Andreas Myklebust Moksnes

Promoting renewable energy

The effects of cap-and-trade and feed-in tariffs on renewable electricity output, 1990-2012

Master's thesis in Political Science
Supervisor: Espen Moe & Simen Rostad Sæther
June 2019

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Abstract

One of the most reliable ways to achieve the goals of the Paris climate agreement is massive adoption of renewable energy. However, scholars disagree about the most effective ways to promote renewables. Some argue that a price on carbon provides incentives to invest in low-carbon technologies in a cost-efficient way, while others suggest that technology policies are needed to drive innovation and diffusion of new technologies. Previous empirical studies often do not account for policy stringency and have largely overlooked the effect of emissions trading policies. In this paper, I examine the effectiveness of two policy instruments that exemplify the opposing schools of thought, namely cap-and-trade schemes and feed-in tariffs. I study the effect of policy stringency on renewable electricity output in 33 developed and emerging economies between 1990 and 2012. The analysis shows that both policies promote higher shares of renewable electricity, but feed-in tariffs are only effective when they are directed at solar energy. These results are robust to several different specifications. I argue that proponents of renewable energy should not pin their hopes on one policy approach to fix the climate problem but rather seek to find the optimal policy mix that can boost the development of renewable energy in time to prevent catastrophic climate change.

Sammendrag

En av de sikreste måtene å oppnå målene i Parisavtalen er massiv utbygging av fornybar energi, men ekspertene er uenige om hva som er den mest effektive måten å få dette til å skje. Noen hevder at en pris på karbonutslipp er en kostnadseffektiv politikk som gir insentiver til å investere i ny energiteknologi, mens andre mener at teknologipolitikk er nødvendig for å skape innovasjon og diffusjon av nye teknologier. Tidligere empiriske studier av dette temaet har både oversett betydningen av hvor streng politikken er og sammenhengen mellom kvotesystemer og fornybarutbygging. I denne oppgaven undersøker jeg effekten av to politiske tiltak fra de ulike perspektivene, nemlig kvotesystemer og innmatingstariffer. Jeg tester betydningen av streng politikk for produksjon av elektrisitet fra fornybare kilder i 33 utviklede og framvoksende økonomier mellom 1990 og 2012. Analysen viser at begge tiltak fører til høyere andeler fornybar energi, men innmatingstariffer er kun effektive når de er rettet mot solenergi. Resultatene er robuste mot ulike spesifikasjoner. Basert på analysen tar jeg til orde for at tilhengere av fornybar energi ikke bør ha forhåpninger om at én type politikk kan løse klimaproblemet, men heller forsøke å finne den optimale kombinasjonen av tiltak som kan akselerere utviklingen av fornybart raskt nok til å unngå katastrofale klimaendringer.

Acknowledgements

When I began working on this thesis in the autumn of 2018, I had a very limited knowledge of the research field of climate policy. In the time that has passed since then I have learned a great deal about the subject, and my writing skills have improved significantly on the way. The process of finishing this thesis has been very challenging but also very rewarding, and I am indebted to many people for their contributions and support.

First, I am deeply grateful to my supervisor Espen Moe for his guidance and especially for helping me narrow down my research question and pointing out inconsistencies in the text. His critical eye has made the thesis much more focused and theoretically relevant than it would otherwise have been.

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Finally, I want to thank my parents for always encouraging me to work hard at my studies; my friends at the master's program for helpful discussions and motivation; and Maria for being patient with me when I am pondering how to save the world from climate catastrophe.

Remaining errors are my own.

Oslo, 30.06.19
Andreas Myklebust Moksnes

Table of contents

List of figures

List of tables

1. Introduction

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) released a report that laid out the steps that must be taken in order to keep global warming below 1.5 degrees Celsius (IPCC, 2018). It showed that global greenhouse gas (GHG) emissions must decline to about half their current levels by 2030 and reach net zero by 2050. These are ambitious targets, and they appear even harder to achieve since new research has shown that global emissions likely *increased* by about 2.7 percent in 2018 (Le Quéré et al., 2018). Furthermore, the global population is growing and many expect energy demand to increase in coming years. Clearly, preventing the climate crisis will be a tremendous challenge.

Renewable energy (RE) is an essential part of the solution to this challenge. The energy sector is the biggest source of GHG emissions in the world (Ram et al., 2019). A recent international study shows that several countries managed to reduce emission levels in the last decade largely by replacing fossil fuels with renewables (Le Quéré et al., 2019). However, there are large differences in shares of renewables and growth rates between countries (Reboredo, 2015). There is a growing body of literature on the impacts of various climate policy instruments, but experts continue to disagree about which policies help us shift to clean energy[1] most efficiently. As the IPCC report makes clear, we are in a hurry to solve climate change. It is therefore hugely important that policy makers make the right choices going forward. Thus, we need more research on impacts of policies to promote renewable energy.

The purpose of this study is to examine the effect of two of the most widely used tools in the climate policy toolkit, cap-and-trade systems and feed-in tariffs, on electricity production from renewable sources other than hydropower. These policies represent two different perspectives on the problem of climate change. Whereas cap-and-trade systems aim to reduce the use of fossil fuels by putting a price on emissions, feed-in tariffs are technology policies that have been implemented to make renewables cost-competitive with coal, oil and gas. In the broader sense, I examine the performance of carbon pricing against direct support for technological innovation. At the same time, I evaluate the success of the climate policy approaches that have been the most popular globally until now. Specifically, I study policy stringency: higher carbon prices and higher tariff levels should be associated with higher RE

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[1] I use the terms *renewable energy* and *clean energy* interchangeably.

production. The research question is as follows: *Have cap-and-trade systems or feed-in tariffs led to higher shares of renewable electricity output?*

The study adds to the existing literature in several important ways. First, no author to my knowledge has tested the effects of cap-and-trade schemes and feed-in tariffs on renewable energy generation in the same empirical analysis. Since these are perhaps the two most popular climate policy instruments globally, the results of this analysis are an indication of whether we are currently doing the right things to prevent dangerous climate change. Second, most previous studies of renewable energy adoption do not take into account policy stringency. Since policy instruments often have different designs across countries and relative price and tariff levels can have a big impact on RE output, I use independent variables that show the relative stringency of policies. This way I can demonstrate if increases in emission trading prices or feed-in tariffs result in a higher share of renewable electricity generation. Finally, I specify my models more strictly than those used in previous similar studies. By taking into account such issues as non-stationarity, I obtain results that are robust to many typical challenges in panel data regression analysis.

I examine the research question using a panel of 33 countries between 1990 and 2012. The lack of data for the critical years after 2012 is a limitation since technologies such as solar and wind energy have experienced massive cost reductions. This makes projections to the future difficult, so the analysis is primarily about the success of policies in the past. The dataset covers the majority of global carbon emissions since it includes both industrialized nations and emerging economies. I focus on electricity production because of limitations to energy system data and because that is where renewables have had the highest penetration rate and will continue to grow with increasing electrification in the next decades. I use the fixed effects estimator to avoid bias from spurious relationships. Based on the theoretical and empirical literature I expect feed-in tariffs to effectively promote RE generation and cap-and-trade to have no effect.

My main finding is that the nations of the world actually appear to be doing the right things. Both for cap-and-trade and feed-in tariffs, increased policy stringency is associated with higher shares of renewable electricity production in this sample. However, feed-in tariffs are only effective when they are directed towards solar energy. Aggregate feed-in tariff levels and support for wind energy has no effect or is negatively associated with renewables in the models. The main conclusions for cap-and-trade and solar energy tariffs, on the other hand, are robust towards a range of alternative specifications. The results suggest that a combination of carbon pricing and technology policy is needed to decarbonize the whole electricity system. Based on the analysis, I recommend that policymakers continue with current policies but ramp up their efforts in order to effectively boost renewable energy and combat climate change.

The structure of the paper is as follows: In section 2, I first describe the status of and barriers to renewable energy adoption. Next, I present two opposing theoretical perspectives on the climate challenge and the policies needed to promote renewable energy. The first is market-based policies and specifically cap-and-trade schemes. The second is technology policies and specifically feed-in tariffs. In section 3, I briefly review previous empirical studies on the subject and present two hypotheses to be tested. Section 4 is a detailed overview of data and methodology. I start by describing the variables I have used and then account for the choice of model specification. Next, I display the results of the analysis in section 5. I include five models in the text, but I also show that the results are quite robust to a series of alternative specifications. In section 6, I discuss the results in light of the theoretical and empirical expectations. Section 7 concludes the paper.

2. Theory

2.1 Promoting renewable energy

2.1.1 Outlooks for the global energy market

According to the Renewable Energy Policy Network for the 21st Century (REN21), there are two ways to describe the current status of renewable energy: "one in which a revolution in the power sector is driving rapid change towards a renewable energy future, and another in which the overall transition is not advancing with the speed needed" (REN21, 2018, p. 15). On the positive side, the world's countries added more renewable energy capacity than ever before in 2017. Developed countries and emerging economies were responsible for the biggest share of investments, but developing countries are also beginning to adopt more clean energy. The groundbreaking rise in renewable energy adoption has taken most experts by surprise. It is happening because the costs of renewable energy have come down massively in the last decades. A new report from the International Renewable Energy Agency (IRENA) shows that wind and solar energy is now the cheapest source of electricity in most places around the world, even without financial assistance (IRENA, 2019). In just one year, the costs of these technologies declined by 13 percent. The average price of generating onshore wind energy has fallen by 35 percent since 2010, and for solar photovoltaic (PV) energy it has fallen by as much as 77 percent. This means that massive adoption of renewable energy can be a cost-effective way to combat climate change.

Despite the rapid growth of renewable energy, the share of fossil fuels in the energy system is not decreasing. As of 2016, clean energy only accounted for around 18 percent of global energy consumption (REN21, 2018). Renewables have started to catch up with fossil fuels in power production, but this process is slower in the rest of the energy system including the important sectors of transport and heating and cooling. Moreover, even though wind and solar energy are growing faster than any other energy sources, the share of fossil fuels in electricity generation is essentially the same as it was 20 years ago. This is putting humanity on a path towards dangerous climate change. 2018 saw the biggest increase in global greenhouse gas emissions in a decade (Ambrose, 2019b). The main reason was that energy demand increased by almost three percent, which led to increased use of fossil fuels and especially coal in many countries. In Europe, renewable energy is beginning to drive coal out of the market. In Asia, on the other hand, the growth of renewables is not able to keep up with the ferocious increase in energy demand. In short, the world is moving towards a climate crisis.

The IPCC's scenarios show that in order to keep warming below 1.5 degrees, we must generate at least 70 to 85 percent of all electricity from renewable sources by 2050 (IPCC, 2018). Gas may supply up to eight percent, while coal use must be close to zero. However, all these scenarios rely to some extent on technologies that can remove carbon, so there is no definitive answer. In any case, the IPCC has made it clear that the challenge ahead is beyond anything humanity has tried to accomplish before:

> Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (high confidence). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (IPCC, 2018, p. 17).

Most expert predictions for the future of the energy market are not in line with the Paris climate goals. The flagship report of the International Energy Agency (IEA), *World Energy Outlook*, is often referred to. It confirms that renewables are growing rapidly, but not rapidly enough to achieve the goals of the Paris agreement (IEA, 2018). The IEA assumes that the global population will increase by two billion people, living standards in developing countries will improve and energy demand will increase by about 25 percent in the next decades. One central driver is Asian emerging economies, which are building new coal power plants that may lock in large amounts of GHG emissions for years to come. In order to reduce emissions at the necessary speed, the world's nations must therefore invest heavily in the renewable energy sector. The IEA claims that investments must increase by a factor of two and a half by 2030 to be in line with the Paris climate goals (Gabbatiss, 2019). In this light, it is a cause for concern that investments in clean energy have not risen in the last couple of years but remained stable.

Others believe that the shift to a world running on renewables will happen faster. Independent think tank Carbon Tracker predicts that fossil fuels will peak in the 2020s, most likely around 2023 (Carbon Tracker, 2018). This relies on the continuation of three energy market trends: The costs of solar PV, wind energy and battery storage continue to drop, developing countries invest in renewables rather than fossil fuels and governments around the world uphold their RE support policies. An equally optimistic assessment from BloombergNEF is that renewables will account for 71 percent in total and that solar and wind energy alone will provide half the world's electricity by 2050 (BloombergNEF, 2019). They expect that the costs of solar, wind and batteries will continue to drop dramatically over the next decades, while coal consumption decreases rapidly and natural gas, nuclear and hydro power remains at current levels of use. BloombergNEF sees Europe decarbonizing first and reaching more than 90 percent renewable electricity generation by 2050, but the United States and China will lag behind. They also believe that more than ten trillion dollars will be invested in clean energy in the next three decades. But while this scenario puts the power sector on a trajectory in line with climate goals, other sectors lag behind.

The level of global energy demand in the future will decide to a large degree if countries can achieve their emissions reduction targets. In Asia alone, the demand for power may double by 2050 and thus encourage higher use of fossil fuels (BloombergNEF, 2018). However, not all experts see continued growth into the foreseeable future. For example, consultancy agency McKinsey & Company believes that it is going to plateau around 2030 (McKinsey, 2019). They argue that increased electrification and penetration of renewables in the electricity mix combined with improvements in energy efficiency will lead to lower energy use. Despite this, neither McKinsey's nor any of the other scenarios deliver emissions reduction in line with keeping warming below 1.5 degrees.

2.1.2 Incentives and barriers to renewable energy adoption

Governments have several reasons to encourage the adoption of renewable energy (Marques & Fuinhas, 2012). First of all, we need massive investments in clean energy to prevent dangerous climate change. Most countries have announced national targets for greenhouse gas emissions reduction, and adoption of renewable energy is an effective way of reaching them. EU countries are also subject to Renewable Energy Directives that require them to have a certain share of renewables in their energy mix. Energy security may be another incentive to invest in renewables, as fossil fuel exporters are often unstable regimes. Highly import-dependent countries may prefer to get their energy from their own renewable sources. Replacing coal, oil and gas with renewable energy sources can make countries less vulnerable to price shocks in the markets for fossil fuels (Carley et al., 2017). Furthermore, governments can profit from investments in innovation for clean energy technologies that help to increase national income and create new jobs (Lehmann & Gawel, 2013). In developing countries, renewable energy also represents an important opportunity to expand energy access to people living without electricity (Pfeiffer & Mulder, 2013). Finally, clean energy can help reduce local water use and pollution levels (Şener, Sharp & Anctil, 2018).

Despite these benefits, renewable energy has not yet replaced fossil fuels on a large scale. In 2012, the last year studied here, around 22 percent of global electricity came from renewable sources, and the majority came from hydropower (Basher, Masini & Aflaki, 2015). Part of the reason for the lack of substitution is that global electricity demand has increased. However, there are more fundamental factors that hold renewables back (Marques, Fuinhas & Pereira, 2018). One central barrier is the fact that wind and solar energy does not produce power continuously and therefore requires backup power from fuels such as natural gas. Because of the intermittent nature of these energy sources, most countries have hesitated to commit fully to RE. This is not likely to change until large-scale storage solutions for renewables become cost-competitive. Unstable policy frameworks and local opposition to renewable energy projects can also have negative effects (Eleftheriadis & Anagnostopoulou, 2015). However, the most effective counter-argument against renewable energy has always been the costs (Union of Concerned Scientists, 2017). Renewable energy plants are relatively cheap to operate once in effect, but for a long time they were expensive to build. Therefore, investors have hesitated to bet on renewables. There is also a lack of necessary infrastructure to build power grids in many places.

Vested interests in the energy market have used these disadvantages as arguments against renewable energy. In countries such as the United States and Australia, alliances of fossil fuel companies, lobbyists, think tanks and politicians have effectively delayed the energy transition this way (Mann & Wright, 2017). Using the same tactics as the tobacco industry once did, they have successfully confused the public about the dangers of climate change and the necessity of replacing coal, oil and gas. By framing climate policy as a partisan issue, they have managed to prevent necessary progress in adopting renewables. Furthermore, many countries continue to subsidize fossil fuels heavily. According to the IMF, the direct subsidies amount to around 500 billion dollars a year (Irfan, 2019). However, if you count in the 87 percent of carbon that is not priced at all, the sum becomes more than five trillion. What is worse, 2017 saw an increase of 11 percent in direct subsidies, and almost all countries in the world provide them in some form (Roberts, 2019).

In theory, renewables should automatically replace fossil fuels as the energy source of choice as soon as they become the cheapest option (Moe, 2015). We are rapidly approaching that moment, and so it is somewhat surprising that the transition is not happening faster. According to Moe (2015), the reason is that fossil fuel industries benefit from more experience. They have an established relationship with existing institutions, while new players from the RE sector often require other kinds of education and expertise to succeed. Fossil fuel industry lobbyists are also very experienced at preventing ambitious support policies for alternative technologies. Thus, one side has multiple advantages over the other and will always win in a free market. Governments that want to boost renewable energy adoption must therefore implement policies at the expense of those powerful vested interests.

In the next section, I present two opposing ways of viewing the climate problem and its solution. For each perspective, I present one policy instrument and a real-world example of where it has been used. These policy instruments are the central focus of the data analysis.

2.2 Carbon pricing

In the first perspective on climate change and clean energy, markets represent both the problem and the solution. Environmental economists believe that many of the ideas from neo-classical economics can also be applied to climate policy (Hanley, Shogren & White, 2013). They argue that both people and companies respond to incentives such as price signals and tend to act in their own self-interest. Governments must therefore offer incentives to act in environmentally friendly ways through the market. Markets are suitable for allocating resources since they can share information about goods effectively. Under the right circumstances, the invisible hand of the market can achieve the common good. Government intervention can potentially damage this flow of information and give perverse incentives to market actors.

Of course, markets are never perfect in reality. *Market failure* occurs when markets are unable to provide the right price signals (Hanley et al., 2013). Climate change is a particularly grave example. The renowned economist Sir Nicholas Stern has called it “the greatest market failure the world has ever seen” (Benjamin, 2007). A free market fails to price greenhouse gas emissions correctly because the emissions lead to negative consequences for people in other places or future generations. Those who emit carbon do not experience the costs of their activities and therefore have no economic incentives to reduce them (Clark, 2012). This particular type of market failure is known as an *externality*, a cost that is not accounted for by market prices.

However, environmental economists argue that the solution to market failure also lies within the market. The key is to put a price on carbon (Union of Concerned Scientists, no date). The cost of emitting greenhouse gases must reflect the actual damage that the emissions are going to cause. When the market gets the price right, it can reduce harmful emissions and drive innovation in alternative technologies efficiently. For economists, a global price on CO_2 emissions is the optimal climate policy (Andreassen, 2018). Since each ton of carbon released causes equal marginal damage, but the cost of reducing emissions varies between countries and regions, pricing policies lead to emissions reductions where they are cheapest. Carbon pricing is a popular solution to climate change among experts and organizations of all kinds (Ball, 2018). Politicians from both sides of the aisle, environmental organizations and even fossil fuel companies have voiced support for pricing mechanisms. It is the preferred policy approach for the World Bank and other multilateral institutions. Professor William Nordhaus, who in 2018 received the Nobel Prize in economics, is among those who have actively championed carbon pricing as the essential solution to climate change (Leonhardt, 2019).

Yet while this solution makes perfect sense to an economist, its political feasibility is more questionable (Leonhardt, 2019). The 'yellow wests' that initiated large demonstrations in France as a response to increased fuel prices illustrate the fact that many citizens are not as keen on strict carbon pricing as the academics. An Australian carbon tax led to the ensuing downfall of the left-wing government that had implemented it (Carbon Tax Center, no date). One central barrier to effective carbon pricing is that income growth has been slow in many countries since the financial crisis, and this makes it hard for people to accept rising energy prices. Moreover, some think that fossil fuel companies support a carbon price because they know that it will never be high enough to induce substantial change. According to climate policy expert Tom Burke, companies are working deliberately "to create the impression of an industry in favour of urgent action whilst actually slowing that action down" (Morris & Jungjohann, 2016, p. 391). That may be an effective strategy to avoid accountability for their emissions. When carbon pricing is the sole instrument in place, companies can blame governments for the lack of results despite doing nothing themselves to help. Furthermore, carbon pricing can benefit some fossil fuel companies because natural gas will be more attractive (Geman, 2015). Another possible reason why they support a price on carbon is that it provides certainty about the future, thereby not endangering the fundamental business model of those companies.

There is also a lot of psychology involved in climate and energy policy. In fact, the key disadvantage of carbon pricing may be that it is not directed at the end goal: “Mechanisms don’t inspire people. Mechanisms are easy to caricature as big-government bureaucracy. (…) You need to be able to inspire people” (Leonhardt, 2019). Many voters are skeptical of policies that increase costs of living. When asked if they support renewables, on the other hand, the vast majority of voters tend to be positive. This suggests that direct support policies for renewables may have a better change of winning over the people.

On the other hand, although carbon pricing may not enough to deal with all greenhouse gas emissions, it can be effective in the power sector (Ball, 2018). This is because companies in the power sector can relatively easily replace polluting energy technologies for cleaner alternatives. Emissions from buildings and transport are harder to reduce based on carbon pricing alone.

Finally, the problem with the idea of ‘getting the price right’ is that it is hard to know what the right price is (Ackerman, 2019a). Prices should ideally reflect the total damage that climate change does and will do in the future. One well-known estimate is that this *social cost of carbon* is around 51 dollars per metric ton. However, such estimates are subject to huge uncertainty. Some experts argue that the true value may be in the thousands of dollars or higher. It is perhaps more realistic, therefore, to set carbon prices at the level we think is necessary to reach climate goals. In order to reach the goals of the Paris agreement, the High-level Commission on Carbon Prices estimates that the price of emitting a ton of carbon has to be at least 40 dollars by 2020 (Ball, 2018). Only a few countries price carbon that high today.

There are two main ways to price emissions: carbon taxes and carbon markets. In the first case, the authorities decide the price per unit of emissions without regulating the quantity. In the second case, they make a certain number of emissions allowances available and let the market determine the price. In theory, both options have the same impact: We punish those who emit a lot of carbon and reward environmentally beneficial actions. Yet there is an important difference: Cap-and-trade should ensure that we reach emissions reduction targets because of the cap, while taxes provide no such security. On the other hand, governments often engage in *grandfathering* in the initial phase of a cap-and-trade scheme, meaning that they give out permits to industry for free (Taschini, Dietz & Hicks, 2013). Taxes, on the other hand, go into effect immediately. Therefore a trading scheme may be a less effective instrument than a tax. Yet cap-and-trade has so far been the more popular of the two around the world (Ackerman, 2019b). Besides, cap-and-trade usually covers the power sector while carbon taxes are directed at other sectors such as transportation. Since I am interested in electricity production, I only examine the effect of cap-and-trade schemes in the analysis.

2.2.1 Trading schemes

In a *cap-and-trade* scheme, regulators put a cap on the total level of emissions and create emission allowances equal to that cap (Ursin, 2018). Companies must hold enough allowances to cover their emissions and can buy and sell them between each other according to their needs. If a company emits a lot, it can either reduce its emissions or buy additional permits. In many systems it is also allowed to hold on to surplus permits for later use. Regulators reduce the cap gradually to ensure that they meet the targets for emission reductions. Essentially, cap-and-trade creates a market for carbon. The price of emission permits depends on supply and demand: When demand is high and supply is low, the price increases and vice versa (Taschini et al., 2013).

Cap-and-trade schemes for GHG emissions have been growing in popularity among policymakers for the last two decades, culminating in China's announcement in 2017 that they are establishing the world's largest system (Wettestad & Gulbrandsen, 2018). According to the World Bank, there were 25 trading systems in the world in 2017 (World Bank and Ecofys, 2018). It has mostly been sub-national governments that have adopted cap-and-trade, while only a few exist at the country-level. The biggest trading scheme in effect today is the EU Emissions Trading Scheme. The second largest was launched in South Korea in 2015. An Australian government tried and failed to implement a trading scheme in 2011. There is no federal cap-and-trade system in the United States, but some US coast states have implemented their own schemes at the sub-national level. The government of California, for instance, recently announced that it would continue its extensive state level scheme until 2030 (Hausfather, 2017).

The primary argument in favor of trading schemes is that they are a cost-effective means of reducing emissions and driving low-carbon innovation. When there is a price on carbon, market forces can identify the efforts that will lower emissions at the lowest cost (Schmalensee & Stavins, 2017). Trading schemes combine control with flexibility; the aggregate emissions cap is politically decided, but how the emissions are reduced is up to the market (Wettestad & Gulbrandsen, 2018). It guarantees achievement of emission reduction goals and can provide incentives for new technology innovation. The flexibility of the system appeals to both governments and businesses. Many environmentalists also view cap-and-trade positively since it should ensure that emissions are reduced in line with targets (McAllister, 2009). Another advantage is that auctioning of emissions allowances can provide revenues for governments to be used for other climate measures (European Commission, 2015).

The problem with cap-and-trade is that the cap must be stringent enough to spark large emissions reductions (McAllister, 2009). As it turns out, policymakers are often not willing to do that. In practice, cap-and-trade has worked well to prevent such problems as acid rain and overfishing, but schemes aimed at GHG emissions have proven less successful (Patt, 2015). Notably, emissions trading will only be as successful as policymakers allow it to be. If governments set a stringent cap, permit prices will go up. High permit prices should guarantee that emissions go down, but prices in most existing trading schemes have not been high enough to promote large-scale market changes (Patt, 2015).

Carbon markets are generally not considered to have been effective at reducing emissions. California's cap-and-trade scheme has experienced similar problems with lack of demand for allowances (Hausfather, 2017). The main reason for this is political: "The fundamental problem is of course that policymakers have been afraid to set ambitious reductions targets and/or to implement policies to achieve them" (Schjølset, 2017). When the supply of emission allowances exceeds demand, businesses have no incentive to cut emissions. Thus, the real issue may not be cap-and-trade as a policy tool, but rather the unwillingness of governments around the world to take meaningful action against climate change.

Despite widespread criticism that has led many to question their potential for combatting climate change, carbon markets have recently made a comeback on the political agenda (Harvey, 2018). China is implementing the largest trading scheme in the world, and the EU has undertaken reforms of its weak-performing system. Half the countries that presented emission reduction plans before the Paris climate meeting mentioned cap-and-trade as one instrument that they were considering (Wettestad & Gulbrandsen, 2018). The revenues that countries gain from carbon markets are increasing steadily, and many governments are eager to use cost-effective means to achieve emissions-reduction targets.

2.2.2 The EU ETS

The European Union Emissions Trading Scheme (EU ETS) was the first big cap-and-trade scheme in the world when it launched in 2005 (Schmalensee & Stavins, 2017). Since most countries that have had trading schemes in the sample have been part of the EU ETS, I provide a brief description of the system in this section. In addition to the EU member countries, Iceland, Liechtenstein and Norway took part from 2008 on so that a total of 31 countries participate as of today. Initially, the system only covered CO_2 emissions, but it has gradually grown to include other greenhouse gases (European Commission, 2015). It now covers two billion tons of CO_2-equivalents from over 11 000 installations, which corresponds to nearly half of all emissions in the EU. The scheme has covered emissions from power production and industry since the beginning. Since 2012, other sectors including carbon capture and storage, petrochemicals and aviation within and between member countries are also covered. Businesses that do not surrender enough permits to cover their emissions face a fine of 100 euros per ton of GHG emissions. The European Commission is the institution in charge of the scheme.

The ETS system is the key instrument that the EU will use to combat climate change. Currently, the goal is to reduce emissions in the sectors that are covered by 21 percent compared to 2005 levels by 2020 and 43 percent by 2030 (European Commission, no date). However, the scheme is also explicitly meant to promote the development of low-carbon technologies. As the price of emissions allowances increases, so does the incentive for businesses to invest in new energy solutions. Furthermore, a share of the revenues from the carbon market goes directly into a funding program for renewable energy technologies.

The EU ETS has functioned in a series of phases and has changed along the way (European Commission, 2015). It began with a pilot phase (2005-2007) and went into full effect with the Kyoto commitment phase (2008-2012). Initially, the authorities did not have solid data on emissions levels on which they could base the cap. They set the cap higher than necessary, and allowance prices plunged as a result (Schmalensee & Stavins, 2017). This phase was a trial period before the Kyoto Protocol came into action (Patt, 2015). Therefore, national authorities were allowed to distribute permits in whatever way they saw fit. Unsurprisingly, most countries gave them away for free so that they would not endanger industry firms. The market price started relatively high because of expectations that the price could increase even more, but it dropped quickly as firms realized that the supply of allowances far exceeded market demand. Between 2006 and 2007, the price went from around 40 dollars per ton of CO_2 to nearly zero (Patt, 2015). In addition, the regulators weakened the efficiency of the scheme by accepting that member countries could offset emissions through the global Clean Development Mechanism (CDM) system, where developed countries finance clean energy projects in developing countries (Wettestad & Gulbrandsen, 2018).

The most significant impact of the initial phase may in fact have been unexpected profits to utilities, which they could then reinvest in new fossil fuel infrastructure (Patt, 2015). In the second ETS phase, the EU Commission took away some control from member countries and made it so that more allowances were auctioned rather than given away for free. This led to a short-lived rise in the allowance price. In 2008, it fell again due to the financial crisis. The crisis led to a decline in economic output from European countries, so that emissions went down by themselves (Ball, 2018). This left a large oversupply of emission allowances, and the price per ton of CO_2 was only five euros by 2013. In the current third phase of the ETS (2013-2020), the Commission has tightened the emission cap. However, the oversupply of allowances lingers. Spurred by a recent reform to the system, the carbon price has begun to increase and is around 30 dollars per ton as of June 2019 (Energi og klima, 2019).

In late 2017, the EU ETS member countries countries agreed on reforms that would be implemented for phase 4 (2021-2030). They increased the annual reduction of the emission cap and introduced a ‘market stability reserve’ that can take surplus permits above a certain level out of the market temporarily and eventually delete them (Evans, 2017). Furthermore, from 2021 it will no longer be possible to buy allowances through the CDM, which has experienced similar problems with over-allocation (Wettestad & Gulbrandsen, 2018). They will also increase the share of permits that are auctioned away, and the revenues will go to innovation funds for low-carbon technologies. However, they will continue to give away nearly half the allowances for free.

Governments gave away practically all permits freely in phase 1 and many continued to do so in phase 2 (Evans, 2017). The rationale was to introduce the system very gradually but also to prevent firms in developing economies with less stringent climate policy regulations from getting a competitive advantage over European businesses, which could in fact result in a net increase in global GHG emissions. This problem of 'carbon leakage' is an important reason why the EU countries have not changed the system towards 100 percent auctioning. Even though installations in the power sector mainly no longer receive any free allowances in the EU ETS, eight member countries in the East with many coal plants have negotiated an exception. Power plants in these countries receive a gradually decreasing amount of free allowances until the end of 2019, and in return they must modernize their electricity production (European Commission, 2015).

2.3 Technology policies

As we have seen, most economists believe that we need a price on carbon to combat climate change. However, some experts suggest that other policy instruments are also necessary to boost adoption of renewable energy. According to Patt (2015), we have considered the climate challenge all wrong. If we want to stop climate change, it is not sufficient to tinker at the margins by gradually increasing carbon prices. Combating climate change will require a complete transformation of the energy system. An *energy transition* in this case means a fundamental change from one stable system to another, and this change builds gradually until it suddenly finishes very fast. In this perspective, the central goal of climate policy should be to induce transformative change, not simply to reduce emissions. And no energy transformation in the past has happened as a result of pricing mechanisms; technological innovation has always been the main driver (Roberts, 2016). To replace fossil fuels with clean energy on a large scale, we need technology policies. This is the second climate policy perspective I am going to examine.

The limitation of market-based policies is that technology alternatives do not appear out of nowhere (Sandén & Azar, 2005). Since pricing instruments can provide incentives to make existing technologies less emission-intensive, they make it possible to achieve short-term climate targets. However, price signals alone will not bring new carbon-free technologies to the shelf. Climate policy contains a *positive externality*: Knowledge can spill over to other companies. Since companies receive fewer benefits from research on clean technologies than society as a whole, they have little incentive to invest in such research. Governments should therefore provide extra support for research and diffusion of new technologies. If we only focus on cost-efficiency, we risk overlooking policies that are truly transformative. We cannot decarbonize the economy unless we make alternative energy sources cost-competitive with fossil fuels. Those alternative technologies require support in the form of "increased public research and development, demonstration, niche market creation, support for networks within the new industries, standard settings and infrastructure policies" (Sandén & Azar, 2005, p. 1557).

The point of technology policy is to make a new technology gradually more attractive to users. As adoption rates go up, production costs start to decrease and users start to experience additional benefits (Sandén & Azar, 2005). Cost reductions happen through a range of different mechanisms. First, as companies increase their production of the new technology, the cost of producing each unit goes down. This is called *economies of scale*. Second, increasing production also increases the worker's skills and allows them to be more effective. This is called *learning by doing*. The same process increased the attractiveness of the product to users. Adoption of the new technology reduces uncertainty among users and helps companies to make it perform better. Finally, *network effects* reduce the cost of a technology and increase its availability as it gets more users. For example, as more and more electric vehicles hit the road, we are going to build more charging points, which again lead to more electric vehicle use and so on. Thus, the benefits of new technologies increase with higher usage over time (Andreassen, 2018).

However, this only shows why we need policy support from a global perspective. At the national level, another rationale for technology policies is that investments in new energy technologies pay off when firms use them to make profits. Thus, subsidizing green technologies can boost national industries, create new jobs and result in a net gain for governments. Renewable energy can be good both for the climate and for the economy. Besides, these policies may only be needed temporarily in order to direct innovation efforts towards environmentally friendly alternatives (Acemoglu et al., 2012). However, the costs of abatement rise the longer that policymakers hesitate with policy responses. Therefore, policymakers should implement support policies for new technologies as early as possible.

One counterargument to strategic technology policies is that the state should not ‘pick winners‘. Government support has led to many grand failures such as the infamous Concorde airplanes. Private companies may be better suited to invest in the technologies that are going to be effective at combatting climate change. On the other hand, it is easy to forget that many technological success stories were made possible by state backing (Rodrik, 2014). Some projects are always going to fail; the more important question is how well government-backed programs are doing at encouraging innovation overall.

The traditional view of innovation is that governments should do nothing more than provide a regulatory framework, but according to Mazzucato (2013), the state can be a true entrepreneur. In fact, the state has led the way in almost all the grand technological innovations throughout the history of capitalism. While private investors often only think short-term, the state can afford to make investments that will pay off in the long run. Countries that are successful in large-scale innovation are those that keep support policies in place even when unforeseen events occur. Mazzucato argues that the state should not only correct market failure, but also strive to actually create new markets. The crucial role of the state is to enter into uncharted territory and take on a lot of risk, so that private companies can follow when a market appears. She sees the state is a visionary actor creating market opportunities and directing private action to where it is needed. The truly revolutionary innovations happen as a result of sustained technology policies from the state. Among other things, this was the case for military technology, nano- and biotechnology and the technology that made the iPhone possible.

When it comes to clean energy, we need policies tailored to both the supply and demand side of the market (Mazzucato, 2013). Governments must offer support policies for renewable energy over time if renewables are to compete on equal terms with fossil fuels. Countries that only implement demand-side instruments provide insufficient incentives to RE producers and become vulnerable to changing political agendas. Mazzucato sees the ‘visible hand’ of the state clearly present in the clean energy revolution that has taken place in Germany and China.

Governments must base technology policies for renewable energy on three guiding objectives (Patt, 2015). The first is to overcome technological *lock-in*. Established technologies have a market advantage simply because they are established; since we have burned fossil fuels for around 200 years, our societies are built around them. Policies must therefore start big to overcome this disadvantage. The second hurdle is related to risk-taking. Users are not willing to take a risk by trying something new when the old alternative works fine. Technology policies must decrease the risk associated with using the new technology and the overall level of risk in the market. The third objective is to make the policy appealing to different societal groups. So-called *clumsy solutions* are not optimal from the viewpoint of any single group, but they work because all groups find them acceptable.

Patt argues that climate policy should focus on replacing fossil fuels with alternative energy technologies. The new technologies must be competitive with fossil fuels both in terms of cost, reliability and potential capacity. And since all the alternative technologies that are available to us today have certain disadvantages, the energy transition will not happen by itself as a result of market forces. Public policy is therefore needed. If we simply wanted to reduce emissions somewhat, market policies would be sufficient. However, somewhere around 2050 global carbon emissions need to be net zero. If there are no pollution rights to allocate, the market doesn't work anymore (Patt, 2018). And since we can't simply prohibit fossil fuels, the remaining solution is to replace all fossil fuels with new technologies. To do that, we should rely on insights from technological transitions rather than the axioms of neo-classical economics.

There are three steps to enabling a technological transition (Patt, 2018). The first is to invest in public research and development (R&D) to invent new technologies. The next is to commercialize those technologies by trying them out in niche markets. Finally, when the new technologies are ready for the open market, the government must establish the necessary institutions to support them. Alternative technologies typically go through a long period of preparation where they need public support, but at a certain point, they start to grow exponentially. This is when the true technological transition happens.

2.3.1 Feed-in tariffs

A *feed-in tariff* (FIT) is a form of technology policy meant to make alternative energy technologies competitive with conventional ones. It guarantees renewable energy producers a higher price for each kilowatt-hour (kWh) of electricity output (Jenner, Groba & Indvik, 2013). It also gives them access to the electricity grid ahead of other energy sources. FITs come in many shapes: as a set price or an addition to the wholesale market price, on long or short contracts, with high or low tariff rates and sometimes gradually reduced rates. Typically, authorities calculate the cost of producing power from the energy technology they want to promote, which is known as the *levelized cost of electricity* (LCOE), and add a premium to that sum (Patt, 2015). The final tariff is the result of the LCOE plus the premium. Renewable energy producers normally receive the same tariff over the project's lifetime. Transmission service operators (TSOs) are bound by law to buy all the surplus electricity from the producer. The costs that the TSOs face as a result of the FIT arrangement are passed on to citizens via their electricity bills.

FITs have been a big part of the RE revolution and have been very popular support schemes. 113 countries and states had feed-in tariffs in 2017 (REN21, 2018). Germany implemented the most famous feed-in tariff for wind and solar energy in 1990. Italy, Denmark and a couple of other European countries followed suit in the next years, but most countries that have implemented FITs did so during the 2000s (Jenner et al., 2013).

One potential issue with support policies such as feed-in tariffs is the 'waterbed effect' (Appunn, 2019b). Since both FITs and cap-and-trade are directed at the power sector, the two policies may have overlapping effects. Some experts therefore argue that FITs that reduce emissions in one place only lead to increased emissions somewhere else, because those policies free up emissions allowances which can then be used by others. Furthermore, lower demand for emissions permits leads to a lower carbon price, and this prevents the carbon market from driving innovation in clean energy. However, it is highly uncertain whether the waterbed effect has been an issue in reality. In the EU ETS in particular, as long as there is a large surplus of allowances, subsidies for renewable energy will not free up any allowances and will likely lead to actual emissions reductions (Whitmore, 2017).

Ironically, the big disadvantage with feed-in tariffs is that the more successful they are, the more expensive they become. If the FIT leads to massive installation rates, the costs can become overwhelming. Many will join in and start producing renewable energy if they can make good profits from it. Someone, either the government or the electricity consumers, has to pay. In this sense, we should primarily think of the FIT as an instrument for the initial phase of development of a renewable energy technology. When the technology becomes cost competitive, the feed-in tariff may no longer be needed to drive adoption.

In recent years, many governments have reduced the FIT rates significantly or abandoned the instrument entirely. In fact, there is a bit of a backlash against feed-in tariffs globally (Chandrashekhar, 2018). Both developed and developing countries have instead shifted their attention towards renewable energy tendering schemes. *Tenders*, also known as *auctions*, allocate renewable energy projects through a bidding process. Many governments that want to reduce costs have turned to auctions, and they are now expected to supply almost half the added RE capacity over the next years. Yet governments continue to use feed-in policies to promote small-scale production and to bring forward new technologies.

Experts have always argued that feed-in tariffs only need to be used temporarily. Eventually, as costs come down, solar and wind energy would be attractive enough to do without subsidies. However, this promise may have been premature. The problem is that prices reach zero or negative numbers when we produce a lot of solar and wind energy (Morris & Jungjohann, 2016). That means that producers cannot make large profits from the electricity market. In this light, we may need continued support policies for the foreseeable future. Feed-in tariffs would be a reliable instrument for continued renewable energy adoption. Auctions may do the job as well, but perhaps not as efficiently.

2.3.2 Germany's feed-in tariff

Germany was the first country to implement the policy that would later become known as the feed-in tariff, and that is also where it has been most successful at promoting a true energy transition (Patt, 2015). It is part of an ongoing political project called the *Energiewende*, a citizen-led move away from coal and nuclear energy to renewable energy and energy efficiency (Morris & Jungjohann, 2016). Many Germans have formed citizen cooperatives where they produce their own electricity, partly driven by the financial support of the FIT. Germany's experience with the feed-in tariff offers insights into both how effective the policy can be at promoting renewables and what potentially negative side effects it can have. Since much of the theoretical literature on FITs builds on the case of Germany, I provide a brief description of the history of the German policy in this section.

In 1991 the Germans enacted a law that guaranteed small-scale producers of renewable energy a higher percentage-based price for their electricity (Patt, 2015). Eight years later, the country was the global leader in wind power production. However, the percentage-based price was not high enough to incentivize investments in the more expensive solar PV technology. Therefore, the government in 2000 introduced the Renewable Energy Act (EEG) and the *feed-in tariff*. They replaced the percentage model with a flat tariff, thus reducing the risk associated with annual fluctuations in the market power price. From then on, investors would receive nearly the exact same profits every year, no matter what. Suddenly, ordinary German citizens found themselves in a position where they could reasonably afford to invest in the expensive solar PV technology.

It turned out that the FIT policy was very efficient not just at increasing renewable electricity production but also at reducing transaction costs (Patt, 2015). Since there was so little risk involved, investors could easily acquire financing from the banks. Moreover, the FIT led to massive technology cost reductions. The high degree of security has allowed start-up companies to enter the market and introduce technological innovations.

The FIT was instrumental in making Germany a global renewable energy frontrunner (Patt, 2015). Five years after its implementation, Germany was the global leader in photovoltaic installed capacity as well as wind. Many countries followed suit and implemented feed-in tariffs modeled on the German policy. Yet the positive development has not been uninterrupted. In 2007, the growth in wind power production fell due to a lack of suitable installation sites, commodity price growth and bad weather conditions. The wind market again began to grow after 2011. Meanwhile, China invested heavily in solar panel manufacturing. In 2012, the German PV industry fell apart as a result of displacement by China.

In 2013, the German government began reigning in the FIT policy. Since China had established market dominance in PV manufacturing, hopes of a large German industry in that area had been crushed. At the same time, the surcharge on customers' electricity bills had become quite large. Two groups of companies criticized the FIT loudly: The traditional electric utilities protested because of huge profit losses, while manufacturing firms were critical of the high cost of power. Both argued that German citizens were paying way too much for the renewable energy development. In 2014, the politicians changed the EEG fundamentally, removing the obligations to pay a surcharge and buy the power from renewable energy producers.

From January 2017, Germany switched from feed-in tariffs to auctions as the primary support policy (Leiren, 2017). As a result, they have been able to reduce the subsidy costs. Many feared that the consumer cooperatives would suffer as a consequence of the switch, but cooperatives in fact won 98 percent of the contracts. However, the policy change did lead to a reduction in new installations of renewable energy. Germany is not on track to meet their emission reduction goals for 2020. Still, renewable electricity output has continued to increase, and in the first five months of 2019 renewables have supplied almost fifty percent of electricity in Germany (Parkinson, 2019).

In the 2020s, more than one million small-scale German producers of solar energy will lose their guaranteed payments (Appunn, 2019a). The same goes for many of the country's wind parks. Priority access to the electricity grid will remain, but this change still comes at a challenging moment as Germany is in the process of phasing out both its nuclear and coal power sources. In order to keep wind and solar PV profitable, Germans are exploring a range of possibilities including new marketing schemes and blockchain technologies.

2.4 Combining different policies

In practice, governments usually implement several climate policy instruments. In a "second-best world" (Bennear & Stavins, 2007, p. 112), this can in fact be the economically optimal approach. When the market or the political situation displays certain characteristics, relying on a market-based policy alone can have undesirable outcomes. Specifically, a combination of an environmental policy and a policy for technology innovation and diffusion is called for. While technology policies help us to develop new technologies, pricing policies can make sure that people and firms actually decide to use them. In other words, a general fee on emissions can increase demand for alternatives, but public support policies are needed to bring forward those alternatives (Andreassen, 2018). Acemoglu et al. (2012) also argue that optimal regulation combines different policies: We need a pricing mechanism to control emissions today, but we also need technology policies to redirect innovation towards cleaner alternatives.

If the real world looked similar to the models that economists use, carbon pricing would probably be enough to stop climate change. But models are never that accurate. The externality of climate change would have to be the only distortion to perfect markets, technologies would have to be equally developed and market-ready and we would need the leadership of an efficient central institution that was independent of political mood swings (Lehmann & Gawel, 2013). In fact, we also have a positive externality of knowledge spillover. In a second-best world, we need to do correct several types of market failure.

Another rationale for using different policies is that policymakers want to achieve different objectives. A good example is the EU, which has separate binding targets for GHG emissions reductions and the share of renewables in total energy consumption. By 2030, the EU aims to reduce emissions by 40 percent and use 32 percent renewable energy (European Commission, no date). Individual EU countries have implemented various policies to meet these targets, but the main strategy is arguably to use the EU ETS to reduce emissions and national renewable energy support schemes to boost renewables use. All EU member states have some form of support instrument for renewables (Lehmann & Gawel, 2013).

There are also other reasons for combining policies (Lehmann & Gawel, 2013). Support schemes may be more politically feasible than strict pricing policies, which often meet with opposition from participating firms. Many countries also have not liberalized their electricity markets. Firms that do not compete, have less incentive to innovate. Finally, the EU ETS exemplifies that carbon markets may not provide adequate long-term pricing signals. It is not obvious how the allowance price will evolve over time, and so far the price level has done little to influence firms' innovation decisions for the next decades. In that sense, a carbon tax may appear to be a better policy choice. However, a sufficiently strict tax is most likely not politically possible. Thus, we are left with support schemes.

Yet it is not obvious that more policies will always lead to better results. Governments that combine different tools, often do so to avoid fluctuating carbon prices. However, this strategy may be misguided: Adding a feed-in tariff to an existing cap-and-trade scheme does not necessarily have any effect on the overall carbon price (Fankhauser, Hepburn & Park, 2011). The way that policies are combined is key: "*multiple* policies is not the same as *hybrid* policies" (ibid., p. 5). Instruments should be used complementarily, instead of stacking them on top of each other to combat the same problem. Otherwise, we risk a waterbed effect. The added instrument does not produce lower emissions; it just shifts them to other sectors.

3. Previous research and hypotheses

3.1 Empirical studies of renewable energy adoption

The field of empirical research on policy effects on renewable energy adoption has been expanding rapidly in recent years, and I therefore briefly review some papers that have been published after 2008. Two things happened that year that sparked an interest in research on clean alternatives to fossil fuels: the mandatory emissions reduction period under the Kyoto agreement started, and oil prices reached a record high (Şener et al., 2018). A considerable amount of studies have emerged since then. Şener et al. (2018), reviewing 60 empirical papers, identified 489 different variables in seven categories: economic, environmental, political, regulatory, social, technical potential and technological factors. Authors have most often used similar samples: They tend to study OECD countries because high-income countries dominate the secondary data, and the time period is usually somewhere between 1990 and 2010.

In previous empirical studies of the relationship between policies and renewable energy adoption, authors have used different dependent variables: renewable energy in final energy consumption (Marques & Fuinhas, 2012; Aguirre & Ibikunle, 2014), total RE capacity (Liu, Zhang & Feng, 2019; Dong, 2012) or annual installed capacity (Polzin et al., 2015; Jenner et al., 2013). Many have also examined electricity generation from renewable sources (Smith & Urpelainen, 2014; Carley et al., 2017; Zhao, Tang & Wang, 2013; Yu, He & Liu, 2017). The dependent variable in this paper excludes hydropower, which others have also done before (Kilinc-Ata, 2016; Pfeiffer & Mulder, 2013).

First of all, does more stringent climate policy in general lead to higher renewable energy deployment? Marques and Fuinhas (2012) use an aggregated measure of policy support and find a positive effect on renewable energy production for 23 EU countries. Aguirre and Ibikunle (2014), however, study a larger sample including the BRICS[2] countries and show that some public policies actually impact RE adoption negatively. Zhao et al. (2013) find an overall positive effect of renewable energy policies, but that effect is reduced when policymakers implement several policies simultaneously. Previous empirical studies have also shown that it is optimal to use a mix of different policies in order to boost renewable energy

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[2] The BRICS countries are Brazil, Russia, India, China and South Africa.

and combat climate change, and a combination of cap-and-trade and feed-in tariffs has been suggested (Polzin et al., 2015).

The literature suggests that feed-in tariffs have been effective at promoting renewables. Carley et al. (2017) find a positive effect for the largest sample in the literature, 164 countries between 1990 and 2010. Kilinc-Ata (2016) studies the EU countries and the US states and demonstrates a positive impact of FITs. Another study shows a positive effect of FITs on solar PV development, but not on wind energy (Jenner et al., 2013). In contrast, Dong (2012) shows that feed-in tariffs increase wind power generation. Smith and Urpelainen (2014) test the causal relationship using instrumental variables and find that FITs have a large and positive effect on renewable electricity generation.

The impact of cap-and-trade on renewables use has not been tested as much as that of feed-in tariffs (Martin, Muûls and Wagner, 2015). Where it has been tested, its impact has been beneficial to renewables. Yu et al. (2017) find that trading schemes have impacted renewable energy output positively. Polzin et al. (2015) study private institutional investments and find that feed-in tariffs are more effective at promoting less mature RE technologies, while cap-and-trade works better for mature ones. Best and Burke (2018) demonstrate a positive impact on renewable electricity production from carbon pricing, while feed-in tariffs had no significant impact. A large literature review of papers studying the impacts of the EU ETS concludes that the scheme appears to have had a positive but limited impact on clean energy innovation (Martin et al., 2015). Laing et al. (2014) find that the scheme led to some emissions reductions in its two first phases, but no discernable impact on investments in long-term innovation.

Few studies of renewable energy adoption have taken into account policy stringency. Jenner et al. (2013) develop a measure of the strength of feed-in tariffs, but only for EU countries and without examining carbon pricing. They conclude that policy design and prices are more important for RE deployment than simply whether or not a FIT policy is in place. Smith and Urpelainen (2014), testing mean FIT rates, also conclude that the effect can be very large with a more nuanced analysis. Where authors have studied both cap-and-trade and feed-in tariffs, they have used binary variables (Best & Burke, 2018; Polzin et al., 2015).

According to some experts, the point of technology support policies was never to immediately get a lot of renewable energy built but to drive down the costs of the new technologies (Naam, 2019). In that sense, it is interesting to consider which instruments are most efficient at reducing technology costs. A recent paper argues that for solar photovoltaic modules, market-stimulating policies have been responsible for around 75 percent of cost reductions between 2000 and 2012 (Kavlak, McNerney & Trancik, 2018). While R&D was the most important driver until around 2000, stimulating policies such as feed-in tariffs have gradually become the most important instrument for reducing costs.

In summary, previous studies clearly indicate that feed-in tariffs have effectively promoted renewable energy generation. Some scholars also point to a positive impact from cap-and-trade, but the empirical literature is very limited. Two methodological limitations of the existing literature are the lack of focus on policy stringency and the failure to control for unit roots. I have taken both these issues into account in this study (see section 4.2). My analysis presents a novel addition to the literature in that I study the effect of both trading schemes and FITs on shares of electricity generated from renewable sources.

3.2 Hypotheses

In theory, both cap-and-trade and feed-in tariffs can be effective ways to adopt more renewable energy. Anecdotal evidence from the EU ETS, however, indicates that carbon markets have not worked very well, while FITs seem to have contributed significantly to the influx of clean energy in the last decades, at least in Germany. The general conclusion in the empirical literature seems to be that feed-in tariffs have significantly increased renewable energy production, while the impact of trading schemes is uncertain. Based on the discussion above, I present the following hypotheses:

H1: More stringent cap-and-trade schemes have not effectively promoted higher shares of renewable electricity output.

H2: More stringent feed-in tariffs have effectively promoted higher shares of renewable electricity output.

4. Data and method

4.1 Data

The dataset contains observations for a large group of countries over several years. This type of panel data is called *time-series cross-sectional* (TSCS) data. Whereas ordinary panel data consists of many units and few time points, TSCS data has fewer units measured at more time points (Mehmetoglu & Jakobsen, 2017). Panel data are useful because they allow the researcher to study the effect of changes over time. That makes it possible to discuss causality in models, not just correlation. More generally, panel data provides more observations, which leads to more variation between data points. This variation allows researchers to do more complex analyses than with cross-sectional data or time series data alone (Park, 2011).

I analyze a sample of 33 OECD- and BRIICS-countries over a period of 23 years[3]. Six OECD member countries are not part of the Environmental Policy Stringency database and are therefore not included[4]. Among the countries in the OECD database, Slovenia was the only one that could not be included because of too many missing observations. Observations start in 1990 and end in 2012 because that is the time period for which the OECD has sufficient data on environmental policy stringency, but 1990 is in any case a good starting point for the analysis since the EU countries began implementing energy policies after that. However, it is unfortunate that I could not analyze data from after 2012, since a lot of groundbreaking developments happened in the world of clean energy in the following years. Notably, some experts argue that the real breakthrough for renewable energy occurred around 2015 (Naam, 2019). The final dataset is balanced, which means that there are observations for all countries and all years (Mehmetoglu & Jakobsen, 2017). Some countries have a few missing observations on the control variables, but this should not affect the results much.

4.1.1 Dependent variable

The dependent variable is *renewable electricity output*, excluding hydropower. It is measured as a percentage share of total annual electricity output and collected from the World Bank's database of World Development Indicators (WDI) (World Bank, no date). The source of the

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[3] The sample consists of the following countries: Australia, Austria, Belgium, Brazil, Canada, China, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, South-Korea, Mexico, the Netherlands, Norway, Poland, Portugal, Russia, the Slovak Republic, South-Africa, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

[4] These are: Chile, Estonia, Iceland, Israel, Luxembourg and New Zealand.

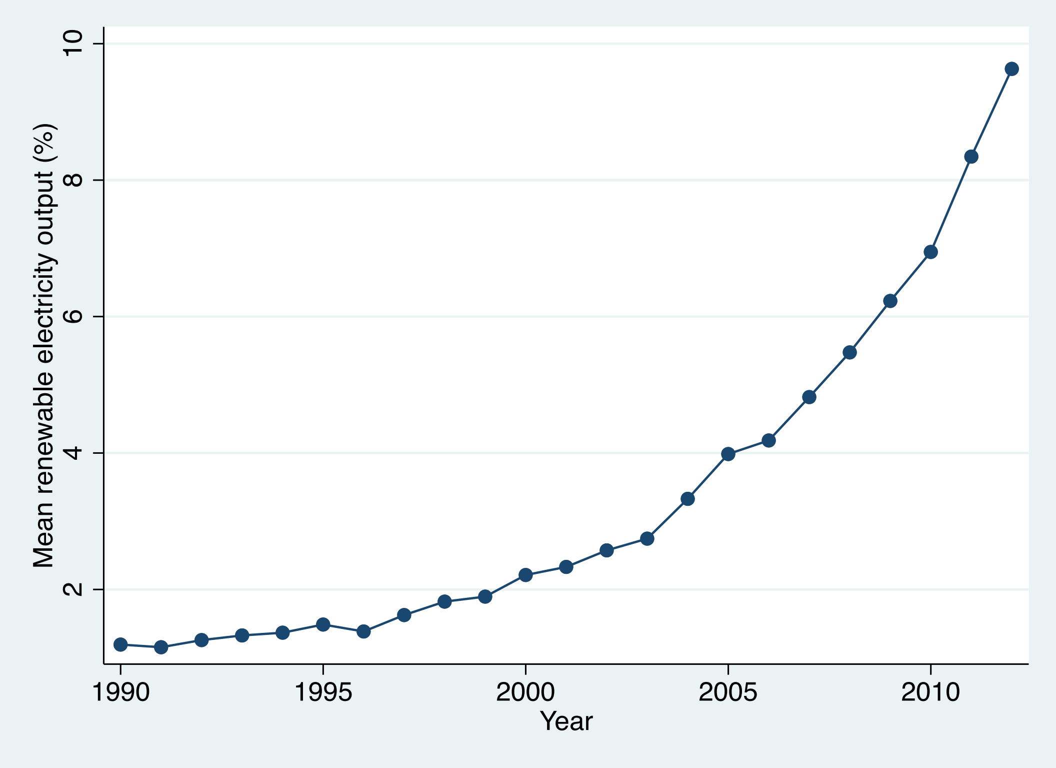
original data is the IEA. Renewable electricity sources include solar, wind and tidal power, biomass, biofuels and geothermal energy.

Alternatively, I could have used an indicator of total production of or investments in renewable energy. I choose to look at shares of electricity output because renewables need to replace fossil fuels and not just come in addition to them (Aguirre & Ibikunle, 2014). If the demand for electricity continues to grow, renewable energy deployment can increase without any effect on the use of fossil fuels and related carbon dioxide emissions. The share of renewable electricity production is a better indicator of the transition towards an economy built on clean energy (Carley et al., 2017).

Part of the reason for excluding hydropower is that such projects can have severe negative effects on local environmental conditions and nearby populations (Zhao et al., 2013). In fact, studies have shown that some hydroelectric dams near the Equator are not very climate-friendly at all since they can produce a lot of methane (Weiser, 2016). Yet the primary rationale for choosing this Y-variable is that feed-in tariffs are often not directed at increasing hydropower generation, only solar and wind energy or various small-scale RE projects (Kilinc-Ata, 2016). Solar and wind power supply only a small share of global electricity today but are expected to play a central part in the ongoing renewable energy revolution. In fact, some scenarios show that these two sources can deliver nearly 90 percent of all energy in the future (Ram et al., 2019). Global hydropower capacity will probably not grow much in the next decades, since most countries have already built all the dams that they want. However, it remains responsible for most of the total RE generation in the world. If I include hydropower in the dependent variable, I risk erroneously ignoring real effects of energy policy on specific technologies because there is no visible impact on total RE shares. With non-hydro renewable electricity output, yearly growth rates are much higher.

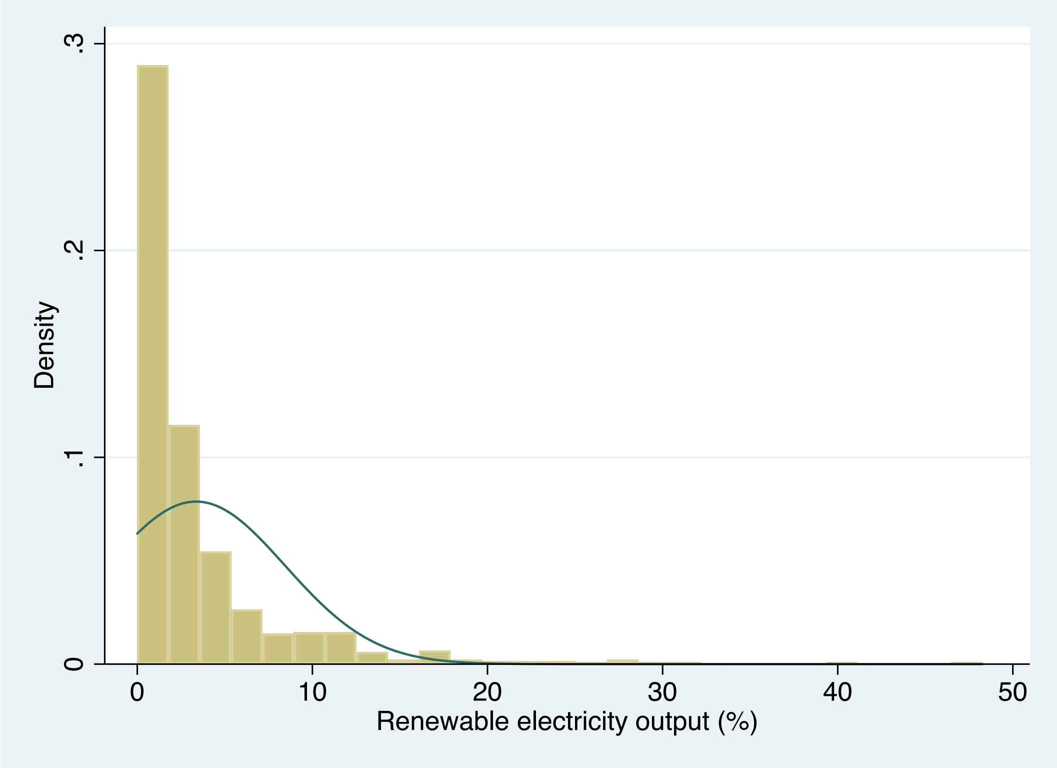
The development of renewable electricity output in the sample over time is illustrated in figure 1. The share of electricity production from other RE sources than hydropower has increased rapidly in this period from a very low level.

Figure 1: Mean renewable electricity output (% of total output), 1990-2012



One potential issue with a variable such as renewable energy shares is that there can be many zero and low values. Ideally, we want something closer to a normal distribution (Mehmetoglu & Jakobsen, 2017). Using the *sktest*, I find a significant difference from a normal distribution (Pr < 0.01). However, this should not be too big a worry in a relatively large sample. We can also look at the distribution graphically. Figure 2 shows a histogram of the dependent variable. The distribution is positively skewed, because most values are at the lower range and there is a tail to the right. Stata displays values for *skewness* as well as *kurtosis*, which is a measurement of how thick the tail of the distribution is. In a normal distribution, those values are zero and three (Mehmetoglu & Jakobsen, 2017). The variable has a skewness of 3.4 and kurtosis of close to 20. Kurtosis values higher than ten are a potential cause for concern (Midtbø, 2012).

Figure 2: Histogram of renewable electricity output



One alternative is to log transform the variable. Log transformation makes distributions more normal (Mehmetoglu & Jakobsen, 2017). However, there are reasons not to do this. First of all, it is not a breach of regression assumptions that I do not have a normal distribution. Non-normal distributions are also less of a concern when we use panel data. Second, log transforming a variable makes it harder to interpret the effects. Since the variable is already expressed in percentages, I can show the substantive effects in the analysis in a meaningful way. Log transformation can also make inferences invalid since the original data have been changed (Feng et al., 2014). For these reasons, I do not log transform the dependent variable.

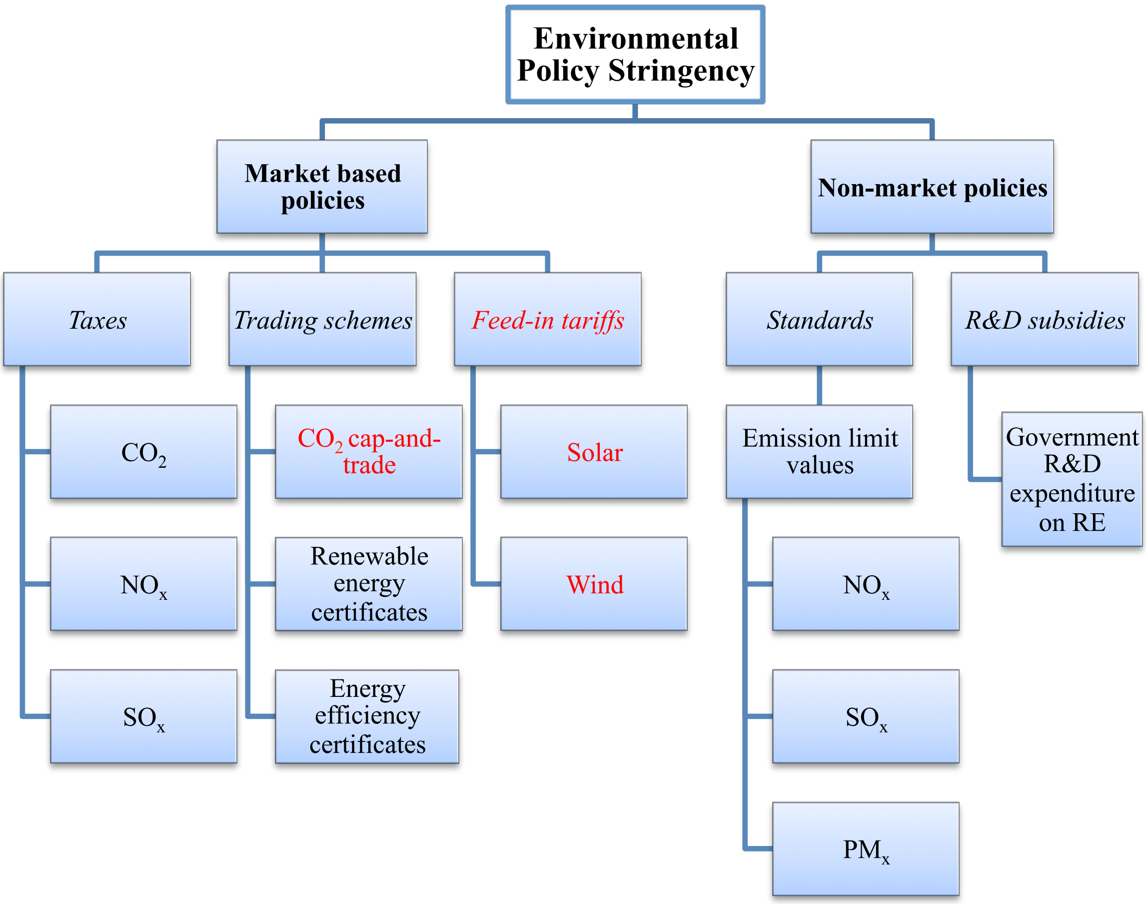
It is worth noting that I examine electricity and not energy production. The reason for this is that the available data does not provide a correct image of the role of renewables in the energy system. Like most other experts, the IEA uses the share of 'total primary energy consumption' to illustrate this in their World Energy Outlook report (IEA, 2018). However, this way of counting power production vastly underestimates the contribution of renewables to the energy supply (Sauar, 2017). For fossil fuels and nuclear power, the IEA counts the 'raw' energy that goes into a power plant or an engine. A lot of that energy, primarily waste heat, is later lost after conversion to 'refined' energy. For solar and wind, on the other hand, the IEA counts the refined energy in the form of electricity produced. This means that their true contribution to the energy mix is three to four times higher than what the IEA reports. Notably, this counting error makes a successful energy transition appear more difficult to achieve than it probably is (Wedege & Sætness, 2018).

Measures of electricity generation do not have the same problems with counting errors discussed above, and therefore I use renewable electricity output as the dependent variables. Yet electricity only makes up around one fifth of total global energy supply (Liebreich, 2018). Furthermore, power production is arguably where we have come the longest way in the energy transition. For other sectors such as transport, heating and agriculture, decarbonizing the energy system may turn out to be more difficult (Patt, 2015). Thus, it is important to keep in mind that the results of this analysis apply to the power sector and may not be transferable to the energy system as a whole.

4.1.2 Independent variables

The independent variables of interest in the analysis are (1) cap-and-trade schemes, (2) aggregate feed-in tariffs, (3) feed-in tariffs for wind energy and (4) feed-in tariffs for solar energy. Among the feed-in tariff variables, I will focus on FITs for wind and solar energy in the discussion because aggregate FIT levels provide limited information. The source of these policy variables is the OECD.Stat database (OECD, no date). I have collected the variables from the *Environmental Policy Stringency Index*, which measures the stringency of different policy instruments across a group of OECD and BRIICS countries. Figure 3 below is an illustration of the index based on Botta and Koźluk (2014, p. 21). Market and non-market policies make up the two wide subcategories of the index. Within those categories we find five types of instruments: taxes, trading schemes, feed-in tariffs, emission standards and subsidies for research and development (R&D). Finally, there are 14 specific policy instruments. The instruments that I use as independent variables in this analysis are marked in red.

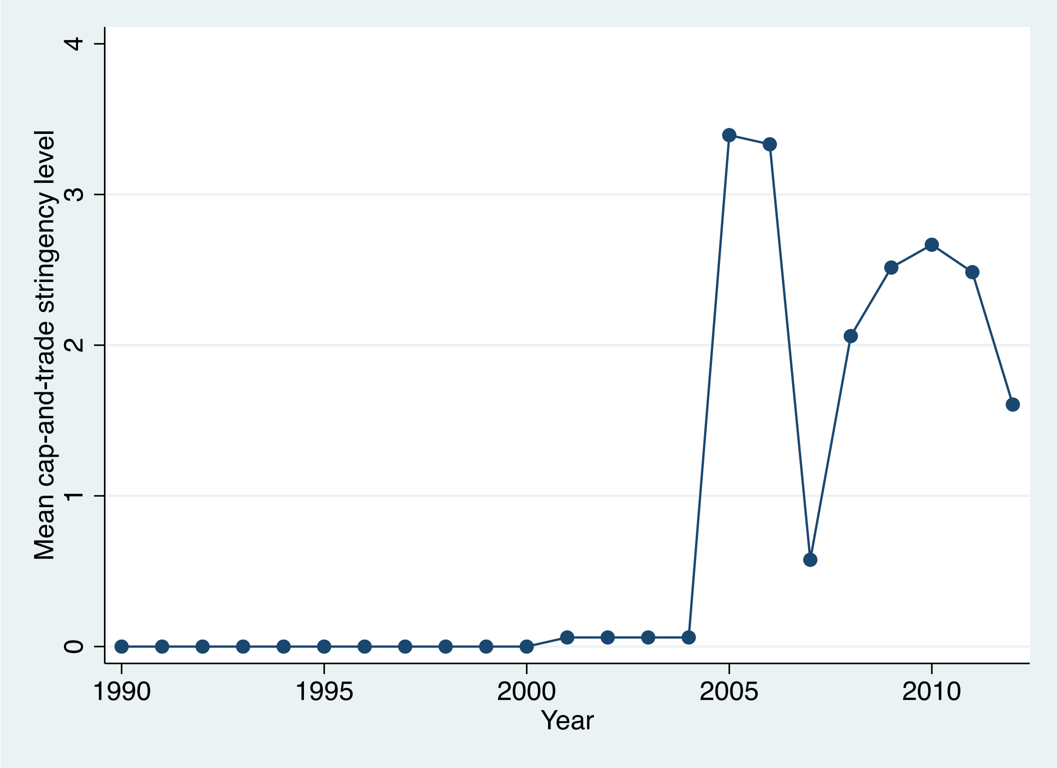
Figure 3: The Environmental Policy Stringency index



In this framework, policies are considered more stringent if they put a higher implicit or explicit cost on environmental damage (Botta and Koźluk, 2014). The OECD assigns a standardized value to the policies based on that cost, normalized by the price of electricity in each country. The resulting seven unique values go from 0 (non-existing) to 6 (most stringent). For cap-and-trade, the cost of environmental damage increases with higher prices for emission permits. For feed-in tariffs, the score increases with higher tariff levels. They increase the cost of polluting indirectly, by providing support for cleaner alternatives.

The first independent variable of interest is *cap-and-trade schemes*. If a country takes part in a trading scheme, it receives a value based on the average price for an emission allowance in a given year. Figure 4 shows how the stringency of cap-and-trade policies in the sample has changed since 1990. There is a huge increase from a mean value of close to zero between 2004 and 2005, owing to the introduction of the EU ETS. In 2007, the mean stringency level falls dramatically because of the price drop in the allowance market. It is worth noting that since the EU ETS is almost the only trading scheme in operation in the sample, most of the countries that have any values other than zero have experienced the same swings[5]. Based on the existing literature I do not expect any significant effects of cap-and-trade schemes on the dependent variable (H1).

Figure 4: Mean stringency level of cap-and-trade schemes, 1990-2012



The second independent variable of interest is *feed-in tariffs* (aggregate). Its value is based on the amount of Euros paid per kilowatthour (kWh) of electricity produced from wind or solar energy in a given year. The mean level of FIT stringency over time is illustrated in figure 5. The figure shows that feed-in tariff levels have evolved much more steadily than cap-and-trade prices. The average tariff has increased significantly since they were first introduced in the early 1990s with very few dips. I expect a positive association between higher feed-in tariffs and higher renewable electricity output, based on the existing literature presented (H2).

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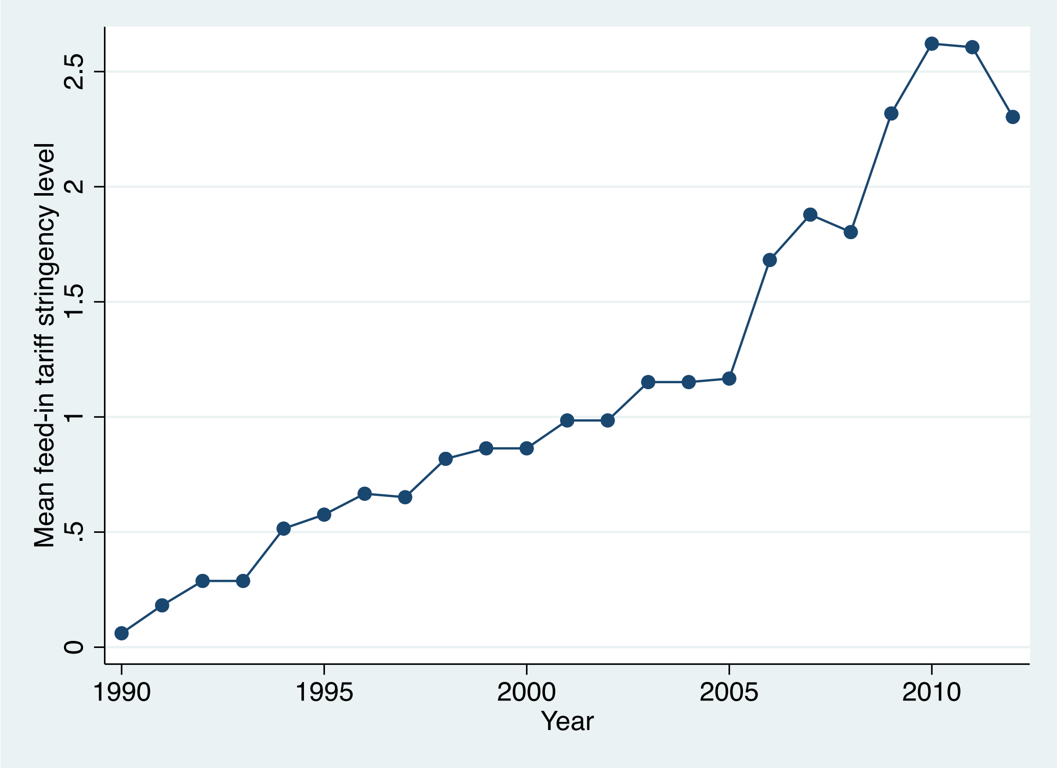
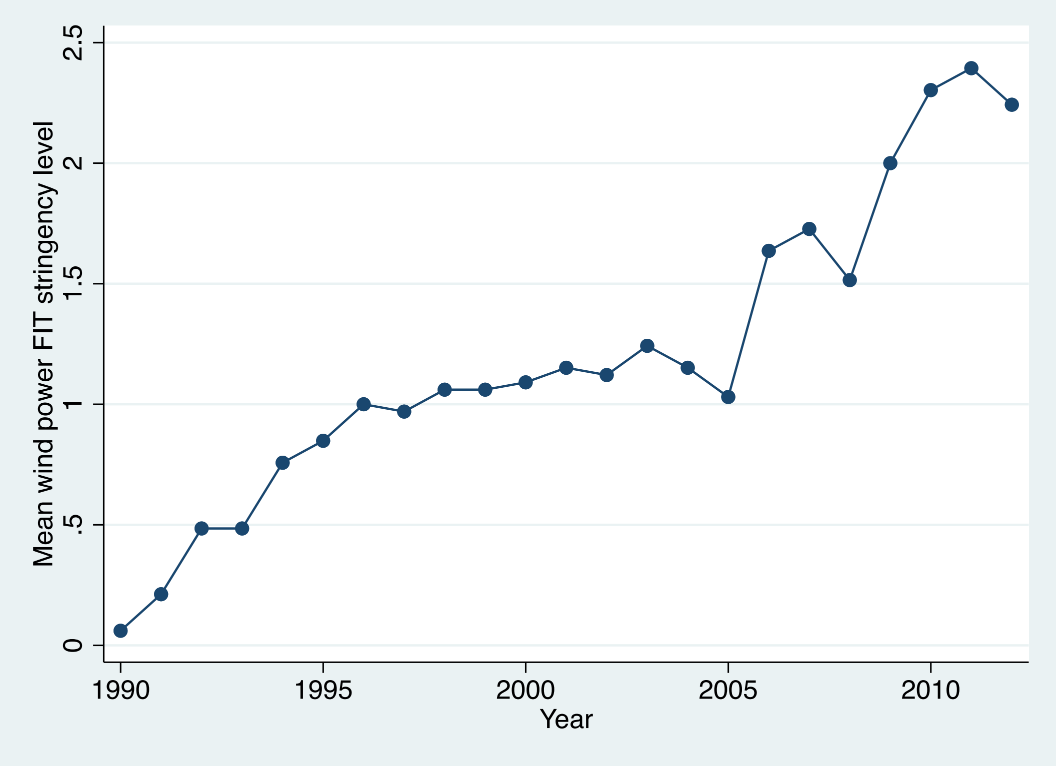
[5] The values for these countries go from zero in 2004 to six in 2005 and 2006, then dropping to one in 2007 before increasing again to around four in 2008.

Figure 5: Mean stringency level of feed-in tariffs, 1990-2012



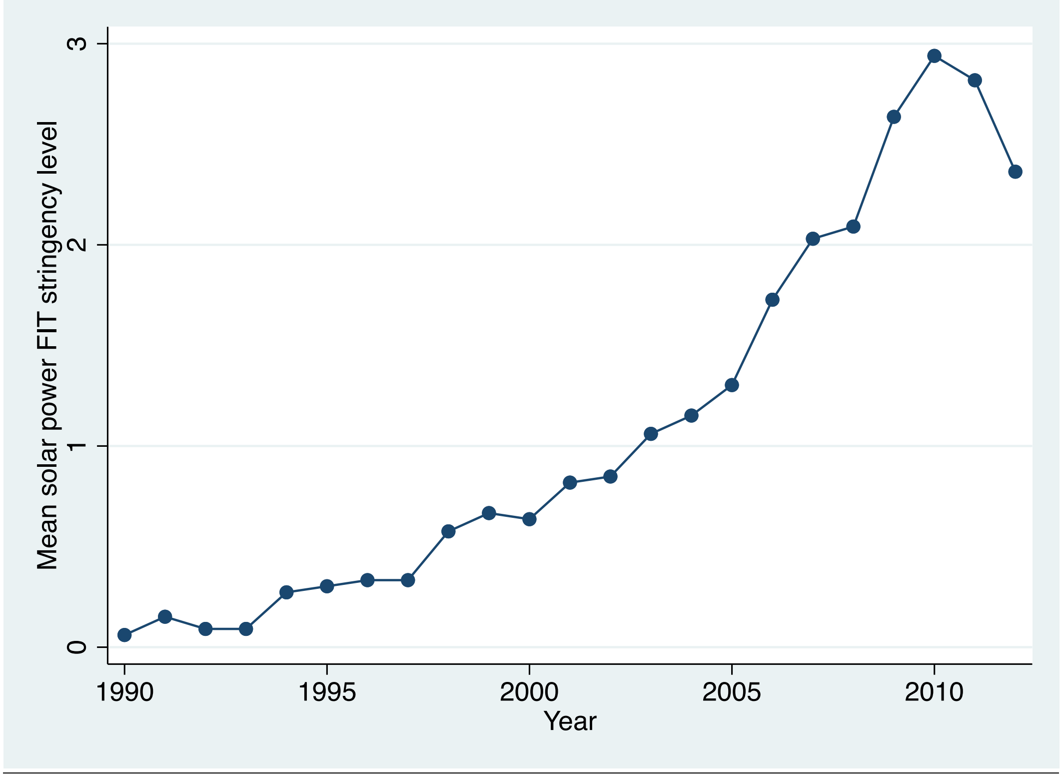
The third independent variable is *feed-in tariffs for wind energy*. This variable measures the stringency of FITs for wind power production alone. Figure 6 shows that the average value over time is very similar to figure 5 for aggregate FITs, but we can also see that there have been a couple of tariff reductions in the sample period. Nevertheless, the overall picture is that the average feed-in tariff stringency has increased since 1990. As with FITs overall, I expect a positive association between feed-in tariffs for wind energy and the dependent variable.

Figure 6: Mean stringency level of feed-in tariffs for wind energy, 1990-2012



The final independent variable of interest is *feed-in tariffs for solar energy*. Figure 6 shows that it has developed similarly as wind energy over time but with almost no dips, steadily increasing from a level of almost zero in the 1990s. However, there is a small reduction in mean solar FIT levels after 2010. This reduction is also visible for wind energy and is most likely caused by the phase-out or reduction of FITs in some European countries after the financial crisis. I also expect a positive association between feed-in tariffs for solar energy and RE output.

Figure 7: Mean stringency level of feed-in tariffs for solar energy, 1990-2012



4.1.3 Control variables

One of the biggest challenges for regression analysis is *spurious relationships* between variables. An association between variable X and variable Y may in reality be the result of an unobserved variable Z (Mehmetoglu & Jakobsen, 2017). In order to avoid problems with spurious relationships, I control for several factors that I expect to have an impact on renewable electricity production. Since the dependent variable in the analysis concerns the power sector, all independent variables must also be related to electricity production. This means that the other policy instruments in the EPS index (see figure 3) should not be used as controls. For instance, nearly every country that has implemented a carbon tax has exempted power production from the tax because they participate in the EU ETS (Carbon Tax Center, no date). The emission standards in the EPS index are directed towards coal power plants, but they only cover particulate matter (PM_x), sulfur oxide (SO_x) and nitrogen oxides (NO_x). Since I am interested in examining impacts on climate change, these emissions are not of much relevance to the research question.

There are four control variables in the analysis. In most of the empirical studies of renewable energy deployment mentioned above, researchers have used a lot more controls. Achen

(2005) calls this a ‘garbage-can’ approach to regression analysis: “In the absence of careful supporting argument, the results belong in the statistical rubbish bin” (Achen, 2005, p. 336). He argues that we should use fewer control variables, so that we can be more certain about the relationships between them. We should base our arguments on formal theory or rigorous data analysis. Due to this, I leave out several control variables that have usually been included in studies of RE output. For instance, I do not control for the influence of fossil fuel industry in a country. This is partly due to the lack of an appropriate indicator. I also leave out countries’ import dependency, a widely used proxy variable for energy security needs. One reason is that this variable also measures imports of oil and gas, which may bias the results.

There are two plausible spurious relationships that I want to control for. Firstly, the level of welfare in a country can influence both political decisions and the use of energy (Carley et al., 2017). I use three variables to capture different aspects of income levels and energy consumption. I collect those variables from the WDI database (World Bank, no date). Secondly, I suspect that research and development spending may affect the relationship between the policies of interest, especially feed-in tariffs, and renewable electricity output. Therefore, the final control variable is investments in R&D for renewable energy technologies, which is collected from the EPS index (OECD, no date).

The first control is *GDP per capita*, measured in constant 2010 US dollars. It measures gross domestic product, which is the total value of all goods and services in the economy, divided by population. I include this variable because the relationship between energy policies and renewable electricity output may be affected by national income. Wealthier countries can invest more in energy technology research and often spend more on deployment of renewables (Aguirre & Ibikunle, 2014). Indeed, most of the growth in solar and wind energy generation so far has happened in high-income countries (Best & Burke, 2018). However, increasing income levels also leads to higher energy demand, which may induce governments to invest more in fossil fuels (Basher, Masini & Aflaki, 2015). Some authors also find that GDP per capita does not have any empirical impact on RE development (e.g. Dong, 2012). Yet in a large literature study, national income was the only individual factor to display overall positive effects on renewable energy deployment (Şener et al., 2018). I therefore expect GDP per capita to promote higher renewable electricity output.

The second control variable is *annual GDP growth* per capita, measured in percentage change. A separate, large strand of literature exists on the two-way relationship between growth and renewables. Increased economic growth should normally lead to increased energy use, which again affects renewable energy shares. Kilinc-Ata (2016) chooses growth over absolute income levels because GDP per capita is non-stationary. Otherwise not many authors include this variable. However, yearly growth levels may be a better predictor of electricity output than the absolute level of economic activity (Tobin & Cho, 2010). If a country experiences abnormally high economic growth in a given year, it may have a particularly big impact on renewable electricity output. As with GDP per capita, I expect a positive influence from GDP growth but cannot be certain that there will be any significant effect (Kilinc-Ata, 2016).

The third control variable is *electricity use*, measured in kWh per capita. This variable specifically controls for factors such as population growth and urbanization, which tend to increase the demand for electricity. Its effect on renewable electricity output could be positive or negative depending on what energy sources a country invests in. If governments need to respond to large electricity demand cost-effectively, they may decide to adopt more conventional energy rather than invest in renewables (Kilinc-Ata, 2016). Since it is not clear whether its effect is positive or negative, I do not expect electricity consumption to display a significant impact on renewable electricity output.

The fourth and final control variable is *R&D subsidies for renewable energy*. It measures annual government expenditures on R&D for renewable energy technologies as a percentage of GDP. Like the other policy instruments, it takes on values from zero to six. Public investments in research and development are considered very important to the development of renewable energy technologies (Kavlak et al., 2018). However, previous studies have not found significant effects of renewable energy R&D investments (e.g. Aguirre & Ibikunle, 2014). Therefore, I do not expect R&D subsidies to have a significant impact on renewable electricity output.

Table 1 displays descriptive statistics for all main variables used in the analysis. There are 759 observations in total. The mean value of the dependent variable, renewable electricity output, is around three percent of total output. The standard deviation is around five percentage points. In other words, most countries in this period produced very little electricity from renewable sources apart from hydropower. The independent variables of interest all have relatively low mean values, considering that the minimum value is zero and the maximum value is six. Both trading schemes and FITs for solar and wind have mean values around one on the stringency scale.

Table 1: Descriptive statistics

Variables	N	Mean	Std. dev.	Min	Max
Renewable electricity output (%)	759	3.362	5.076	0	48.27
GDP per capita	756	28986.16	20045.16	530.9	91617.28
GDP annual growth (%)	752	2.820	3.512	-14.53	14.23
Electricity use	759	6764.41	5087.2	162.5	25591.61
Cap-and-trade	759	0.821	1.781	0	6
Feed-in tariffs	759	1.149	1.787	0	6
FIT wind power	759	1.198	1.958	0	6
FIT solar power	759	1.100	1.920	0	6
R&D subsidies for renewables	759	1.887	1.241	0	6

4.2 Method

The standard way of performing regression analysis involves using *ordinary least squares* (OLS) estimation. OLS regression is built upon some basic assumptions. If these assumptions do not hold in a particular dataset, the researcher must choose a different specification. Most of the assumptions relate to the errors, also known as *residuals*:

> Ordinary least squares is optimal (best linear unbiased) for TSCS models if the errors are assumed to be generated in an uncomplicated ("spherical") manner. In particular, for OLS to be optimal it is necessary to assume that all the error processes have the same variance (homoscedasticity) and that all of the error processes are independent of each other (Beck & Katz, 1995, p. 636).

In practice, regular OLS is normally not well suited to analyze TSCS data (Beck & Katz, 1995). In such data, residuals tend to be heteroskedastic or correlated across time or units. Without correcting for such problems, the researcher risks underestimating standard errors and concluding wrongly about the statistical significance of her findings (Mehmetoglu & Jakobsen, 2017). We need to make sure that the standard errors are correct in order to get a clear image of the statistical variability involved in our findings (Beck & Katz, 1995). There are several different estimators to choose from, and the choice has large impacts on the results that one finds (Reed & Ye, 2011).

In order to decide which estimator to use, I perform a series of tests. The results of these tests lead me to choose a two-way fixed effects-model with a lagged dependent variable for analyzing the relationship between energy policies and renewable electricity deployment.

4.2.1 Estimator choice

I begin by checking for *multicollinearity* in the model. Independent variables must not be perfectly or very highly correlated, or estimation results will be biased (Mehmetoglu & Jakobsen, 2017). In other words, we want to avoid having several X-variables that represent the same phenomenon. I test for multicollinearity by checking the *variance inflation factor* (VIF) of the variables. No variable in the model should have VIF values higher than five. Here, the mean VIF is 2.03, and the highest value is 3.41 for *GDP per capita*. Multicollinearity is not a problem in the model.

If specific time shocks influence the values of the dependent variable, we should control for the effect of time (Torres-Reyna, 2007). As mentioned, 2008 was a decisive year for renewable energy because of the oil price shock and the Kyoto Protocol coming into force. The financial crisis, which happened at the same time, is likely to have affected energy policies and energy production as well (Basher, Masini & Afliki, 2015). Furthermore, there may have been an increase in RE generation around 2011 because of the Fukushima accident that turned Germany in particular against nuclear energy (Morris & Jungjohann, 2016). I include year dummies in the model and run *testparm*, which tests whether their total effect is equal to zero. The p-value is less than 0.01, which means that the year dummies have a significant impact on renewable electricity output. By keeping the dummies in the model I estimate both country fixed effects and time fixed effects, also known as a *two-way fixed effects model* (Park, 2011).

Table 2 shows the results of a series of further specification tests, both with and without the year dummies included in the regression[6].

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[6] The tests were performed on the variables in model 2 (see section 5.1).

Table 2: Model specification tests

Test	No year dummies	Year dummies
Groupwise heteroscedasticity (*Modified Wald test*)	74448.88***	6198.07***
Autocorrelation (*Wooldridge test*)	70.99***	
Cross-sectional correlation (*Pesaran CD test*)	17.24***	3.26***
Fixed vs. random effects (*Hausman test*)	90.17***	

*** p<0.01, ** p<0.05, * p<0.1
Modified Wald test: H_0 = no groupwise heteroscedasticity
Wooldridge test: H_0 = no autocorrelation
Pesaran CD test: H_0 = no cross-sectional correlation
Hausman test: H_0 = random effects model is consistent

The first problem I test for is *heteroscedasticity*. Residuals should be homoscedastic, which means that the variance should be the same for low and high values (Mehmetoglu & Jakobsen, 2017). In panel data we encounter the additional problem of *groupwise heteroscedasticity*, which means that units have different levels of variance (Baum, 2001). Constant variance is one of the assumptions of OLS regression analysis. The null hypothesis of no groupwise heteroscedasticity is rejected both with and without year dummies in the regression equation. I should therefore control for heteroskedasticity.

Secondly, I examine whether *autocorrelation* is a problem in the model. Autocorrelation or serial correlation means that the residuals of each unit correlate over time (Mehmetoglu & Jakobsen, 2017). This is another violation of OLS assumptions; residuals should be independent of each other. The Wooldridge test for first order autocorrelation produces a highly significant result. Thus, I can reject the null hypothesis and conclude that the residuals are serially correlated.

Cross-sectional correlation is a third issue that is typically present in geographical data (Mehmetoglu & Jakobsen, 2017). Cross-sectional correlation[7] means that the residuals of different units are correlated (Beck & Katz, 1995). It is especially important to control for this form of correlation in TSCS data where the units are countries. There is often a considerable amount of mutual dependence between countries, especially neighboring ones (Hoechle, 2007). Globalization has led to increasing interdependencies between many economies, which

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[7] Cross-sectional correlation is also referred to in the literature as *contemporaneous correlation* (Beck & Katz, 1995), *cross-sectional dependence* or *spatial dependence* (Hoechle, 2007).

means that they often share many traits and tend to behave similarly (De Hoyos & Sarafidis, 2006). In particular, energy policies and renewable energy deployment may vary similarly between countries due to international commitments and institutional regulations such as EU directives (Marques & Fuinhas, 2012).

I use Pesaran's CD test to examine whether cross-sectional correlation is present in the model (Hoechle, 2007). The null hypothesis is that the units are independent of each other. The test statistic is highly significant both with and without year dummies in the model (Pr < 0.01). The average absolute correlation between the units is relatively high in both cases (< 0.45). This means that the residuals are correlated. In fact, some argue that the Pesaran test has low statistical power and may report less cross-sectional correlation that what is really present in the data (De Hoyos & Sarafidis, 2006). The alternative tests of Frees and Friedman both produce highly significant results as well. Cross-sectional correlation is clearly a problem in the model.

TSCS data are vulnerable to another problem called *non-stationarity* (Mehmetoglu & Jakobsen, 2017). Stationary data, also known as 'white noise', vary randomly around the mean. Non-stationary data, on the other hand, have a trend line in one direction over time. This is known as a 'random walk'. The problem with non-stationarity is that we risk finding a spurious association between two variables simply because both have a time trend. According to the World Bank, most countries have increased their environmental policy stringency since 1990 (Botta & Koźluk, 2014). I have already noted that the dependent variable, renewable electricity output, has an upward trend (see figure 1). In fact, empirical research has shown that the time trend of non-hydro renewable electricity output in most OECD countries is not stationary between 1990 and 2012 (Basher, Masini & Aflaki, 2015). Thus, it is possible that I will find a spurious relationship between these variables if left unchecked.

The test for non-stationarity, also known as *unit root*, is the augmented Dickey-Fuller (ADF) test (Mehmetoglu & Jakobsen, 2017). The null hypothesis is that the variable is non-stationary. I test for unit roots in the dependent variable for each unit separately using a one-year lag. The test results show that I cannot reject the null hypothesis for any of the units. All countries in the sample have non-stationary distributions.

The common solution to non-stationarity is to include a lagged dependent variable (LDV) in the regression as an independent variable (Mehmetoglu & Jakobsen, 2017). Since the value of a variable last year is usually very close to its value the next year, we often include that value as an explanatory variable of its own. This way, we control for several unobserved factors that are hard to identify. Yet in some cases, we need a different lag than one time unit. In order to decide, I look at correlograms for each of the units. Unsurprisingly, the correlation is highest for the previous years' values. Therefore, I use a one-year lag in the analysis.

One potential issue with a lagged dependent variable is that its inclusion has such a large impact on the other independent variables in the analysis (Achen, 2000). This is especially problematic if autocorrelation is present. Including a LDV may lead to a large reduction of the coefficients of other independent variables, even turning positive effects into negative effects and vice versa. However, according to Beck and Katz (2011, p. 350-351), "there is nothing about lagged dependent variables that makes them generically harmful". As long as researchers pay close attention to their specifications, it is possible to use them appropriately in many models. They also provide evidence from Monte Carlo simulations that LDV models with fixed effects produce consistent results when the number of time points is sufficiently large (T > 20).

Finally, I also use one-year lags for the independent variables in the analysis. In many cases, it is likely that it takes some time before the effects of explanatory factors materialize in the dependent variable (Mehmetoglu & Jakobsen, 2017). This way, I model causality more directly. In any case, I have to lag the X-variables since I have included an LDV to make sure that X comes before Y.

4.2.2 The fixed effects model

There are two main ways to try to solve the problem of spurious relationships in regression analysis (Mehmetoglu & Jakobsen, 2017). First, we can include the relevant missing variables as control variables in the model. However, we often do not know what all the relevant variables are. This approach depends on identifying all the explanatory factors that have an impact on variable Y, which is normally very difficult. The second solution is much more simple. It allows us to control for all the unobserved independent variables that do not vary over time. This estimation method is called a *fixed effects* (FE) model.

Fixed effects models allow us to control for *unit heterogeneity*. This means controlling for unobserved time-constant variables that can influence the dependent variable (Wilson & Butler, 2007). If the researcher is aware of all the explanatory factors that affect Y, it is better to model them directly. However, in almost all cases there are variables unknown to the researcher that have a significant effect on the dependent variable. Controlling for unit heterogeneity takes into account local factors that can be hard to identify. In the case of renewable energy production in this analysis, fixed effects control for such things as natural resource potential and static environmental attitudes (Jenner et al., 2013).

In a fixed effects model, we essentially include dummies for all units in the sample[8] (Mehmetoglu & Jakobsen, 2017). This way, we account for all explanatory variables that are constant over time, or all the 'fixed effects'. The remaining variation is only within the units, as changes from the mean value. In FE regression, the actual procedure is to estimate unit means, generate new variables measuring changes from the mean and regress the transformed variables (Park, 2011). We refer to this method as *within estimation*. Since time-constant variation is removed, we can only include variables that vary over time in a FE model. Crucially, this means that we interpret the coefficients like this: "for a given country, as X varies *across time* by one unit, Y increases or decreases by β units" (Bartels, 2008, p. 6).

The regression equation for a FE model is:

$$Y_{it} = \beta_1 X_{it} + \alpha_i + u_{it}$$

Where Y_{it} is the value of the dependent variable for unit i at time t; X_{it} is an independent variable and β_1 is its coefficient; α_i is the unit-specific unknown intercept; and u_{it} is the error term (Torres-Reyna, 2007).

Fixed effects models are appropriate when we suspect that spurious relationships plague our data (Mehmetoglu & Jakobsen, 2017). The central reason for choosing a FE model is that we can control for all time-constant effects, which makes it much easier to identify the direct impacts of our explanatory variables on the dependent variable. The disadvantage, however, is directly related to that advantage: Since we eliminate the time-constant variation, we cannot model variables that do not change over time. In many cases, the theoretically interesting

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[8] A similar estimation technique using actual dummy variables is *least squares dummy variable* regression (Wilson & Butler, 2007).

variables are time-constant. For example, cross-country differences in institutional frameworks or geography may have a large impact on variables such as renewable electricity output. Arguably, the differences between countries are the theoretically most interesting ones rather than each country's variation across years (Plümper, Troeger & Manow, 2005).

Another problem for FE models is that slowly changing variables will rarely show statistically significant effects (Wilson & Butler, 2007). The fixed effects will inflate their standard errors, leading to increased risk of committing type II errors by incorrectly failing to reject the null hypothesis. As we have seen, feed-in tariff stringency has changed slowly over time and can therefore be vulnerable to this error. However, it is more important to avoid a type I error, rejecting a true null hypothesis (Wilson & Butler, 2007). Using fixed effects models makes it harder to find significant regression results, but any significant findings will on the other hand be all the more trustworthy for it.

Reed and Ye (2011) use Monte Carlo simulations to provide estimator recommendations for datasets with relatively few units and time periods ($N < 100$ and T between 10 and 25). They study fixed effects models where both autocorrelation and cross-sectional correlation is present using simulations mimicking real-world data. When the researcher is most concerned with estimating confidence intervals covering the true parameter values, OLS with robust standard errors is one of their recommended estimators.

We test for fixed effects in the model using an F-test, which compares a FE model to ordinary OLS (Park, 2011). The null hypothesis is that the impact of all country dummies is equal to zero. The test result is highly significant ($p < 0.01$). The country dummy variables have a significant effect on renewable electricity output and should be included in the analysis.

When a model has omitted variables, we can choose between a fixed effects model and a *random effects* model (Mehmetoglu & Jakobsen, 2017). Unlike FE, random effects models can account for variation both within units and between units. However, they are not consistent if an unmeasured variable is correlated with one or more X-variables. Usually we use fixed effects models with TSCS data, because the units are not drawn from a larger population (Beck, 2001). The Hausman test checks formally whether we should use a FE or a RE model. The null hypothesis is that the random effects model gives consistent results. If the p-value is significant, the error term is correlated with an independent variable and we should use fixed effects. Here, the p-value is significant at the .05 level (p = 0.02), and thus the model should be estimated using fixed effects.

Fixed effects regression models with a lagged dependent variable and dummy variables for units and time periods deal with all the typical issues in panel data analysis. However, there are drawbacks to this approach. Using so many control mechanisms comes with the risk of absorbing most of the interesting variation in the data (Plümper et al., 2005). Country fixed effects may remove too much cross-sectional variance, and the LDV plus time fixed effects may remove too much time series variance. In short, this model specification may prevent me from finding statistically significant relationships between variables. On the other hand, I can be confident about the significance of the effects that I actually find.

4.2.3 Final model presentation

The regression equation for the two-way fixed effects model with a lagged dependent variable becomes:

$$Y_{it} = \beta_0 + \beta_1 Y_{it-1} + \beta_2 X_{1it-1} + \beta_3 X_{2it-1} + \beta_4 X_{3it-1} + \beta_5 X_{4it-1} + \beta_6 X_{5it-1} + \beta_7 X_{6it-1} + \beta_9 D_{1it} + \beta_{10} D_{2it} + \epsilon_{it}$$

Where $\beta_1 Y_{it-1}$ is the coefficient for the LDV, $\beta_{(2,\ldots,n)} X_{1(1,\ldots,n)it-1}\ldots$ are the coefficients for the independent variables, $\beta_9 D_{1it}$ and $\beta_{10} D_{2it}$ are the coefficients for the unit and time dummy variables and ϵ is the error term.

5. Results

5.1 Main models

5.1.1 Individual effects

Table 3 presents the regression results of my two main models. In model 1, I test the effects of cap-and-trade schemes versus aggregate feed-in tariffs. In model 2, I divide FITs up by energy source and test the impacts of subsidies for wind energy and solar energy separately. The effects of the year dummies are not shown here (for the complete table, see Appendix A).

Table 3: The relationship between policy stringency and renewable electricity output, 1990-2012

Variables	**Model 1**	**Model 2**
Renewable electricity output (t-1)	1.0922***	1.0871***
(% of total)	(0.0144)	(0.0146)
Cap-and-trade schemes (t-1)	0.0644**	0.0576*
	(0.0291)	(0.0286)
Feed-in tariffs (t-1)	0.0201	
	(0.0228)	
Feed-in tariffs for wind energy (t-1)		-0.0345*
		(0.0183)
Feed-in tariffs for solar energy (t-1)		0.0599**
		(0.0248)
GDP per capita (t-1)	-0.0000	-0.0000
	(0.0000)	(0.0000)
Annual GDP growth (t-1)	-0.0139	-0.0132
(Annual %)	(0.0083)	(0.0083)
Electricity use (t-1)	0.0000	0.0000
(kWh per capita)	(0.0001)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0493	-0.0482
(% of GDP)	(0.0448)	(0.0436)
Constant	0.1761	0.1875
	(0.4018)	(0.3967)
Country FE	YES	YES
Time FE	YES	YES
N		
Number of observations	719	719
Number of countries	33	33
Goodness-of-fit		
R^2 (within)	0.9576	0.9578
F-test	19093.67***	20287.78***
rho	0.22	0.2045

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Starting with goodness-of-fit, the F-tests show that the coefficients together are significantly different from zero in both model 1 and 2. The *rho* value indicates that within-unit differences are responsible for around 20 percent of the variance in the data. This means that the fixed effect model can only explain a limited part of the differences in RE output. From the R^2 values, we see that both models seem to explain more than 90 percent of the variance in renewable electricity output in the data. However, since the intercept is suppressed, R^2 values in fixed effects models are often incorrect (Park, 2011). We also expect the lagged dependent variable to explain a lot of the variance. Running a model without the LDV (not shown) produces an R^2 value of around 57 percent, which seems like a more reasonable level of explained variance. Furthermore, running an OLS model with the same variables produces an R^2 value of around 40 percent.

Even though they are not presented in table 3, it is worth noting that several year dummies have a positive, statistically significant independent effect on the dependent variable. This underscores the importance of controlling for the effects of time. The dummy variables for 2004, 2005, 2008, 2009, 2011 and 2012 are highly significant (see table A1). The first two are probably significant due to the introduction of the EU ETS. As mentioned, the financial crisis and the introduction of the Kyoto Protocol may also have had an impact on renewable electricity output. The significant increases in 2008 and 2009 are therefore not surprising. As for 2011 and 2012, this probably reflects the increasing headway that solar and wind energy have made in recent years, and perhaps the Fukushima accident.

The lagged dependent variable has a large, positive effect at the .01 significance level in both models. This is not surprising. We would expect that the level of renewable electricity production in one year closely resembles that of the year before. This also confirms that the values of the dependent variable are serially correlated. The LDV coefficient is much larger than any other coefficient in both models, which means that this variable soaks up a lot of variation. Yet there is little use in interpreting the coefficient substantively. Its purpose is only to control for the non-stationary time series of the Y variable. When looking at the effects of the other variables, I am looking at the rest-variance that is not explained by the LDV.

The control variables mostly display the expected effects. None of them have a statistically significant impact on renewable electricity output in any of the models. For electricity use and renewable energy R&D investments, this is in line with what I expect from theory and existing literature, especially since the model should be very robust to spurious relationships. It would be surprising if the negative effect found here from R&D investments was significant, but the lack of a substantial impact is in line with previous research. The GDP variables are not significant, which was not completely expected. The coefficients have negative signs, but this appears to be a result of randomness and not a substantial effect. The relationship between increased electricity use and renewable energy is also not significant. This means that the energy policy variables of interest are the only ones to produce a significant change in the dependent variable in this analysis. That alone makes the following conclusions more robust.

The first independent variable of interest, *cap-and-trade schemes*, has a positive effect on renewable electricity output. Controlled for several other variables including aggregate feed-in tariff levels, the coefficient is statistically significant at the .05 level. In model 2, the p-value is just above the conventional alpha level of five percent. That is a basis for some caution in interpretation. The substantive interpretation of this result is that for a given country, a one unit increase in cap-and-trade stringency across time should lead to an average 0.06 percent increase in RE output, ceteris paribus ($p = 0.052$). This impact is very small, but we should keep in mind that the lagged dependent variable absorbs a lot of variance. Besides, we are only looking at the 'within' effect of trading schemes. Thus, *I must reject H1*: in this sample, cap-and-trade schemes have in fact effectively promoted higher shares of renewable electricity production.

There is no statistically significant effect of *aggregate feed-in tariffs* in model 1. The coefficient has a positive sign indicating that there may be a beneficial impact from FITs, but the standard errors are too big to give a reliable answer. From this, it appears that feed-in tariffs have not effectively promoted higher shares of renewable electricity output. This goes against H2. The lack of a significant effect from feed-in tariffs overall is an interesting finding. However, previous research suggests that FITs for wind and solar energy may have different outcomes. Therefore, I do not study this variable in any other models but focus instead on feed-in tariffs for wind and solar energy individually.

Moving on to *feed-in-tariffs for wind energy*, I find a negative effect that is significant at the .1 level in model 2. This indicates that wind energy FITs are in fact associated with lower levels of renewable electricity production. On average, increasing wind energy FIT should lead to 0.03 percent less RE output (p = 0.068). The p-value is high enough that this may be a result of statistical randomness. Yet this contradicts the theoretical and empirical literature, which mostly holds that feed-in-tariffs have been beneficial for renewable energy production.

However, I finally find that *feed-in-tariffs for solar energy* have a positive effect on renewable electricity production that is significant at the .05 level. Substantively, a country that increases its solar energy FIT by one unit across time can expect an increase in renewable electricity output of 0.06 percent (p = 0.022). Again, the effect is small, but it is not realistic because there is an LDV in the model. The coefficient is the same as for cap-and-trade, but because of the smaller standard errors I can be even more confident that it is a real effect. *This finding provides partial support for H2:* In the case of solar energy, more stringent feed-in-tariffs have effectively promoted higher shares of renewable electricity output.

5.1.2 Interaction

It is possible that some of the variables interact with each other to affect the dependent variable. For instance, we have seen that both cap-and-trade schemes and feed-in-tariffs for solar energy have a significant impact on renewable electricity output. Could it be that a combination of those two policy instruments is even more effective at promoting renewable energy? I test this possibility by including an interaction variable in the regression equation. The results of model 3 with an interaction between cap-and-trade and FITs for solar energy are presented in table 4. An expanded model including year dummy effects can be found in table A2 (Appendix A).

Model 3 has an R^2 value of 95.8 percent, only a minimal increase from model 1. There are no changes in the effects of the control variables. The cap-and-trade variable is no longer significant in this model, while the solar energy FIT variable is significant at the .1 level. The coefficient to pay attention to, however, is the interaction variable (*cap-and-trade * feed-in tariffs for solar energy*). It has a positive effect that is only just significant at the .05 level. Increased policy stringency for a combination of a trading scheme and an FIT policy should on average increase the share of renewable electricity generation by an additional 0.02 percent (p = 0.05). This is an interesting finding that strengthens the general conclusion that cap-and-trade and feed-in tariffs are both important policies to spur more renewable energy. Apparently, countries that introduce just one of the instruments should see a real increase in renewable electricity output, but countries that combine the two can expect an additional effect.

Table 4: Interaction effects of policy stringency on renewable electricity output, 1990-2012

Variables	**Model 3**
Renewable electricity output (t-1)	1.0865***
(% of total)	(0.0144)
Cap-and-trade schemes (t-1)	0.0460
	(0.0286)
Feed-in tariffs for wind energy (t-1)	-0.0252
	(0.0162)
Feed-in tariffs for solar energy (t-1)	0.0370*
	(0.0200)
GDP per capita (t-1)	-0.0000
	(0.0000)
Annual GDP growth (t-1)	-0.0126
(Annual %)	(0.0084)
Electricity use (t-1)	0.0000
(kWh per capita)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0437
(% of GDP)	(0.0432)
Cap-and-trade * Feed-in tariffs for solar energy	0.0210*
	(0.0103)
Constant	0.1403
	(0.3732)
Country FE	YES
Year FE	YES
N	
Number of observations	719
Number of countries	33
Goodness-of-fit	
R^2	0.9580
F-test	34139.19***
rho	0.1864

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

5.2 Robustness tests

5.2.1 Driscoll-Kraay standard errors

In section 4.2, I noted that cross-sectional correlation could be a potential issue in the analysis. The main models do not account for this. The most important robustness test is therefore to run the main model using Driscoll-Kraay cross-sectional correlation robust standard errors. These standard errors are also robust to heteroskedasticity and some degree of autocorrelation. The resulting model 4 is presented below, in table 5.

Table 5: The relationship between policy stringency and renewable electricity output, 1990-2012 (Driscoll-Kraay standard errors)

Variables	**Model 4**
Renewable electricity output (t-1)	1.0871***
(% of total)	(0.0413)
Cap-and-trade schemes (t-1)	0.0576***
	(0.0179)
Feed-in tariffs for wind energy (t-1)	-0.0345
	(0.0266)
Feed-in tariffs for solar energy (t-1)	0.0599**
	(0.0245)
GDP per capita (t-1)	-0.0000
	(0.0000)
Annual GDP growth (t-1)	-0.0132
(Annual %)	(0.0083)
Electricity use (t-1)	0.0000
(kWh per capita)	(0.0000)
R&D subsidies for renewable energy (t-1)	-0.0482
(% of GDP)	(0.0484)
Constant	0.0000
	(0.0000)
Country FE	YES
Time FE	YES
N	
Number of observations	719
Number of ID	33
Goodness-of-fit	
R^2 (within)	0.9578
F-test	2376.54***

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Controlling for cross-sectional correlation makes very few differences to the model results. The positive impact of cap-and-trade is now highly significant at the .01 level (p = 0.004), while feed-in-tariffs for wind energy no longer significantly reduce renewable electricity output. Solar energy FITs, on the other hand, continue to promote higher shares of renewable energy generation. The p-value for this variable stays remarkably stable below five percent across specifications (p = 0.023).

5.2.2 Controlling for other policy instruments

I explained the decision not to include more energy policy variables in the main models in section 4.1. However, I also test the effects of those instruments as a robustness check. The point here is not to examine the relationship between those policy instruments and the Y variable, but to see if their inclusion changes the effects of the independent variables of interest. I add three variables: *CO_2 taxes*, *renewable energy certificates* (trading schemes for obligations to produce renewable electricity) and *emission standards* (an aggregated measure of emission limit values for NO_x, SO_x and PM_x). The results can be found in Appendix B (table B1).

When I control for other policy instruments, cap-and-trade schemes no longer have a significant impact on renewable electricity output. However, the negative effect of feed-in-tariffs for wind energy remains. The variable is here significant at the .05 level, so I should take this effect seriously. Finally, feed-in-tariffs for solar energy continue to affect renewable electricity output positively. The effect size is still around 0.06 percent, and the p-value is almost exactly the same as in model 1 ($p = 0.023$). So while the result for wind power FITs is not as expected, solar power FITs have a robust positive effect on renewable energy production.

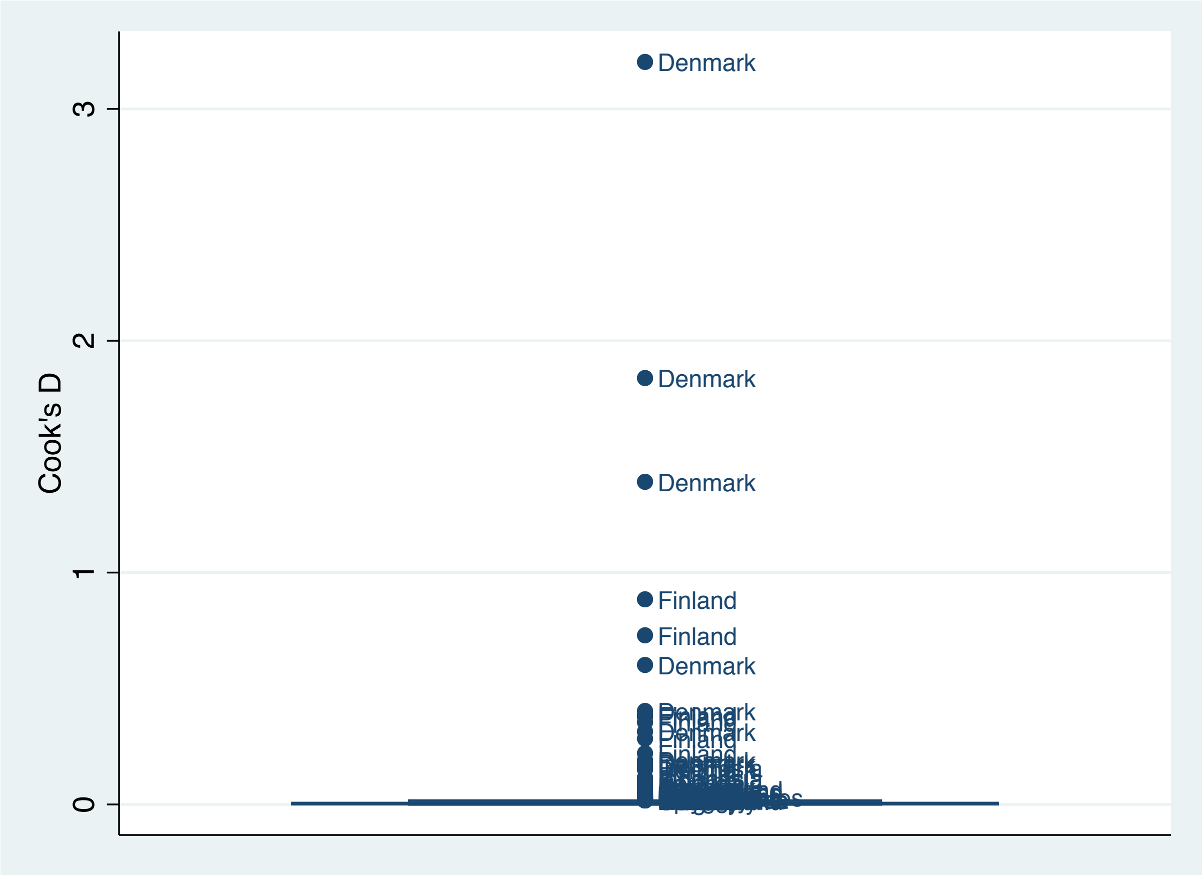
The results for the other policy variables are not of interest to the analysis, but I note that their effects are mostly not significant. Higher CO_2 taxes have not promoted renewable electricity growth since none of the sample countries tax their power sectors. Nor do I find an impact of higher prices in renewable energy certificate trading schemes. On the other hand, more stringent *emission standards* have a large, positive impact on renewable electricity generation at the .05 significance level. Yet as mentioned, this finding is of little interest since the variable does not directly measure GHG emissions.

5.2.3 Influential observations

If one observation has an abnormally big impact on the regression results, it is *influential* (Mehmetoglu & Jakobsen, 2017). By excluding observations with extreme values, we often get a different model outcome. *Cook's distance* is a measure of how much the individual observations affect the whole model. The results of estimating Cook's D for model 1 is presented in figure 7. I have to run the model without cluster-robust standard errors to be able to perform the Cook's D test.

In this case, three observations from Denmark fall above the cut-off point of 1. After dropping those observations, I run the model again for the remaining sample (not shown). The results do not change, other than the fact that the independent variables of interest become more statistically significant than in the original model 1. Cap-and-trade schemes now have a significant effect at the .05 level. Thus, influential observations do not appear to be an issue.

Figure 8: Cook's distance (model 1)



5.2.4 Excluding emerging economies

I included the BRIICS countries in the main model in order to account for differences among industrialized and emerging economies and thus get more widely applicable findings. However, it is possible that the financial and social factors are so different in emerging economies that they disproportionately affect the model results. I examine this potential issue by excluding the BRIICS countries and running the model anew (see table B2).

Solely analyzing the 27 OECD countries produces some small differences from the main model. Cap-and-trade schemes do not have a significant effect on renewable electricity production for this smaller sample. This is somewhat surprising since none of the BRIICS countries use cap-and-trade during the sample time period. The reason could be that there is too little variation in the variable among OECD countries, of which the majority participate in the EU ETS. Meanwhile, the results for feed-in tariffs hold. Wind energy feed-in-tariffs still have a negative effect at the .1 significance level. Meanwhile, more stringent solar tariffs still produce an average increase of 0.06 percent in renewable electricity output across time ($p = 0.043$).

5.2.5 Recoding independent variables

Independent variables with many values may fail to adequately describe the relationship between policy stringency and renewable electricity output. The main models rest on the assumption that the relationship is completely linear, so that all one-unit increases in the X-variables should produce the same outcome in Y. That may be too much to ask. For instance, the value for cap-and-trade in Australia goes from zero to six in 2012 due to the introduction of the federal scheme. It does not make much sense to expect an immediate effect corresponding to such an increase. Therefore, I try to recode the energy policy variables to see if the results change (see table B3).

First, I test the three main independent variables with values zero, one (1-3) and two (4-6). The new variables are called *recoded* (model B3). Feed-in tariffs for wind energy have no significant effect on the dependent variable. However, both cap-and-trade and solar energy FITs are significant at the .05 level. Here, a one-unit increase in policy stringency produces a much larger average increase than in the main models. These results indicate that the effects of these policies are not strictly linear when we follow the scores on the EPS index, but that increasing policy stringency more generally has a very big effect on renewables. For instance, we can say that going from a ‘weak’ trading system to a ‘strong’ one by increasing carbon prices should raise renewable electricity output significantly.

Next, I test whether the results hold for the presence of the policies alone, by recoding all values to only zeros and ones. The new variables are called *binary* (model B4). This leads to some interesting results. Feed-in tariffs for solar energy still have a positive effect and a big coefficient, albeit less significant. However, the coefficient for cap-and-trade is now even bigger and significant at the .01 level. It seems that the marginal effect of increasing policy stringency is quite similar between the two instruments, but the introduction of a trading scheme has a much bigger impact on renewable electricity output than just implementing a solar energy feed-in tariff.

Finally, I try to use longer time lags for the cap-and-trade variable. This is because it may take more than one year for the effects of trading schemes to materialize. In contrast to feed-in tariffs, which we can expect to affect renewable electricity output relatively quickly, cap-and-trade is not such a direct instrument. Power producers may need time to transform their businesses to higher shares of renewable energy. Perhaps it takes two or three years before those decisions have an impact. I test this by recoding the cap-and-trade variable with longer time lags (see table B4). The results do not change in any meaningful way, except that the coefficient is significant at the .05 level for a time lag of three years.

5.2.6 Including hydropower

As a final robustness test, I try a different dependent variable: electricity production from all renewable sources, including hydropower. This too is measured as a percentage share of total annual electricity output and collected from the World Development Indicators (World Bank, no date). As mentioned, there are good reasons to exclude hydropower from the analysis. However, it is interesting to see whether the results of the main models hold for the total share of renewable electricity output. If they do, I am able to make more firm policy recommendations.

When hydropower is included in the Y variable, cap-and-trade schemes have a big, positive effect on renewables that is significant at the .05 level (table B5). Wind energy FITs affect RE production negatively at the .1 level as in model 1. However, the most notable difference is that solar energy FITs have no significant impact on the dependent variable. This is the only model in which feed-in-tariffs for solar power do not promote higher shares of renewables. Clearly, it makes a big difference to the results whether or not one considers hydropower.

6. Discussion

6.1 Explaining the model results

The analysis shows that both increased cap-and-trade prices and higher feed-in tariffs have spurred more renewable power generation. These results are controlled for several relevant factors such as income levels and R&D spending. The fixed effects specification is another precaution against spurious relationships in the models. I have controlled for the common issues associated with the error terms in time series cross-sectional data, and I have included a lagged dependent variable to account for non-stationarity of the unit distributions. Moreover, the results are robust to recoded variables and alternative model specifications. With all these control measures, it could have been hard to find statistically significant results. However, the effects of trading schemes and FITs for solar energy are highly significant in almost all models. There is also an additional interaction effect between the two variables, which indicates that they are the most effective when they are combined. Taken together, these findings strengthen the argument that cap-and-trade and feed-in tariffs are well-suited policy instruments to promote more renewable energy in electricity production.

First of all, the results confirm that policy choices are crucially important for renewable energy adoption. Not one of the four control variables, which are all typically mentioned as central determinants, has an impact on the dependent variable in this analysis. I show that income levels and energy consumption does not influence the use of renewables, and I demonstrate that government spending on R&D is not by itself enough. However, both cap-and-trade schemes and feed-in tariffs are positively associated with RE at very high levels of significance. Since there is no significant effect from a binary variable measuring solar energy FITs, I also emphasize that researchers should always consider policy stringency when they study the effects of energy policies.

The main finding that both cap-and-trade and feed-in tariffs can effectively promote renewable energy confirms what previous empirical research has also indicated. Polzin et al. (2015) found similar results for the relationship between energy policies and annual installed capacity. They conclude that trading schemes are most effective for mature technologies including wind energy, while less mature technologies such as solar PV require support policies such as feed-in tariffs. This analysis seems to indicate a similar pattern, and that may be the reason why the variable for cap-and-trade schemes does not have a highly significant effect in all models. The novelty of this study is that I show that the same effect exists for the *share* of renewable energy and not just installed capacity.

The lack of impact from feed-in tariffs for wind energy is surprising on the surface. On the other hand, there is a plausible explanation for this: Wind energy generally became cost-competitive with fossil fuels before solar energy, and so it may not have been as dependent on policy support, at least not in the last years of the sample period (Best & Burke, 2018). Jenner et al. (2013) note that the LCOE of wind energy was competitive with conventional energy in many countries by the end of the last decade.

6.2 Is the criticism against cap-and-trade unfair?

The positive effect of increased cap-and-trade stringency goes against H1, which states that carbon markets have not effectively promoted renewables. Most experts believe that the EU ETS, the only proper system in existence at the national level in the sample period, has not been a success story so far. The Commision's decision to engage in grandfathering and the extreme price volatility in the first two phases of the scheme led to a vast oversupply of permits that never disappeared in the following years. From this, it seems strange that cap-and-trade is associated with higher levels of renewable electricity output.

However, one should keep in mind that this positive relationship has been reported before in empirical studies. For instance, Yu et al. (2017) studied 60 countries between 2002 and 2013 and found a positive effect from the introduction of an ETS. They attributed the effect to the second phase of the EU ETS. Martin et al. (2015) reviewed the very limited empirical literature on the EU ETS and found a small but significant impact on clean energy innovation in the power sector. Best and Burke (2018) found a positive impact from carbon pricing instruments for a sample of 139 countries using a binary variable. One unique trait of this study is that I find the same positive effect on renewable energy adoption when I account for policy stringency.

One possible reason why cap-and-trade schemes drive renewable energy growth is that the implementation and strengthening of such a scheme can be a powerful signal to the market. The fact that the effect becomes more significant when I lag the independent variable by several years indicates that this is a reasonable explanation. Emission trading provides certainty about the future: Companies are going to have to reduce emissions, and one way to do so is to gradually shift from fossil fuels to renewables. Businesses usually think long-term and probably expect higher carbon prices in the future (Wettestad & Gulbrandsen, 2018). Perhaps the introduction of the EU ETS led companies to go for the 'low hanging fruit', investing more in renewable electricity generation and efficiencies where it was economical and less in highly polluting coal factories.

Since we already see a real impact on renewable energy generation despite fairly low permit prices, the reforms to the EU ETS can potentially make it a much more effective trading scheme. However, experts are unsure whether the reforms are strong enough to avoid the fundamental problem of over-allocation of permits (Evans, 2017). Even though it has grown rapidly since the reform was agreed, it is still unclear how high the carbon price will become in the next years. The introduction of the market stability reserve is likely to reduce the number of available allowances significantly, but perhaps not enough to bring the level of supply in line with demand. If current annual levels of emission reduction in the EU continue, there will be little demand for emissions allowances. Furthermore, environmental organizations have criticized the agreement as too weak for allowing the free allocation of permits to heavy industry and for not implementing strong measures before 2023 (WWF, 2017).

The answer to whether emissions trading can work is actually quite simple: If the carbon price is high enough, businesses will respond by reducing emissions and investing in low-carbon technologies. Apart from this, the experience with cap-and-trade so far offers a few lessons for policies in the future (Schmalensee & Stavins, 2017). From what we have seen in the EU ETS, it is clear that a well-functioning trading scheme must have the necessary rules in place before it goes into action, use reliable data to allocate the appropriate amount of allowances and allow banking of allowances between phases. Generally, for cap-and-trade to be effective the cap must be set low enough and there must be a mechanism to ensure compliance. As this analysis has shown, the design of carbon markets has a big impact on whether or not they are successful at driving low-carbon innovation and lowering emissions.

The definitive test of what cap-and-trade can achieve for climate policy will take place in China (Schjølset, 2017). If the Chinese can implement a truly effective system in the world's largest economy, then carbon trading can be critically important towards the Paris goals.

However, the signals from China are not very encouraging. There will apparently not be a hard cap in the system, which means that there will not be much pressure to reduce emissions (Gan, 2018). Experts believe that the scheme risks running into the familiar problem of over-allocation and that the focus will be on efficiency rather than the large-scale transition to clean energy.

Despite its shortcomings, carbon trading must probably be a part of the way forward in spurring renewables and reducing emissions. Even though the EU ETS has failed to drive large-scale changes in the energy market, it is reasonable to assume that it could have done more if not for the generous support policies that many member countries have used simultaneously (Schjølset, 2017). The effectiveness of feed-in tariffs and other subsidy policies has led to reduced GHG emissions, which has reduced the need for emissions allowances in the EU ETS. In other words, we have perhaps not allowed the carbon market to be as effective as it could have been. Today, only around 20 percent of global GHG emissions face a carbon price based on the implemented and planned pricing policies around the world (World Bank and Ecofys, 2018). Since trading schemes have been effective at promoting renewables, countries should continue to implement more so that we can cover a higher share of emissions worldwide and minimize the risk of carbon leakage from the countries that have pricing policies in place.

Cap-and-trade can do a lot, but it almost certainly cannot get us to net-zero emissions by itself. A steadily increasing price on carbon up to a level where fossil fuels become uneconomical is an effective tool, but it is also likely to be politically unrealistic. For instance, politicians in countries such as Poland and Germany vehemently oppose higher carbon prices because they have large coal industry interests to cater to (Øvrebø, 2016). Since we only have around thirty years to decarbonize the entire global economy in order to uphold the Paris accord, we will need other policies than just carbon pricing.

6.3 Do feed-in tariffs have a role to play in energy policy in the future?

The regression results for feed-in tariff stringency can be interpreted in multiple ways. If we look at aggregate tariff levels, there is no significant effect on renewable electricity output. This would lead me to reject H2. The explanation is that feed-in tariffs for wind energy are negatively associated with RE generation, a result that is significant in some models.

However, I have chosen instead to focus on the positive effect from solar energy FITs, which is consistently highly significant across specifications. It is arguably more relevant to look at feed-in tariffs directed at individual energy technologies since they are supposed to promote those technologies specifically. Based on this, I consider H2 strengthened. In the realm of solar PV, there is a positive relationship between FIT stringency and renewable energy.

One plausible explanation is that feed-in tariffs are very effective in the initial phase of the energy transition. This finding is in line with most other empirical studies of feed-in tariff effectiveness. There seems to be a clear consensus among researchers that FITs are a reliable way to increase renewable energy generation. Notably, I find similar results as Jenner et al. (2013). In their study of 26 EU countries between 1992 and 2008, feed-in tariffs have led to more solar PV installations but not more wind energy. Their independent variable is a self-constructed stringency indicator. Indeed, the authors find that there is no effect from FITs when they do not account for policy stringency, which is the same result as I have found (table B3).

The significantly positive effect of feed-in tariffs for solar energy is even more impressive since they are not specifically meant to increase the share of electricity from renewable sources, only installation rates. In fact, the share of renewable electricity output may vary independent of increasing renewable energy capacity (Jenner et al., 2013). If for instance a country experiences large growth in natural gas markets, then the share of renewables in electricity generation can decrease even though the absolute amount of renewable energy is growing.

The enormous cost reductions mean that renewables may not need so much assistance from policy in the future. Up until the end of the sample period, solar and wind were dependent on government support in order to be competitive with fossil fuels. Now, the costs have come down so much that these technologies are cost-effective by themselves in many places. This also means that the findings in this analysis may no longer be valid in the real world. Even though I have found a significant impact from the policy instruments I studied before 2012, the results cannot be applied to an energy market that is in the middle of a complete transformation. There is definitely less need for subsidies to renewables today than there was when Germany implemented theirs around 2000.

However, it is too early to abandon FITs entirely. Many countries still have no renewable energy sector to speak of and may need a strong support policy to attract investments. And where solar energy has become cost-competitive at a commercial scale, feed-in tariffs can still be critical for small-scale rooftop installations of solar PV. As mentioned, the most important role of FITs is probably not to drive immediate adoption of renewables but to drive down costs (Naam, 2019). When new technologies are cost-competitive with conventional energy, governments can reduce the subsidies or abandon them altogether. But electricity costs vary around the world, so there are many countries that still require subsidies to make renewables more attractive. Furthermore, feed-in tariffs can boost the development of other important energy technologies that are currently more expensive, such as offshore wind and energy storage.

It is true that feed-in tariffs often become very expensive to electricity consumers, but if this is such a big issue then we should expect German citizens to have rebelled against the FIT long ago. The reason it has never happened is probably that the *Energiewende* was always as much about ‘energy democracy’ as about environmental policy (Morris, 2015). Many Germans like producing their own energy and are willing to pay more for power if it is made locally. The shift from feed-in tariffs to more competition from 2012 on came after pressure from utilities, not citizens.

If we want rapid adoption of solar and wind energy we may still have to pay for it. Experience shows that newly installed capacity goes down when governments abandon feed-in tariffs. This has happened not only in Germany but also in the United Kingdom, where installation rates among homeowners fell by 94 percent after the government scrapped the subsidy system (Ambrose, 2019a). Furthermore, moving away from subsidies also means putting jobs at risk. Without a strong support system, producers of energy technology in developed countries can hardly hope to compete with cheaper companies abroad.

When a policy works, we should not abandon it. Instead, we should reform it gradually to account for changing contexts (Patt, 2015). We do not need any radical new solutions in the power sector, but we should continue doing more of what has been effective so far. The feed-in tariff has proven itself as a powerful instrument for boosting the share of renewable electricity in many countries. It is not the most cost-effective instrument available, but it represents the perhaps best combination of political feasibility and effectiveness at producing the desired outcome. At least for solar energy, which has been slower to achieve cost-effectiveness than wind energy, we still need feed-in tariffs for the time being.

The feed-in tariff is a policy in line with the three principles of Patt (2015) for driving an energy transition. It overcomes the problem of lock-in by supporting the alternative technology until it becomes cost-competitive. It also reduces the risk to the investor by keeping costs down. And it addresses other problems in society such as energy security and clean air, thus making it interesting to other groups than just those who are concerned about climate change.

Tendering may be the solution to the problems of the feed-in tariff. However, there is mixed evidence of their success in promoting renewable energy adoption so far. Research has shown that deployment rates tend go down with a shift to tendering (Ram et al., 2019). Yet in Brazil, India and China they have led to reduced electricity costs (Azuela et al., 2014). They have an added benefit in developing countries where they can attract foreign companies to the energy sector. One disadvantage of auctions is that they are more complex and require more monitoring than FITs. It is also commonly believed that a move to auctions will hurt energy cooperatives. However, anecdotal evidence from Germany suggests that this may not be the case. In the first auction from wind energy, energy cooperatives won most of the bids (May, Ison & Hicks, 2018). Some also argue that auctions and FITs can serve different purposes, with auctions driving the deployment of wind energy and feed-in tariffs promoting solar PV (Jenner et al., 2013).

6.4 Is a combination of cap-and-trade and feed-in tariffs effective?

Table 4 shows that there is an interaction effect between cap-and-trade and feed-in tariffs for solar energy. This indicates that implementing both these policies and increasing their stringency is even more effective for higher renewable electricity generation than to rely on only one of them. A combination of carbon pricing and technology policies seems to be useful in this regard. This is in line with much of the theory that I have referred to, which says that multiple policies are needed to drive a successful energy transition.

If the results of the analysis are right and cap-and-trade successfully promotes renewables in a cost-effective way, then arguably we do not need any other climate policies. The problem with such an interpretation is that solving climate change is not only a question of correcting market failure with marginal changes. The changes that are happening in the energy market represent a disruptive energy transition. As climate policy expert David Roberts has written, the task is not simply to reduce emissions but to overturn an entire system:

> Reducing carbon emissions is easy; lots of policies can do that. We need to reduce emissions *a lot* – to zero, or close to it – as fast as possible. That's going to require more than changes at the margins. It's going to require phasing out virtually our entire installed industrial base and replacing it with new, low-carbon technologies and practices. It's going to require an explosion of innovation and building, the likes of which hasn't been seen since the Industrial revolution – only much, much faster, constrained by a tight carbon budget (Roberts, 2016).

Carbon pricing alone will probably not be enough to reach the Paris climate goals, primarily because we are in such a hurry. The IPCC has established the rough time frame that we have to deal with climate change. By 2050, we must have reached net-zero emissions. This means that there is limited time to make the energy transition happen. One big problem is that delayed action can lock in GHG emissions for decades to come (Sovacool, 2016). Paradoxically, we may reach that point before we fully understand the need to change the structure of our society. The upside is that energy transitions can happen relatively quickly; some transitions in the past have done so once all the pieces were in place, and the transition from fossil fuels to renewables is likely to occur faster than previous one partly because it is now a central political goal and the increasingly serious impacts of climate change will push decision makers to adopt more ambitious legislation.

The results of the analysis seem to justify the distinction between short-term and long-term goals made by Sandén and Azar (2005). Economy-wide instruments such as a cap-and-trade scheme can indeed be effective at reducing emissions in the short term. They can induce a shift to higher energy efficiency and encourage the use of existing low-carbon technologies that are cost-competitive. Technology policies such as the feed-in tariff play a different part: They help new technologies enter the market by driving down costs and providing markets for testing and demonstration. These technologies are crucial in the long term, when emissions reduction targets become increasingly ambitious.

It is futile to believe that one policy or one technology is coming to save us. More likely, the way to accelerate deployment of renewables and prevent catastrophic climate change is to make the most of the technologies that have worked so far and electrify as much as we can. We do not have to choose just one solution or the other one. Rather, as one expert says, “we sit before a smorgasbord of options, and we need to prioritize how to fill our plate” (Griffith, 2019).

Many have criticized European national governments for having renewable energy support systems in addition to the EU ETS (Lehmann & Gawel, 2013). The typical argument is that they do not lead to any additional GHG emission reductions in electricity production, but rather allow companies in other sectors to pollute more instead. Furthermore, the cost of reaching climate goals goes up if governments introduce subsidy policies. But there are other factors that suggest that carbon pricing is not sufficient for an optimal climate policy strategy (ibid.). First, several barriers hold back new low-carbon technologies. One issue is positive externalities: since knowledge can spill over to others, companies have little incentive to invest in developing new technologies. Furthermore, the carbon price is usually not high enough to drive large-scale low-carbon innovation. Second, governments have other objectives than GHG emissions reductions alone. Renewable energy can reduce local air pollution, increase energy security and create new industrial opportunities. Increased use of renewables can be especially beneficial for small and medium-scale electricity producers.

There are drawbacks to technology policies as well. The future is uncertain and it can be dangerous to ‘pick winners’. For instance, we may create lock-in of new technologies that end up being ineffective at reducing emissions (Lehmann & Gawel, 2013). Moreover, expensive subsidies can have negative economic effects if they lead to higher electricity prices, though this may actually be a positive outcome if it induces energy saving. Another problem is that support policies can attract rent-seeking behavior. But all this does not mean that we should lose hope in technology policies. Instead, we should focus on designing effective instruments that take into account both emissions reduction potential, costs and other concerns such as equity.

6.5 Limitations to the study: beyond electricity

One of the limitations to this analysis is that it only applies to the electricity sector. As mentioned, experts believe that renewables will continue to grow rapidly in the next decades, but not fast enough to effectively replace fossil fuels and keep global temperature rise below

1.5 degrees. The energy transition is unfolding most rapidly in the power sector, but even there renewables will meet with obstacles. Wind, solar and batteries with flexible demand response can plausibly get us to 80 percent low-carbon electricity in many places, but for the last parts we likely need additional technologies such as nuclear energy, natural gas with carbon removal or hydrogen (BloombergNEF, 2019).

The big hurdle, however, to achieving a net-zero emissions energy system is the task of replacing fossil fuels in other sectors than electricity. As of 2016, renewables supplied 26 percent of global electricity but only around ten percent of heating and cooling and three percent of transportation (Roberts, 2019). Moreover, governments have not implemented nearly as many policies in these sectors as in the power sector. However, in the transportation sector we are now beginning to see rapid growth in electric vehicles led by countries such as China and Norway.

Heating may be the most difficult issue of all to solve (Liebreich, 2018). Renewables are as of now not able to meet the varying demand that many countries experience in the winter months. As a matter of fact, heating represents the biggest energy-related source of GHG emissions, which makes it even more important to find viable solutions for it (Patt, 2015). In the case of heating of buildings, we must rely on large improvements in energy efficiency combined with heat pumps. When it comes to industrial heating, one of the solutions is to replace carbon-heavy cement with clean geopolymer cement, but this technology is very far from cost-competitive today. In order to develop these substitutes further and bring down costs, we need technology policy; governments must invest in continued R&D and provide market opportunities for companies to test these technologies in the real world.

Transportation can be electrified to a large degree, and here we are starting to see a shift happening. This is another example of what technology policies can do; by providing a range of different incentives, Norway has become a market leader in electric vehicles (Patt, 2015). It has become a laboratory for car companies to introduce new models to the public, thus driving innovation and cost reductions that have contributed to many electric cars being cost-competitive today. However, for long-distance transport we may need alternative technologies that do not rely on charging. Ships and long-distance trains, for instance, can run on hydrogen (Liebreich, 2018). But to make hydrogen with electrolysis a cost-competitive solution will probably require a high carbon price.

In general, we are making progress on new low-carbon technologies that can be important in all these sectors (Liebreich, 2018). Digitalization will add even more speed to the energy transition. However, we are not on track to decarbonize heating and transportation by 2050. We need to ramp up our efforts.

6.6 Limitations to the study: beyond renewables

As this analysis has shown, renewable energy can play a key role in combatting climate change. Yet there are limits to what renewables alone can do, and there are many other solutions out there that may turn out to be important in the next decades. In this section, I quickly discuss the possibilities and limits of these alternative solutions.

Firstly, many argue that we should focus more on a different low-carbon energy technology, namely *nuclear energy*. However, these technologies are not cost-competitive with renewables. New nuclear power stations require huge subsidies and are often not finished on time (Liebreich, 2018). There are several interesting modern nuclear plants being built that deal with many of the issues typically associated with the energy source, but it is not clear whether they can produce power cheaply enough. Despite this, nuclear energy may continue to play a part in the energy system beside renewable energy because it can generate heat. Most likely, political and not economical considerations will decide what role nuclear will have in the future.

Carbon capture and storage (CCS) also comes up in many discussions as the miracle technology that can save the planet. This refers to different ways of removing carbon from the atmosphere. It is true that the IPCC considers CCS absolutely necessary to keep temperature rise below 1.5 degrees. And yet, the technology is extremely costly and will require using vast land areas for storing carbon. There are several possible ways to produce negative emissions, among which bioenergy combined with CCS has received the most attention (Anderson & Peters, 2016). However, scaling that technology to the level necessary to avoid dangerous climate impacts will come into conflict with other concerns such as biodiversity and food production. Pinning our hopes on negative emissions is a high-risk strategy. This is why the prestigious *Nature* magazine has called strategies that rely on large-scale CCS ‘magical thinking’ (Nature, 2018).

All energy models that come close to the Paris climate targets also rely crucially on increased *energy efficiency* (Roberts, 2019). This means that we want to produce as much as we do today with less use of energy. The climate targets require global energy intensity to go down by four to ten percent annually. With the current rate of 0.4 percent we are way off that trajectory. However, we should keep in mind that burning fossil fuels wastes a huge amount of energy, while renewables have much higher energy efficiency. Therefore, increasing the share of renewable energy will reduce total energy demand enormously, and we will not need to replace the full amount of energy that fossil fuels are supplying today (ibid.).

It is worth noting that arguments for using these alternative solutions always start from the assumption that renewable energy only has a limited potential, especially because of the intermittent nature of solar and wind power. But the intermittency problem can be overcome (Fares, 2015). For the very short-time fluctuations in power supply, the law of large numbers tells us that the need for backup power actually decreases as we add more renewable energy. Second, we can use increasingly advanced weather forecasts to predict reasonably well the amount of wind and solar we can produce on an hourly basis. For daily electricity output, it is possible to exploit the fact that different RE sources tend to peak at different times of day to establish an effective mix of sources.

6.7 Limitations to the study: Time period

The sample period in this analysis ends in 2012. This is unfortunate, as there have been rapid developments in the world of renewable energy since then. Currently, it appears that we are in the middle of a renewable energy revolution. Wind and solar power are now the cheapest sources of electricity in two thirds of the world (BloombergNEF, 2019). Another big milestone was achieved this year as building new solar and wind energy is now cheaper than *existing* fossil fuel generation in several places. Technologist Ramez Naam calls this the "third phase of renewable energy" (Naam, 2019). When renewables are the cheapest source of energy, they will increasingly become the natural first choice around the world. That could change everything we know about the energy market today.

For a long time, many believed that an energy system based on 100 percent renewable energy was impossible. But a large study released this year shows that this is not only possible, but also likely to be cheaper than operating the current energy system (Ram et al., 2019). The study is a collaboration between researchers from the Laappenranta University in Finland and German think tank Energy Watch Group and illustrates the most cost-efficient way to reach net zero emissions by mid-century, with existing technologies and without the use of carbon removal from the atmosphere. According to this study, the key to reach the goal is massive electrification and a rapid phase-out of fossil fuels in electricity. Solar energy will supply as much as 69 percent of all energy in this scenario. Added benefits include a reduction in air pollution and improved public health, plus increased political stability as a result of more decentralized energy. The energy transition will create 15 million new jobs in the sector of renewable energy. It will take place across all sectors – power, heat, transport and desalination.

One of the authors' central policy recommendations is that governments should use feed-in tariffs to promote small- to medium-scale production of renewable energy (Ram et al., 2019). This is an effective way to make sure that individuals and cooperatives become part of the energy transition. Feed-in tariffs allow RE producers to sell excess power at a profit, which can be very important for a stable electricity system in the future. The report authors believe that governments should only rely on tendering for large-scale installations over 40 MW. We need these support policies because even as many renewable energy sources have become cost-competitive with fossil fuels, we are not on a pathway to reach the Paris climate goals. Since feed-in tariffs provide a fixed price of electricity and priority access to the grid, they lead to stability and certainty about potential future profits. This is important to investors and should make sure that we generate as much renewable energy as we need to achieve full decarbonization by 2050.

After Germany shifted completely to auctions in 2017, investments have fallen drastically (Ram et al., 2019). This again led to a large reduction in wind energy expansion in the last two years. In India, many companies have not installed renewable energy capacity on time after having won the auctions. Furthermore, the government has in some cases not upheld agreements when prices at auctions have gone up. The authors from Laappenranta University and Energy Watch Group therefore argue that tendering has not been as successful an instrument as many hoped for and cannot completely replace feed-in tariffs for effective renewable energy adoption.

One important takeaway from this analysis is that we do not have to wait for some miracle technology to appear before we can solve the climate problem. The technologies that we need already exist. Wind power, solar power and battery storage helped by a range of other energy technologies can take us to a completely emissions-free energy system by mid-century. Rather, solving climate change is a question of political will. If political leaders can simply agree to support renewable energy at the expense of fossil fuels, they have the instruments that they need to effectively boost RE adoption. A combination of pricing carbon and supporting the development of new technologies is evidently an effective strategy. Yet it is up to decision makers to implement these policies and make sure that they are sufficiently stringent.

At the end it is worth emphasizing once more that the future is uncertain and that we cannot know what will happen to the energy system in the next decades. In the words of BloombergNEF's Michael Leibreich, "Anyone who says they know which technologies will be dominant in thirty years or more is fooling themselves" (Liebreich, 2018). There are many solutions that may be able to contribute to a low-carbon energy system. Which ones that succeed will depend on technological advances, economic developments and the decisions of politicians around the world. This study does not conclude as to what we should do to combat climate change, but I have demonstrated that renewable energy is a promising solution and that public policies will be vital in promoting it.

7. Conclusion

In this paper, I have examined the effects of increasing stringency for several environmental policies on renewable electricity output in a sample of 33 industrialized and emerging economies. Based on theory and previous research, the hypotheses have been that feed-in tariffs have effectively promoted higher shares of renewable energy in electricity generation while cap-and-trade schemes have not. The empirical analysis shows that, in fact, cap-and-trade schemes have had a positive effect on the use of renewable sources other than hydropower. For feed-in tariffs, the results are mixed: FITs for wind energy are associated with decreasing renewable electricity output, but I find a positive impact from FITs for solar energy. I argue that this finding owes to the fact that wind energy became cost-competitive with conventional energy in many places in the sample time period while solar PV did not. The positive effect of feed-in tariffs for solar energy is more interesting in that sense, and this leads me to conclude that both policies can be important to the current energy transition. Furthermore, there is a positive interaction effect from higher carbon prices and higher feed-in tariffs, suggesting that countries can increase their renewable energy output even more by combining the two policies.

The results are mostly in line with similar empirical studies and robust to a battery of alternative specifications. The robustness tests show that the impacts of cap-and-trade and feed-in tariffs are even bigger if we only look at differences between ‘weak’ and ‘strong’ policies. Notably, the effect of feed-in tariffs for solar energy is hidden when we do not account for policy stringency.

I provide evidence that each of the two perspectives on climate change presented here make important contributions to the debate. Environmental economists argue that putting a price on carbon is the most effective way to get market actors to change their behavior and that trading schemes promote a shift to cleaner energy sources. The positive impact of cap-and-trade in this analysis suggests that they have a point. However, this may not be enough to drive a rapid energy transition. Technologists believe that the most effective way to replace fossil fuels with renewables is to support the development and diffusion of new technologies. I have shown that this seems to be true at least for subsidies to solar energy. In conclusion, it seems that a combination of carbon pricing and technology policies can be the engine we need to further accelerate the shift to clean energy.

In this light, the analysis suggests that experts need to stop arguing about which solutions are perfect and rather start discussing how we can make the most of the ones we have. The window of opportunity for dealing with climate change is closing. Therefore, we do not have the luxury of choosing between punishing the old system or supporting the new one. It is time to abandon the widely held idea that there is one solution that will 'fix' the climate challenge. This is firstly because we are dealing with overlapping problems that require different solutions. Specifically, market-based policies such as cap-and-trade may be efficient at reducing emissions at the margins, but we also need support policies such as feed-in tariffs to promote innovation and diffusion of new technologies. Secondly, we are in a hurry to reach net-zero GHG emissions. This means that we will probably need to use all the tools in our toolbox if we are going to get there fast enough. Researchers and policymakers alike should focus less on cost-efficiency and more on efficiency in achieving the primary goal of rapidly reducing emissions. Thirty years from now, the global energy system has to be virtually free from carbon emissions. The longer we wait with serious action, the more costly it will be to achieve the goals of the Paris climate agreement.

Based on my findings I can provide some policy recommendations that are likely to increase the use of renewable energy and limit the impacts of the climate crisis. First, we need continued investments in R&D to develop new technologies that can complement wind and solar energy and batteries in building a completely emissions-free energy system by 2050. Second, a combination of cap-and-trade schemes and feed-in tariffs for less mature energy technologies seems to be an effective policy mix to drive renewable electricity generation. Finally, politicians should be willing to raise prices in carbon markets and increase energy technology support, and they should do so for as long as it takes to make renewable energy sources cost-competitive. This analysis has demonstrated that the design of policies to support renewable energy is very important. Thus, it will be up to global leaders to make sure that the energy transition picks up speed so that we can keep temperature rise below 1.5 degrees in accordance with the Paris climate agreement.

This study is an important addition to the existing literature on the effectiveness of energy policies in several regards. In contrast to most previous studies, I consider policy stringency and find that it makes a critical difference to the results. Another methodological strength is that I control for unit roots in the dependent variable. I also present evidence of the effect of cap-and-trade schemes, which represents a big gap in the literature. Still, there are several interesting avenues for further research on this subject. Most importantly, researchers should repeat the analysis for a time period including the years after 2012 when data become available. The years leading up to and following the Paris climate conference in 2015 can tell us a lot about what drives renewable energy generation and implementation of support policies. As the cost of renewables continues to plummet, we should expect the impact of policy to change as well. Furthermore, we need analyses of the relationship between policies and energy production in other developing countries than the BRICS countries. The policy decisions that these countries make in the next few decades will have a large impact on the future of energy and the climate. Finally, this quantitative analysis shows that both cap-and-trade and feed-in tariffs work to promote renewables, but it does not show *how* this happens. An important research task in the future is to uncover the circumstances under which each of these policies effectively boost the development of renewable energy, so that political leaders have a blueprint for how they can accelerate the energy transition in their own country.

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Appendix A

Table A 1: The relationship between policy stringency and renewable electricity output, 1990-2012 (expanded)

Variables	**Model 1**	**Model 2**
Renewable electricity output (t-1)	1.0922***	1.0871***
(% of total)	(0.0144)	(0.0146)
Cap-and-trade schemes (t-1)	0.0644**	0.0576*
	(0.0291)	(0.0286)
Feed-in tariffs (t-1)	0.0201	
	(0.0228)	
Feed-in tariffs for wind energy (t-1)		-0.0345*
		(0.0183)
Feed-in tariffs for solar energy (t-1)		0.0599**
		(0.0248)
GDP per capita (t-1)	-0.0000	-0.0000
	(0.0000)	(0.0000)
Annual GDP growth (t-1)	-0.0139	-0.0132
(Annual %)	(0.0083)	(0.0083)
Electricity use (t-1)	0.0000	0.0000
(kWh per capita)	(0.0001)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0493	-0.0482
(% of GDP)	(0.0448)	(0.0436)
1992	0.1290	0.1350
	(0.0922)	(0.0933)
1993	0.0979	0.1185
	(0.0923)	(0.0985)
1994	0.0572	0.0787
	(0.1061)	(0.1084)
1995	0.1574*	0.1803*
	(0.0917)	(0.0992)
1996	-0.0653	-0.0397
	(0.1030)	(0.1018)
1997	0.2920	0.3222
	(0.1874)	(0.1956)
1998	0.2481	0.2764
	(0.1648)	(0.1737)
1999	0.0886	0.1103
	(0.1060)	(0.1112)
2000	0.3526*	0.3681*
	(0.1802)	(0.1852)
2001	0.1521	0.1705
	(0.1033)	(0.1071)
2002	0.2325	0.2472
	(0.1480)	(0.1504)
2003	0.1522	0.1644

	(0.1131)	(0.1151)
2004	0.5481**	0.5555**
	(0.2229)	(0.2251)
2005	0.6053***	0.6051***
	(0.1944)	(0.1927)
2006	-0.1291	-0.1170
	(0.3433)	(0.3373)
2007	0.3173	0.3331*
	(0.1991)	(0.1966)
2008	0.4590**	0.4467**
	(0.2225)	(0.2181)
2009	0.3812**	0.3710**
	(0.1708)	(0.1627)
2010	0.1891	0.1825
	(0.2353)	(0.2346)
2011	0.8648**	0.8592**
	(0.3587)	(0.3484)
2012	0.6537**	0.6613**
	(0.3147)	(0.3122)
Constant	0.1761	0.1875
	(0.4018)	(0.3967)
Country FE	YES	YES
Time FE	YES	YES
N		
Number of observations	719	719
Number of countries	33	33
Goodness-of-fit		
R^2 (within)	0.9576	0.9578
F-test	19093.67***	20287.78***
rho	0.22	0.2045

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Table A 2: Interaction effects of policy stringency on renewable electricity output, 1990-2012 (expanded)

Variables	**Model 3**
Renewable electricity output (t-1)	1.0865***
(% of total)	(0.0144)
Cap-and-trade schemes (t-1)	0.0460
	(0.0286)
Feed-in tariffs for wind energy (t-1)	-0.0252
	(0.0162)
Feed-in tariffs for solar energy (t-1)	0.0370*
	(0.0200)
GDP per capita (t-1)	-0.0000
	(0.0000)
Annual GDP growth (t-1)	-0.0126
(Annual %)	(0.0084)
Electricity use (t-1)	0.0000
(kWh per capita)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0437
(% of GDP)	(0.0432)
Cap-and-trade * Feed-in tariffs for solar energy	0.0210*
	(0.0103)
1992	0.1356
	(0.0933)
1993	0.1137
	(0.0970)
1994	0.0743
	(0.1079)
1995	0.1758*
	(0.0972)
1996	-0.0454
	(0.1011)
1997	0.3146
	(0.1936)
1998	0.2674
	(0.1707)
1999	0.1060
	(0.1097)
2000	0.3639*
	(0.1846)
2001	0.1598
	(0.1062)
2002	0.2419
	(0.1486)
2003	0.1613
	(0.1130)
2004	0.5557**
	(0.2249)

2005	0.5532***
	(0.1885)
2006	-0.1430
	(0.3439)
2007	0.3605*
	(0.2010)
2008	0.4175*
	(0.2182)
2009	0.3443**
	(0.1632)
2010	0.1490
	(0.2257)
2011	0.8398**
	(0.3420)
2012	0.6526**
	(0.3042)
Constant	0.1403
	(0.3732)
Country FE	YES
Year FE	YES
N	
Number of observations	719
Number of countries	33
Goodness-of-fit	
R^2	0.9580
F-test	34139.19***
rho	0.1864

Cluster-robust standard errors in parentheses (*** $p<0.01$, ** $p<0.05$, * $p<0.1$)
(t-1) = one-year lag

Appendix B

Table B 1: The relationship between policy stringency and renewable electricity output, 1990-2012 (other policy instruments)

Variables	**Model B1**
Renewable electricity output (t-1)	1.0856***
(% of total)	(0.0141)
Cap-and-trade schemes (t-1)	0.0331
	(0.0268)
Feed-in tariffs for wind energy (t-1)	-0.0333**
	(0.0155)
Feed-in tariffs for solar energy (t-1)	0.0588**
	(0.0247)
GDP per capita (t-1)	-0.0000
	(0.0000)
Annual GDP growth (t-1)	-0.0110
(Annual %)	(0.0081)
Electricity use (t-1)	0.0000
(kWh per capita)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0566
(% of GDP)	(0.0451)
CO_2 taxes (t-1)	-0.0548
	(0.0378)
Renewable energy certificates (t-1)	0.0628
	(0.0417)
Emission standards (t-1)	0.1041**
	(0.0396)
Constant	0.2821
	(0.4302)
Country FE	YES
Time FE	YES
N	
Number of observations	719
Number of ID	33
Goodness-of-fit	
R-squared	0.9585
F-test	3.22e+06***
rho	0.2846

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Table B 2: The relationship between policy stringency and renewable electricity output, 1990-2012 (only OECD countries)

Variables	**Model B2**
Renewable electricity output (t-1)	1.0829***
(% of total)	(0.0139)
Cap-and-trade schemes (t-1)	0.0552
	(0.0324)
Feed-in tariffs for wind energy (t-1)	-0.0273*
	(0.0150)
Feed-in tariffs for solar energy (t-1)	0.0558**
	(0.0262)
GDP per capita (t-1)	-0.0000
	(0.0000)
Annual GDP growth (t-1)	-0.0106
(Annual %)	(0.0132)
Electricity use (t-1)	0.0000
(kWh per capita)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0692
(% of GDP)	(0.0501)
Constant	0.6883
	(0.6268)
Country FE	YES
Year FE	YES
N	
Number of observations	587
Number of countries	27
Goodness-of-fit	
R^2	0.9596
F-test	.
rho	0.3071

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Table B 3: The relationship between policy stringency and renewable electricity output, 1990-2012 (recoded variables)

Variables	**Model B3**	**Model B4**
Renewable electricity output (t-1)	1.0827***	1.0826***
(% of total)	(0.0143)	(0.0122)
Cap-and-trade schemes (recoded) (t-1)	0.2161**	
	(0.0921)	
Feed-in tariffs for wind energy (recoded) (t-1)	-0.0668	
	(0.0520)	
Feed-in tariffs for solar energy (recoded) (t-1)	0.1560**	
	(0.0666)	
Cap-and-trade schemes (binary) (t-1)		0.4255***
		(0.1207)
Feed-in tariffs for wind energy (binary) (t-1)		-0.1237
		(0.0910)
Feed-in tariffs for solar energy (binary) (t-1)		0.1962*
		(0.1054)
GDP per capita (t-1)	-0.0000	-0.0000
	(0.0000)	(0.0000)
Annual GDP growth (t-1)	-0.0122	-0.0126
(Annual %)	(0.0084)	(0.0086)
Electricity use (t-1)	0.0000	0.0001
(kWh per capita)	(0.0001)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0527	-0.0523
(% of GDP)	(0.0441)	(0.0408)
Constant	0.1975	0.1483
	(0.3799)	(0.3879)
Country FE	YES	YES
Time FE	YES	YES
N		
Number of observations	719	719
Number of ID	33	33
Goodness-of-fit		
R-squared	0.9580	0.9580
F-test	30212.55	29601.47***
rho	0.2147	0.2289

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Table B 4: The relationship between policy stringency and renewable electricity output, 1990-2012 (longer time lags)

Variables	**Model B5**	**Model B6**
Renewable electricity output (t-1)	1.0805***	1.0817***
(% of total)	(0.0151)	(0.0158)
Cap-and-trade schemes (t-2)	0.0702*	
	(0.0351)	
Cap-and-trade schemes (t-3)		0.0663**
		(0.0296)
Feed-in tariffs for wind energy (t-1)	-0.0384*	-0.0385*
	(0.0200)	(0.0208)
Feed-in tariffs for solar energy (t-1)	0.0625**	0.0646**
	(0.0263)	(0.0272)
GDP per capita (t-1)	-0.0000	-0.0000
	(0.0000)	(0.0000)
Annual GDP growth (t-1)	-0.0156*	-0.0193*
(Annual %)	(0.0085)	(0.0098)
Electricity use (t-1)	0.0000	0.0000
(kWh per capita)	(0.0001)	(0.0001)
R&D subsidies for renewable energy (t-1)	-0.0654	-0.0628
(% of GDP)	(0.0441)	(0.0432)
Constant	0.4473	0.5463
	(0.4807)	(0.5208)
Country FE	YES	YES
Year FE	YES	YES
N		
Number of observations	690	659
Number of countries	33	33
Goodness-of-fit		
R^2	0.9565	0.9545
F-test	13818.16***	13818.16***
rho	0.2875	0.2875

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

Table B 5: The relationship between policy stringency and renewable electricity output, 1990-2012 (including hydropower)

Variables	**Model B6**
Renewable electricity output (t-1)	0.6733***
(% of total)	(0.1243)
Cap-and-trade schemes (t-1)	0.4224**
	(0.1723)
Feed-in tariffs for wind energy (t-1)	-0.1903*
	(0.0965)
Feed-in tariffs for solar energy (t-1)	0.1154
	(0.0879)
GDP per capita (t-1)	0.0001
	(0.0001)
Annual GDP growth (t-1)	-0.0340
(Annual %)	(0.0240)
Electricity use (t-1)	-0.0001
(kWh per capita)	(0.0002)
R&D subsidies for renewable energy (t-1)	-0.1599
(% of GDP)	(0.1653)
Constant	6.0824**
	(2.5039)
Country FE	YES
Time FE	YES
N	
Number of observations	719
Number of ID	33
Goodness-of-fit	
R^2 (within)	0.5993
F-test	228.35***
rho	0.8857

Cluster-robust standard errors in parentheses (*** p<0.01, ** p<0.05, * p<0.1)
(t-1) = one-year lag

NTNU
Norwegian University of
Science and Technology