, JPO, the Korean Intellectual Property Office (KIPO), the USPTO, and the State Intellectual Property Office of the People's Republic of China (CNIPA). The B60 patent class is defined by the WIPO and is similar to the transport (WIPO) predictor but refers to those patents that concern all vehicles except rail, maritime aircraft, or space-related vehicles. I include those B60 patents that are filed at the EPO. Including predictors that refer to patent applications at all three, at least two of the three, and only one of the three, I create robustness against possible selection bias.

The predictors total climate change mitigation patents, climate transport EPO, and Transport (WIPO) IP5 patent family measure how much knowledge a country has concerning climate change mitigation technologies and automobile-specific technologies (OECD, 2018a). Total climate change mitigation patents are those filed at the EPO; climate transport EPO are those patents that concern climate mitigation technology in the entire transport sector filed at the EPO. The larger the value of accumulated knowledge, the lower the cost to innovate in the same domain in the future. Hence, countries that invented clean technologies in the past will likely continue to do so in the future. The total triadic patent variable serves as a proxy of the country's innovative capacity. I follow Abadie's (2021) logic and include the outcome variable as a predictor variable, as this usually increases the model's predictive power.

Similar to Raghupathi and Raghupathi (2017), I include GDP and enrollment in tertiary education as economic in-

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[3] The inpadoc family id concerns all patent application documents covering a certain technology (European Patent Office, 2022)

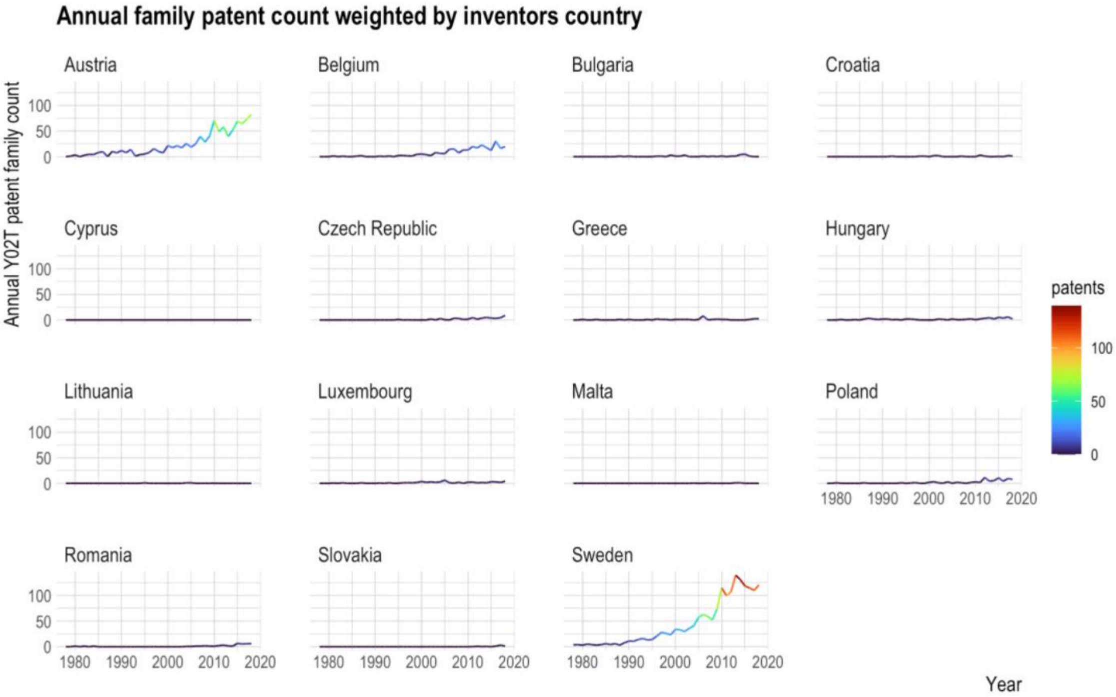

Figure 2: Trend Y02T patents by country from 1978 until 2018 (European Patent Office, 2022)

Table 1: Predictors of YO2T patents

Predictor	Source
Total climate change mitigation patents	OECD Statistics
Total triadic patents	OECD Statistics
Transport (WIPO) IP5 patent family	OECD Statistics
Y02T patents	PATSTAT
Climate transport EPO	OECD Statistics
B60 (WIPO) patents	OECD Statistics
GDP	Penn World Table
Enrollment in tertiary education	The World Bank

dicators to predict country-level innovation. GDP is stated as expenditure-side real GDP at chained PPP in millions of USD, with 2017 as the base year (Penn World Table, 2021). Enrollment in tertiary education is measured as the gross enrollment ratio in tertiary education of both sexes regardless of age (World Bank, 2016).

Y02T patents are those patents that concern climate mitigation technology in transportation. According to Abadie (2021), it is common to include the outcome variables as one of the predictors as this improves model results. This does not introduce a bias. The exact methodology behind Y02T patents is described in Chapter 3.1.

4. Results: A Large Gap between Sweden and Synthetic Sweden

In this section, I first present my findings concerning the analysis on the effect of the introduction of the carbon tax in 1990 on clean innovation in the transport sector in Sweden. Next, I conduct tests to verify that my results are not driven by chance.

4.1. Results of the Synthetic Control Method

Implementing a simple DiD regression for the data analyzed is unfeasible. In the case of a DiD regression, a bias is introduced as the parallel trends assumption is violated. Appendix 5 plots the development in Y02T patent families per year for Sweden and the mean of the donor pool countries. Panel (A) shows the years 1985 until 2018, while panel (B) zooms into the timeframe 1985 until 1995. Appendix 5 suggests that the equally weighted donor pool is unsuitable as a comparison group for Sweden to study the effect of the carbon tax on Y02T patents. In panel (B), the graph shows that the time series of Y02T patents in Sweden and the donor pool differs notably. There is no parallel trend. Hence, the implementation of a standard DiD model would be biased.

For the synthetic control method, no parallel trends assumption is needed. The central question to assess the effect of the introduction of the carbon tax in 1990 on Y02T patents in Sweden is how the Y02T patent trajectory would have developed after 1990 without the introduction of the carbon tax. As explained in chapter 3.2, I construct synthetic Sweden as the convex combination of countries in the donor pool, which are the closest resemblance of Sweden concerning the pre-policy values of Y02T predictors.

Table 2 shows the predictors included in the analysis and their respective weights assigned, which sum up to one. To test whether the result is robust when certain weights are not included in the analysis, I ran the entire synthetic control method multiple times, leaving the predictors out every time. The weights assigned to the countries constructing synthetic Sweden in the leave-one-out test remain unchanged. This indicates that predictors are similar as they predict the same countries to be chosen when creating synthetic Sweden. Including all of the predictors, triadic patent families and GDP receive the largest weights. The model computes that these predictors are best suited to minimize the mean squared prediction error (MSPE) of the synthetic control unit.

Table 3 provides a comparison between the mean values of Y02T predictors of Sweden, synthetic Sweden, and the donor pool mean. The values reported concern only the pretreatment period from 1985 to 1989. Comparing the values between the three groups, the assumption that the mean of the donor pool itself is not well suited as a control group is corroborated. The mean values of the donor pool are significantly lower than those of Sweden. Although the values of synthetic Sweden are still lower than the ones of real Sweden, they are substantially higher and a much better approximation of actual Sweden during the pre-treatment period.

Appendix 6 displays the weights for each country in the donor pool. The outcome of the synthetic control model indicates that Y02T patents in Sweden pre-intervention can be most closely reproduced by a weighted combination of 63.8% Austria and 36.2% Belgium. All the other states are assigned a weight of 0%. As can be seen in Figure 2, the other countries in the donor pool, next to Austria and Belgium, have substantially fewer Y02T patents than Sweden. Similarly, the patent predictors during the pre-treatment period also have substantially lower values for the other countries next to Austria and Belgium. Hence, those countries are assigned zero percentage weights in the estimation of synthetic Sweden. According to the Bureau of Transport Statistics (2022), Sweden's annual number of vehicles produced is similar to that of Belgium and Austria, with 258, 224, and 125 thousand vehicles, respectively. Surprisingly, Slovakia and the Czech Republic have even larger vehicle exports, with over one million vehicles annually, but show fewer Y02T patent applications than Austria or Belgium. One possible explanation is that the innovation infrastructure in those countries is less established than in Austria or Belgium. Enrollment in tertiary education, one of my predictor variables for Y02T patents, is more than three times larger for Austria and Belgium than for Slovakia or the Czech Republic.

Appendix 7 shows the Y02T family patents trend from 1985 until 1995. During the pre-treatment period from 1985 until 1989, we can see that the trend of Y02T family patents of Sweden and synthetic Sweden is a better match than in Appendix 5, panel (B).

Figure 3 panel (A) plots the Y02T patent families for Sweden and its synthetic counterpart for the entire period analyzed. In panel (A), we can see that a large gap between Sweden and synthetic Sweden started to emerge around 1990. This explicit difference between the treated variable and the control group is plotted in panel (B). The estimate of the effect of the introduction of the carbon tax on innovation in clean transportation, Y02T patent families, in Sweden is the gap between Y02T patent families in Sweden and its synthetic counterpart after the introduction of the carbon tax. The strong positive trend of the gap in panel (B) suggests that the positive effect introduction of the carbon tax in 1990 on Y02T patents has a large magnitude. The results of the synthetic control method indicate that for the entire 1985-2018 period, Y02T patent family applications per year increased by 35.853 patents on average per year. The value of 35.853 is calculated by taking the mean of all the gap values from 1990 until 2018. Compared to the synthetic control group, I estimate that Sweden has 2.555 times more patents from 1990 until 2018. However, the estimated result overstates the actual effect of the carbon tax introduction on clean technology patents because in 1990, Sweden also broadened the coverage of its existing VAT, levied at 25%, to include transport fuels (Andersson, 2019). Andersson (2019) and Moore et al. (2021) disentangle the effect of the carbon tax and the VAT on the price elasticities of gasoline demand. Andersson (2019) uses a time-series analysis concerning the tax-exclusive price of gasoline, which refers to the gas price subtracted by the carbon tax on consumption. Moore et al. (2021) also use a time-series analysis and estimate the effect of the different fuel price components on clean patents. They both find that the effect of the carbon tax is larger than the effect of the VAT. More specifically, Moore et al. (2021) estimate that the effect of the carbon tax is double as large as that of the carbon-tax exclusive gasoline price. Therefore, the effect of the carbon tax is larger than that of the VAT on innovation in clean technology. Due to data availability concerning historical data on the gasoline and VAT price in Sweden, I cannot conduct such a time-series analysis. Nevertheless, Andersson's (2019) and Moore et al.'s (2021) findings on VAT will likely hold for my period analyzed.

My estimated result of the effect of the introduction of the carbon tax is significantly larger than Moore et al.'s (2021) analysis. Moore et al. (2021) estimate an average increase of 7.37 per year. However, they investigate the effect of introducing the carbon tax in Sweden on Y02T patents from 1990 until 1999. According to Figure 3, the patent frequency increased substantially after 1999, which certainly is one reason my estimation is larger.

Table 2: Y02T patent predictors and their weights

Predictor	Weight
Total triadic patents	0.361
GDP	0.321
Total climate change mitigation patents	0.186
Climate transport EPO	0.048
Enrollment in tertiary education	0.04
Y02T patents	0.036
Transport (WIPO) IP5 patent family	0.008
B60 (WIPO) patents	0.001

Table 3: Mean values of Y02T patent predictors

Predictors	Sweden	Synthetic Sweden	Donor Pool Mean
Transport (WIPO) IP5 patent family	57.705	26.702	4.153
Total triadic patents	422.515	188.038	31.896
Y02T patents	6.250	5.205	0.792
Total climate change mitigation patents	33.257	31.487	4.690
Climate transport EPO	6	5.283	0.830
Enrollment in tertiary education	30.368	30.717	17.494
GDP	239, 209.000	202, 904.200	134, 954.100
B60 (WIPO) patents	27.519	14.498	2.365

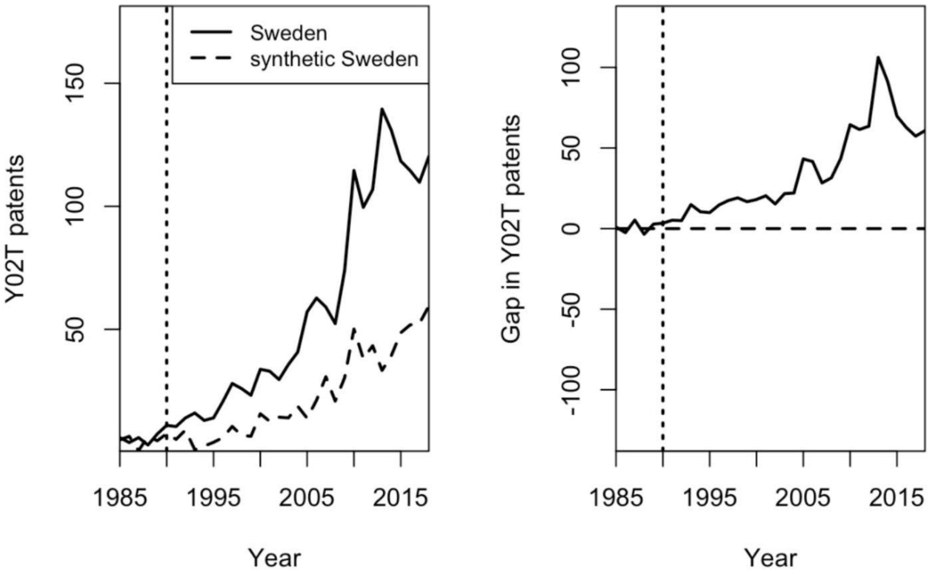

Figure 3: Trends and gap in Y02T patents: Sweden vs. synthetic Sweden

4.2. Inferences: The Result is Not Driven by Change

According to Abadie et al. (2010), the statistical significance of the estimates presented in the previous chapter is to be evaluated by answering whether the outcome might be driven by chance. I answer the question: How often would I obtain an outcome of at least the same magnitude if I had chosen another country in my donor pool instead of Sweden? I use the same methodology as Bertrand et al. (2004), Abadie and Gardeazabal (2003), and Abadie et al. (2010) by running placebo tests. I apply the same synthetic control algorithm to countries in the donor pool. Those countries did not implement a carbon tax during the period analyzed (1985-2018). If the placebo tests show that the gap estimated for Sweden is extraordinarily large, I interpret the the analysis provides significant evidence that the introduction of the carbon tax has a positive effect on Y02T patent applications in Sweden. However, if the placebo runs create similar gaps to the one observed for Sweden, I cannot conclude that my analysis provides significant evidence.

According to Lehmann and Romano (2005), running placebo tests is analogous to conducting permutation tests in which the distribution of the test statistic is modeled by random permutations. Here the sample unit is assigned to the treatment and untreated groups.

I run placebo tests by applying the synthetic control method iteratively to the countries in the donor pool. This allows me to assess the significance of my estimates. In every interaction in the loop, I reassign the introduction of the carbon tax to one of the 14 countries in the donor pool and estimate the effect associated with the respective iteration. My result is a plot that shows me the trajectories of estimated gaps for the countries in which no carbon tax was introduced in reality.

Figure 4 shows the outcomes of the placebo test. The black line shows the estimated gap for Sweden, while the gray lines show the gap for each country in the donor pool and their created synthetic control group. It can be seen that the estimated gap for Sweden from 1990 until 2018 is large compared to the distribution of the gaps of the countries in the donor pool. Moreover, it is shown that the Y02T family patents for the period 1985 until 1990 can be well-reproduced for the other country by the convex combination. Placebo tests with a dissimilar fit prior to the policy intervention do not contribute to understanding the relative rarity of estimating a sizeable gap after the intervention for a country that actually had a good fit pre-intervention. One approach is to recreate Figure 4 by continually lowering the MSPE limit. By default, the MSPE limit is set to 20. Hence, only countries with a MSPE for the pre-treatment period of maximally 20 times larger than the treatment country are included. Abadie et al. (2010), for instance, lower the threshold until a value of 2 times the MSPE of the treatment country. In their case, some of the units investigated have very large MSPEs of over 1000, which create noise in the plot. In my analysis, I do not have countries with such a large MSPE. Therefore, only a slight visual difference can be seen when the MSPE limit is lowered. Lowering the MSPE limit to 5 results in the upper grey line disappearing in Figure 4. Further lowering the MSPE limit does not result in further changes.

Another popular method to evaluate the rarity of the gap analyzed for the treatment country compared to the countries in the donor pool is to look at the distribution of the pre-treatment MSPE ratio. A high ratio is desirable as it indicates a relatively small pre-treatment prediction error, indicating a good synthetic control, and a high post-treatment MSPE, indicating a large gap between the treated unit and its synthetic control after the treatment. However, as some countries in the donor pool do not have any Y02T patents during the pre-treatment period, the MSPE ratio test is biased. For example, Romania has not had Y02T patents during the pre-treatment period. Running the placebo for Romania, its synthetic control group is formed by the Czech Republic and Slovakia. Like Romania, The Czech Republic and Slovakia both had no Y02T patents during the pre-treatment period. The MSPE is very low for Romania during the pre-treatment period because synthetic Romania almost perfectly matches Romania. The distribution of the pre-treatment MSPE ratio is non-informative if countries with zero values during the pre-treatment period are present.

I bootstrap the synthetic control by drawing sub-samples from the donor pool. I conduct this 500 times to get the average placebo treatment effects distribution. I plot the distribution of the actual average treatment effect on the treated (ATT) with a dashed vertical line. The result of this bootstrapping is shown in Appendix 8. The distribution of the actual ATT is on the right and far away from most of the placebo ATTs, indicating that the outcome is substantially different from the placebo ATTs.

5. Discussion and Limitations

In this chapter, the results of my analysis are critically evaluated and scrutinized. Furthermore, I contextualize my results in the literature reviewed and present future research opportunities.

The results of my analysis on the effect of the introduction of the carbon tax in Sweden in 1990 on clean innovation have an economically relevant magnitude and are significant. My result is that there are 35.853 more clean transportation patents per year in Sweden than in a hypothetical scenario in which no carbon tax has been introduced. My findings align with those of Moore et al. (2021), who analyze the introduction of the carbon tax in Sweden on clean patents from 1990 until 1999. Similarly to my findings, they record a positive increase in clean patent frequency due to the introduction of the carbon tax. They find an average increase of 7.37 per year. As mentioned in chapter 4, my finding likely has a larger magnitude because the patent frequency of countries such as Austria, Belgium, and Sweden increased substantially after 1999. Moore et al. (2021) use a donor pool comprising 15 selected OECD countries, of which Belgium, France, Spain, and the United States receive a weight. Presumably, OECD countries were used for the donor pool because of high data availability. However, some OECD countries might be less than ideal to include in the donor pool when creating the counterfactual. OECD countries such as the United States or Japan are geographically distant, have a substantially larger population, and a history of filing the largest amount of patents at the main patent offices in the world (WIPO, 2022). The absolute number of patents issued by the United States or Japan is more than ten times larger than that of Sweden. While this might not have significantly impacted Moore et al. (2021) analysis, as it only reaches until 1999, it most certainly introduced a bias when conducting the analysis during a more recent period. If one chooses to include the United States or Japan in the analysis, one should find a suitable method to control for the significant innovative infrastructure that exists in those countries. Furthermore, Lee et al. (2011) find evidence that the United States auto industry had a strong innovation response to the United States performance-based technology-forcing

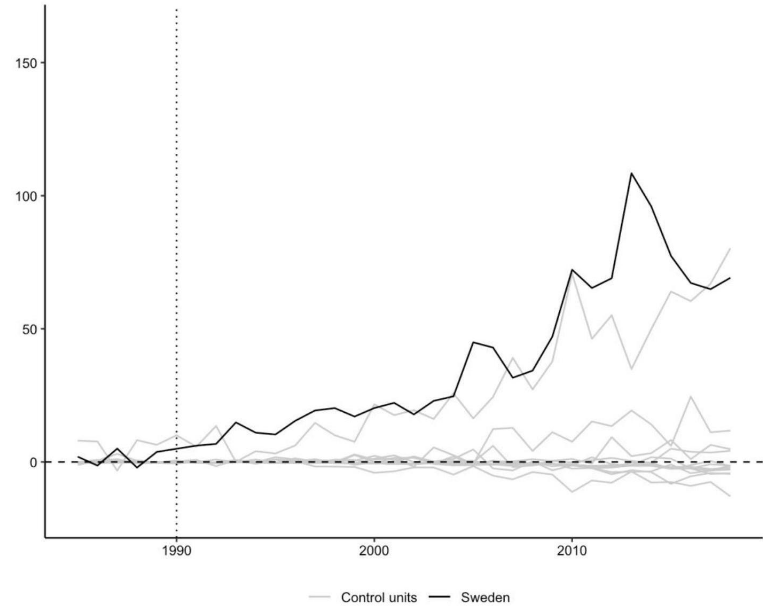

Figure 4: Difference between actual and synthetic countries (gaps) for Sweden (black) and control countries (grey)

command-and-control regulation between 1970 and 1998. This policy is not accounted for in Moore et al.'s (2021) analysis, although it influenced the patent frequency for the United States, one of the countries which constitutes a part of their synthetic Sweden.

Calel and Dechezleprêtre (2016), who investigate the effect of the EU ETS on low-carbon innovation, also find that the policy intervention increased low-carbon innovation among regulated companies compared to non-regulated ones.

As the preferred method of analysis, I choose the synthetic control method. The synthetic control method is especially well suited as I have only one treatment unit and aggregate data. In this case, the synthetic control method provides advantages over the DiD estimator. First, by implementing the synthetic control method, I can relax the parallel trends assumption of the DiD estimator by permitting the effects of potential confounding variables to change over time (Abadie et al., 2010). Second, I use predictors of Y02T patents to create a synthetic Sweden out of countries from the donor pool. The addition of the covariates total climate change mitigation-related patents, total triadic patents, transport IP5 patents, climate transport patents filed at the EPO, B60 patents, GDP, or ratio of people enrolled in tertiary education is not possible when using the DiD regression. These covariates are likely affected by the carbon tax implementation or are outcome variables themselves. Hence, they are considered suboptimal controls for the DiD regression. In the synthetic control method, I use the predictors to produce synthetic Sweden without creating a confounding effect during the post-treatment period (Andersson, 2019). Third, according to Card (1990) and Lin and Li (2011), the ambiguity when choosing comparison units is reduced as the synthetic control method chooses them through a data-driven method while they have to be chosen manually in the construction of the DiD method.

Although the relationship between the carbon tax price and patents is not the focus of my research, I analyze whether a larger carbon tax has a more significant impact on patents than a smaller one. To this end, I conduct a simple OLS regression with the annual Y02T patent count as my dependent variable and the carbon tax price as my independent variable. The regression is conducted during the period 1990 to 2018 and is specified as follows:

$$Y02T_t = \beta_1 * x + \varepsilon_t \tag{5}$$

Appendix 9 presents the regression results from estimating equation 5. The dependent variable, Y02Tt, depicts Sweden's absolute annual number of Y02T patents, and the independent variable represents the yearly carbon tax rate. The result is a slope on Y02T patents of .715 (Std. Error = .067), indicating that there are, on average, .715 Y02T patents more per year in Sweden for a one unit increase in the carbon tax, ceteris paribus. To assess whether the OLS assumptions are met, I assess whether nonlinearity is present with a residual plot in Appendix 10. Appendix 10 (left) shows that the relationship between the carbon tax price and the Y02T patents is linear. Appendix 10 (right) affirms this by plotting the residual with the geometric smooth fitting function using the loess method. Appendix 12 plots the residuals against the normal distribution and presents that the gaussianity assumption holds. The diagnostics plot in Appendix 12 shows that heteroscedasticity is not present. Hence, the i.i.d. assumption of the errors is not violated.

To assess whether my findings may apply to the transport sector in other countries, I carefully examine Sweden's political and social characteristics and determine how they might differ from those of other countries.

Although Sweden is among the smaller-sized countries within the EU, it has often formed coalitions with other countries such as Austria, Belgium, Denmark, Finland, Luxembourg, and the Netherlands to support aggressive climate actions at the EU level (Schreurs & Tiberghien, 2007). Moreover, Sweden has been recognized as the country in the EU that has engaged in the largest number of climate policy initiatives (Burck et al., 2006). Sweden has been able to construct and implement environmental policies designed to be effective throughout the course of decades. 'New politics', a social and political movement concerning, inter alia, environmental pollution, strongly influenced Swedish politics in the 1970s and 1980s. In Sweden, this new social movement is characterized as being especially pragmatic and consensus-oriented, whereas in Germany student movements such as the Außerparlamentarische Opposition were opposed to the state and other larger institutions. While 'new politics' in most EU countries rarely got their voices heard politically, the movement got political attention in Sweden. It was even allowed to participate in the design of energy politics (Jahn, 1993).

Furthermore, Sweden's stable political system, which was represented by the Social Democratic Party (SAP), the Moderate Party (M), and the Left Party (V) since the 1920 s, created credibility, showed political commitment, and created a good government reputation (Jahn, 1993). Policies originating from a government that consistently acts in a credible manner have especially strong thrust as firms realize that policies are meant to stay. Thus, firms are able to make the necessary long-term strategic investments to respond accordingly (Brunner et al., 2012). However, it must be noted that political stability has decreased in recent years as the right-wing populist party Sweden Democrats (SD) managed to get a significant number of seats in the Swedish Riksdag (Jylhä et al., 2019).

According to G. Hofstede and Bond (1984), a country's culture can be described by a model assessing the characteristics: Power Distance, Individualism-Collectivism, Masculinity-Femininity, Uncertainty Avoidance, Long-Term Orientation, and Indulgence on a scale from 0-100. Shane (1995) shows that national differences concerning the ability to innovate do not only result from economic factors such as the industry structure, infrastructure, or societal welfare but also from cultural values people hold. Shane (1995) points out that uncertainty-accepting societies are more innovative than uncertainty-avoiding societies because roles such as transformational leaders have greater legitimacy. In Hofstede et al.'s (1984) model Sweden, Denmark, the Netherlands, and Finland score especially low on uncertainty avoidance (Hofstede, 2017). Simultaneously, these countries have especially high research systems, R&D expenditure, venture capital financing, public-private collaborations, and patent applications (Serafeim, 2015).

The social and political considerations show that Sweden indeed occupies a unique position as it scores low on uncertainty avoidance, green social movements influence politics, and the political system possesses sufficient stability to allow companies to respond adequately to climate policies. Therefore, introducing a carbon tax in other countries in the EU will likely not have as large of a positive effect on clean innovation. Nevertheless, as countries in the EU must follow the ESR, there is a new urgency to implement effective climate policy. This might help overcome obstacles such as high uncertainty avoidance. Moreover, environmental citizenship, which entails the right to participate in creating environmental policies, increasingly gains support through climate youth movements around Europe, such as Friday's for future (Wahlström et al., 2019).

The result found for the transport sector is to be compared to other sectors of the economy under careful consideration of the following factors. First, the transport sector in Sweden is of high materiality as it is an important constituent of the economy and a large employer (OEC, 2022). Other sectors which are of less economic importance might exhibit less public-private cooperation and, subsequently, less patent applications. Second, internationalized firms, which are present in the transport sector, file more patents than companies with less international presence. Internationalized firms see patents as a strategic protection against imitation (Neuhäusler, 2012). Third, infrastructure sectors like energy, sanitation, transportation, or water supply differ from other sectors in terms of significant degrees of capital intensity, sector-specific regulation, and long-lived assets. These characteristics create barriers to change and often result in path-dependent, incremental improvements rather than disruptive innovation. Hence, when applied to sectors that score low on the before mentioned characteristics, the carbon tax might have a more considerable impact on innovation than on the transport sector, which is considered to possess the aforementioned barriers to change (Markard, 2011). Summarizing, one might compare the result found to other sectors but most always contextualize the results and estimate the effect of innovation-inducing and inhibiting factors.

One limitation of my study is that the pre-treatment period only stretches from 1985 until 1989. Therefore, it cannot be verified over a prolonged period whether Sweden and synthetic Sweden follow the same trend pre-treatment. A more extended pre-treatment period might allow for even more precise construction of synthetic Sweden as the model can use a longer time series to create synthetic Sweden. Since I use OECD data for most of my predictor variables, which dates back to 1985 earliest, I cannot construct a larger pre-treatment period. The availability of a dataset dating back five to ten years might help construct an even closer matching synthetic Sweden.

One possible confounding factor might be that those companies impacted by the carbon tax might not innovate themselves but procure clean technology from a third party. This might bias my results because I measure innovation based on the investor's country of residence. While it is challenging to compute the extract effect this confounding variable might have, Fischer et al. (2003) and Milliman and Prince (1989) estimate that developing proprietary technology is often of strategic advantage to companies compared to purchasing it from others.

Another caveat of my study is that I can only analyze patent data from PATSTAT until 2018. Patent applications are continuously filled to the large patent offices but only gradually uploaded to the PATSTAT database. Therefore, not every patent has been uploaded for the most recent years.

6. Conclusion and Opportunities for Future Research

This paper empirically shows that a carbon tax policy can successfully drive clean innovation. Clean innovation is important for long-term GHG emission reduction. Therefore, a carbon tax is an important tool to achieve the target under the Paris Climate Agreement to limit GHG emissions to well below 2°C compared to pre-industrial levels. In my empirical ex-post analysis, I find that after Sweden implemented a carbon tax and VAT on transport fuels, clean patents in the transportation sector increased by an average of 35.853 patent annually, compared to a scenario without a carbon tax, from 1990 until 2018. In my analysis, I do not disentangle the effect of the VAT due to data availability. However, Andersson's (2019) and Moore et al.'s (2021) studies indicate that the effect of the carbon tax on innovation is significantly stronger than that of the VAT. Although the exact magnitude of my finding is not directly generalizable to other countries or periods, my analysis shows that introducing a carbon tax can significantly affect clean innovation. As only a small number of predominantly Nordic countries have introduced a carbon tax at a meaningful rate, it is now at the time that other European governments as well consider implementing a carbon tax. This would allow them to achieve innovation and subsequently lower GHG emissions in the long run for those sectors that the EU ETS does not cover. My result is in line with Andersson's (2019) and Moore et al.'s (2021) findings, as they also find a positive and economically significant effect. I find a larger magnitude in my study, which is likely the case as I investigate a more recent period in which patent frequency has increased.

In my identification strategy, I carefully construct synthetic Sweden out of a donor pool of countries that did not implement a carbon tax or comparable policies. I show that my synthetic Sweden is a better counterfactual than the average of the donor pool countries during the pre-treatment period. Synthetic Sweden reproduces actual Sweden based on a set of predictors of Y02T patents. The results I obtain are robust, which I show through placebo tests and bootstrapping. Opportunities for future research are especially present concerning the moderating effect of clean innovation on GHG emissions. While there are numerous studies on the effect of carbon pricing on GHG emissions and the effect on innovation now has been estimated it is to be determined how strong the moderating effect of innovation on GHG emission is.

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