Three essays on regulation in Energy and Environmental Economics

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Abstract

There are four chapters in this thesis. The first is an introductory chapter, and the remaining three are composed of the research papers. The first part of the introductory chapter presents the problem of negative externalities, and a discussion of regulation in economics. The common theme for the papers is the importance of economic principles for effective regulation. While each paper considers different problems and sectors, they all focus on the regulation of negative externalities using economic instruments. In the second part of the introductory chapter, a summary of the papers is provided. The discussion addresses how the papers contribute to the literature, their research focus, the methods used, and the results obtained.

The first paper co-authored with Eirik S. Amundsen, examines the problem facing a regulator wanting to achieve a specific target path of CO_2-emission reductions in the electricity sector. The goal of the paper is to analyze the suitability of a tradable green certificate (TGC) scheme in achieving the target set by the regulator. In addition, we examine the incentives for construction of new renewable generation capacity. The previous literature on TGC schemes, consists mainly of theoretical contributions. They have focused on the interaction of a TGC scheme with other instruments, and the effect of using a TGC scheme as an instrument for promoting renewable energy or reducing emissions from energy production. Static models have been used in the analyses in these contributions. Our paper is a novel contribution to the TGC literature by using a dynamic model. Contrary to static models, a dynamic model allows us to analyze time-related issues. We examine price profiles for electricity and investment profiles for new green generation capacity, resulting from technological progress in green generation technology. We also have a specific focus on the calibration of the time-path of percentage requirements, the key component in a TGC scheme. Previous contributions in the TGC literature have treated the percentage requirement as given. Finally, we compare the results from using a TGC scheme with results derived from using an emission fee and a green subsidy, and conduct a welfare ranking of the instruments. Our results show that the use of a TGC scheme *will* reduce emissions from fossil-based electricity generation. Further, we find that with a properly calibrated time path of percentage requirements, a TGC scheme can achieve the specific target path announced by the regulator. However, regardless of the time path chosen, the use of a TGC scheme leads to overinvestment in green generation capacity compared with the optimal social solution. Moreover, the price path for electricity will fall below the socially

optimal level, resulting in overconsumption of electricity. While a TGC scheme is not as cost-effective as the emission fee, it is less wasteful than the subsidy.

The second paper examines whether a refunded emission payments (REP) scheme can be used as a cost-effective instrument achieving a dynamic emission target for NO_x emissions. With a REP scheme, a charge is put on the regulated firms' emissions, and the revenues are recycled back to the firms. I look at the problem where a regulator wants to reduce emissions in accordance with an exogenously given target path, and first-best emission pricing is assumed unavailable due to political constraints. The emitting firms are heterogenous and emit NO_x through energy production. Emissions can be reduced by cutting output or by investing in new abatement technology. I analyze two REP schemes and examine their incentives for emission mitigation at the firm level. In the first version, refunds are given based on the emission cuts of the firms, and the second version gives refunds in proportion to energy produced. In the REP literature, the focus has been mainly on output-based refunding, and its incentives for emission reductions. These analyses have been conducted with static models. There have also been papers examining the incentives provided by a REP scheme for adoption of abatement technologies. The paper contributes to the REP literature in several regards. First, to the best of my knowledge, this is the first paper to analyze REP schemes using a dynamic model. This allows me to investigate time-variant issues such as the time path of instruments and the evolution of mitigation incentives for firms. Second, I derive analytical expressions and conditions for a REP scheme able to achieve cost-effective regulation of NO_x-emissions. Third, by assuming heterogenous firms, I can compare mitigation incentives for different firm types across the two REP schemes and look at the distributional outcomes for different firm types with the two instruments. Both REP schemes can achieve the specific target path of emission reductions. However, it is only cost-effective when all emission cuts are eligible for refunds. The choice of refund affects the costs of regulation and distributional outcome for different firm types. My results suggest that if a Pigouvian tax is unavailable, then a REP scheme is not necessarily an inferior second-best alternative.

The third and final paper of the thesis is concerned with the regulation of negative externalities from road transport. Using a partial equilibrium model, I analyze the problem of transport choice for a fixed number of commuters who make an essential work trip in a congested urban area. The commuters use either fossil car, electric car, or public transport. Each alternative is responsible for a different composition of negative externalities. The long-term equilibrium outcomes for transport choice in the private and socially optimal outcomes are analyzed, and I discuss the importance of economic principles for optimal regulation of the externalities. There is a rich strand of literature on negative externalities from road transport. While congestion has received much attention, the literature has expanded to include externalities such as global and local emissions, accidents, and noise. There have been many contributions focusing on policy instruments to internalize negative externalities from road transport. These include both theoretical and empirical papers, studying both command-and-control, and market-based instruments. The paper is a contribution to the literature on the regulation of negative externalities from road transport. I focus on the difference in the long-run private and socially optimal outcomes on the transport choice of commuters and consider the effect from four categories of externalities. My approach allows me to study the effect of the different externalities on the equilibrium outcomes. This is examined thoroughly, using comparative statics. Further, I discuss important economic principles for achieving a socially optimal outcome. The inclusion of electric cars enables me to highlight the trade-off in the regulation of local and global negative externalities. To the best of my knowledge, there are no other papers using a similar setup. The results from the paper show the importance of the different externality cost on transport choice, where congestion costs prove to be particularly important. An optimal internalization of the externalities can be achieved with a "sandwich" of economic instruments that are differentiated to account for different damage intensities from the various vehicle types. This key result is underscored with comparisons of long-run outcomes from partial instrument use. Such strategies *will* be insufficient and can also be costly and even counterproductive.

Contents

Chapter 1

Introduction

Introduction

The climate problem is one of mankind's biggest challenges. Averting disaster requires nothing less than worldwide collective policy action. However, policies that ignore the laws of economics may prove futile, if not downright counterproductive.

- Hans-Werner Sinn (2015)

1. Background

The concern of this thesis in environmental economics is the regulation of negative externalities. In this introductory chapter, I look at the concept of a negative externality, and show the importance of regulation of such a market failure. Further, I examine important principles of regulation of negative externalities in economics, with a particular focus on the use of market-based instruments. Then, I discuss the difference of static and dynamic analyses of policy instruments. Finally, I look at some notable environmental targets and discuss the use of market-based instruments in achieving these targets. Throughout this introductory chapter, I highlight how my contributions fit in to the different topics concerning the regulation of negative externalities.

An external effect is a market failure. It is an unintended side and uncompensated side effect of an agent's activities on another (Sterner & Coria, 2013). Since the focus of the thesis is on negative externalities, I will concentrate on these in the following. Although externalities are a basic concept in economics, it remains an important subject of analysis.

The negative externality which has probably received the most attention in recent years is climate change. In 2006, the Stern Review on the Economics of Climate Change, was released. It was a comprehensive report ordered the by the government of United Kingdom, charged with studying the effect of global warming on the world economy. The report clearly states that climate change could have serious impacts on both growth and development, but that if strong action is taken now, the worst impacts of climate change can still be avoided. Calculations indicate that in the absence of decisive action, the total costs and risks of climate change can be equivalent to a loss of global GDP of at least 5 percent each year from now on. As the report states: "Climate change presents a unique challenge for economics: it is the greatest example of market failure we have ever seen" (Stern, 2007). Since the release of the Stern Review, climate change has been a much discussed and researched topic, but the perceived lack of action has also led many to grow impatient for a credible response. In recent years, there has been a growing climate concern among young people. Activists such as Greta Thunberg have also been instrumental in keeping the consequences of anthropogenic climate change high on the international agenda and demanding efficient regulation.

Apart from climate change, local pollutants are another important category of negative externalities. While global emissions and the contribution to damages from climate change are important, local emissions have a potential to cause adverse health effects and negative impacts on nature. One example of local pollutants is nitrogen oxides (NO_x) NO_x emissions lead to acid deposition and eutrophication, causing detrimental effects on both soil and water quality (European Environment Agency, 2018).

The transport sector stands out in that it is not only a significant source of annual greenhouse gas (GHG) emissions but is also responsible for various other local externalities that have noticeable effects on people's wellbeing in daily life. Congestion is perhaps the one that has received most attention. Although seminal works, discussing the social costs of congestion were published decades ago (Vickrey, 1963; Walters, 1961), congestion is still a major problem in large urban areas. There are also other externalities linked to the transport sector, such as accidents, noise, and road wear.

All three papers in this thesis focus on the regulation of negative externalities. In the first paper, we consider the problem where a regulator seeks to reduce GHG emissions from the electricity sector. The second paper is concerned with regulation of NO_x emissions from energy producing firms. In the third, and final paper, I discuss the importance of implementing key insights from economics in the regulation of various negative externalities from road transport.

2. Regulation of negative externalities in economics

The goal in economics is to organize economic efficiency for the benefit of individuals in society without wasting resources, i.e., achieving this at the least cost for society. Under the very strict necessary assumptions for undistorted competitive markets, the mechanisms of the free market could bring about this situation. In practice though, the presence of market failures such as externalities, requires some form of regulation. Since the introduction of the concept of externalities and the principles of optimal regulation by Pigou (1920), there has been considerable work dedicated to the regulation of externalities.

This regulation is often considered a public responsibility, but if the problems could be solved through private solutions, there would be no need to involve public regulatory bodies. Prominent economists such as Ronald Coase, have argued in favor of such private solutions. The so-called Coase theorem stated that with a clear assignment of property rights and low transaction costs, a private bargain solution could ensure an efficient market outcome in the presence of externalities. This result would hold regardless of the initial allocation of property rights (Coase, 1960). In practice, there are limits to private solutions when the necessary conditions do not hold. High transaction costs (i.e., many parties involved) and problems concerning the assignment of property rights (i.e., right to clean air) have shown that public involvement in regulation is a necessity to achieve efficient regulation.

The choice for regulators concerning policy instruments can be divided into two main categories: command-and-control and market-based instruments. In the former category we have instruments such as standards, while market-based instruments can be taxes, subsidies, tradable emission permits etc. Generally, economists prefer market-based instruments. Unlike command-and-control instruments, they do not specify a certain behavior or impose specific solutions for achieving emission targets. With market-based instruments, polluters face either price or quantity signals meant to incentivize them to change their behavior. Market mechanisms can then be used to achieve an efficient allocation of emission mitigation among polluters. Further, since market-based incentives allow polluters more flexibility in their abatement efforts, emission mitigation can be achieved at lower costs. Economic efficiency through internalization should be done at the least cost to avoid waste of resources. Wasteful regulation could also diminish the support for regulation since there are other important areas in need of funding as well. It should be noted that even though economist might prefer the use of market-based instrument, there are sometimes rationale for using command-and-control instruments. This can be the case if emissions cannot be efficiently measured or monitored, or to avoid geographic concentration of certain pollution types. Since the concern of this thesis is analyses of the use of different market-based instruments, they will be the focus in the following. For a discussion on the use of indirect regulation instruments such as standards, I refer to other contributions in the literature of instrument choice (see, e.g., Amundsen, Hansen, & Whitta-Jacobsen, 2018).

Pigou argued that the use of a corrective (Pigouvian) tax, could be used to internalize negative externalities. The conclusions derived by Pigou have later been promoted by William Baumol who showed that with regulation of the polluter with a tax set equal to the marginal costs of an externality (e.g., pollution) the socially optimal outcome could be achieved (first-best solution). Further, there would be no need for additional regulation of those who were affected by the externality, in the form of a compensation (Baumol, 1972). The use of a tax on emissions, incentivizes the firms to change their behavior and set their marginal abatement costs equal to the price. With the use of a tax, the price is fixed, but the quantity of emissions is determined by the market.

An alternative to using a price instrument is the use of a quantity instrument, such as tradable emission permits. In this system, also referred to as cap-and-trade, the regulator determines the total amount of emissions (the "cap"), through the number of permits. The permits are then allocated to the regulated firms, either for free or at a cost. With unrestricted trade of permits, the optimal internalization of the externality can be achieved, regardless of the initial allocation of permits (Montgomery, 1972). Under the condition of a binding emission cap, i.e., a cap lower than total emissions, the quantity of emission reductions is given, but the price of the emission permits is determined by the supply and demand for permits.

The third main option of market-based instruments is subsidies, where firms receive a payment to alter their behavior. If a subsidy is given per unit of emission reduced, below a specified baseline level, the instrument can provide the same marginal incentives as a tax or a system of tradable emission permits. However, even under idealized conditions, a subsidy is a less cost-effective instrument since the average costs of the regulated firms decrease. This can result in increased entry since it provides non-optimal incentives for output (Baumol & Oates, 1988). For these reasons, economists generally prefer taxes or tradable emission permits in favor of subsidies in the regulation of negative externalities.

The preceding discussion on instrument use assumes that there is one externality that requires regulation, and that optimal use of market-based instruments can internalize this externality and achieve the socially optimal outcome. Further, it is also assumed that there are no constraints on the choice of policy instruments for the regulating body. In practice, however, such first-best solutions cannot always be obtained. Regulation is then considered second-best when optimal instruments or optimal outcomes are not feasible. I will review these issues in turn.

With the absence of additional market failures such as uncertainty and asymmetric information, both an emission tax and a system of tradable emission permits could achieve the same efficient result. In a second-best setting, however, the effect of using different instrument can be different. In his classic paper “Prices vs Quantities”, Weitzman demonstrated that in the event of uncertainty, a price and quantity instrument would not result in the same outcome. He showed that if there was uncertainty in the marginal cost of supplying a good, then a price instrument would be more efficient than a quantity instrument, if the marginal the cost curve was steeper than the marginal benefit curve for that good. In the opposite case, a quantity instrument would be more efficient. Depending on the relative curvatures of the marginal cost and benefit functions, either a price or a quantity instrument would result in the least distortion compared to the socially optimal outcome (Weitzman, 1974). For other contributions analyzing this important result with the presence of uncertainty, see, e.g., Adar & Griffin (1976), Fishelson (1976) and Newell & Pizer (2003). In an extension to Weitzman’s analysis, Robert Stavins considers correlated uncertainty for both marginal costs and benefits. He argues that the presence of simultaneous and correlated uncertainty can alter the recommendation of the most efficient policy instrument (Stavins, 1996).

Kwerel (1977), studies the situation of asymmetric information where the information necessary for optimal regulation is known to the regulated firms but not the regulator. This can create incentives for firms to deceive the regulator when asked to disclose their information. In the context of pollution control, Kwerel shows that depending on whether the regulator considers using a price or quantity instrument, the regulated firms can either under- or overstate their abatement costs. To induce firms to reveal their true information, Kwerel suggests a combination of transferable emission permits and a subsidy per permit more than actual emissions, paid to the regulated firms holding permits above their emissions. In their seminal paper, Roberts & Spence (1976) argue that when the regulator has insufficient information about firms’ abatement costs, a combination of an emission permits scheme with subsidies and penalties can reduce the sum of damages from pollution, and abatement costs. For other contributions on the use of hybrid instruments, see, e.g., Pizer (2002) and Jacoby & Ellerman (2004).

If a polluting industry is characterized by imperfect competition as well, there is an incentive to provide insufficient output compared to a competitive situation. If this industry is levied an emission tax, the existing market failure is exacerbated. In such instances, an efficient regulation requires additional instruments (Fischer, 2011; Gersbach & Requate, 2004)

Finally, another obstacle for the optimal regulation postulated by Pigou and others, is a constraint on the use of optimal policy instruments. While economic theory has warm thoughts about the use of pricing instruments such as emission taxes, this sentiment is not necessarily shared by the public or policy makers. Lack of public and political acceptability can arise for several reasons, but such constraints can impede the introduction of effective pricing instruments (Dresner, Dunne, Clinch, & Beuermann, 2006; Kallbekken, Kroll, & Cherry, 2011; Rivlin, 1989).

In the first two papers I look at the use of alternative instruments in instances where pricing instruments such as Pigouvian taxes are unavailable. The first paper is concerned with the problem facing a regulator who wants to reduce GHG emissions in the electricity sector in accordance with a politically determined target path. The objective of the paper is to examine the properties of a tradable green certificate (TGC) scheme and study its suitability as a policy instrument for reducing GHG emissions. In the second paper, the negative externality concerned is emission of NO_x from energy producing firms. The regulator seeks to attain a specific dynamic emission target in a cost-effective manner. With the assumption that the use of a Pigouvian tax is politically unacceptable, the regulator will use a refunded emissions payment (REP) scheme to achieve the stated target.

3. From static to dynamic analyses

Quite a few contributions have used static theoretical models to analyze the properties of different policy instruments (see, e.g.,Downing & White, 1986; Milliman & Prince, 1989; Spulber, 1985). However, there are several compelling reasons for the use of dynamic analyses of the properties of policy instruments. While static equilibriums are obviously interesting, environmental targets such as emission reductions, support for renewables and energy efficiency are dynamic and can span over many years. Hence, efficient regulation requires knowledge about the effects of policy instruments over time. The use of dynamic models also allows for investigations of time-related issues such as the dynamic incentives arising from policy instruments, and their evolution over time.

Optimal control theory, an important tool in capital theory is very suitable for the use of dynamic analyses in environmental economics (Dorfman, 1969). With the combination of dynamic analysis and incorporation of stock variables, the method has been widely applied for topics such as economic growth and extraction of natural resources (Sydsæter, Hammond, Seierstad, & Strom, 2008). Further, it can be used to derive time paths for policy instruments and assess their dynamic properties. It can also be used to examine capacity building of variables, such as new renewable generation capacity which I do in this thesis.

The use of dynamic analyses, using optimal control theory have long been an important part of natural and resource economics. In the field of resource management, Hotelling models used to derive optimal price and extraction paths for non-renewable resources are notable examples of dynamic models using optimal control theory (Perman, Ma, McGilvray, & Common, 2003).

Optimal control theory has also proved useful in analyses of the Green Paradox. The term, coined by Hans-Werner Sinn, refers to the problem where environmental policies targeting carbon emissions result in adverse effects on the environment. The use of demand-side policies such as carbon taxes ignore the supply-side effect. Owners of fossil resources can react to regulation (or even merely the signal of such regulations) by increasing their extraction, and hence carbon emissions (Sinn, 2008). For contributions to the discussion of the Green Paradox, see, e.g., Gerlagh (2011), Long (2015) and Van der Ploeg & Withagen (2015). While the concern previously was concentrated on the optimal extraction of fossil resources for economic growth. the focus has recently turned more towards the negative effects from extracting and burning those same fossil fuels.

On the properties of policy instruments for regulation of negative externalities, Ulph & Ulph (1994) derive the optimal time path for a carbon tax. Since burning of fossil fuels, which is an exhaustible resource, is the main source of CO_2 emissions, they point to the literature of exhaustible resources and argue that the important property of a carbon tax, is the time path. With the backdrop of increased attention towards emission permit markets, several contributions emerged, focusing on intertemporal markets for tradable emission permits (see, e.g., Cronshaw & Kruse, 1996). Rubin (1996) and Kling & Rubin (1997) study the dynamic efficiency properties of a system of tradable emission permits. With the use of optimal control theory, they focus on intertemporal trading of emission permits, where they consider both the possibility of banking and borrowing of permits.

The first two papers in the thesis look at the dynamic properties of policy instruments. In the first paper, we examine how well suited a TGC scheme is in achieving a specific target path of GHG emissions in the electricity sector. Specifically, we consider the incentives from using a TGC scheme on reducing electricity generation from fossil sources, and its effect on investment in new renewable generation capacity. In the second paper, I study whether a REP scheme could be used as a cost-effective instrument for reducing NO_x emissions from energy producing firms, in accordance with a politically determined target path.

4. Environmental targets and the use of policy instruments

In the effort to internalize various global and local externalities, a variety of national and international initiatives have emerged over the years. These have been accompanied by different policy instruments. It is far beyond the scope of this text to give a comprehensive review. Instead, I will look at a few notable examples of environmental policy objectives and policy instruments. The endeavors made by the European Union (EU) are perhaps the most well-known.

In 1997, the Kyoto Protocol was adopted, and came into effect in 2005. The objective of the Protocol was to commit industrialized countries and emerging economies to reduce greenhouse gases in accordance with individual targets. The targets added up to an average emission reduction of 5 percent, compared to 1990-levels over the period 2008-2012. An important aspect of the Kyoto Protocol was the introduction of market-based instruments such as international emission trading, Clean Development Mechanism (CDM) and Joint Implementation (JI) (UNFCCC, 2020b).

In 2015, the Paris Agreement was adopted by 196 signatories and came into effect the following year. The Agreement increased the ambitions from the Kyoto Protocol, and the goal is to limit global warming below 2 degrees Celsius, and preferably to 1.5 degrees Celsius, compared to pre-industrial levels. Unlike the Kyoto Protocol, there was a bottom-up approach where countries submit their plans for climate action that are updated every five year (UNFCCC, 2020a).

While the EU had worked on implementing a carbon energy tax as an instrument to reduce GHG gases, this never materialized. The EU instead introduced a system of tradable emission permits, the EU Emission Trading Scheme (EU-ETS) in 2005 as their main tool to achieve a cost-effective reduction of GHGs in accordance with the Kyoto Protocol (Convery, 2009). In 2007, the EU set forth its 2020 climate & energy package. This included the so-called 20-20-20 targets, which stipulated: a 20 percent reduction in GHGs from 1990 levels, 20 percent of energy in EU to come from renewables, and a 20 percent improvement in energy efficiency. While the EU-ETS remained the main instrument for cutting GHG emissions, there were also industries not regulated by the emission trading scheme, so-called non-EU-ETS sectors (housing, agriculture, waste, and transport (excluding aviation)). In these sectors, EU member states adopted national targets (European Union, 2020a). As their contribution to the Paris Agreement, the EU proposed the 2030 climate & energy framework. The targets from 2030 were set to at least: 40 percent cut in GHG emissions[1], 32 percent renewable target, and 32.5 percent improvement in energy efficiency (European Union, 2020b). Further, the long-term target of the Paris Agreement is to achieve a climate-neutral world by mid-century. In accordance with this, the EU is also aiming for climate-neutral economy by 2050 (UNFCCC, 2020a).

The targets set by the EU is a good example of long-term environmental targets, coupled with the 2030 targets as milestones along the way. To ensure that these targets are met in an efficient manner, the dynamic properties of the chosen policy instruments are important. The EU-ETS is the centerpiece in the effort by the EU to reduce GHG emissions. As I have discussed above, under idealized conditions, a tradable emission permit scheme could be used as a cost-effective instrument for pollution control (Montgomery, 1972) and it could achieve the same result as a Pigouvian tax (Weitzman, 1974). However, experience with the EU-ETS has shown that when idealized conditions are not met, mainly due to political compromises, the first-best outcome depicted in the economics literature is not realized. The EU-ETS has received quite a bit of criticism. These grievances concern the efficiency to reduce emissions and the ability of the instrument to induce long-term technological change due to low permit prices. Over-allocation of emission permits, an inflexible supply mechanism and the use of offsets have been cited as contributing factors for the challenges facing the EU-ETS (see, e.g., Ellerman & Buchner, 2008; Laing, Sato, Grubb, & Comberti, 2013). Recognizing the need for reform, several changes are being planned or have been implemented in the EU-ETS design in recent years. For analyses

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[1] This was later revised upwards to at least 55 percent by 2030.

of the reform of the EU-ETS, see, e.g., Perino & Willner (2016), Bocklet, Hintermayer, Schmidt, & Wildgrube and Beck & Kruse-Andersen (2020).

In the first paper, we study the use of a Nordic TGC scheme to achieve a dynamic emission target in the electricity sector. Our target is like the EU target for GHG emission reductions. Their target consists of a final target with milestones underway (i.e., the 2030 target). Further, with a binding emission cap that decreases annually, there is a politically determined path of emission reductions. In our model, we fill in the gaps by assuming a smooth decreasing target path of emission reductions. Versions of a TGC scheme have a quite widespread use. Primarily, TGC schemes have been designed to stimulate the construction of new renewable electricity generation capacity (for analyses of the effectiveness of a TGC scheme as a support system for renewable energy, see, e.g., Aune, Dalen, & Hagem (2012), Dong (2012) and Abrell, Rausch, & Streitberger (2019)). However, the main objective is to displace fossil-based electricity generation with emission-free, technologies. The static properties of TGC schemes have been studied previously (e.g., Amundsen & Mortensen (2001)). Our paper is a novel contribution to the TGC literature with the use of a dynamic model to analyze the properties of a TGC scheme as a policy instrument to obtain GHG emission reductions.

As mentioned previously, local externalities can also cause considerable damage, and require efficient regulation as well. The Gothenburg Protocol concerns the problems of local pollutants and has set national emission ceilings for sulfur (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ammonia (NH_3) (UNECE, 2020). Like the targets set by the EU, the Gothenburg Protocol determines long-term emission ceilings for the signatory countries for the different pollutants. These targets are set as percentage reductions from their 2005-levels.

The US-based initiative, the Acid Rain Program is perhaps the most well-known initiative against local pollutants. Under Title IV of amendments Clean Air Act in 1990, it was determined that sulfur dioxide (SO_2) emissions nationwide in 2000 were to be cut below 50 percent of the level in 1980. The chosen tool to achieve this was a tradable emission permits program for SO_2, primarily targeting coal-firing power plants (Stavins, 1998).

In principle, negative externalities such as local pollutant could be handled efficiently by using a tax instrument. A tax set equal to the marginal costs of the externality would achieve the first-best solution. However, in practice, this is not easy to achieve. Further, even if a tax could be implemented, there is no guarantee that the tax is set at a sufficient high level to achieve the targets desired by regulators (Johnson, 2007). With this backdrop, the second paper considers the problem of regulating emissions of the local pollutants NO_x from energy producing firms, under the condition that Pigou taxes are infeasible, and the regulator opts for the use of a REP scheme instead. A justification for introducing a REP scheme rather than a traditional emission tax has also been that it allows for a higher charge level, compared to a tax with no refund (Sterner & Isaksson, 2006). I consider a dynamic emission target and examine whether a REP scheme can be used as a cost-effective policy instrument to reduce NO_x emissions.

After discussing the regulation of global and local emissions and, I turn the attention to the transport sector, more precisely, road transport. This sector is responsible for a considerable share of annual CO_2 emissions globally. The transport sector was responsible for 24 percent of direct CO_2 emissions from fuel combustion in 2019. Road transport (cars, trucks, buses and two- and three-wheelers) accounted for around three-quarters of this (IEA, 2020). Further, road transport is also a source of various local negative externalities that can cause considerable damage. While congestion is considered the most costly negative externality stemming from road transport in urban areas in peak periods (Small, Verhoef, & Lindsey, 2007), there are also other externalities that can severely impact people's daily life. These include local pollution (NO_x and particulate matter (PM)) noise and accidents. Traffic is the main source of PM in urban areas. Exhaust PM can contribute to respiratory disease or increased incidence of cancer, while non-exhaust PM can cause lung-inflammation (Timmers & Achten, 2016).

Over the years, numerous policy instruments have been introduced to curtail the various negative externalities from road transport. These include both command-and-control (i.e., standards and low-emission-zones) and market-based instruments (e.g., congestion charges, fuel taxes, subsidies) (see, e.g., Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010). In the third paper in the thesis, I highlight the significance of transport choice to the contribution of negative externalities and discuss important economic principles for effective regulation. I show the necessity of coherent regulation, using targeted instruments to achieve an optimal internalization of the negative externalities. This important result is highlighted by analyzing different outcomes from partial instrument use.

5. Summary of the papers

I now turn to the papers that constitute this thesis. While the papers focus on different sectors and problems, each paper is concerned with the regulation of negative externalities and focuses on properties of policy instruments.

5.1 Prices vs. percentages: Use of tradable green certificates as an instrument of greenhouse gas mitigation (coauthored with Eirik S. Amundsen)

Through fossil-fueled generation of electricity, the electricity sector is a considerable contributor to global GHG emissions. Hence, reducing carbon emissions from electricity generation is a key component in the strategy to reduce the effect of anthropogenic climate change (Williams et al., 2012). Reduction of GHG emissions is the cornerstone of international initiatives such as the Kyoto Protocol and the Paris Accord. Market-based policy instruments have been important in the effort to reduce GHG emissions (see, e.g., Metcalf, 2009; Tietenberg, 2013). In practice, efficient emission pricing is not necessarily feasible. Hence, in this paper, we examine the use of a TGC scheme as a policy instrument to reduce GHG emissions in the electricity sector.

In this paper, we study the problem where a regulator seeks to achieve a politically determined target path of GHG emission reductions in the electricity sector. Generation stems from two sources: renewable (green) and fossil (black) sources, which cause emissions. Using a dynamic model with optimal control theory, we explore the properties of a TGC scheme in achieving the specific target path. While TGC schemes are primarily designed to incentivize the construction of new green electricity generation capacity, the main objective is to replace fossil-based electricity generation with emission-free technologies. We focus on emission reductions, through reduction of fossil-based electricity. Further, we study the incentives from using a TGC scheme on the construction of new green generation capacity. Our contribution is a novel addition to the TGC literature with the use of a dynamic model. This allows us to analyze time-related issues such as price and investment profiles resulting from technological progress in green capacity construction. We also analyze the percentage requirement used in TGC schemes explicitly. Instead of treating it as exogenously given, we calculate two versions for the time path of the percentage requirements. Finally, we compare the outcomes obtained with the use of a TGC scheme with those from using an optimal emission fee and a subsidy for generators of green electricity.

We find that using a TGC scheme reduces emissions from fossil-based electricity generation, independent of time path of the percentage requirements chosen. Further, there exists a time path for the percentage requirements that can obtain the specific target path of emission reductions exactly. However, regardless of the time path chosen for the percentage requirements, there will be too much construction of new green generation capacity, compared to the outcome desired by the regulator. Hence, total electricity generation exceeds the social optimal level. This results in a higher demand for electricity since the price of electricity will be too low. For the sake of comparison, we include an emission fee and a green subsidy and derive necessary conditions for these instruments to achieve the target path announced by the regulator. While the emission fee results in the first-best solution, using a subsidy reduces electricity prices considerably and leads to excessive demand for electricity. A comparison of social surplus for the three instruments shows that while a TGC scheme is not as cost-effective as the emission fee, it produces higher social surplus than the subsidy.

5.2 Refunded emission payments scheme – a cost-effective *and* politically acceptable instrument for NO_x emissions reduction

In addition to its contribution to climate change, emission of NO_x has the potential to cause considerable local damage as well. Emissions lead to acid deposition and eutrophication, causing detrimental effects on both soil and water quality. NO_x emissions can also have significant adverse impacts on human health. High concentrations contribute to formation of local air pollutants and lead to inflammation of the airways (European Environment Agency, 2018). While an emission fee set at the level of marginal externality costs of NO_x emissions would result in a first-best solution, a variety of constraints can restrict a regulators' choice of policy instrument. In this paper, I examine the problem facing a regulator who seeks to reduce NO_x emissions under the assumption that first-best pricing instruments (Pigouvian taxes) are unavailable. The paper is then concerned with whether a REP scheme can be a cost-effective instrument for achieving a dynamic target of NO_x emission reductions.

In a REP scheme, a charge is levied per kilogram of NO_x emissions from the regulated firms, and the collected revenues are refunded back to the same firms. I examine the problem where a regulator seeks to achieve an announced target path of NO_x emission reductions from energy producing firms. The firms decide on output, which causes the emissions, and investments in abatement technology. Hence, the firms have two ways of reducing emissions. I construct a dynamic model for the analysis of the use of a REP scheme, and I consider two versions. In the first version, firms receive a refund in accordance with their emission cuts, and in the second, they receive a refund in proportion to their output. The firms in the model are heterogenous, and I can study the resulting incentives for different firm types from the two instruments. The paper provides a contribution to the REP literature in several ways. I provide analytical results for a cost-effective REP scheme and derive necessary conditions for this. Further, the use of a dynamic model allows me to study time-related issues such as the mitigation incentives for different firm types over time, and time paths for policy instruments. The inclusion of heterogenous firms also provide an opportunity to study differences in distributional outcomes for different firm types.

From the results, I show that a properly derived REP scheme can obtain a cost-effective solution to the regulators' problem. This requires that the firms must be allowed flexibility by making all emission cuts eligible for refunds. The necessary REP charge is then lower than the Pigouvian tax, and the charge and the refund must be derived such that the sum of these equal the Pigouvian tax in a specific way. These results are derived analytically and the time paths for the REP charge and refund are calculated. A REP scheme where refunds are given in proportion to output can also achieve the specific target path. However, this is not a cost-effective instrument. Incentives for production adjustments and investments in abatement technology are non-optimal, and the necessary REP charge must be higher than the Pigouvian tax. By studying heterogenous firms, I show how the two instruments provide different mitigation incentives and distributional outcomes for different firm types. In addition, I also discuss policy-related issues concerning the use of a REP scheme. Refunding can increase support for regulation (Kallbekken et al., 2011) and allow for implementation of higher charge levels than otherwise possible (Johnson, 2007). Refunding can also address concerns for competitiveness of regulated firms (Sterner & Isaksson, 2006) and carbon leakage (Fischer & Fox, 2012; Fischer, Greaker, & Rosendahl, 2017). However, compared to instruments such as taxes and auctioned emission permits, a REP scheme does not generate revenue that could be valuable for the governmental budget (Goulder, Parry, Williams III, & Burtraw, 1999). Further, by refunding revenues back to emitting firms, a REP scheme does not adhere strictly to the polluter-pays-principle. To summarize, the findings show that if efficient pricing instruments are unavailable, a REP scheme can prove to be an effective and politically feasible alternative.

5.3 **Transport choice and negative externalities in a congested urban area**

Apart from being a considerable source of global emissions and an important contributor to climate change, road transport is responsible for a variety of negative externalities as well. These include congestion, local emissions, noise, accidents, and road wear. These externalities can negatively affect the daily life for many people and cause considerable social costs. Over decades, a comprehensive literature has focused on the regulation of negative externalities from road transport. The studied policy instruments include a wide range of command-and-control and market-based instruments. I consider a problem of transport choice for commuters where congestion costs faced by the commuters play a significant part. Equilibrium outcomes for transport choice are analyzed both with and without inclusion of externalities. Further, I discuss regulation of the externalities and focus on the importance of key economic principles for regulation.

In the paper, I consider the problem of a fixed number of commuters making an essential work trip in a congested urban area. They can choose between fossil or electric car or public transport, where each mode of transport is responsible for a distinct combination of negative externalities. Using a partial equilibrium model, I analyze optimal transport choice and the effect when negative externalities are internalized in long-run equilibrium solutions. Further, I examine how the use of economic principles of regulation can ensure an optimal internalization of the negative externalities. This outcome is compared with resulting long-run equilibriums when different strategies of partial instrument use are applied. Finally, I conduct comparative statics for different cost parameters and discuss the long-run equilibriums concerning transport choice and regulation. The paper is a contribution to the literature on the regulation of negative externalities from road transport, by analyzing long-run equilibrium outcomes for transport choice. I am not aware of other papers using a similar setup. The approach allows me to consider private and socially optimal outcomes, as well as the possibility to compare long-run outcomes from different regulatory strategies. The effect of different negative externalities on transport choice are examined. This is explored thoroughly using comparative statics. Finally, the inclusion of electric cars as a transport mode enables me to highlight the trade-off in the regulation of local and global negative externalities.

I show that with a “sandwich” of economic instruments, the regulator can achieve the socially optimal outcome with internalization of the negative externalities. This is a key result, and I highlight its importance by analyzing several long-run equilibrium outcomes from partial instrument use. Three economic instruments and one technical instrument are considered in turn, and I show that their use *will* result in insufficient regulation. Further the results show that such a partial strategy can be very costly and result in unintended consequences as well. Using comparative statics for different cost parameters, I examine the importance of the different costs on transport choice and regulation. Specifically, I note the importance of the congestion costs. The results are derived from a stylized model. In practice, things quickly become more complicated. Public and political constraints can restrict the choice of policy instruments for regulators. However, effective regulation of transport-related externalities is important, and application of key economic principles can improve this regulation. This is a goal worth striving for.

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Chapter 2

Prices vs. percentages: Use of tradable green certificates as an instrument of greenhouse gas mitigation

Prices vs. percentages: Use of tradable green certificates as an instrument of greenhouse gas mitigation[1]

Arild Heimvik[2] and Eirik S. Amundsen[3]

Abstract

We consider a regulator who seeks to achieve a specific target path of greenhouse gas emission reductions in the electricity sector. Generation stems from two sources: renewable (green) and fossil (black) sources, which cause emissions. We construct a dynamic model and explore the suitability of a tradable green certificate (TGC) scheme for solving this problem. Further, we study the resulting incentives for construction of new green generation capacity. We provide a novel contribution to the TGC literature by using a dynamic model that allows analyses of time-related issues that are inaccessible with static models. Further, we focus explicitly on calibration of the time path of percentage requirements. We devise two specific time paths and show that the use of a TGC scheme *can* achieve a specific dynamic emission target but always results in overinvestment in new green generation capacity. We also derive results from using an emission fee and a green subsidy, compare the different instruments, and conduct a welfare ranking. A TGC scheme is not as cost-effective as an optimal emission fee but is less wasteful than a green subsidy.

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1. Introduction

The electricity sector is a major contributor to greenhouse gas (GHG) emission through fossil-fueled electricity generation. Hence, reducing carbon emission from electricity generation is a key component in the strategy to reduce the effect of anthropogenic climate change (Williams et al., 2012). In this paper, we analyze the effectiveness of a system of tradable green certificates (TGCs) in achieving a specific target path of GHG emission reductions in the electricity sector.

Tradable green certificate schemes[4] are primarily designed to stimulate the construction of new renewable electricity generation capacity, but the main objective is to replace fossil-based electricity generation with emission-free technologies. With a TGC scheme, a separate market for green certificates is created and linked to the electricity market. The regulator allocates certificates to generators of renewable electricity in accordance with electricity generated. The certificates are sold on the certificate market and compensate generators of renewable electricity in addition to the wholesale price of electricity. Since electricity is a homogenous good, the regulator must create a demand for TGCs to ensure a well-functioning market. Retailers of electricity are therefore obligated to hold a certain share of certificates out of the total demand for electricity that they sell to consumers. This share is the percentage requirement. The TGC scheme is ultimately financed by consumers of electricity since the costs of the certificates are passed on to them. The objective of the TGC scheme is to render green electricity more competitive over time[5]. A TGC scheme is a self-contained system where the regulator (government) is not directly involved in giving subsidies and levying taxes. The role of the regulator is to announce the time path of the percentage requirement, issue certificates and ensure compliance in the scheme.

In this paper, we investigate whether a TGC scheme can be used as a cost-effective instrument to achieve a specific target path of emission reductions announced by the regulator in the electricity sector. The electricity sector consists of two sources of electricity generation: renewable (green) and fossil (black) sources, the latter of which is responsible for GHG emissions. Optimal carbon pricing can be used to internalize negative external effects from emissions (see, e.g., Metcalf, 2009; Tietenberg, 2013). However, introducing such an

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[4] In this paper, we analyze a TGC scheme such as the Nordic TGC scheme.

[5] With a technological neutral scheme, the most mature renewable technologies will enter the market. The system can be adapted to stimulate investments in less mature technologies by giving more certificates to these. This concept of "banding" was an important feature in the Renewables Obligation scheme in the UK (Woodman & Mitchell, 2011).

instrument can be politically infeasible. Hence, it is interesting to explore whether a TGC scheme can work as an effective substitute. Further, we consider the effects of using a TGC scheme on the investment in new green generation capacity. To the best of our knowledge, this is the first paper to analyze the use of a TGC scheme with a dynamic model. A dynamic model, in contrast to existing static models, enables analyses of time-related issues such as price and investment profiles resulting from technological progress in green capacity construction. Hence, this is a novel addition to the TGC literature. For comparison, we analyze the outcomes of using an emission fee and a green subsidy. We also look at the resulting price paths and conduct a welfare ranking of the different instruments. The question of the effectiveness of a TGC scheme as an instrument for emission reductions has real-world policy relevance. Variations of TGC schemes are used in various places, including Norway, Sweden, the United Kingdom, Belgium, and several states in the US[6].

Notably, the objective of the paper is not to derive an optimal path for GHG emission reductions. Instead, we assume that the regulator announces a specific target path of emission reductions to be achieved in a cost - effective manner. The target path itself may be the result of political decisions in the economy considered. Hence, we do not claim that this target path is socially optimal (However, even if the target path were optimal, it would not alter the necessary mechanisms for obtaining it which we examine in this paper). The objective of our regulator is comparable to other recognized policy objectives. For instance, the European Union has a commitment to reduce CO_2 emission in accordance with a specific path as determined by an emission cap, where the number of issued quotas decreases annually through a percentage reduction[7].

The use of an exogenous emissions reduction target to analyze different instruments is well established in the economics literature (see, e.g., Fell & Linn, 2013). Abrell, Rausch, & Streitberger (2019) assess optimal policies for supporting renewable energies and compare their cost-effectiveness against an exogenous emission target. Coulomb, Lecuyer, & Vogt-Schilb (2019) derive the optimal transition from coal to gas and renewable energy in the presence of an exogenous cap on carbon emissions. Since we use a target path of emission reductions, we

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[6] In the US, the system of tradable green certificates is known as a renewable portfolio standard (RPS).

[7] An alternative is the implementation of a price target, with a specified price path for CO_2 emissions, which can be achieved with different instruments, but the resulting emission quantities would differ. Since the primary policy goal is normally a quantity target, this is also the focus here.

do not include a damage function to describe the evolution of emissions over time. Instead, the cost of the negative externality effect of GHG emission is expressed through the shadow price of the emission constraint. Further, we focus on the negative externality of one type of emission in one market. This feature is then adequately captured with the shadow price. However, if we analyzed damages in several markets in a global model, a damage function would be more appropriate.

The problem studied in this paper, is the regulation of a negative externality in the form of GHG emissions in the electricity sector. Since the emissions stem from the generation of fossil-based electricity, the regulation entails a decarbonization of the electricity sector, with an energy transition from fossil to renewable based electricity generation. Ambec & Crampes (2019) and Abrell, Rausch, & Streitberger (2019) discuss the decarbonization of the electricity sector, and asses different support schemes for renewable energy. These contributions differ from our paper with their focus on the intermittency of renewable energy sources. Neetzow (2019) looks at decarbonization of the power system in the presence of flexible generation and variable renewable energies (VREs). He determines an optimal transition from fossil to renewable generation, rather than examining the achievement of a given emission target as we do. Pommeret & Schubert (2019) conduct a similar analysis but they include investments in energy storage in their analysis as well. Helm & Mier (2019) show that if the externality cost of fossils is internalized with a Pigouvian tax, then under perfect competition, the optimal energy mix of fossil and renewables is achieved. Coram & Katzner (2018) and Coulomb, Lecuyer, & Vogt-Schilb (2019) study the optimal transition from fossil-based to renewable energy with the use of optimal control theory. While the former derives an optimal strategy for energy transition, the latter includes nonrenewable resources and investment under adjustment costs in the analysis. Hence, both papers differ from the setup that we use.

There is a comprehensive strand of literature on instrument choice for regulating negative externalities in economics. For a review on the use of market-based instruments such as taxes, subsidies and tradable emission permits see, e.g., Dröge & Schröder (2005), Hepburn (2006), Goulder & Parry (2008), Metcalf (2009) and Tietenberg (2013). As previously mentioned, a TGC scheme is primarily designed to incentivize the construction of new renewable electricity generation capacity. However, with an increasing capacity of green electricity generation, fossil-based electricity generation will be crowded out. Further, with our comparison of outcomes with a TGC scheme to those using an emission fee and a green subsidy, our paper contributes to the literature on instrument choice.

In the literature on the properties of a TGC scheme, several papers have examined the interaction effects between a TGC scheme and other instruments (Amundsen & Bye, 2018; Amundsen & Mortensen, 2001; Böhringer & Rosendahl, 2010; Fischer & Preonas, 2010; Meran & Wittmann, 2012; Unger & Ahlgren, 2005). Using a stylized model, Amundsen & Mortensen (2001) show that in general, an increase in the percentage requirement does not result in a higher capacity of green electricity in the long run, but the share of green electricity out of the total demand for electricity will increase. Böhringer & Rosendahl (2010) show that the combination of a TGC scheme (labeled "green quota" in their paper) and CO_2 emission regulation is not cost-effective for reducing emissions since the TGC scheme effectively reduces the shadow price of the emission constraint. Other contributions have analyzed the properties of a TGC scheme with the inclusion of uncertainty (Amundsen, Baldursson, & Mortensen, 2006); in the presence of market power (Amundsen & Bergman, 2012; Amundsen & Nese, 2017); and with cross-country integration of certificate markets (Amundsen & Nese, 2009). We expand the literature by conducting a dynamic analysis of the suitability of using a TGC scheme as an instrument to reduce GHG emissions.

Although TGC schemes have been mostly analyzed as a support scheme for renewables, there are some papers that have examined the properties of TGC schemes as an instrument to reduce GHG emissions. Palmer & Burtraw (2005) assess the cost-effectiveness of different policies in reducing GHG emissions in the electricity sector. They analyze the effect of a renewable portfolio standard (RPS) for different levels of the percentage requirement. Their numerical analysis shows that although the RPS is effective in promoting the generation of renewable energy, it is less efficient as an instrument to reduce emissions. Fischer & Newell (2008) compare different policies for reducing GHG emissions and promoting renewable energy. They find that a RPS can crowd out emitting energy generation but provides insufficient incentives for energy conservation. Hence, higher expansion in renewable energy is required to achieve the given emission target. Ambec & Crampes (2019) and Abrell, Rausch, & Streitberger (2019) compare the cost-effectiveness for support schemes with intermittent renewable sources against an exogenous emission target. Both papers show that the use of an RPS cannot be socially optimal since the revenue-neutrality of the instrument provides insufficient incentives for energy conservation. Our paper contributes to the literature on the use of a TGC scheme as an instrument for reduction of GHG emissions in several ways. We use a dynamic model to analyze the properties of a TGC scheme. Further, optimal control theory is applied to examine the incentives from using a TGC scheme on the construction of new green generation capacity. Finally, we focus explicitly on the calculation of the percentage requirement rather than treating it as exogenous. In addition, time paths are derived for the percentage requirement to assess the dynamic properties of a TGC scheme.

This article is structured as follows: Section 2 presents the theoretical model along with corresponding assumptions. Section 3 first examines a base scenario in which no regulations are imposed. Then, solutions from solving the regulator's problem are derived. The paper next examines the use of a TGC scheme in more general terms. In section 4, we analyze and discuss the effects of specific time paths of the percentage requirement in a TGC scheme, which are compared with the outcomes of using an emission fee and a green subsidy. An illustrative numerical model is used to enhance the understanding of our results where necessary. Section 5 discusses policy implications and provides concluding remarks.

2. A dynamic model[8]

In accordance with established policies such as the EU target for emission reductions, we focus on a target where the regulator wants to reduce the quantity of GHG emissions as given by an announced target path. The model focuses on the electricity market, with two kinds of electricity generation, green (z_t) and black (y_t), the latter of which is the cause of emissions. For simplicity, we assume a one-to-one relationship between black electricity generation and emissions. In equilibrium we must have that supply equals demand in each period, such that $x_t = y_t + z_t$, where x_t denotes the demand for electricity. While there are two distinct sources of electricity generation, consumers do not distinguish between them. They only demand electricity, regardless of its source of generation. We assume perfect competitive markets all around. Two types of active decision makers exist: generators and consumers of electricity. Hence, since our qualitative results will not be affected, we assume that retailers and distributors are simply intermediaries between generators and consumers. Further, we follow Amundsen & Nese (2009) and assume that retailing and distribution of electricity are costless for simplicity. The wholesale price of electricity is w_t, and the end-user price of electricity is denoted by p_t. The inverse demand function for electricity, $p_t = p(x_t)$, is negatively sloped, $\frac{\partial p_t}{\partial x_t} < 0$.

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[8] Notations used for the parameters and variables are summarized in Appendix A

We assume that the generation of green electricity always takes place at full capacity utilization ($z_t = \bar{z}_t$). The corresponding rationale is that the marginal costs of electricity generation from the most mature technologies, such as wind power, are very low and close to zero. Accordingly, we assume zero short run (operating) generation costs of green electricity generation. Hence, using the existing green generation capacity is costless; only additional green generation capacity and maintenance of capacity carry a cost. For the generation of black electricity, we assume that an abundant capacity exists at the outset, resulting in no need for capacity investments. This assumption is also made in Coulomb et al. (2019). An increasingly important concern in the decarbonization of the electricity sector is the intermittency of renewable sources of electricity. In this paper, we abstract from this concern and regard black and green electricity generation as perfect substitutes. For a treatment on the intermittency of renewables, we refer to other studies (Abrell et al., 2019; Ambec & Crampes, 2019; Helm & Mier, 2019; Hirth, 2015; Pommeret & Schubert, 2019).

The cost function for black electricity is denoted $c(y_t)$. Costs increase in generation and are convex; hence, $\frac{\partial c}{\partial y_t} > 0$ and $\frac{\partial^2 c}{\partial {y_t}^2} \geq 0$. The capacity costs for green generation capacity, $g(\bar{z}_t)$ have increasing marginal costs and are convex as well, i.e., $\frac{\partial g}{\partial \bar{z}_t} > 0$ and $\frac{\partial^2 g}{\partial {\bar{z}_t}^2} \geq 0$. The physical investment in new generation capacity is denoted by k_t. We apply a multiplicative cost function for total green costs and denote this as $g(\bar{z}_t) k_t e^{-\rho t}$. Since we are solving the model for investments in new green generation capacity, this depiction of the cost function has convenient properties. We allow for green technology costs to decrease over time with the rate ρ. This technological progress is exogenous[9] and captures the considerable cost reductions in mature green technologies in recent years (notably for PV technologies[10]). The equation of motion for green generation capacity is: $\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$. In our model, k_t is the instrument variable, and $\bar{z}_t$ represents the state variable. The green generation capacity is assumed to depreciate at a rate of κ. For simplicity, we do not include depreciation of black electricity generation. Similar assumptions are made in Coram & Katzner (2018) and Neetzow (2019).

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[9] We do not consider why green technology becomes cheaper over time since this is not of major relevance. This assumption is also made in Helm & Mier (2019)

[10] The price of solar PV modules has decreased approximately 80% from the end of 2009 through the end of 2015. The costs are projected to decrease further, approximately 42% from 2015 to 2025 (IRENA, 2016)

3. Model applications

3.1. Base scenario - no regulation

In this scenario, no regulations are imposed on the generators. The optimization problem for the generators is to maximize the difference between the revenue from sale of electricity and the costs of electricity generation, subject to the equation of motion for the capacity of green electricity, and green generation at full capacity utilization until a terminating period denoted T. Since this is a dynamic problem, we discount by the social discount rate r:

$$\max_{y_t,k_t,\bar{z}_t} \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

subject to

$$\dot{z}_t = k_t - \kappa \bar{z}_t$$
$$z_t \leq \bar{z}_t$$

The first constraint is the equation of motion for the capacity of green electricity generation. The second constraint denotes that green electricity generation takes place at full capacity utilization. This constraint is assumed binding. Denoting the costate variable by λ_t and the Lagrange multiplier ϑ_t, the corresponding present value Hamiltonian reads:

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \lambda_t(k_t - \kappa\bar{z}_t) - \vartheta_t(z_t - \bar{z}_t)$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial y_t} = [p_t - c'(y_t)]e^{-rt} = 0 \tag{1}$$

$$\frac{\partial H_t}{\partial z_t} = p_t e^{-rt} - \vartheta_t = 0 \tag{2}$$

$$\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \lambda_t = 0 \tag{3}$$

$$\frac{\partial H_t}{\partial \bar{z}_t} = -[g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \lambda_t\kappa + \vartheta_t = -\dot{\lambda}_t \tag{4}$$

$$\lambda_T \geq 0 \tag{5}$$

$$H_T = [p(x_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T]e^{-rT} + \lambda_T(k_T - \kappa\bar{z}_T) - \vartheta_T(z_T - \bar{z}_T) = 0 \quad (6)$$

By taking the derivative of (3) with respect to time and applying the equation of motion ($\dot{\bar{z}}_t = k_t - \kappa\bar{z}_t$), we obtain:

$$-[g'(\bar{z}_t)e^{-\rho t}(k_t - \kappa\bar{z}_t) - \rho g(\bar{z}_t)e^{-\rho t}]e^{-rt} + r[g(\bar{z}_t)e^{-\rho t}]e^{-rt} = -\dot{\lambda}_t \quad (7)$$

Equalizing (7) with (4) and inserting (2), we derive the optimality condition for the price of electricity. Furthermore, from (1), the price of electricity must satisfy $p_t = c'(y_t)$. We then obtain:

$$p_t = c'(y_t) = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} \quad (8)$$

The price of electricity equals the marginal costs of black electricity generation, which is again equal to the (annualized) marginal costs of green electricity generation. As shown in Appendix B, the electricity price will decrease over time together with increasing consumption of electricity. Furthermore, the generation of black electricity will decrease over time, whereas the generation of green electricity will increase with technological progress. The increasing generation of green electricity will more than outweigh the decreasing generation of black electricity. With no technological progress ($\rho = 0$), price, consumption and black and green electricity generation will be constant over time.

Hence, even in the unregulated case, the generation of black electricity – and therefore emissions – will fall over time as investments in green generation capacity become cheaper. However, the reduction of emissions may fall short of the target, thus warranting additional regulation.

3.2. Constrained social optimum

We assume that the regulator has announced a specific target path for emission reductions. We do not explore the motivations behind the choice of the target path and simply propose that an emission target should be achieved in a cost-effective manner. For simplicity, we assume the following expression for the target path of emission reductions: $\hat{y}_t = y_0 e^{-\chi t}$, where χ is the reduction rate desired by the regulator, and y_0 is the initial level of black electricity generation. The binding target path of emission reductions gives rise to a specific investment profile in new green generation capacity. Henceforth, we refer to results attained in this section as solutions of the social optimum. The optimization problem reads:

$$\max_{y_t,k_t,\bar{z}_t} \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

subject to:

$$\dot{z}_t = k_t - \kappa\bar{z}_t$$
$$z_t \leq \bar{z}_t$$
$$y_t \leq \hat{y}_t$$

The first two constraints are the same as before. The third constraint expresses the emission reductions announced by the regulator. We assume that this constraint is binding, i.e., the generation of black electricity is always less than the generation of black electricity in the unregulated case. Hence, we obtain a positive shadow price of the emission constraint.

Denoting the costate variable by β_t, the Lagrange multiplier υ_t, and the shadow price of the generation constraint by ω_t, the corresponding present value Hamiltonian reads:

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \beta_t(k_t - \kappa\bar{z}_t) - \upsilon_t(z_t - \bar{z}_t) - \omega_t(y_t - \hat{y}_t)$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial y_t} = [p_t - c'(\hat{y}_t)]e^{-rt} - \omega_t = 0 \tag{9}$$

$$\frac{\partial H_t}{\partial z_t} = p_t e^{-rt} - \upsilon_t = 0 \tag{10}$$

$$\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \beta_t \tag{11}$$

$$\frac{\partial H_t}{\partial \bar{z}_t} = -[g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \beta_t\kappa + \upsilon_t = -\dot{\beta}_t \tag{12}$$

$$\beta_T \geq 0 \tag{13}$$

$$H_T = [p(x_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T]e^{-rT} + \beta_T(k_T - \kappa\bar{z}_T) - \upsilon_T(z_T - \bar{z}_T) + \omega_T(\hat{y}_T - y_T) = 0 \tag{14}$$

We take the time derivative of (11), equalize the expression with (12) and insert (10). We then obtain the following expression for the price of electricity:

$$p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t}$$

This expression is inserted into (9) to solve for the shadow price of the emission constraint:

$$\omega_t = \left[[(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(\hat{y}_t)\right]e^{-rt} \tag{15}$$

From (15), the shadow price equals the discounted difference between the (annualized) marginal costs of green electricity generation and the marginal generation costs of black electricity, with a binding emission constraint. If green electricity generation becomes cheaper over time through technological progress ($\rho > 0$), the shadow price decreases over time. Then, cheaper green electricity generation displaces the generation of black electricity at a lower cost.

We obtain the optimality condition for the price of electricity by substituting the shadow price into (9):

$$p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} = c'(\hat{y}_t) + \omega_t e^{rt} \tag{16}$$

The price of electricity is equal to the (annualized) marginal costs of green electricity generation, which must equal the sum of the marginal generation costs of black electricity with the binding emission constraint and the shadow price of the emission constraint.

As shown in Appendix C, the electricity price will increase over time in the absence of technological progress ($\rho = 0$). In this case, the generation of green electricity increases over time (with investments above depreciation), while black electricity generation decreases over time in accordance with the regulation. In sum, total electricity generation falls over time. However, in the case of technological progress, electricity price development is indeterminate.

With a price of electricity that decreases over time, the generation of green electricity must increase. A decreasing electricity price necessitates an increase in green electricity generation when the generation of black electricity is decreasing, and the demand function is assumed to be time invariant. Hence, the generation of green electricity in the social optimum increases over time irrespective of the degree of technological progress.

We can now find the investment profile for new green generation capacity associated with the binding emission constraint. We take the time derivative of (16). Further, we apply the equation of motion, use the relationship, $x_t = y_t + z_t$, and solve for investments in new green generation capacity to obtain:

$$k_t = \frac{-\frac{\partial p_t}{\partial x_t}\left(\dot{\hat{y}}_t - \kappa\bar{z}_t\right) - [(r + 2\rho + 2\kappa)\kappa\bar{z}_t g'(\bar{z}_t) + (\kappa\bar{z}_t)^2 g''(\bar{z}_t) + \rho(r + \rho + \kappa)g(\bar{z}_t)]e^{-\rho t}}{\frac{\partial p_t}{\partial x_t} - (r + \rho + 2\kappa)g'(\bar{z}_t)e^{-\rho t} - \kappa\bar{z}_t g''(\bar{z}_t)e^{-\rho t}} \tag{17}$$

Inspection of the signs of (17) shows that the numerator is negative. The first term, $-\frac{\partial p_t}{\partial x_t}\left(\dot{\hat{y}}_t - \kappa\bar{z}_t\right)$ is negative, since $\frac{\partial p_t}{\partial x_t} < 0$ and the target path $\dot{\hat{y}}_t$ is negative. In the second term, the content in the square bracket consists of only positive cost expressions of green electricity generation. With a negative sign in front of it, it becomes negative. The denominator is also negative since it consists of two negative terms: $(\frac{\partial p_t}{\partial x_t}) < 0$ and $-[(r + \rho + 2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} < 0$. Investments in new green generation capacity is therefore positive.

3.3. The TGC scheme

In this section, we analyze a TGC scheme such as the Nordic TGC scheme. Generators receive a TGC (s_t) per unit of green electricity generated (z_t) from the issuing body (the regulator) and sell these on the TGC market. Thus, the generators of green electricity obtain remuneration (the price of TGCs) on top of the wholesale price for electricity $(\mathrm{i.e.}, \mathrm{s_t} + \mathrm{w_t})$. The demand for TGCs arises in that electricity retailers and certain larger electricity customers have an obligation to buy TGCs corresponding to a given percentage as determined by the regulator (the percentage requirement, α_t) out of the total electricity delivered/consumed $(\mathrm{\alpha_t x_t})$. We do not include retailers and distributors of electricity since their role is strictly as intermediaries. The obligation is therefore imposed on the consumers. The end-user price of electricity is then determined by the wholesale price of electricity and the obligation to hold green TGCs. With competitive markets, the equilibrium end-user price for electricity can be expressed as $\mathrm{p_t} = \mathrm{w_t} + \mathrm{\alpha_t s_t}$. As the supply of certificates is equal to z_t and the demand for certificates is $\mathrm{\alpha_t x_t}$, the equilibrium condition for the TGC market is simply: $z_t = \mathrm{\alpha_t x_t}$.

When using a TGC scheme, the optimization problem reads[11]:

$$\max_{y_t, k_t, \bar{z}_t} \int_0^T [(p_t - \alpha_t s_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + s_t z_t]e^{-rt}$$

subject to

$$\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$$
$$z_t \leq \bar{z}_t$$

Denoting the costate variable γ_t and the Lagrange multiplier φ_t, the corresponding present value Hamiltonian to this problem amounts to:

$$H_t = [(p_t - \alpha_t s_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + s_t z_t]e^{-rt} + \gamma_t(k_t - \kappa \bar{z}_t) - \varphi_t(z_t - \bar{z}_t)$$

The first-order conditions are: [12]

$$\frac{\partial H_t}{\partial y_t} = [w_t - c'(y_t)]e^{-rt} = 0 \tag{18}$$

$$\frac{\partial H_t}{\partial z_t} = (w_t + s_t)e^{-rt} - \varphi_t = 0 \tag{19}$$

$$\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \gamma_t = 0 \tag{20}$$

$$\frac{\partial H_t}{\partial \bar{z}_t} = -[g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \gamma_t \kappa + \varphi_t = -\dot{\gamma}_t \tag{21}$$

$$\gamma_T \geq 0 \tag{22}$$

$$\begin{aligned} H_T = {} & [(p_T - \alpha_T s_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T + s_T z_T]e^{-rT} \\ & + \gamma_T(k_T - \kappa \bar{z}_T) - \varphi_T(z_T - \bar{z}_T) = 0 \end{aligned} \tag{23}$$

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[11] Observe that $\mathrm{\alpha_t s_t x_t} = s_t \mathrm{z_t}$

[12] The end-user price in equilibrium is given by: $\mathrm{p_t} = \mathrm{w_t} + \mathrm{\alpha_t s_t}$

To derive an expression for the TGC price, we take the time derivative of (20), equalize it with (21) and insert (19). From (18), we observe that $w_t = c'(y_t)$. We then obtain the following expression:

$$s_t = [(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(y_t) \tag{24}$$

The TGC price is the difference between the (annualized) marginal costs of green electricity generation and the marginal cost of black electricity generation. Hence, the objective of the TGC scheme is to promote the generation of green electricity by reducing the gap between the marginal costs of the two types of generation technologies. If green generation technology becomes cheaper $(\rho > 0)$, the gap and the TGC price decrease.

To derive an expression for the end-user price of electricity, we observe from (18) that the wholesale price of electricity is equal to the marginal cost of black electricity generation, insert this relationship along with the TGC price from (24) into the expression for the end-user price $p_t = w_t + \alpha_t s_t$, and obtain:

$$p_t = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + (1-\alpha_t)c'(y_t) \tag{25}$$

The end-user price of electricity is thus a weighted sum of the (annualized) marginal costs of green electricity generation and the marginal cost of black electricity generation, with the percentage requirement as the weight. The absence of a percentage requirement $(\alpha_t = 0)$ implies no regulation, and the price of electricity is determined solely by the marginal costs of black electricity generation.

Next, we seek to characterize the effects of a TGC scheme on the generation of black and green electricity. Hence, consider any (continuous and differentiable) time path of percentage requirements as announced by the regulator to be followed in the electricity market. Accordingly, take the total time derivative of (25), use the fact that $z_t = \bar{z}_t = \frac{\alpha_t y}{1-\alpha_t}$, and solve for $\dot{y}_t$.

$$\dot{y}_t = \frac{\dot{\alpha}_t\left[(1-\alpha_t)^2 s_t - y_t\left(\frac{\partial p_t}{\partial x_t} - \alpha_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t}\right)\right] - (1-\alpha_t)^2\alpha_t\rho((r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t))e^{-\rho t}}{(1-\alpha_t)\left[\frac{\partial p_t}{\partial x_t} - {\alpha_t}^2[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right]} \tag{26}$$

As shown in (26), the effect on black electricity generation (and emission) is not clear-cut. The denominator is negative since $0 < \alpha_t < 1$, $\frac{\partial p_t}{\partial x_t} < 0$, and the generation costs of electricity are positive. The numerator, on the other hand, is indeterminate. However, if we assume that green technology does not become cheaper over time ($\rho = 0$), then the last term of the numerator ($(1-\alpha_t)^2\alpha_t\rho((r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t))e^{-\rho t}$) disappears. The expression inside the square bracket is positive; thus, if $\rho = 0$ and $\dot{\alpha}_t > 0$, then $\dot{y}_t$ is negative. In the TGC literature, using static models, an increase of the percentage requirement has been previously shown to have a strictly negative effect on black electricity generation (see e.g. Amundsen & Mortensen, 2001). This result carries over to the dynamic model. However, previous theoretical models have not included cost decreases in green electricity generation ($\rho > 0$). From (26) we see that the last term of the numerator is negative and works in the opposite direction to dampen the reduction in black electricity generation, and therefore also emission, when $\rho > 0$and $\dot{\alpha}_t > 0$.

The next expression shows investment in new green generation capacity[13]:

$$k_t = \frac{\dot{\alpha}_t\left(\alpha_t(1-\alpha_t)s_t - \left((1-\alpha_t)c''(y_t) - \frac{\partial p_t}{\partial x_t}\right)y_t\right) - {\alpha_t}^2(1-\alpha_t)(r+\rho+\kappa)\rho g(\bar{z}_t)e^{-\rho t}}{(1-\alpha_t)\left[\frac{\partial p_t}{\partial x_t} - {\alpha_t}^2(r+\rho)g'(\bar{z}_t)e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right]} + D \tag{27}$$

Inspection of signs shows that the denominator of (27) is negative, while the numerator is indeterminate. The D -term in (27) is also indeterminate. Hence, the effect on green investment of an increasing path of percentage requirements is in general inconclusive. This holds even if green technology does not become cheaper over time ($\rho = 0$). However, as ρ takes on higher values, the second negative element in the numerator of (27) increases in strength and may turn the numerator strictly positive. Such an inconclusive effect has been remarked earlier in the theoretical literature. The point being that an increasing share of renewables could well be achieved solely through a reduction of black electricity (see e.g. Amundsen & Mortensen,

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[13] The term D is written in its entirety in Appendix D.

2001). However, in a dynamic model with technological progress in green capacity generation, expansion of green electricity generation becomes more likely.

In general, a TGC scheme gives rise to a subsidy of green electricity generation at the expense of black electricity generation. In some cases, the stimulus of green electricity may be so strong for example, due to technological progress in green electricity generation that it more than compensates for the declining generation of black electricity, thus giving rise to falling prices and increasing electricity consumption. A similar conclusion is found in Ambec & Crampes (2019). Along the same lines, Abrell et al. (2019) argue that a TGC scheme has insufficient incentives for energy conservation compared to the socially optimal outcome.

4. Analyses and discussion

4.1. The regulator´s choice of percentage requirements

In this section, we examine whether a TGC scheme may be used to achieve the target path for emission reduction in an optimal manner, i.e., in accordance with the optimal social solution in section 3.2, which amounts to determining a time path of percentage requirements that the regulator should announce for the market to comply with. Here, we consider two candidates: a path of percentage requirements calculated from the optimal social solution and a path of percentage requirements specifically designed to attain the target path for the reduction of black electricity generation.

A natural thought would be to use the values from the optimal social solution and calculate a percentage requirement at each date. Hence, from the optimal social solution, we calculate:

$$\alpha_t^* = \frac{z_t^*}{x_t^*} \tag{28}$$

where z_t^* and x_t^* represent optimal social generation of green electricity and optimal total social generation of electricity, respectively. Hence, the regulator announces the exact same shares of green electricity as in the optimal social solution, with the percentage requirement, believing that this would result in the optimal social outcomes.

We can characterize the time path emanating from (28), (e.g., whether it is increasing or decreasing). Note that $x_t^* = z_t^* + \hat{y}_t$. Taking the time derivative of (28), we obtain:

$$\dot{\alpha}_t^* = \left(\frac{\dot{z}_t^* x_t^* - z_t^* \dot{x}_t^*}{x_t^{*2}}\right) \quad (29)$$

From Appendix C, we know that the social optimum is characterized by $\dot{z}_t^* > 0$ regardless of technological progress in green capacity construction. Hence, the first term of the numerator of (29) is positive. However, it is not necessarily the case that $\dot{x}_t^*(\dot{\hat{y}} + \dot{z}_t^*) > 0$ in the second term of the numerator. With no technological progress ($\rho = 0$), we must have $\dot{x}_t^* < 0$, which results in $\dot{p}_t^* > 0$ and $\dot{\alpha}_t > 0$. However, in the case where green electricity generation capacity becomes cheaper ($\rho > 0$), we can have $\dot{x}_t^* > 0$ such that $\dot{p}_t^* < 0$. In this case, the time path of the percentage requirement is indeterminate.

A comparison of the first-order conditions in (9) – (12) and (18) – (21) lead us to conclude that a TGC scheme based on the time path of percentage requirements calculated from (28) cannot achieve the socially optimal social solution. Furthermore, a comparison of the optimality conditions for the electricity price in (16) and (25) shows that these can only be equal if $\alpha_t$equals one. However, since $0 < \alpha_t < 1$, this is not feasible.

In fact, a TGC scheme using a time path of percentage requirements given in (28) will give rise to higher total electricity generation, higher black electricity generation and higher green electricity generation compared with the social optimum. Hence, we have: $x_t^{TGC} > x_t^*$, $y_t^{TGC} > \hat{y}_t$, and $z_t^{TGC} > z_t^*$, where the superscript, TGC, denotes the TGC solution. Since we obtain the result that $x_t^{TGC} > x_t^*$, we must then have $p_t^{TGC} < p_t^*$. The main reason for the result that $p_t^{TGC} < p_t^*$, is simply that the generators of black electricity subsidize the production of green electricity so that the generation of green electricity is stimulated above what is socially optimal (z_t^*). A formal proof is given in Appendix E.

To enhance the understanding of this result, we apply an illustrative numerical model based on the theoretical results. The numerical model is described in Appendix F.

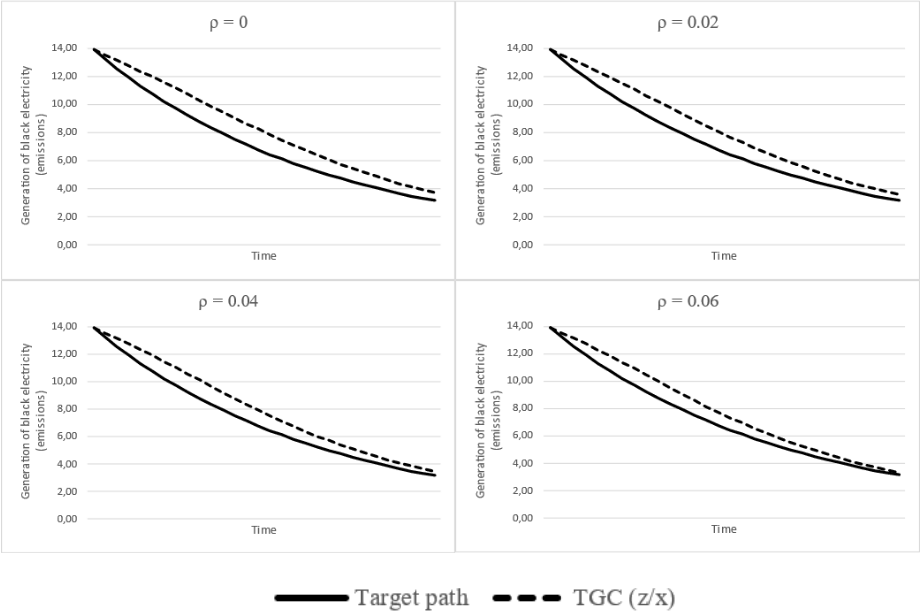

Figure 1: The use of a TGC scheme to achieve the announced target path of emission reductions when the time path of percentage requirements is calculated from (28)

Figure 1 shows the announced target path (solid line) and the emission reductions obtained from using the TGC scheme (dashed line,). The figure also illustrates the effect of cheaper green technology with an increasing value of ρ. If the regulator uses the TGC scheme based on the shares of the social optimum as given in (28), emissions *will* be reduced, but the target path is not obtained. Figure 1 also shows that emissions will be insufficiently reduced even for higher levels of cost reductions in green technology. The chosen parameter values and functional forms determine the actual curvatures, but the numerical model highlights our theoretical findings that are also in line with previous findings in the literature.

Hence, as concluded, the percentage requirement derived in (28) cannot be used successfully to simultaneously attain the outcomes from the social optimum. Thus, whether a TGC scheme can be used to achieve socially optimal values is uncertain. The aim is to characterize an alternative candidate for the regulator´s choice of a time path of percentage requirements, i.e., a path where a TGC scheme attains the target path for decreasing black electricity generation. Subsequently, we ask whether such a time path will also achieve the socially optimal solution for green electricity generation. This solution is numerically determined, hence, we cannot provide analytical expressions for this time path.

We calculate a time path of α_t^{TGC}'s that, when applied in a TGC scheme, results in a path of green electricity that displaces black electricity exactly in accordance with the specific target path of black electricity, i.e., such that $y_t^{TGC} = \hat{y}_t$ at all dates. More precisely, we apply the optimality condition for the electricity price in (25), include the binding constraint $y_t^{TGC} = \hat{y}_t$, and use the equilibrium condition for the certificate market for replacement $\left(z_t^{TGC} = \frac{\alpha_t}{1-\alpha_t}\hat{y}_\mathrm{t}\right)$. We can then solve for the path of the percentage requirements (α_t^{TGC}'s) that meets the announced target path explicitly. Clearly, this path cannot be identical to the path calculated from the shares of the optimal social solution as expressed in (28).

Along with the development of black electricity generation, a corresponding development of green electricity generation can be calculated from the condition $\left(z_t^{TGC} = \frac{\alpha_t^{TGC}}{1-\alpha_t^{TGC}}\hat{y}_\mathrm{t}\right)$. Comparing this development with the development of green electricity generation in the optimal social solution, we find that the generation of green electricity for the case considered here is larger. Hence, a TGC scheme that achieves the target path of black electricity generation results in overinvestment in green generation capacity. As with the other version of the time path for the percentage requirement, we again obtain the result that $x_t^{TGC} > x_t^*$, and hence, $p_t^{TGC} < p_t^*$. A formal proof of this scenario is provided in Appendix H.

4.2. Emission fee on black electricity generation

In this section, we derive the outcomes when using an emission fee to achieve the announced target path of emission reductions. The fee (τ_t) is levied on generators of black electricity for each unit of output. The optimization problem reads:

$$\max_{y_t, k_t, \bar{z}_t} \int_0^T [p(x_t)x_t - c(y_t) - \tau_t y_t - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt}$$

subject to:

$$\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$$

$z_t \leq \bar{z}_t$

Denoting the costate variable by ε_t and the Lagrange multiplier ς_t, the present value Hamiltonian takes the following form:

$$H_t = [p(x_t)x_t - c(y_t) - \tau_t y_t - g(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} + \epsilon_t(k_t - \kappa\bar{z}_t) - \varsigma_t(z_t - \bar{z}_t)$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial y_t} = [p_t - c'(y_t) - \tau_t]e^{-rt} = 0 \tag{30}$$

$$\frac{\partial H_t}{\partial z_t} = p_t e^{-rt} - \varsigma_t = 0 \tag{31}$$

$$\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \epsilon_t = 0 \tag{32}$$

$$\frac{\partial H_t}{\partial \bar{z}_t} = -[g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \epsilon_t\kappa + \varsigma_t = -\dot{\epsilon}_t \tag{33}$$

$$\epsilon_T \geq 0 \tag{34}$$

$$H_T = [p(x_T)x_T - c(y_T) - \tau_T y_T - g(\bar{z}_T)e^{-\rho T}k_T]e^{-rT} + \epsilon_T(k_T - \kappa\bar{z}_T) - \varsigma_T(z_T - \bar{z}_T) \tag{35}$$

By taking the time derivative of (32), equalizing it with (33) and inserting (31), we obtain the optimality condition for the price of electricity. Furthermore, from (30), we observe that $p_t = c'(y_t) + \tau_t$. We then obtain the following result:

$$p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} = c'(y_t) + \tau_t \tag{36}$$

The condition in (36) mirrors the result from the social optimum in (16). The price of electricity is determined by the (annualized) marginal costs of green electricity generation. To achieve the optimality outcome from (16), we derive an expression for the necessary emission fee. From (36), we obtain:

$$\tau_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(y_t) \tag{37}$$

The emission fee is the difference between the (annualized) marginal costs of green electricity generation and the marginal costs of black electricity generation. To obtain socially optimal results, the regulator must set the emission fee equal to the shadow price of the emission constraint ($\omega_t e^{rt}$). As with the TGC price in (24), cheaper green technology reduces the size of the necessary emission fee. With the condition that $\tau_t = \omega_t e^{rt}$, the emission fee is an optimal policy instrument. The investment profile in new green generation capacity will then be equal to the solution in the social optimum derived in (17).

4.3. Subsidy for green electricity generation

Finally, we consider whether the regulator can use a subsidy for green electricity generation to achieve the announced target path. The subsidy (σ_t) is given per unit of output to generators of green electricity. The optimization problem reads:

$$\max_{y_t, k_t, \bar{z}_t} \int_0^T [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + \sigma_t z_t]e^{-rt}$$

subject to

$$\dot{\bar{z}}_t = k_t - \kappa \bar{z}_t$$
$$z_t \leq \bar{z}_t$$

Denoting the costate variable by δ_t and the Lagrange multiplier ν_t, the present value Hamiltonian reads:

$$H_t = [p(x_t)x_t - c(y_t) - g(\bar{z}_t)e^{-\rho t}k_t + \sigma_t z_t]e^{-rt} + \delta_t(k_t - \kappa \bar{z}_t) - \nu_t(z_t - \bar{z}_t)$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial y_t} = [p_t - c'(y_t)]e^{-rt} = 0 \tag{38}$$

$$\frac{\partial H_t}{\partial z_t} = [p_t + \sigma_t]\, e^{-rt} - \nu_t = 0 \tag{39}$$

$$\frac{\partial H_t}{\partial k_t} = -[g(\bar{z}_t)e^{-\rho t}]e^{-rt} + \delta_t = 0 \tag{40}$$

$$\frac{\partial H_t}{\partial \bar{z}_t} = -[g'(\bar{z}_t)e^{-\rho t}k_t]e^{-rt} - \delta_t\kappa + \nu_t = -\dot{\delta}_t \tag{41}$$

$$\delta_T \geq 0 \tag{42}$$

$$\begin{aligned} H_T = {} & [p(x_T)x_T - c(y_T) - g(\bar{z}_T)e^{-\rho T}k_T + \sigma_T z_T]e^{-rT} + \delta_T(k_T - \kappa\bar{z}_T) \\ & - \nu_T(z_T - \bar{z}_T) \end{aligned} \tag{43}$$

By taking the time derivative of (40), equalizing it with (41) and inserting (39), we get the optimality condition for the price of electricity. We then obtain the following result:

$$p_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - \sigma_t \tag{44}$$

The price of electricity is equal to the difference between the (annualized) marginal costs of green electricity generation and the green subsidy. The expression for the subsidy is obtained by combining (38) and (44):

$$\sigma_t = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(y_t) \tag{45}$$

By using (44) and (45), we can find that for the subsidy to be able to achieve the announced target path of emission reductions, we must have:

$$\begin{aligned} p_t = {} & [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} \\ & - \big([(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} - c'(\hat{y}_t)\big) = c'(\hat{y}_t) \end{aligned} \tag{46}$$

If the regulator uses a subsidy to attain the announced target path, the electricity price is equal to the marginal costs of black electricity generation, with the binding emission constraint ($y_t = \hat{y}_t$). Comparing (46) and (16), the subsidy reduces the end-user price of electricity and increases the consumption of electricity. The subsidy, as the emission fee, is the difference between the (annualized) marginal costs of green and black electricity generation. They are, however, not equivalent in value. When an emission fee and a subsidy achieve the same emission reductions, the subsidy must be larger since it increases the consumption of electricity through a reduction in the price of electricity (Fischer & Newell, 2008). As with the emission fee, cheaper green generation technology reduces the size of the subsidy.

The investment profile for new green generation capacity is obtained by taking the time derivative of (46) and using the equilibrium condition for the electricity market. We then obtain the following result:

$$k_t = \frac{\dot{\hat{y}}_t\left[c''(\hat{y}_t) - \frac{\partial p_t}{\partial x_t}\right] + \frac{\partial p_t}{\partial x_t}\kappa \bar{z}_t}{\frac{\partial p_t}{\partial x_t}} \tag{47}$$

Investments in new green generation capacity are positive and higher than the solution desired by the regulator, as mentioned earlier. Unlike the investment profiles for the TGC scheme and the emission fee, the investment profile in (47) is not affected by technological progress in green generation technology (ρ). The reason is that the price of electricity is determined by the marginal costs of black electricity generation.

4.4. Price paths of electricity and social surplus – a comparison of instruments

A general expression for the price path of electricity when using a TGC scheme may be found by taking the time derivative of (25):

$$\begin{aligned}\dot{p}_t = {} & \dot{\alpha}_t s_t + \alpha_t\big((r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)\big)\dot{\bar{z}}_t e^{-\rho t} \\ & - \alpha_t\rho\big((r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)\big)e^{-\rho t} + (1-\alpha_t)c''(y_t)\dot{y}_t\end{aligned} \tag{48}$$

The general result is that the price path is indeterminate even if we assume no cost reductions in green technology $(\rho = 0)$. The challenge faced by the regulator is to find a time path of percentage requirements that may achieve the socially optimal solution when using a TGC scheme. From section 4.1, we know that the TGC scheme with a time path of percentage requirements based on (28) is unable to achieve the emission reductions and investments in new green generation capacity desired by the regulator. Hence, for a TGC scheme to meet the emission constraints, the regulator must calculate a time path of percentage requirements that achieves the announced target path exactly. From the analysis, we know that even for this case, the development of the price path of electricity is indeterminate. This version of the time path of the percentage requirements is included in Figure 2 for comparison.

The price path of electricity when using the emission fee is obtained by taking the time derivative of (36):

$$\dot{p}_t = \Big(\big((r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)\big)\dot{\bar{z}}_t - \rho\big((r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)\big)\Big)e^{-\rho t} \tag{49}$$

From (49), we can see that even if an expansion of green generation capacity occurs ($\dot{\bar{z}}_t > 0$), the price path is ambiguous due to cost reductions in green technology. However, if we assume that $\rho = 0$, then the price of electricity is monotonically increasing. We illustrate this path using the numerical model in Figure 2.

We showed that the price of electricity when using the subsidy is equal to the marginal costs of black electricity generation, with the binding emission constraint. The price path is obtained by taking the time derivative of (46):

$$\dot{p}_t = c''(\hat{y}_t)\dot{\hat{y}}_t \tag{50}$$

Since the announced target path is negative, we know that the price of electricity using the subsidy is decreasing and that the path is unaffected by an increase in ρ.

Figure 2 displays the price path of electricity for the different instruments, with different values for ρ.[14]. The emission fee is the solid line, and the dashed dotted line represents the subsidy. The dashed line is the TGC scheme where the time path of the percentage requirement is derived from (28) (denoted TGC (z/x)), and the round dotted line represents the TGC scheme where the time path of the percentage requirement is calibrated to achieve the target path exactly (denoted TGC (y)).

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[14] The results in this paper rest on the premise that the demand for electricity is time invariant. However, good reasons to expect that the demand for electricity will change over time may exist, which we explore by assuming that a drift in demand over time. We show that the general results of the paper still hold. The results are summarized in Appendix G.

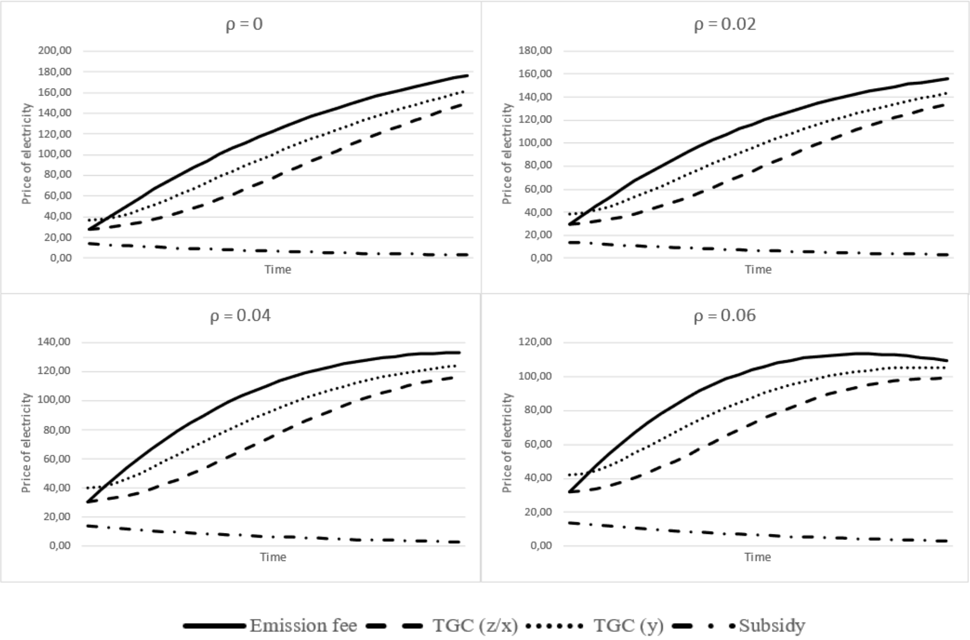

Figure 2: The price path of electricity for the different instruments

From Figure 2, we can see that cheaper green technology has an impact on the price path of electricity for all the instruments, except the subsidy. As shown in (46), the price of electricity when using the subsidy is determined by the marginal costs of black electricity generation. Hence, cheaper green technology does not affect the price path. Use of the subsidy also results in the lowest price and thus excessive demand for electricity. On the other hand, the emission fee produces the highest price of electricity. The illustrations in Figure 2 also clarify the ambiguity of the price path from (49). As green generation technology becomes cheaper, the price of electricity stops increasing, and the price path eventually starts falling. This is a reasonable result since the price of electricity is determined by the (annualized) marginal generation costs of green electricity.

Regardless of the calculation of the time path of the percentage requirements, the use of a TGC scheme results in a lower price of electricity than the socially optimal price attained with the emission fee. The price paths with both percentage requirements, however, are similar to the path resulting from the emission fee. With the TGC scheme, the price of electricity is the weighted sum of the (annualized) marginal costs of green electricity generation and the marginal cost of black electricity generation, with the percentage requirement as the weight.

Cheaper green technology therefore reduces the price of electricity but less than by using the emission fee. We can therefore see that the price paths with the emission fee and the TGC scheme start to converge for higher values of ρ. The illustrations in Figure 2 also show that out of the two versions of the time path of the percentage requirements, the price of electricity is highest when the time path of the percentage requirement is calibrated to achieve the target path exactly. In this case, there will be overinvestment in new green generation capacity. If the time path of the percentage requirement is derived from (28) instead, we know that not only will there be overinvestment in new green generation capacity, but generation of black electricity will be higher than the target path as well.

Next, we construct a ranking of the economic efficiency of the instruments in terms of social surpluses. For the TGC scheme, only one of the versions of the percentage requirement obtains the announced target path of emission reductions. This is the version where the time path of percentage requirements is calibrated to achieve the target path exactly. We will focus on this version and compare it with the emission fee and the subsidy.

For the emission fee, we have the following expression for the social surplus:

$$W^{\tau} = \int_{0}^{T} \left[\int_{0}^{x_t^{\tau}} \mathrm{p}(x_t^{\tau})dx - \mathrm{c}(y_t^{\tau}) - \tau_t y_t^{\tau} - \mathrm{g}(\bar{z}_t^{\tau})e^{-\rho t}k_t^{\tau} \right] \mathrm{e}^{-\mathrm{rt}}dt + l^{\tau}$$

We know that if the emission fee is set equal to the shadow price of the emission constraint, it achieves the solutions of the social optimum, denoted by $\mathrm{y}_t^* = \hat{y}_t$, $\bar{\mathrm{z}}_t^*$ and x_t^*. The symbol l^{τ} is an expression of the lump sum present value of the total emission fee subtracted from the electricity sector ($\int_0^{\mathrm{T}} \tau_t \hat{y}_t \mathrm{e}^{-\mathrm{rt}} \mathrm{dt}$). This amount must be added when calculating the social surplus. The expression for the social surplus when using the emission fee can then be written as:

$$W^{\tau} = \int_{0}^{T} \left[\int_{0}^{\mathrm{x}_t^*} \mathrm{p}(\mathrm{x}_t^*)dx - \mathrm{c}(\hat{y}_t) - \mathrm{g}(\bar{\mathrm{z}}_t^*)e^{-\rho t}k_t^* \right] \mathrm{e}^{-\mathrm{rt}}dt \tag{51}$$

With the subsidy, the superscript σ denotes the values of the variables when the subsidy is used. The expression for the social surplus when using the subsidy reads:

$$W^{\sigma} = \int_{0}^{T} \left[\int_{0}^{x^{\sigma}} \mathrm{p}(x_t^{\sigma})dx - \mathrm{c}(y_t^{\sigma}) - g(\bar{z}_t^{\sigma})e^{-\rho t}k_t^{\sigma} + \sigma_t z_t^{\sigma} \right] e^{-rt}\, dt - l^{\sigma}$$

The symbol l^{σ} is the total present value of the subsidy $(\int_0^{\mathrm{T}} \sigma_{\mathrm{t}} z_t^{\sigma} \mathrm{e}^{-\mathrm{rt}}\mathrm{dt})$ added from outside the electricity sector. We must subtract this amount when calculating the social surplus. We can then rewrite the social surplus when using a subsidy as:

$$W^{\sigma} = \int_{0}^{T} \left[\int_{0}^{x^{\sigma}} \mathrm{p}(x_t^{\sigma})dx - \mathrm{c}(\hat{y}_t) - g(x_t^{\sigma} - \hat{y}_t)e^{-\rho t}k_t^{\sigma} \right] e^{-rt}\, dt \tag{52}$$

If we compare the optimality condition for the subsidy in (46) with the optimal outcome for the regulator in (16), we have that $\mathrm{p}(x_t^{\sigma}) = \mathrm{c}'(\hat{y}_t) < \mathrm{p}(\mathrm{x}_t^{*}) = \mathrm{c}'(\hat{y}_t) + \omega_t e^{rt}$. Using a subsidy to achieve the target path of emission reductions results in excessive investments in new green generation capacity. The social surplus is maximized if $x_t = x_t^{*}$. Hence, since $x_t^{\sigma} > x_t^{*}$, $W^{\tau} > W^{\sigma}$.

With the TGC scheme, we discuss the version where the percentage requirement is calibrated to achieve the announced target path exactly ($y_t = \hat{y}_t$). Since the TGC scheme is a self-contained system, we do not have to add or subtract anything to calculate the social surplus. The expression for the social surplus can then be written as:

$$W^{TGC(\hat{y})} = \int_{0}^{T} \left[\int_{0}^{x^{TGC(\hat{y})}} \mathrm{p}\left(x_t^{TGC(\hat{y})}\right) dx - c\left(y_t^{TGC(\hat{y})}\right) - g\left(\bar{z}_t^{TGC(\hat{y})}\right) e^{-\rho t} k_t^{TGC(\hat{y})} \right] e^{-rt}\, dt$$

We show in Appendix H that when the TGC scheme achieves the target path of emission reductions exactly, then $z_t^{TGC} > z_t^{*}$ and $x_t^{TGC} > x_t^{*}$ (which also entails $k_t^{TGC(\hat{y})} > k_t^{*}$). Since we have that $z_t^{TGC} = \alpha_t x_t^{TGC}$ and $\hat{y}_t = (1 - \alpha_t)x_t^{TGC}$, we can rewrite the expression for the social surplus:

$$\begin{aligned} W^{TGC(\hat{y})} &= \int_0^T \left[\int_0^{x^{TGC(\hat{y})}} \mathrm{p}\left(x_t^{TGC(\hat{y})}\right) dx - c\left((1-\alpha_t)x_t^{TGC(\hat{y})}\right) \right. \\ &\quad \left. - g\left(\alpha_t x_t^{TGC(\hat{y})}\right) e^{-\rho t} k_t^{TGC(\hat{y})} \right] e^{-rt}\, dt \\ &= \int_0^T \left[\int_0^{x^{TGC(\hat{y})}} \mathrm{p}\left(x_t^{TGC(\hat{y})}\right) dx - c(\hat{y}_t) \right. \\ &\quad \left. - g\left(x_t^{TGC(\hat{y})} - \hat{y}_t\right) e^{-\rho t} k_t^{TGC(\hat{y})} \right] e^{-rt}\, dt \end{aligned} \tag{53}$$

The social surplus is maximized when $x_t = x_t^*$. Hence, since $x_t^{TGC} > x_t^*$, $W^\tau > W^{TGC(\hat{y})}$.

We now finalize the ranking of the instruments by comparing the TGC scheme and the subsidy. We can compare the optimality conditions for the TGC scheme (when the target path of emission reductions is attained) and the subsidy from (25) and (46).

We have that $\mathrm{p}(x_t^\sigma) = \mathrm{c}'(\hat{y}_t)$, and $\mathrm{p}\left(x_t^{TGC(\hat{y})}\right) = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} + (1-\alpha_t)\mathrm{c}'(\hat{y}_t)$. Since both instruments achieve the target path of emission reductions, the level of black electricity generation is the same for both instruments in every period. Further, $[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} > \mathrm{c}'(\hat{y}_t)$ and $0 < \alpha_t < 1$. This entails that $\mathrm{p}(x_t^\sigma) < \mathrm{p}\left(x_t^{TGC(\hat{y})}\right)$. Since $\frac{\partial p_t}{\partial x_t} < 0$, we must have that $x_t^\sigma > x_t^{TGC(\hat{y})}$, and hence, $W^{TGC(\hat{y})} > W^\sigma$.

To summarize, when the regulator wants to achieve a specific target path of emission reductions, we obtain the following ranking of social surplus for the different instruments:

$$W^\tau > W^{TGC(\hat{y})} > W^\sigma \tag{54}$$

While both the TGC scheme and the subsidy achieve the target path by crowding out the generation of black electricity, they provide insufficient incentives for energy conservation. Hence, the consumption of electricity increases through lower electricity prices. With the emission fee, better incentives for energy conservation exist, and the target path is achieved while avoiding excessive consumption of electricity.

5. Summary and concluding remarks

In this paper, we consider the problem of regulation of negative externalities in the form of GHG emissions. We explore the effectiveness of using a TGC scheme to achieve a specific target path of emission reductions in the electricity sector. The results are compared with the outcomes from using an emission fee and a green subsidy.

If the regulator uses a TGC scheme and derives the time path of the percentage requirement from the socially optimal target share of green electricity, the generation of black electricity is reduced but not in accordance with the announced target path. In fact, the TGC scheme results in an overinvestment in new green generation capacity, an insufficient reduction of black electricity generation, and thus emissions. An alternative strategy to determine a time path of percentage requirements would be to calculate the percentage requirements that exactly attain the target path for black electricity and then announce this to the participants in the electricity market. We show that such a path of percentage requirements exists, but that this would still result in an overinvestment in green capacity compared with the optimal social solution. Regardless of the time path chosen for the percentage requirements, total electricity generation exceeds the socially optimal level; thus, the price of electricity will be too low.

The optimal instrument to use is a path of emission fees where the fee at all dates is set equal to the shadow price of the emission constraint. The price of electricity is determined by the (annualized) marginal costs of green electricity generation. If green generation technology becomes cheaper over time, the price of electricity no longer increases monotonically, and the price path may eventually fall. This effect is also present for the price path of electricity when using a TGC scheme, but the effect is less pronounced due to the presence of the percentage requirement. We also derive the necessary conditions for a subsidy to achieve the announced target path. The subsidy lowers the price of electricity down to the marginal cost of black electricity generation, with the binding emission constraint. Hence, the resulting consumption of electricity is excessive. Since generation costs for black electricity determine the price of electricity, the price path is not affected by cheaper green generation technology. A comparison of the resulting social surplus shows that the maximum social surplus is attained by using a time path of emission fees and that the largest loss of surplus occurs when using a time path of subsidies.

Our results affirm that an optimal emission fee is a cost-effective strategy to manage negative externalities (Baumol & Oates, 1988). In practice, however, this option might not be available (Dresner, Dunne, Clinch, & Beuermann, 2006; Rivlin, 1989). For example, the EU explored the possibility of a tax, but eventually ended up introducing an emission trading scheme (Convery, 2009). Further, even if an emission fee is implemented, it is not necessarily set at an efficient level (Johnson, 2007).

The use of a TGC scheme reduces emissions from fossil-based electricity generation for any time path of the percentage requirements chosen. With a properly calibrated percentage requirement, it can also achieve a specific reduction of emission over time such as the target for the reduction of black electricity generation. A TGC scheme is a self-contained subsidy system for the electricity sector where the government only announces a binding path of percentage requirements without being directly involved in funding. Generators of green electricity receive green certificates in proportion to the amount of electricity generated, while end-users of electricity are requested to buy the certificates and thereby provide funding for the TGC scheme. A TGC scheme with allocation of certificates is similar to using an emission trading scheme with free allocation of permits. This allocation method has been cited as a reason for the political acceptability of emission trading systems (Harstad & Eskeland, 2010; Stavins, 1998). Apart from reducing emissions, a TGC scheme is also designed to provide incentives for construction of new green generation capacity, which is not only an important step towards decarbonization of the electricity sector but can also release positive externalities related to technological innovation (learning by doing and spill-over effects). This may also be a reason for choosing support schemes for renewables over pricing instruments (Acemoglu, Aghion, Bursztyn, & Hemous, 2012; Jaffe, Newell, & Stavins, 2005). Further, promotion of electricity from renewables can also be motivated by concerns such as energy security and the creation of green jobs (Fischer & Preonas, 2010).

On the other hand, while a TGC scheme can be used to reduce emissions, it is not necessarily a very accurate instrument. In terms of cost-effectiveness, a TGC performs better than a subsidy and, as mentioned, is a self-contained subsidy system where the funding is passed on to the consumers of electricity. Hence, unlike emission fees and auctioned emission permits, a TGC scheme does not raise any revenue. A revenue-raising instrument has the advantage that the collected revenue can be used to offset distorting taxes (Goulder, Parry, Williams III, & Burtraw, 1999). Finally, additional motivations for choosing a support scheme for renewables over pricing instruments may exist, but not all concerns are equally valid. A technology-neutral TGC scheme favors the most mature technologies (Unger & Ahlgren, 2005), which does not necessarily entail promotion of technological innovation. This may be achieved through differentiation of technologies, where less mature technologies receive more TGCs per MWh generated (Woodman & Mitchell, 2011). Finally, even if energy security is used as justification for promoting construction of new green generation capacity, a high share of renewables is not necessarily an obvious solution (Löschel, Moslener, & Rübbelke, 2010).

Our findings show that a TGC scheme can be used as an instrument to reduce emissions from the electricity sector. It can also be calibrated to achieve a specific path of emission reductions. However, the incentives for investment in new green generation capacity will be nonoptimal. Further, insufficient incentives for energy conservation will result in a higher demand for electricity compared to the use of direct emission pricing. A TGC scheme is designed to incentivize more construction of green generation capacity, but whether it is the best solution if promotion of technological innovation is an important objective is uncertain. Compared to an optimal emission fee, a TGC scheme is less cost-effective. Additionally, it does not generate revenue for the government. Nevertheless, a TGC scheme is more cost-effective than a green subsidy and results in less welfare loss. Thus, if effective pricing instruments are unavailable, a TGC scheme may well emerge as a politically feasible second-best solution.

Appendix

A. Functional forms and notations used in the model.

Symbol	Description
p_t	End-user price of electricity at date t
w_t	Wholesale price of electricity at date t
y_t	Generation of black electricity at date t
$\hat{y}_t$	Target level of black electricity generation at date t, announced by the regulator
z_t	Generation of green electricity at date t
$\bar{z}_t$	Green generation capacity at date t
x_t	Consumption of electricity at date t
k_t	Investment in new green generation capacity at date t, with $k_t \geq 0$
s_t	TGC price at date t
α_t	Percentage requirement at date t
τ_t	Emission fee at date t
σ_t	Subsidy at date t
r	Social discount rate
P	The rate of technological change for green generation technology
κ	Depreciation rate of green generation capacity
χ	The rate of decrease in emissions announced by the regulator
T	Termination date of the problem considered

B. Proof of the price evolution of electricity from section 3.1.

In the case with no regulations and technological progress in green generation technology ($\rho > 0$), the price of electricity decreases over time. The price decrease results from a decrease in the generation of black electricity and an increase in green generation capacity, where the latter will dominate.

The optimality condition without regulation reads:

$$p_t = c'(y_t) = [(r + \rho + \kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} \qquad \text{B.I.}$$

We must have $\dot{p}_t < 0$. To prove this, assume the opposite, i.e., that $\dot{p}_t \geq 0$, which leads to a contradiction.

Take the time derivative of B.I. to obtain:

$$\dot{p}_t = c''(y_t)\dot{y}_t \qquad \text{B.II.}$$

If $\dot{p}_t \geq 0$, then $\dot{y}_t \geq 0$ since $c''(y_t) \geq 0$.

Further, from B.I., we must have:

$$\begin{aligned}\dot{p}_t = -\rho[(r+\rho+\kappa)g(\bar{z}_t) + \kappa\bar{z}_t g'(\bar{z}_t)]e^{-\rho t} \qquad \text{B.III.}\\ + [(r+\rho+\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t) + \kappa g'(\bar{z}_t)]\dot{\bar{z}}_t e^{-\rho t}\end{aligned}$$

If $\dot{p}_t \geq 0$, then from B.III, $\dot{\bar{z}}_t > 0$ since $g'(\bar{z}_t)$ and $g''(\bar{z}_t) > 0$.

However, if $\dot{y}_t \geq 0$ and $\dot{z}_t$[15] > 0, then $\dot{x}_t > 0$ such that $\dot{p}_t < 0$, which contradicts the assumption that $\dot{p}_t \geq 0$. Therefore, we must have $\dot{p}_t < 0$ as we set out to show. ■

C. Proof of the price evolution of electricity from section 3.2.

In the case where the regulator has announced a target path of emission reductions (which is assumed to be binding), denoting the outcomes of this constrained social optimum by $y_t^* = \hat{y}_t$, $\bar{z}_t^*$, x_t^*, the optimality condition states:

$$p_t = [(r+\rho+\kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} = \omega_t e^{rt} + c'(\hat{y}_t) \qquad \text{C.I.}$$

ρ = 0

With depreciation of green generation capacity (κ > 0) and no technological progress for green generation technology (ρ = 0), we claim that $\dot{p}_t > 0$.

We take the time derivative of C.I. to obtain:

$$\dot{p}_t = [(r+2\kappa)g'(\bar{z}_t^*) + \kappa\bar{z}_t g''(\bar{z}_t^*)]\dot{\bar{z}}_t^* \qquad \text{C.II.}$$

---

[15] Recall that we always have $z_t = \bar{z}_t$

Then, from C.II., sign $\dot{p}_t$ = sign $\dot{\bar{z}}_t^*$ since $g'(\bar{z}_t^*)$ and $g''(\bar{z}_t^*) > 0$.

Taking the time derivative of the other optimality condition in C.I., we obtain:

$$\dot{p}_t = [r\omega_t + \dot{\omega}_t]e^{rt} + c''(\hat{y}_t)\dot{\hat{y}}_t \qquad \text{C.III.}$$

We know that the announced target path set by the regulator is characterized by $\dot{\hat{y}}_t < 0$.

To obtain a proof through contradiction, assume that $\dot{p}_t \leq 0$, which leads to $\dot{\bar{z}}_t^* \leq 0$. Since $\dot{\hat{y}}_t < 0$, we have $(\dot{\hat{y}}_t + \dot{z}_t^*) = \dot{x}_t < 0$ such that $\dot{p}_t > 0$, which contradicts the assumption that $\dot{p}_t \leq 0$.

Therefore, we must have $\dot{\hat{y}}_t < 0, \dot{z}_t^* > 0$ and $(\dot{\hat{y}}_t + \dot{z}_t^*) = \dot{x}_t < 0$, resulting in $\dot{p}_t > 0$, which we set out to prove.

ρ > 0

In the case with technological progress for green generation technology (ρ > 0), $\dot{p}_t$ will be indeterminate.

The time derivative of C.I. then provides the following:

$$\begin{aligned}\dot{p}_t = -\rho[(r+\rho+\kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} \\ + [(r+\rho+2\kappa)g'(\bar{z}_t^*) + \kappa\bar{z}_t^* g''(\bar{z}_t^*)]\dot{\bar{z}}_t^* e^{-\rho t}\end{aligned} \qquad \text{C.IV.}$$

Thus, the equality sign $\dot{p}_t$ = sign $\dot{\bar{z}}_t^*$ no longer holds with certainty. As a result, $\dot{p}_t$ is indeterminate. ■

D. Expression of the last term from (29) in its entirety

D

$$= \frac{\kappa\bar{z}_t\left[\begin{array}{c}\left(\frac{\partial p_t}{\partial x_t} - \alpha_t(r+2\rho+2\kappa)g'(\bar{z}_t)e^{-\rho t} - \alpha_t\kappa\bar{z}_t g''(\bar{z}_t)e^{-\rho t}\right)\left(\frac{\partial p_t}{\partial x_t} - \alpha_t{}^2[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right) \\ -(1-\alpha_t)\alpha_t\rho g'(\bar{z}_t)e^{-\rho t}\left((1-\alpha_t)c''(y_t) - \frac{\partial p_t}{\partial x_t}\right)\end{array}\right]}{\left(\frac{\partial p_t}{\partial x_t} - \alpha_t[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t}\right)\left[\frac{\partial p_t}{\partial x_t} - \alpha_t{}^2[(r+\rho+2\kappa)g'(\bar{z}_t) + \kappa\bar{z}_t g''(\bar{z}_t)]e^{-\rho t} - (1-\alpha_t)^2 c''(y_t)\right]}$$

E. Proof of $x_t^{TGC} > x_t^*, y_t^{TGC} > \hat{y}_t,\ z_t^{TGC} > z_t^*$ when $\alpha_t = \alpha_t^*$

Denote the outcomes of the constrained social optimum by $y_t^* = \hat{y}_t$, $\bar{z}_t^*$, x_t^*, and the outcomes of the TGC scheme by y_t^{TGC}, $\bar{z}_t^{TGC}$ and x_t^{TGC}. Recall that $\alpha_t^* = \left(\frac{z_t^*}{x_t^*}\right)$ and observe that $\hat{y}_t = (1 - \alpha_t^*)x_t^*$ and that $z_t^* = \bar{z}_t^* = \alpha_t^* x_t^*$. Observe further that $y_t^{TGC} = (1 - \alpha_t^*)x_t^{TGC}$ and that $z_t^{TGC} = \bar{z}_t^{TGC} = \alpha_t^* x_t^{TGC}$ due to the design of the TGC scheme. Hence, if $x_t^{TGC} > x_t^*$, then $y_t^{TGC} > \hat{y}_t$, and $z_t^{TGC} > z_t^*$. We show this by a proof of contradiction, i.e., we assume that $x_t^{TGC} \le x_t^*$ and show that a contradiction appears. Next, we rewrite the optimality condition for the social solution (16):

$$p_t(x_t^*) = [(r + \rho + \kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} = c'(\hat{y}_t) + \omega_t e^{rt}$$

By using the fact that: if a = b, then αa + (1- α)b = a = b, if 0 < α <1, we obtain:

$$\begin{aligned} p_t(x_t^*) = \alpha_t^*[(r + \rho + \kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} \\ + (1 - \alpha_t^*)(c'(\hat{y}_t) + \omega_t e^{rt}) \end{aligned} \qquad \text{E.I.}$$

From (25), we have:

$$\begin{aligned} p_t(x_t^{TGC}) = \alpha_t^*[(r + \rho + \kappa)g(\bar{z}_t^{TGC}) + \kappa\bar{z}_t^{TGC} g'(\bar{z}_t^{TGC})]e^{-\rho t} \\ + (1 - \alpha_t^*)c'(y_t^{TGC}) \end{aligned} \qquad \text{E.II.}$$

Clearly, if by assumption $x_t^{TGC} \le x_t^*$, then $p_t(x_t^*) \le p_t(x_t^{TGC})$ since $\frac{\partial p_t}{\partial x_t} < 0$. From E.I. and E.II., we then have:

$$\begin{aligned} & p_t(x_t^*) = \alpha_t^*[(r + \rho + \kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} + (1 - \alpha_t^*)(c'(\hat{y}_t) + \omega_t e^{rt}) \le \\ & p_t(x_t^{TGC}) = \alpha_t^*[(r + \rho + \kappa)g(\bar{z}_t^{TGC}) + \kappa\bar{z}_t^{TGC} g'(\bar{z}_t^{TGC})]e^{-\rho t} + (1 - \alpha_t^*)c'(y_t^{TGC}) \end{aligned}$$

However, this obviously cannot be the case since the assumption $x_t^{TGC} \le x_t^*$ implies that $\bar{z}_t^{TGC} = \alpha_t^* x_t^{TGC} \le \bar{z}_t^* = \alpha_t^* x_t^*$, $y_t^{TGC} = (1 - \alpha_t^*)x_t^{TGC} \le \hat{y}_t = (1 - \alpha_t^*)x_t^*$, $g(\bar{z}_t) > 0$,

$g'(\bar{z}_t) > 0$ and $\omega_t > 0$. Hence, we must have: $x_t^{TGC} > x_t^*$,, $y_t^{TGC} > \hat{y}_t$, $z_t^{TGC} = \bar{z}_t^{TGC} > z_t^* = \bar{z}_t^*$ when $\alpha_t = \alpha_t^*$. [16]■

F. Functional forms and parameter values used in the illustrative numerical model

$$P(x_t) = a - b\mathrm{x}_t$$

$$c(y_t) = \frac{1}{2}{y_t}^2$$

$$g(z_t)e^{-\rho t} = \left(\frac{m{\bar{z}_t}^2}{2} + n\bar{z}_t\right)e^{-\rho t}$$

a, b, m, and n are all strictly positive constants with values of a: 340, b: 20, m: 57, and n: 47. Further, we set the social discount rate and the depreciation rate of the existing green generation capacity to 0.05 (r = κ = 0.05). Finally, the desired rate of emission reductions announced by the regulator is also set to 0.05 (χ = 0.05).

G. The price path of electricity with the inclusion of drift in the demand over time

To control for the scenario where drift exists in the demand for electricity over time, we construct a new function for the demand for electricity, $\mathrm{p}_\mathrm{t}^\mathrm{N} = \mathrm{p}(\mathrm{x}_\mathrm{t})\mathrm{e}^{-\eta \mathrm{t}}$. With a linear demand function, we can find numerical solutions with the expression $p_t = (A - bx_t)\mathrm{e}^{\eta \mathrm{t}}$. The parameter η is an expression of positive drift in demand due to, e.g., electrification of the transport sector.

We show that the general results of the paper still hold when controlling for drift in electricity demand over time. We perform the simulation with a value of 0.03 for η. The first-order conditions are the same, and the optimality results are therefore unchanged. Of course, differences in the values will exist; a higher demand over time will result in both a higher price and higher levels of new green generation capacity (the target path of emission reductions will still be met). The results are also robust for a negative value of η. A negative drift for the electricity demand over time could arise because of policies focusing on extensive energy efficiency.

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[16] This proof is a generalization of a proof in Amundsen, Andersen and Mortensen (2018) for a static case.

The inclusion of positive drift in demand is illustrated in Figure G.1. The price path of electricity without drift is the solid line, while the dotted line shows the price path with drift. As we can see, even with the inclusion of drift, the trajectories for the two price paths are qualitatively similar and differ only with respect to the included drift, and as the price increases, the two price paths diverge.

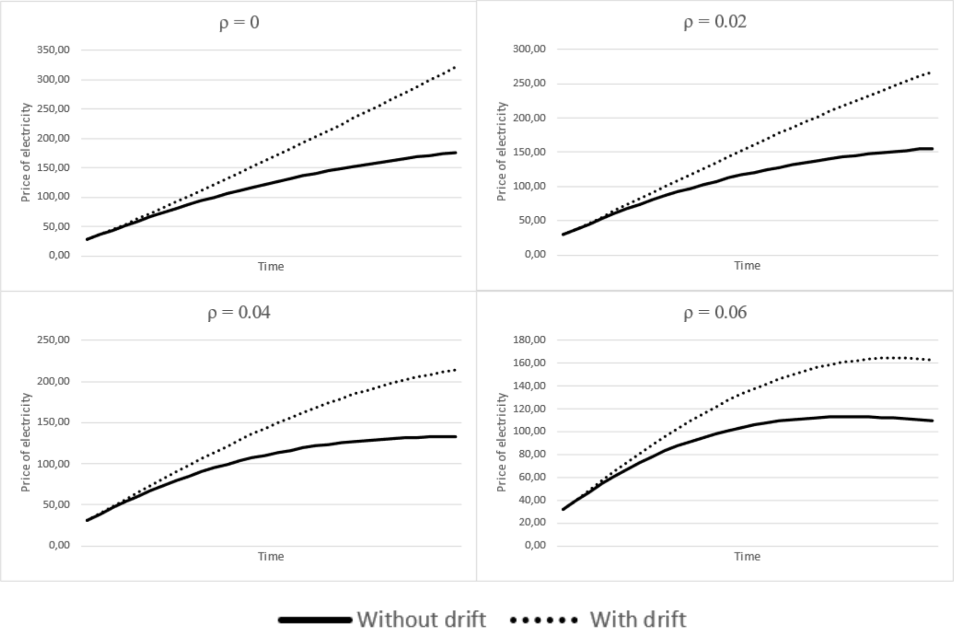

Figure G.1: The price of electricity – socially optimal solutions with and without drift

H. Proof of $\bar{z}_t^{TGC} > \bar{z}_t^*$ and $x_t^{TGC} > x_t^*$ as $y_t^{TGC} = \hat{y}_t$

In this case, the percentage requirement, α_t, is determined such that the target path of black electricity is attained at all dates. Using the same notation as in Appendix E, we know that $z_t^{TGC} = \alpha_t x_t^{TGC}$ and that $\hat{y}_t = (1-\alpha_t)x_t^{TGC}$. Next, as in Appendix E, we rewrite the optimality condition for the social solution (16) as:

$$p_t(x_t^*) = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} + (1-\alpha_t)(c'(\hat{y}_t) + \omega_t e^{rt}) \quad \text{H.I.}$$

Further, from (25), we have:

$$p_t(x_t^{TGC}) = \alpha_t\big[(r+\rho+\kappa)g\big(\bar{z}_t^{TGC}\big) + \kappa\bar{z}_t^{TGC}\, g'\big(\bar{z}_t^{TGC}\big)\big]e^{-\rho t} \\ + (1-\alpha_t)c'(\hat{y}_t) \qquad \text{H.II.}$$

Clearly, the conditions G.I. and G.II., as well as the solutions, are not generally identical. We set out to prove that $\bar{z}_t^{TGC} > \bar{z}_t^*$ and $x_t^{TGC} > x_t^*$. Therefore, we apply a proof by contradiction. Hence, we assume the opposite, i.e., $\bar{z}_t^{TGC} \leq \bar{z}_t^*$ and $x_t^{TGC} \leq x_t^*$, and show that this leads to a contradiction. Clearly, if $x_t^{TGC} \leq x_t^*$, then $p_t(x_t^{TGC}) \geq p_t(x_t^*)$.

Hence, we must have:

$$p_t(x_t^{TGC}) = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t^{TGC}) + \kappa\bar{z}_t^{TGC} g'(\bar{z}_t^{TGC})]e^{-\rho t} + (1-\alpha_t)c'(\hat{y}_t) \geq p_t(x_t^*) \\ = \alpha_t[(r+\rho+\kappa)g(\bar{z}_t^*) + \kappa\bar{z}_t^* g'(\bar{z}_t^*)]e^{-\rho t} + (1-\alpha_t)(c'(\hat{y}_t) + \omega_t e^{rt}) \qquad \text{H.III.}$$

As the assumption is that $\bar{z}_t^{TGC} \leq \bar{z}_t^*$ and $x_t^{TGC} \leq x_t^*$ and that $g(\bar{z}_t) > 0$, $g'(\bar{z}_t) > 0$ and $\omega_t > 0$, we clearly have a contradiction. Hence, we must have $\bar{z}_t^{TGC} > \bar{z}_t^* = z_t^*$ and $x_t^{TGC} > x_t^*$. ■

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Chapter 3

Refunded emission payments scheme – a cost-effective *and* politically acceptable instrument for NOx emissions reduction?

Refunded emission payments scheme – a cost-effective *and* politically acceptable instrument for NO_x emissions reduction?[1]

Arild Heimvik[2]

Abstract

In this paper, we investigate whether a refunded emission payments (REP) scheme can cost-effectively achieve a specific target path of nitrogen oxides (NO_x) emission reductions. We examine two REP schemes and analyze their incentives for emission mitigation of energy-producing firms. Firms can reduce their emissions through production cuts or investments in abatement technology. In the first scheme, firms pay a charge per unit of NO_x emission and receive refunds based on their emission cuts. In the second, refunds are given in proportion to energy produced. The paper contributes to the REP literature by deriving analytical results for a cost-effective REP scheme. Further, we use a dynamic model to analyze the REP schemes. This allows us to examine time paths for the economic instruments and the mitigation incentives they provide. Finally, we examine heterogeneous firms' behavior under the two REP schemes and study their distributional outcomes. Both REP schemes can achieve the emission target. However, it is only cost-effective when all emission cuts are eligible for refunds. The choice of refund also affects the distributional outcome for different firm types. Our results suggest that if a Pigouvian tax is unavailable, then a REP scheme is not necessarily an inferior second-best alternative.

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1. Introduction

Nitrogen oxides (NO_x), which consist of nitric oxide (NO) and nitrogen dioxide (NO_2), are potent greenhouse gases that are also able to cause considerable local damage. The main source of NO_x emissions is the combustion of fossil fuels. These emissions lead to acid deposition and eutrophication, causing detrimental effects on both soil and water quality. NO_x (in the form of NO_2) can also have significant adverse impacts on human health. High concentrations contribute to local air pollutants' formation and lead to inflammation of the airways (European Environment Agency, 2018). Negative externalities like pollution can be internalized with corrective instruments, such as Pigouvian taxes (Baumol & Oates, 1988). In practice, political constraints can restrict the instrument choice of regulators[3].

With a refunded emission payments (REP) scheme, a charge is put on the regulated firms' emissions, and the revenues are recycled back to the firms. Currently, there is limited experience with the use of REP schemes. Perhaps the most well-known example is Sweden, which introduced a REP scheme in 1992. A charge is levied per kilogram of NO_x emitted, and the collected funds are recycled back to the same firms in proportion to their output of useful energy[4] (Sterner & Isaksson, 2006). France operated with a similar system where the revenues were recycled back to firms as subsidies for abatement measures (Millock, Nauges, & Sterner, 2004). In 2008, Norway introduced a voluntary solution called the NO_x fund. The participating business organizations pay a charge upfront to the fund per kilogram of NO_x emitted. These revenues are then recycled back based on verified emission cuts (NOx-fondet, 2019).

In this paper, we investigate the regulation of negative externalities, where the regulator wants to achieve a specific target path of NO_x emission reductions. However, due to political constraints, a first best Pigouvian tax is not available. Hence, the regulator tries to achieve cost-effective regulation with the use of a REP scheme. Since the presence of constraints on regulation is not uncommon, it is an interesting analysis whether a REP scheme can act as a cost-effective instrument for reducing NO_x emissions.

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[3] See Amundsen, Hansen, & Whitta-Jacobsen (2018) for an analysis of indirect regulation of location-specific externalities from small-time polluters.

[4] "Useful energy" is generally accepted as a benchmark for measuring output for industries as varied as those regulated under the Swedish REP scheme, since the primary goal of the scheme is to affect the combustion technologies. Useful energy for power plants and district heating plants equals the energy sold. For other industries, useful energy is comprised of hot water, steam or electricity produced in the boiler, used in heating or factory buildings or the production process (Sterner & Isaksson, 2006).

The firms studied in the model produce energy that causes NO_x emissions, and they can invest in new abatement technology. Hence, firms can reduce emissions through production cuts or by investing in new abatement capacity. We examine two different designs of a REP scheme. First, we look at a scheme where firms pay a charge per unit of emissions and receive refunds based on emissions cuts. This scheme is based on the scheme currently in use in Norway. The second is an output-based scheme, where firms pay a charge per unit of emissions and receive refunds in proportion to their output. This version is based on the system in place in Sweden and has a prominent place in the REP literature. We study the effects of the two REP schemes on output and investment incentives in new abatement technology. To the best of our knowledge, this is the first paper to analyze the use of REP schemes using a dynamic model. Using a dynamic model allows us to analyze time-related issues such as time paths for economic instruments, paths for emission reductions, and investment profiles for abatement technology. Further, our model assumes heterogeneous firms. We can then examine the effects of the two REP schemes on different firm types, given an exogenous emission target. Finally, since REP schemes are more recent additions as environmental policy, it is interesting to assess their potential and limitations as an alternative to a Pigouvian tax.

A key assumption in the paper is that the regulator announces a target path of NO_x emission reductions that must be achieved using a REP scheme. It is not an assertion that the announced target path is the optimal solution for mitigating NO_x emissions. We do not discuss the justification for this target path but merely assume that the regulator has announced it and that it is binding. The objective for the regulator in this paper is comparable to other established dynamic emission targets. For example, the emission target for CO_2 in the European Union (EU) is determined by the total emission cap, which is reduced by an annual percentage reduction. This increasingly stringent and binding cap raises the price of emission permits and reduces CO_2 emissions to achieve the EU's long-term target. The Gothenburg Protocol establishes commitments for, among other things, the reduction of NO_x emissions, where final targets are set for the signatory countries. Furthermore, countries such as Norway have set commitments to ensure that the total NO_x emissions over periods of two years do not exceed specified emission ceilings that decrease over time (NHO, 2020). In our model, we capture the cost of NOx emissions' negative external effects by the shadow price of the emission constraint. The emissions in our model are a function of the output of firms, as in Gersbach & Requate (2004), Sterner & Isaksson (2006), Fischer (2011) and Hagem et al. (2015).

Analyses of exogenous emission targets' achievement are common in the environmental economics literature (Fell & Linn, 2013; Goulder & Parry, 2008; Wibulpolprasert, 2016). In the REP literature, the focus has been mainly on using REP schemes to reduce emissions. Sterner & Isaksson (2006) discuss the theory of an output-based REP scheme and the Swedish experience from using this instrument. Gersbach and Requate (2004) showed that refunding based on market shares under perfect competition causes distortions since output levels become excessive. Under imperfect competition, however, a combination of an emission tax and an output subsidy could result in the first-best outcome. This result was confirmed by Fischer (2011), who also showed that with imperfect competition and endogenous refunds, significant market shares could result in reduced abatement incentives. Further, in an asymmetric Cournot duopoly, endogenous refunds could result in too high output and emission levels. Hagem et al. (2015) used a static model to compare two REP schemes under perfect competition, where refunds are given in proportion to output and as a share of expenditures for abatement equipment. They found that both schemes result in cost-ineffective abatement compared to a Pigouvian tax. Bontems (2019) combined both output- and expenditure-based refunding. He showed that this combination could remedy REP schemes' drawbacks where refunds are given for either output or abatement equipment.

Using econometric methods, other contributions have focused on the effect of REP schemes on the adoption of abatement technologies. Sterner & Turnheim (2009) studied the development of technical change for NO_x abatement from large stationary sources in Sweden. They found that an output-based REP scheme was important in reducing emission intensities. Furthermore, Bonilla et al. (2015) found that the REP scheme in Sweden had a positive effect on adopting post combustion technologies to mitigate NO_x emissions. On the other hand, Coria and Mohlin (2017) argued that it is not unambiguous whether a REP scheme provided better incentives than a standard emission tax for technological upgrades over time. The effect of the refund diminishes as the regulated sector becomes cleaner.

Our paper contributes to the REP literature in several ways. First, we examine whether a REP scheme can be an effective instrument for reducing NO_x emissions, and we derive and discuss the necessary conditions for this to be the case in competitive markets. These results are compared with outcomes from using an output-based REP scheme. Second, we use a dynamic model in our analysis. This allows us to investigate how a dynamic emission target can be achieved and how output, investments in new abatement technology, and economic instruments evolve over time. Third, the use of heterogeneous firms in a dynamic model allows us to explore how different firm types behave under different REP schemes for the same emission target. These results are highlighted using an illustrative numerical model. We are also able to compare the distributional effect for different firms with the two instruments.

The rest of the paper is organized as follows. In section 2, the theoretical model and its assumptions are introduced. Section 3 begins by deriving the solutions to the problem of the regulator. Next, we derive the results from the two REP schemes and discuss their implications. The analysis is extended in section 4, where we conduct comparative statics to study different firms' behavior under the two REP schemes. Where appropriate, an illustrative numerical model is used to highlight the results. Further, we look at the distributional effect for different firms in terms of net payments. The paper is summarized, and concluding remarks are delivered in section 5.

2. The model[5]

The objective of the regulator is to reduce NO_x emissions in accordance with an announced target path. This can be expressed as $M_t = \sum_{i=1}^{n} m_{it} \leq \bar{M}_t = \bar{M}_0 e^{-\omega t}$, where $m_{io}$is firm i's (i=1, …, n) initial emission level and ω is the rate of emission reductions the regulator wants to achieve. The model focuses on energy-producing firms that emit NO_x as part of their production process. Firms are heterogeneous, and we assume competitive markets. There are N profit-maximizing firms, and they take output prices and the actions of the other firms as given. We analyze an arbitrarily chosen firm. Production costs are integrated into a concave profit function, $\pi_i(q_{it})$. The capacity costs for abatement technology are denoted as $h_i(K_{it})$, where K_{it} is the capacity of abatement technology for firm i. The function is increasing and convex in the capacity level of abatement technology, i.e., $\frac{\partial h_i}{\partial K_{it}} > 0$ and $\frac{\partial^2 h_i}{\partial {K_{it}}^2} \geq 0$. Investment in new abatement technology is denoted by k_t. The total cost function for abatement technology is multiplicative and expressed as $h_i(K_{it})k_{it}$. Since we solve explicitly for investment in new technology capacity, the multiplicative form of the cost function has convenient properties. We use optimal control theory to highlight the accumulation of new abatement technology. The stock of technology acts as the state variable, and investments in new technology represent the

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[5] The nomenclature for the model is summarized in Appendix A

control variable. The depreciation of the existing stock of abatement technology is denoted δ. The evolution of a firm's capacity of abatement technology is then expressed as $\mathrm{k_{it}} - \delta\mathrm{K_{it}}$[6].

For simplicity, we assume a proportional relationship between energy production and $\mathrm{NO_x}$ emissions. Firms can reduce emissions in two ways. They can reduce production or invest in new abatement technology. In this model, there is one relevant type of abatement technology[7]. It can be thought of as end-of-pipe technology. This is an add-on measure used to comply with environmental regulations that reduces harmful substances arising as byproducts from production. Examples are scrubbers and catalytic converters (Frondel, Horbach, & Rennings, 2007). Bonilla et al. (2015) argued that using a REP scheme has a positive effect on the adoption of end-of-pipe post combustion technologies. The emission function has the following characteristics: $\frac{\partial\,\mathrm{m_{it}}}{\partial\,\mathrm{q_{it}}} > 0, \frac{\partial^2\,\mathrm{m_{it}}}{\partial\,\mathrm{q_{it}}^2} \geq 0, \frac{\partial\,\mathrm{m_{it}}}{\partial\,\mathrm{K_{it}}} < 0$ and $\frac{\partial^2\,\mathrm{m_{it}}}{\partial\,\mathrm{K_{it}}^2} \geq 0$. Further, the function is separable, i.e., $\frac{\partial^2\,\mathrm{m_{it}}}{\partial\,\mathrm{q_{it}}\,\partial\,\mathrm{K_{it}}} = 0$.

3. Model applications and analyses

3.1.Emission constrained social optimum

In this section, we solve the optimization problem for the regulator. The objective is to maximize the total net present value of the difference between profit and the costs of abatement technology capacity over the period from 0 to the terminating period T, given the regulator's binding target path of emission reductions. Henceforth, the solutions obtained in this section are referred to as solutions of the social optimum or socially optimal solutions. Denoting the social discount rate by r, the optimization problem reads:

$$\max_{\mathrm{q_{it}},\mathrm{k_{it}},K_{\mathrm{it}}} \int_0^{\mathrm{T}} \sum_{i=1}^{n} [\pi_i(\mathrm{q_{it}}) - \mathrm{h}_i(\mathrm{K_{it}})\mathrm{k_{it}}]\mathrm{e}^{-\mathrm{rt}}$$

subject to:

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[6] Capacity-related issues for the output variable are not included. We are interested in studying the effect of the stock of abatement technology on emission reductions. Inclusion of capacity concerns for output would complicate the model further. We would have to add an additional state variable without a qualitative alteration of our main results.

[7] This is the same assumption made in Hagem et al (2015)

$$\dot{K}_{it} = k_{it} - \delta K_{it}$$

$$\sum_{i=1}^{n} m_{it} \leq \bar{M}_t$$

The first constraint denotes the equation of motion for the abatement technology capacity. The second constraint is the target of emission reductions announced by the regulator. By assumption, this constraint is binding. This results in a positive shadow price for the emission constraint. This is an expression of the costs of achieving the target path. Denoting the costate variable by λ_{it} and the shadow price by η_t, the corresponding present-value Hamiltonian reads:

$$H_t = \sum_{i=1}^{n} [\pi_i(q_{it}) - h_i(K_{it})k_{it}]e^{-rt} + \sum_{i=1}^{n} \lambda_{it}(k_{it} - \delta K_{it}) + \eta_t\left(\bar{M}_t - \sum_{i=1}^{n} m_{it}\right)$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial q_{it}} = [\pi'_i(q_{it})]e^{-rt} - \eta_t m_{iq} = 0 \quad (1)$$

$$\frac{\partial H_t}{\partial k_{it}} = -h_i(K_{it})e^{-rt} + \lambda_{it} = 0 \quad (2)$$

$$\frac{\partial H_t}{\partial K_{it}} = -h'_i(K_{it})k_{it}e^{-rt} - \delta\lambda_{it} - \eta_t m_{iK} = -\dot{\lambda}_{it} \quad (3)$$

$$\lambda_{iT} \geq 0 \quad (4)$$

$$H_T = \sum_{i=1}^{n} [\pi_i(q_{iT}) - h_i(K_{iT})k_{iT}]e^{-rT} + \sum_{I=1}^{n} \lambda_{iT}(k_{iT} - \delta K_{iT}) + \eta_T\left(\overline{M}_T - \sum_{i=1}^{n} m_{iT}\right) \quad (5)$$

We take the time derivative of (2), set it equal to (3), and apply the equation of motion. Solving for the shadow price, we obtain the following expression:

$$\eta_t = -\frac{(r+\delta)h_i(K_{it}) + h'_i(K_{it})\delta K_{it}}{m_{iK}} e^{-rt} \quad (6)$$

Further, we insert (6) into (1) to obtain:

$$\frac{\pi'_i(q_{it})}{m_{iq}} = -\frac{(r+\delta)h_i(K_{it}) + h'_i(K_{it})\delta K_{it}}{m_{iK}} = \eta_t e^{rt} \tag{7}$$

From (7), we have obtained conditions for the marginal cost of emission reductions related to production adjustment and to the use of abatement technology. For both mitigation measures, marginal costs of emission reductions divided by the marginal effect on emission reductions must be equal to the shadow price for the emission constraint. If emissions are reduced by reducing output, the marginal cost of emission reductions is the foregone marginal profit divided by its marginal product on emission reduction. If a firm cuts emission through investment in abatement technology, the marginal cost is the extra abatement costs, divided by its marginal product on mission reduction.

If the regulator introduces an emission tax, i.e., τ_t, equal to $\eta_t e^{rt}$, per unit of emission, every single firm arrives at the same first-order conditions as those given in (1) to (5), and socially optimal solutions are obtained. This optimal tax increases in both measures of emission mitigation. A key assumption in this paper, however, is that the optimal emission tax is unavailable. In the next two sections, we analyze outcomes from using REP schemes where refunds are given for emission cuts and output.

3.2.Refunds based on emission reductions

The REP scheme in this section is based on the scheme currently in use in Norway. In 2007, Norway introduced a tax on NO_x emissions for specified emission sources[8]. As a response to the tax, several business organizations came together and proposed a solution called the NO_x fund, which came into effect in 2008. The fund's purpose was to reduce NO_x emissions and contribute to meeting Norway's obligation under the Gothenburg Protocol (NOx-avtalen 2018-2025, 2017). The fund is a voluntary arrangement where the participating firms pay a charge to the fund per kilogram of NO_x emitted. These revenues are then recycled back to the same firms based on verified emission cuts (NOx-fondet, 2019). Further, there is a constraint on the refund, such that it cannot exceed 70 percent of the cost of the NO_x-reducing measure (NOx-fondet, 2019). If the firms meet their obligations through the NO_x fund, they are exempted from the

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[8] The fee was levied on NO_x emissions in energy production from: **1)** propulsion machinery with total installed effect on more than 750 kW **2)** engines, boilers, and turbines with a total effect of more than 10 MW and **3)** flares on offshore installations and onshore facilities. These sources comprise approximately 55 percent of the total NOx emissions in Norway (Hagem, Holtsmark, & Sterner, 2014).

government's alternative NO_x tax. If the firms are noncompliant, however, they must pay the tax in proportion to their emissions (NOx-avtalen 2018-2025, 2017).

In published guides to the NO_x fund, it is specified that the refund rate is given in proportion to annual NO_x reductions, but that refunds are also restricted to cover technical installations on both existing and new sources of emissions (NOx-fondet, 2019). In this paper, the goal is to examine whether a REP scheme can be used as a cost-effective instrument to achieve a dynamic emission target. Hence, we model the REP scheme such that refunds are linked directly to firms' emission cuts. We show that it is optimal to give refunds based on emission cuts and that additional restrictions hamper the instrument's efficiency.

Firms pay a charge, ρ_t, per unit of NO_x emissions upfront and receive a refund, $\beta\varphi_t$, in proportion to their actual emission cuts. These emission cuts are defined as the difference from their emissions with no mitigation, $\widehat{m}_i$. If there are no emission regulations, then from (1), the firm upholds production until marginal profit is zero. Then, there is no incentive to invest in abatement technology. Hence, the unregulated emission level is constant over time[9]. The refund consists of the refund rate φ_t and the constant refund constraint, β, with $0 < \beta < 1$. The optimization problem for firm i reads:

$$\max_{q_{it},k_{it},K_{it}} \int_0^T [\pi_i(q_{it}) - h_i(K_{it})k_{it} - \rho_t m_{it} + \beta\varphi_t(\widehat{m}_i - m_{it})]e^{-rt}$$

subject to:

$$\dot{K}_{it} = k_{it} - \delta K_{it}$$

Denoting the costate variable by ξ_{it}, the corresponding present-value Hamiltonian reads:

$$H_t = [\pi_i(q_{it}) - h_i(K_{it})k_{it} - \rho_t m_{it} + \beta\varphi_t(\widehat{m}_i - m_{it})]e^{-rt} + \xi_{it}(k_{it} - \delta K_{it})$$

The first-order conditions are:

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[9] This result is conditional upon an emission function without drift over time. If drift is included, unregulated emission for the firm would be time-variant. This is not pursued further in this paper.

$$\frac{\partial H_t}{\partial q_{it}} = [\pi'_i(q_{it}) - \rho_t m_{iq} - \beta\varphi_t m_{iq}]e^{-rt} = 0 \tag{8}$$

$$\frac{\partial H_t}{\partial k_{it}} = -h_i(K_{it})e^{-rt} + \xi_{it} = 0 \tag{9}$$

$$\frac{\partial H_t}{\partial K_{it}} = [-h'_i(K_{it})k_{it} - \rho_t m_{iK} - \beta\varphi_t m_{iK}]e^{-rt} - \delta\xi_{it} = -\dot{\xi}_{it} \tag{10}$$

$$\xi_{iT} \geq 0 \tag{11}$$

$$H_T = [\pi_i(q_{iT}) - h_i(K_{it})k_{it} - \rho_T m_{iT} + \beta\varphi_T(\widehat{m}_i - m_{iT})]e^{-rT} + \xi_{iT}(k_{iT} - \delta K_{iT}) \tag{12}$$

We take the time derivative of (9), set it equal to (10), and solve for the sum of the REP charge and the refund. The following expression is obtained:

$$\rho_t + \beta\varphi_t = -\frac{(r+\delta)h_i(K_{it}) + h'_i(K_{it})\delta K_{it}}{m_{iK}} \tag{13}$$

By inserting (13) into (8), we obtain the following expression:

$$\frac{\pi'_i(q_{it})}{m_{iq}} = -\frac{(r+\delta)h_i(K_{it}) + h'_i(K_{it})\delta K_{it}}{m_{iK}} = \rho_t + \beta\varphi_t \tag{14}$$

The optimality conditions in (14) equal those in (7). A combination of the emission charge and the refund can achieve socially optimal solutions if:

$$\rho_t + \beta\varphi_t = \tau_t = \eta_t e^{rt} \tag{15}$$

A REP scheme is characterized by revenue neutrality. The budget constraint is binding for the sum of all the regulated firms. Denoting the optimal emission level at date t for firm i, given the regulation as m_{it}^*, the budget constraint can be expressed as:

$$\rho_t \sum_{i=1}^{n} m_{it}^* = \beta\varphi_t \sum_{i=1}^{n} (\widehat{m}_i - m_{it}^*) \tag{16}$$

With the use of (15) and (16), we obtain an analytical expression for the REP charge:

$$\rho_t = \tau_t\left(1 - \frac{\sum_{i=1}^{n} m_{it}^*}{\sum_{i=1}^{n} \widehat{m}_i}\right) \tag{17}$$

The REP charge is a share of the optimal emission tax, determined by the emission regulation's stringency. The socially optimal solutions can then be achieved using a REP scheme where the charge is at a lower level than the optimal emission tax. Hagem et al. (2015) showed that when refunds are given for abatement technology costs, the REP charge is also below the first-best emission tax. However, this scheme was not cost-effective. In the Norwegian NO_x fund, the REP charge is also at a lower level than the NO_x tax set by the government. This was meant as an incentive to join the NO_x fund in addition to the refund firms received (NOx-fondet, 2018).

To obtain the time path of the REP charge, we take the time derivative of (17):

$$\dot{\rho}_t = \dot{\tau}_t\left(1 - \frac{\sum_{i=1}^{n} m_{it}^*}{\sum_{i=1}^{n} \widehat{m}_{it}}\right) - \tau_t\frac{\sum_{i=1}^{n} \dot{m}_{it}^*}{\sum_{i=1}^{n} \widehat{m}_i} \tag{18}$$

The first term on the right side is positive since the optimal emission tax increases to achieve the target path. The second term is negative since the target path decreases over time ($\sum_{i=1}^{n} \dot{m}_{it}^* < 0$). Hence, the REP charge must increase over time to achieve the target path.

We can derive an expression for the refund by inserting (17) into (15) and rearranging:

$$\beta\varphi_t = \tau_t\frac{\sum_{i=1}^{n} m_{it}^*}{\sum_{i=1}^{n} \widehat{m}_i} \tag{19}$$

The refund is also derived as a share of the optimal emission tax and is determined by the emission regulations' stringency. The refund constraint β is meant to ensure that the refund does not exceed a given share of the cost of the NO_x-reducing measure undertaken by the firm. If it is reduced, then the refund rate φ_t must increase to ensure that (19) holds. Hence, if refunds are given for all emission cuts, then the refund constraint does not determine the value of the refund[10].

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[10] For a discussion on when the regulator decides upon the share of revenues to be refunded, see Gersbach & Requate (2004).

The time path for the refund is obtained by taking the time derivative of (19):

$$\beta\dot{\varphi}_t = \frac{\dot{\tau}_t \sum_{i=1}^{n} m_{it}^{*} + \tau_t \sum_{i=1}^{n} \dot{m}_t^{*}}{\sum_{i=1}^{n} \widehat{m}_i} \tag{20}$$

From (20), we can see that the time path of the refund is ambiguous. The denominator is positive, but the numerator is indeterminate. We know that to achieve the announced target path, the optimal emission tax must increase. From (18), we saw that the REP charge also increases over time to achieve the announced target path. If we take the time derivative of (15) and rearrange, we find that if the emission tax increases at a higher rate than the REP charge, the refund increases as well.

3.3. Refunds based on output

The REP scheme analyzed in this section is based on the one used in Sweden. A charge is levied per kilogram of NO_x emitted, and the funds are recycled back in proportion to the output of useful energy. The model in this section is based on the contributions of Gersbach & Requate (2004) and Sterner & Isaksson (2006). Both apply the same static model. We analyze a REP scheme where firms pay a charge (μ_t) per unit of emissions and receive a refund (σ_t) proportional to their output. We assume that output and emissions can be aggregated such that $\sum_{i=1}^{n} q_{it} = Q_t$ and $\sum_{i=1}^{n} m_{it} = M_t$ [11]. Further, the market share of firm i is defined as $s_{it} = \frac{q_{it}}{Q_t}$. The optimization problem for firm i then reads[12]:

$$\max_{q_{it}, k_{it}, K_{it}} \int_0^T \left[\pi_i(q_{it}) - h_i(K_{it})k_{it} - \mu_t m_{it} + \sigma_t q_{it} \frac{\sum_{i=1}^{n} m_{it}}{\sum_{i=1}^{n} q_{it}}\right] e^{-rt}$$

subject to:

$$\dot{K}_{it} = k_{it} - \delta K_{it}$$

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[11] This is the same assumption made in Sterner & Isaksson (2006).

[12] Here, we follow Sterner & Isaksson (2006). In their paper, they argue that firm i knows that there are other firms with total emissions (M_{-i}) and output (Q_{-i}). Although the firm may have expectations about these variables (based on previous years), they are treated as unknown constants in the firm's optimization.

Denoting the costate variable ε_{it}, the corresponding present-value Hamiltonian reads:

$$H_t = \left[\pi_i(q_{it}) - h_i(K_{it})k_{it} - \mu_t m_{it} + \sigma_t q_{it}\frac{\sum_{i=1}^{n} m_{it}}{\sum_{i=1}^{n} q_{it}}\right] e^{-rt} + \varepsilon_{it}(k_{it} - \delta K_{it})$$

The first-order conditions are:

$$\frac{\partial H_t}{\partial q_{it}} = \left[\pi'_i(q_{it}) - \mu_t m_{iq} + \sigma_t\left(\frac{M_t}{Q_t} + s_{it}\left(m_{iq} - \frac{M_t}{Q_t}\right)\right)\right] e^{-rt} = 0 \tag{21}$$

$$\frac{\partial H_t}{\partial k_{it}} = -h_i(K_{it})e^{-rt} + \varepsilon_{it} = 0 \tag{22}$$

$$\frac{\partial H_t}{\partial K_{it}} = [-h'_i(K_{it})k_{it} - \mu_t m_{iK} + \sigma_t s_{it} m_{iK}]e^{-rt} - \delta\varepsilon_{it} = -\dot{\varepsilon}_{it} \tag{23}$$

$$\varepsilon_{iT} \geq 0 \tag{24}$$

$$H_T = \left[\pi_i(q_{iT}) - h_i(K_{iT})k_{iT} - \mu_t m_{iT} + \sigma_t q_{iT}\frac{\sum_{i=1}^{n} m_{iT}}{\sum_{i=1}^{n} q_{iT}}\right] e^{-rT} + \varepsilon_{iT}(k_{iT} - \delta K_{iT}) \tag{25}$$

Before we continue, we derive the budget constraint. This can be expressed as:

$$\mu_t \sum_{i=1}^{n} m_{it} = \sigma_t \sum_{i=1}^{n} q_{it}\frac{\sum_{i=1}^{n} m_{it}}{\sum_{i=1}^{n} q_{it}} \tag{26}$$

From the budget constraint, the value of the REP charge must be equal to refund:

$$\mu_t = \sigma_t \tag{27}$$

To derive an expression for the REP charge, we first take the time derivative of (22) and set it equal to (23). Then, we substitute for the market share of firm i to obtain:

$$\mu_t = -\frac{(r + \delta)h_i(K_{it}) + h_i'(K_{it})\delta K_{it}}{(1 - s_{it})m_{iK}} \tag{28}$$

Inserting (28) into (21) provides us with the following expression:

$$\frac{\pi'_i(q_{it})}{(1-s_{it})(m_{iq}-\frac{M_t}{Q_t})} = -\frac{(r+\delta)h_i(K_{it}) + h_i'(K_{it})\delta K_{it}}{(1-s_{it})m_{iK}} = \mu_t \tag{29}$$

We can see from the conditions in (29) and (7) that if output-based refunding is used to achieve the target path, emission mitigation incentives differ from the first-best solution.

With output-based refunding, optimality conditions for both mitigation measures are influenced by the firm's output share. Further, the condition for production adjustments is affected by the difference between the emission intensity of firm i and the average emission intensity for all firms $\left(m_{iq} - \frac{M_t}{Q_t}\right)$. We review these in turn.

In the special case where $s_{it} \rightarrow 1$, i.e., one firm contributes to all the output, (21) collapses to $\pi'_i(q_{it})e^{-rt} = 0$. The firm produces until the marginal profit equals zero and the production level equals $\widehat{m}_i$. With one firm paying for all emissions and receiving all the recycled revenues, there are no incentives to reduce emissions. Hence, there is no investment in abatement technology. In the other special case, $s_{it} \rightarrow 0$, there are many firms with insignificant output shares. From (23) and (28), the incentives for investment in abatement technology move towards the solution desired by the regulator (see condition (7)). If the emission function is separable, i.e., $\frac{\partial^2 m_{it}}{\partial K_{it} \partial q_{it}} = 0$, then the incentives for investment in new abatement technology are socially optimal if $\mu_t = \tau_t$. The condition for production adjustments, however, is determined by the difference between m_{iq} and $\frac{M_t}{Q_t}$. Even if no firm has significant market shares, the output-based REP scheme still provides nonoptimal incentives for production adjustments. Finally, when $0 < s_{it} < 1$, investments in abatement technology decrease in output share, from (28). An increase in s_{it} also reduces marginal profit with increased production.

If $m_{iq} < \frac{M_t}{Q_t}$, then from (29), the denominator in the first term is negative. Since $\mu_t > 0$, marginal profit must also be negative. The optimal production level for the firm (q^*_{it}) then exceeds its unregulated production level $(\hat{q}_i)$. Hence, $q^*_{it} > \hat{q}_i$. Conversely, if $m_{iq} > \frac{M_t}{Q_t}$, the denominator in (29) is positive, and the numerator must decrease along with reduced production for a given μ_t. Production is still higher than the socially optimal level $\left(q^{so}_{it}\right)$; hence, $\hat{q}_i >$

$q_{it}^{*} > q_{it}^{SO}$. Finally, if $\mathrm{m_{iq}} = \frac{\mathrm{M_t}}{\mathrm{Q_t}}$, then (21) collapses to $\pi'_{\mathrm{i}}(\mathrm{q_{it}})\mathrm{e}^{-\mathrm{rt}} = 0$ and the firm produces until $q_{it}^{*} = \hat{q}_{it}$. Unlike the case where $s_{it} \to 1$, however, the firm invests in abatement technology, such that $\mathrm{K_{it}} > 0$ (from the condition in (23)).

We can now show that to achieve the specific target path, the REP charge must be higher than the Pigouvian tax, τ_t in section 3.1. For simplicity, assume insignificant output shares. We can then write (29) as:

$$\frac{\pi'_i(\mathrm{q_{it}}) + \sigma_\mathrm{t}\frac{\mathrm{M_t}}{\mathrm{Q_t}}}{\mathrm{m_{iq}}} = -\frac{(\mathrm{r}+\delta)\mathrm{h}_i(\mathrm{K_{it}}) + \mathrm{h}_i'(\mathrm{K_{it}})\delta\mathrm{K_{it}}}{\mathrm{m_{iK}}} = \mu_\mathrm{t}$$

Focusing on the condition for production adjustments, we can write:

$$\frac{\pi'_i(\mathrm{q_{it}})}{\mathrm{m_{iq}}} = \mu_\mathrm{t} - \sigma_\mathrm{t}\frac{\mathrm{M_t}}{\mathrm{m_{iq}Q_t}} \tag{30}$$

If the regulator uses output-based refunding to achieve the target path, we have that (30) must equal the condition in (7), which in turn is equal to the Pigouvian tax. Then, we obtain:

$$\mu_\mathrm{t} - \sigma_\mathrm{t}\frac{\mathrm{M_t}}{\mathrm{m_{iq}Q_t}} = \tau_\mathrm{t} \tag{31}$$

For (31) to hold, we have that the REP charge must be higher than the optimal emission tax. Furthermore, since the output subsidy incentivizes production above the socially optimal level, investments in abatement technology must also be higher to ensure that the target path is met.

4. Comparative statics

In the following sections, we examine the behavior of different firms under the two REP schemes using comparative statics. More precisely, we consider two firms under the same equilibrium solution (i.e., confronted with the same values of the policy instruments) and investigate where one of them has a marginally higher value of the parameter considered[13]. We focus on the parameters $\mathrm{m_{iq}}$, $\mathrm{m_{iK}}$, $\mathrm{h_i(K_{it})}$ and $\pi_{\mathrm{i}}(\mathrm{q_{it}})$. The results are summarized in Table 1.

4.1. The difference in emission per unit of output

4.1.1. REP scheme based on emission reductions

For simplicity, we do not use symbols for individual firms and define the following emission function: $\mathrm{m(q, K) = x(q) - y(K)}$. This function is separable and additive. The second-order derivatives can be either zero or strictly positive (in this paper, they are zero).

A higher emission per unit of output is denoted $\mathrm{m} = \Lambda \mathrm{x}\big(\mathrm{q}(\Lambda)\big) - \mathrm{y(K)}$, where Λ is a scalar and x and y are function symbols. We use the optimality condition $\frac{\pi'(\mathrm{q}(\Lambda))}{\Lambda \mathrm{x}'(\mathrm{q}(\Lambda))} = \tau$ and take the total derivative. Since we consider two firms under the same equilibrium solution and thus face the same value of τ at a given point in time, the total derivative of τ is equal to zero. This procedure is used for the comparative statics in the subsequent sections. We then obtain:

$$\frac{dq}{d\Lambda} = \frac{\tau x'(q)}{\pi''(q) - \Lambda \tau x''(q)} < 0 \tag{32}$$

From (32), we can see that a firm with higher emissions per unit of output has lower production than an otherwise identical but less emitting firm. The effect on emissions can be derived from the emission function:

$$\frac{dm}{d\Lambda} = x(q) + \Lambda x'(q) \frac{dq}{d\Lambda} \tag{33}$$

We have that $\frac{\mathrm{dm}}{\mathrm{d}\Lambda} > 0$ if $\mathrm{x(q)} > \Lambda \mathrm{x}'(\mathrm{q}) \frac{\mathrm{dq}}{\mathrm{d}\Lambda}$. Otherwise, $\frac{\mathrm{dm}}{\mathrm{d}\Lambda} \leq 0$. The final effect is determined by the parameter values.

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[13] Alternatively, but more cumbersome, one might make a discrete comparison of two firms (i and j) under the same regime. As $\frac{\pi_{\mathrm{i}}'(q_i(\Lambda_i))}{\Lambda_i x_i(q_i(\Lambda_i))} = \frac{\pi_{\mathrm{j}}'\big(q_j(\Lambda_j)\big)}{\Lambda_j x_j\big(q_j(\Lambda_j)\big)} = \tau$, we have: $\frac{\pi_{\mathrm{i}}'(q_i(\Lambda_i))}{\Lambda_i x_i(q_i(\Lambda_i))} - \frac{\pi_{\mathrm{j}}'\big(q_j(\Lambda_j)\big)}{\Lambda_j x_j\big(q_j(\Lambda_j)\big)} = 0$. A further reduction of this expression, along with inspection of signs would lead to the same conclusion as in the main text.

4.1.2. REP scheme based on output

We use the optimality condition $\frac{\pi'(q(\Lambda))}{(1-s)(\Lambda x\prime(q)-\frac{\Lambda M}{Q})} = \mu$ and take the total derivative. We then obtain:

$$\frac{dq}{d\Lambda} = \frac{(1-s)\mu\left(x'(q) - \frac{M}{Q}\right)}{(\pi''(q) - (1-s)\mu\Lambda x''(q))} \tag{34}$$

From (34), we observe that the denominator is negative. Hence, the sign is determined by the numerator. The sign depends on the difference between the firm's emission intensity and the average intensity of all firms. If $x'(q) > \frac{M}{Q}$, the numerator is positive, and hence, a more emitting firm reduces its production more than a less emitting but otherwise equal firm. Conversely, if $x'(q) < \frac{M}{Q}$, the numerator is negative, and the firm has a higher production. Finally, for a firm with emission intensity equal to the average level, $\frac{dq}{d\Lambda} = 0$.

If the firm's emission intensity is lower than or equal to the average level, then emissions are unambiguously higher. For a firm with higher emission intensity than average, the effect is unambiguous. This can be seen from the following expression:

$$\frac{dm}{d\Lambda} = x(q) + \Lambda x'(q)\frac{dq}{d\Lambda} \tag{35}$$

If $x'(q) \leq \frac{M}{Q}$, we have $\frac{dq}{d\Lambda} > 0$ and hence, $\frac{dm}{d\Lambda} > 0$. On the other hand, if $x'(q) > \frac{M}{Q}$, then $\frac{dq}{d\Lambda} < 0$. We then obtain the same result as we did in (33).

To enhance the understanding of our results in sections 4.1.1. and 4.1.2., we use an illustrative numerical model[14]. The numerical model results are obtained by using values for a "base" scenario to calculate the optimal emission tax, REP charges, and average emission intensity. These are then stored and used for all the firm types, such that we can consider firms under the same equilibrium solution (i.e., confronted with the same values of the policy instruments). In sections 4.1.1. and 4.1.2, we considered two firms where one of them had a marginally higher

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[14] The functional forms and underlying assumptions used are shown in Appendix B.

value of m_{iq}. In Figure 1, we conduct a discrete comparison by looking at the difference between firms where the parameter difference is slightly larger than marginal. The average emission intensity decreases over time in the numerical model. This corresponds to the actual development in Sweden, where over the period 1992-2013, the average emission intensity for the regulated firms decreased 56 percent, while NO_x emissions decreased 14 percent (Naturvårdsverket, 2014).

The top graph in Figure 1 shows the behavior of firms that differ in terms of emission intensity (m_{iq}) but are otherwise identical. The bottom graph shows the emissions from the same firms. The emission intensity can take values between 0 and 1. In the "base" scenario, it is set to 0.5 and at 0.4 and 0.6 in the "low" and "high" scenarios, respectively.

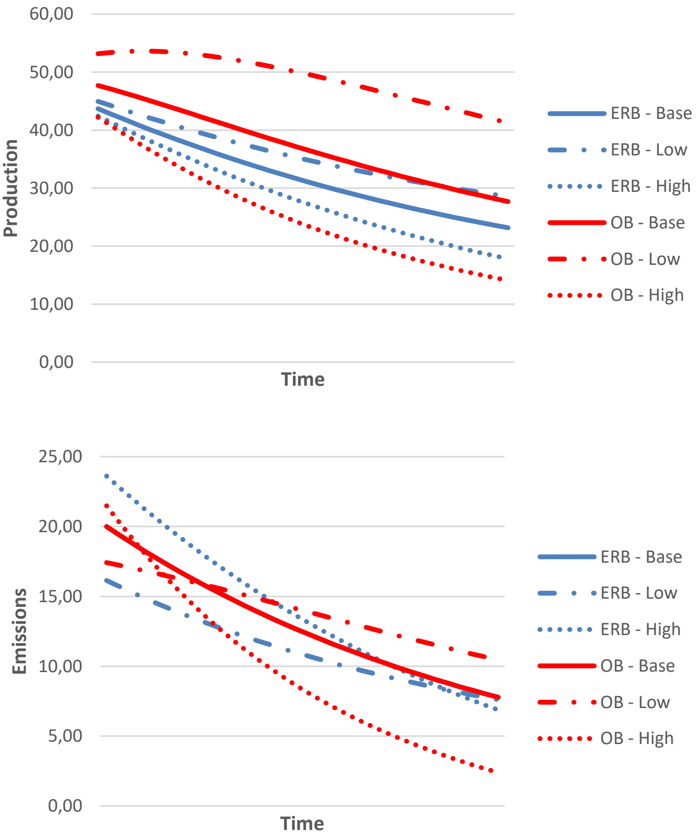

Figure 1: Production (top) and emissions (bottom) for otherwise identical firms with different emission intensities

With the emission-reduction REP scheme (ERB in Figure 1, in blue), a firm with higher emission intensity has a lower output than an otherwise identical firm with lower emission intensity. Further, production monotonically decreases over time for the different firms to adhere to the announced target path. With the output-based REP scheme (OB in Figure 1, in red), it matters whether the emission intensity for a firm is higher or lower than the average emission intensity for all firms. In the illustrative numerical model, the average emission intensity has an initial level of 0.46 and decreases over time. This means that the firm from the "low" scenario, with an emission intensity of 0.4, initially has an emission intensity below the average level. As the average level decreases over time, it becomes a firm with an emission intensity level above average. The top graph in Figure 1 shows that its production first increases before it eventually decreases. For the firms in the "base" and "high" scenarios, their emission intensities are consistently above the average level, and their production decrease monotonically.

The bottom graph of Figure 1 shows the emissions of the different firms. Since both REP schemes are used to obtain the announced target path, the "base" scenario is equal for both instruments. There is no clear-cut result for different firms with each REP scheme. However, we can compare the different firms across the two instruments. A firm with higher emission intensity has higher emissions in the emission reduction-based REP scheme than an otherwise equal firm with lower emission intensity. Furthermore, a firm with low emission intensity has lower emissions under the emission reduction-based REP scheme.

4.2. The difference in abatement ability

4.2.1. REP scheme based on emission reductions

In this section, we examine the role of a firm's ability to use abatement technology to reduce NO_x emissions (m_{iK}). We define $m = x(q) - \kappa y\big(K(\kappa)\big)$. Using the optimality condition $\frac{(r+\delta)h(K(\kappa))+h\prime\big(K(\kappa)\big)\delta K(\kappa)}{\kappa y'\big(K(\kappa)\big)} = \tau$, we take the total derivative and obtain:

$$\frac{dK}{d\kappa} = \frac{\tau y'(K)}{\big((r+2\delta)h'(K) + h''(K)\delta - \tau\kappa y''(K)\big)} > 0, \text{since } y''(K) = 0 \text{ in the model} \qquad (36)$$

From (36), a firm with a higher abatement ability invests more in technology than an otherwise identical firm with lower abatement ability. Emissions for the firm are also lower.

4.2.2. REP scheme based on output

We use the optimality condition $\frac{(r+\delta)h(K(\kappa))+h'(K(\kappa))\delta K(\kappa)}{(1-s)\kappa y'(K(\kappa))} = \mu$. By taking the total derivative, we obtain:

$$\frac{dK}{d\kappa} = \frac{\mu(1-s)y'(K)}{(r+2\delta)h'(K)+\delta K h''(K)-\mu(1-s)\kappa y''(K)} > 0, \text{since } y''(K) = 0 \text{ in the model} \tag{37}$$

A firm with a higher abatement ability invests more than an otherwise identical firm with a lower abatement ability. Again, emissions for firms with higher abatement ability are lower.

The results from sections 4.2.1. and 4.2.2. are illustrated in Figure 2. The abatement ability (m_{iK}) can take values between 0 and 1. In the "base" scenario, m_{iK} is 0.3, while it is set to 0.2 and 0.4 in the "low" and "high" scenarios, respectively. As we did in Figure 1, we consider firms under the same equilibrium solution and the parameter difference for m_{iK} between firms is slightly larger than marginal.

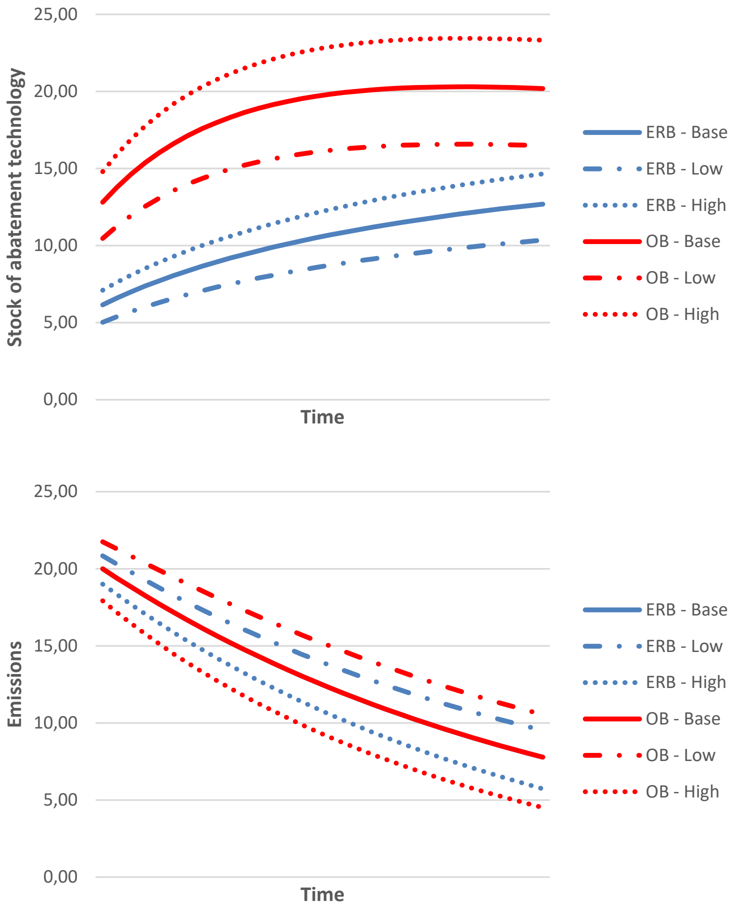

Figure 2: Stock of abatement technology (top) and emissions (bottom) for otherwise identical firms with different abatement abilities

Regardless of the REP scheme, a firm with higher abatement ability invests more in new capacity of abatement technology than an otherwise equal firm with lower abatement ability. From the top graph in Figure 2, abatement technology's acquired capacity is higher for all firms under the output-based REP scheme. This is in accordance with the result derived in (31). For the same emission target, the output-based REP scheme creates stronger incentives for investment in abatement technology. When Sweden designed their REP scheme, it was a deliberate decision to include strong incentives to adopt abatement technologies (Bonilla et al., 2015).

From the bottom graph in Figure 2, we see that even if investments in abatement technology are higher for all firms under the output-based REP scheme, emissions are not necessarily lower. A comparison across the two instruments shows that a firm with high abatement ability has lower emissions in the output-based REP scheme. However, a firm with low abatement ability can have higher emissions with the output-based refunding. This is a result of the output subsidy that firms receive in the output-based scheme.

4.3. The difference in abatement technology costs

4.3.1. REP scheme based on emission reductions

We define the function $\Phi h(K(\Phi))$, where Φ is a scalar. Using the optimality condition, $\frac{(r+\delta)\Phi h(K(\Phi))+\Phi h'(K(\Phi))\delta K(\Phi)}{(1-s)y'(K(\kappa))} = \tau$, we take the total derivative to obtain:

$$\frac{dK}{d\Phi} = \frac{(r+\delta)h(K)+h'(K)\delta K}{\left((r+2\delta)\Phi h'(K)+h''(K)\delta K-\tau y''(K)\right)} < 0, \text{since } y''(K)=0 \text{ in the model} \tag{38}$$

A firm with higher abatement technology costs invests less in new capacity of abatement technology than an otherwise identical firm with lower costs. Hence, the stock of technology is lower. With less installed abatement technology, emissions are also higher.

4.3.2. REP scheme based on output

We use the optimality condition $\frac{(r+\delta)\Phi h(K(\Phi))+\Phi h'(K(\Phi))\delta K(\Phi)}{(1-s)y'(K(\kappa))} = \mu$. By taking the total derivative, we obtain:

$$\frac{dK}{d\Phi} = -\frac{(r+\delta)h(K)+h'(K)\delta K}{(r+2\delta)\Phi h'(K)+\Phi h''(K)\delta K-(1-s)\mu y''(K)} < 0, \text{since } y''(K)=0 \text{ in the model} \tag{39}$$

As in section 4.3.1., a firm facing higher costs invests less and has higher emissions than an otherwise identical firm with lower abatement technology costs.

4.4. The difference in profit per unit of production

4.4.1. REP scheme based on emission reductions

We define $\Omega\pi'(q(\Omega))$, where Ω is a scalar. With the optimality condition $\frac{\Omega\pi'(q(\Omega))}{(1-s)(x'(q)-\frac{M}{Q})} = \tau$,

we take the total derivative to obtain:

$$\frac{dq}{d\Omega} = \frac{\pi'(q)}{\tau x''(q) - \Omega \pi''(q)} > 0 \tag{40}$$

A firm that earns a higher profit per unit of output has higher production than an otherwise identical firm with lower profitability. In turn, higher production leads to higher emissions.

4.4.2. REP scheme based on output

With the optimality condition $\frac{\Omega \pi\prime(q(\Omega))}{(1-s)(x'(q)-\frac{M}{Q})} = \mu.s$ We take the total derivative to obtain the following expression:

$$\frac{dq}{d\Omega} = -\frac{\pi'(q)}{\Omega \pi''(q) - \mu(1-s)x''(q)} > 0 \tag{41}$$

A firm with higher profit per unit of output has higher production and hence higher emissions than an otherwise equal firm that earns less per unit of output.

Table 1 shows the outcomes for a firm that is otherwise identical but has a higher emission per unit of output, abatement ability, technology costs, and profit per unit of production. An increase is denoted +, a decrease is denoted -, and nonapplicable results are denoted N/A.

Table 1: Results from comparative statics

Scenarios	**Refunds based on emission reductions**			**Refunds based on an output**		
	q	**K**	**m(q,K)**	**q**	**K**	**m(q,K)**
Difference in emissions per unit of output	-	N/A	*[15]	**[16]	N/A	***[17]
Difference in abatement ability	N/A	+	-	N/A	+	-
Difference in abatement technology costs	N/A	-	+	N/A	-	+
Difference in profit per unit of production	+	N/A	+	+	N/A	+

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[15] If $x(q) > \Lambda x'(q)\frac{dq}{d\Lambda}$, then +. Otherwise, $-$

[16] **1)** If $x'(q) > \frac{M}{Q}$, then - **2)** If $x'(q) = \frac{M}{Q}$, then 0 **3) If** $x'(q) < \frac{M}{Q}$, then +

[17] **1)** If $x'(q) > \frac{M}{Q}$, then + if $x(q) > \Lambda x'(q)\frac{dq}{d\Lambda}$. Otherwise, $-$ **2)** If $x'(q) = \frac{M}{Q}$, then 0 **3) If** $x'(q) < \frac{M}{Q}$, then +

4.5. Comparison of distributional outcomes

With a REP scheme, total revenues from emission payments must equal total refunds to satisfy the property of revenue neutrality. However, for an individual firm, refunds can be lower, equal to, or higher than their emission payments. In this section, we examine the distributional outcomes for different firms with the two REP schemes. The net payment is the difference between emission payments and refunds. The expressions for the net payment of a firm in the emission-reductions and output-based REP scheme are shown in (42) and (43), respectively.

$$\rho_t m_{it}^{*} - \beta\varphi_t(\widehat{m}_i - m_{it}^{*}) \tag{42}$$

$$\mu_t m_{it}^{**} - \sigma_t q_{it}\frac{\overline{M}_t}{Q_t} \tag{43}$$

The optimal emission level for firm i at date t, with the REP scheme based on emission reductions, given the binding announced target path, is denoted m_{it}^{*} in (42). With the output-based scheme, this is denoted m_{it}^{**} in (43).

In the following, we restrict ourselves to discussing firms with insignificant market shares ($s_{it} \rightarrow 0$). We do this for three reasons. First, from (34), the output share does not alter the sign of the effect. Second, we compare different firms with the two REP schemes. In the emission reduction-based scheme, the output share is not pertinent to the analysis. Finally, the output-based scheme is based on the system currently in place in Sweden. There, no firm has had an output share of more than just above 2 percent (Sterner & Isaksson, 2006). Hence, market power has not been a serious source of concern.

4.5.1. The difference in emission per unit of output

For the emission reduction-based REP scheme, we know that a firm with higher emission intensity has a lower production level than an otherwise identical firm with lower emission intensity. With a negative effect from (33), emissions are also lower. This effect is also suggested from the results in Figure 1. Then, from (42), a firm with higher emission intensity has a lower emission payment than an otherwise identical firm with lower emission intensity. Further, the firm has a higher unregulated emission level, but actual emission cuts are also higher. Hence, a firm with higher emission intensity gains a higher net payment than an otherwise identical firm with lower emission intensity.

With the output-based REP scheme, it matters whether the firm's emission intensity is larger or smaller than the average level for all firms. If $m_{iq} > \frac{M_t}{Q_t}$, we obtain the same result as in the emission reduction-based scheme. If $m_{iq} < \frac{M_t}{Q_t}$, a firm has a higher production. With a higher production, emissions are also higher. Emission payments are then higher, but the firm benefits from an increased refund. Consequently, a firm characterized by $m_{iq} < \frac{M_t}{Q_t}$ gains most in terms of net payments.

4.5.2. The difference in abatement ability

From our analytical results, we know that a firm with higher abatement ability invests more in new abatement technology than an otherwise identical firm with lower abatement ability under both REP schemes. This results in lower emissions and hence lower emission payments.

In the emission reduction-based REP scheme, a firm with higher abatement ability has a lower unregulated emission level and a larger emission reduction than an otherwise equal firm with lower abatement ability. Hence, the refunds are larger, resulting in higher net payments. In the output-based REP scheme, with the assumption of an additive emission function $\left(\frac{\partial^2 m_{it}}{\partial q_{it} \partial K_{it}} = 0\right)$, refunds are not affected by the stock of abatement technology. Hence, a firm with higher abatement ability receives larger net payment than an otherwise identical firm with lower abatement ability.

4.5.3. The difference in abatement technology costs

With both REP schemes, a firm with higher abatement technology costs invests less in abatement technology and has larger emissions than an otherwise identical firm with lower technology costs. Hence, emission payments are larger. In the emission reduction-based scheme, a firm facing high technology costs receives a smaller refund than an otherwise identical firm with lower technology costs since the difference between regulated and unregulated emissions is smaller. Hence, a firm with lower costs of abatement technology receives the largest net payment. With the assumption of an additive emission function, in the output-based REP scheme, a firm facing lower abatement technology costs receives higher net payments than an otherwise identical firm with higher costs.

4.5.4. The difference in profit per unit of production

In the emission-reduction REP scheme, a firm with a higher profit per unit of production has a higher production level than an otherwise equal firm with less profitability. This results in higher emissions and hence emission payments. Refunds, however, are lower since the difference between unregulated and regulated emissions is smaller. Hence, a firm with *lower* profit per unit of output receives a higher net payment than an otherwise identical but more profitable firm.

In the output-based REP scheme, a firm with higher profit per unit of production has higher production and emissions than an otherwise identical firm with lower profit per unit of output. This results in higher emission payments. However, since refunds are given in proportion to output, refunds are higher as well. Hence, it is not apparent which firms receive the highest net payments in this scenario.

5. Summary and concluding remarks

In a REP scheme, a charge is levied per kilogram of NO_x emissions from the regulated firms, and the collected revenues are refunded back to the same firms. In this paper, we analyze the use of two refund alternatives as instruments to regulate a negative externality. In the first version, firms receive refunds for their total emission cuts. In the second, refunds are given in the proportion to the firms' output.

Using a theoretical model, we show that a properly designed REP scheme can achieve the results from using a Pigouvian tax. First, both production adjustments and installment of abatement technology must be eligible for refunds. Second, the necessary REP charge is then lower than the optimal emission tax. Finally, the REP charge and the refund must be derived appropriately such that the sum of these two equals the optimal emission tax in each period. The optimal REP charge and refund are derived analytically, and their time paths are calculated. An output-based REP scheme can also be used to achieve the specified target path, but it provides nonoptimal incentives for both mitigation measures. The necessary REP charge must be higher than the optimal emission tax, and with refunds given in proportion to output, investments in new abatement technology must exceed the first-best levels as well.

The firms studied in our model are heterogeneous. This allows us to study how different firms behave under the two REP schemes, given the binding target path of emission reductions. We use comparative statics to marginally alter firm characteristics and compare otherwise identical firms. When both production adjustments and investments in abatement technology are eligible for refunds, a firm with higher emission intensity reduces production more than an otherwise identical firm with lower emission intensity. Our results show that the same effect applies to emissions. With output-based refunding, the difference between the emission intensity of a firm and the average emission intensity for all firms plays an important part. If the emission intensity is higher than average, then we derive similar results as in the emission reduction-based scheme. However, if a firm has a lower emission intensity than average, then a firm can *increase* its output and emissions. Further, our results show that an otherwise identical firm with either higher abatement ability or lower technology costs invests more in abatement technology under both schemes, but investment levels are higher when refunds are given in proportion to output. This is a consequence of the output subsidy since investments in abatement technology must be higher to assure that the emission target is met.

By examining net payments for individual firms with the two instruments, we evaluate different firms' distributional outcomes. In the emission reduction-based scheme, a firm with higher emission intensity receives larger net payment than an otherwise identical firm with lower emission intensity. In the output-based REP scheme, the net winners are firms with an emission intensity that is low *and* below the average level. If refunds are given for all emission cuts, we find that a firm with lower profit per unit of output receives the highest net payment. The firm benefits from a combination of lower emission payments and higher refunds compared to an otherwise identical firm with higher profitability. With output-based refunding, the emission payments and refunds both move in the same direction, and we do not obtain a similar clear-cut result.

Apart from the ability of the studied REP schemes to achieve a specific target path of emission reductions, there are also additional arguments in favor of introducing this type of instrument[18]. In an experimental setting, Kallbekken, Kroll, & Cherry (2011) found that recycling tax revenues can increase public support for environmental taxation. The use of a refunding mechanism could also make it easier to introduce charges to obtain efficient emission reductions (Johnson, 2007; Sterner & Isaksson, 2006). Further, refunds can address concerns

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[18] For a discussion about political economy and lobbying concerning REP schemes, see Fredriksson & Sterner (2005) and Aidt (2010).

about regulated firms' competitiveness (Sterner & Isaksson, 2006). Finally, the use of refunding could reduce the problem of emission leakage (Bernard, Fischer, & Fox, 2007; Fischer & Fox, 2012; Fischer, Greaker, & Rosendahl, 2017). While the use of a REP scheme could be appealing for a regulator, there are also possible drawbacks from using this instrument rather than an emission tax or auctioned emission permits. Such instruments generate revenue that can be used to reduce distortionary taxes (Goulder, Parry, Williams III, & Burtraw, 1999). Furthermore, REP schemes violate the pure polluter pays principle since emitting firms receive refunds even though they are responsible for emissions.

Our results show that a REP scheme can achieve a specific dynamic emission target. However, the choice of refund mechanism affects both the costs of regulation and the distributional outcome for individual firms. As mentioned above, there are also accompanying arguments in favor of using a REP scheme. Hence, if optimal pricing instruments such as a Pigouvian tax are unavailable, a REP scheme is not necessarily an inferior second-best alternative.

Appendix

A. The nomenclature used in the model

Symbol	Description
m_{it}	Emission level of NO_x at date t for firm i
$\widehat{m}_i$	Emission level for firm i, with no regulations
m_{it}^*	Optimal emission level at date t for firm i, given the binding target path
$\bar{M}_t$	Total target level of NO_x emissions at date t
ω	Rate of emission reductions desired by the regulator
q_{it}	Production at date t for firm i
$\hat{q}_i$	Production for firm i, with no regulations
q_{it}^*	Optimal production at date t for firm i, given the binding target path
K_{it}	Capacity of abatement technology at date t for firm i
k_{it}	Investment in new capacity of abatement technology for firm i at date t, with $k_{it} \geq 0$
$\pi_i(q_{it})$	Profit for firm i at date t
τ_t	Optimal emission tax at date t
ρ_t	REP charge in the emission reductions REP scheme at date t
φ_t	Support rate in the emission reductions REP scheme at date t
β	Refund constraint the emission reductions REP scheme, with $0 < \beta < 1$
$\beta\varphi_t$	Refund in the emission reductions REP scheme
μ_t	REP charge in the output REP scheme at date t
σ_t	Refund in the output REP scheme at date t
m_{iq}	Marginal effect of production on emissions for firm i
m_{iK}	Marginal effect of abatement technology on emissions for firm i
r	Market discount rate
δ	Depreciation rate of abatement technology capacity
T	Termination date of problem considered

B. Functional forms and assumptions used in the illustrative numerical model

$\pi_i'(q_{it}) = A_i - q_{it}(2c_i + b_i)$, $h_i(K_{it}) = p_iK_{it}^2$, $h'_i(K_{it}) = 2p_iK_{it}$, $h''_i(K_{it}) = 2p_i$ and $m_{it} = (\theta_i q_{it} - \alpha_i K_{it})$

The "base" scenario uses the following parameter values:

$A = 200$, $b = 3$, $r = 0.05$, $\delta = 0.05$, $\theta = 0.5$, $\alpha = 0.3$, $c = 0.5$ and $p = 2$

When we illustrate the output-based REP scheme, we simplify by assuming that firms have insignificant output shares. For the numerical illustration, the optimization problem for firm i can then be written as:

$$\max_{\mathrm{q_{it}, k_{it}, K_{it}}} \int_{0}^{\mathrm{T}} [\pi_i(\mathrm{q_t}) - \mathrm{h}_i(\mathrm{K_t})\mathrm{k_t} - \mu_{\mathrm{t}}\mathrm{m_t} + \sigma_{\mathrm{t}}\mathrm{q_t}]\mathrm{e}^{-\mathrm{rt}}$$

subject to:

$$\dot{\mathrm{K}}_{\mathrm{it}} = \mathrm{k_{it}} - \delta\mathrm{K_{it}}$$

The budget constraint is then:

$$\mu_{\mathrm{t}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{m_{it}^{**}} = \sigma_{\mathrm{t}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{q_{it}} \tag{B.I.}$$

We then obtain the following expression for the refund:

$$\sigma_{\mathrm{t}} = \frac{\mu_{\mathrm{t}}\bar{\mathrm{M}}_{\mathrm{t}}}{\mathrm{Q_t}} \tag{B.II.}$$

From B.II, the refund is now a share of the REP charge, determined by the size of the average emission intensity. The expression of B.II. is a good representation of how the refund is defined in the Swedish REP scheme. There, it is calculated as total paid emission charges divided by total useful energy produced (Naturvärdsverket, 2014).

With the changes made, the optimality conditions for the illustrative numerical model read:

$$\frac{\pi'_i(\mathrm{q_{it}})}{(\mathrm{m_{iq}} - \frac{\mathrm{M_t}}{\mathrm{Q_t}})} = -\frac{(\mathrm{r} + \delta)\mathrm{h}_i(\mathrm{K_{it}}) + \mathrm{h}_i{}'(\mathrm{K_{it}})\delta\mathrm{K_{it}}}{\mathrm{m_{iK}}} = \mu_{\mathrm{t}} \tag{3.III.}$$

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Chapter 4

Transport choice and negative externalities in a congested urban area

Transport choice and negative externalities in a congested urban area[1]

Arild Heimvik[2]

Abstract

This paper is concerned with the regulation of negative externalities from road transport. We study the problem of transport choice for a fixed number of commuters who make a required work trip in a congested urban area. They can use either a fossil car, an electric car or public transport. Each alternative is responsible for a specific set of negative externalities. Four types of externalities are considered (congestion, crowding, CO_2 emission and other local externalities).The long-term equilibrium outcomes for transport choice in the private and socially optimal outcomes are analyzed and we discuss the use of instruments for optimal regulation. By including electric cars, we can study the trade-offs for regulation of local and global externalities. The effect of the different externalities is explored using comparative statics. Congestion costs are shown to be particularly important. An optimal internalization of the externalities can be achieved with a "sandwich" of economic instruments that are differentiated to account for different damage intensities from different vehicle types. This key result is underscored with comparisons of long-run outcomes from partial instrument use. Such strategies *will* be insufficient and can also be costly and even counterproductive.

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1. Introduction

The transport sector is a considerable source of emissions of greenhouse gases, such as CO_2. In 2019, the sector was responsible for 24 percent of direct CO_2 emissions from fuel combustion. Road transport (cars, trucks, buses and two- and three-wheelers) accounted for around three-quarters of this (IEA, 2020b). Further, the transport sector is responsible for local negative externalities (congestion, local emissions, noise, accidents, and road wear). These externalities can impose considerable costs on society, highlighting the importance of efficient regulation.

The objective of this paper is to examine some important economic principles for the regulation of negative externalities from road transport. Using a partial equilibrium model, we analyze the problem of transport choice for a fixed number of commuters making an essential work trip in an urban area. The commuters can use either a fossil car, an electric car, or public transport. Each mode is responsible for a specific composition of negative externalities. We consider four categories of externalities: congestion, crowding, CO_2 emissions, and other local externalities (local pollution (NO_x and particulate matter); noise; accidents; and road wear). The equilibrium conditions studied in this paper are long-term. Hence, we focus on the following problem: if there are no regulations, what will the equilibrium condition for transport choice look like, and if the negative externalities are internalized, what will this new equilibrium look like? We stress the importance of coherent regulation, in which each externality is taken into account through the use of a targeted economic instrument differentiated to account for differences in emission intensities. Within our framework, we show that with a "sandwich" of instruments comprising a uniform congestion tax and a differentiated pollution tax for cars, a CO_2 tax for fossil cars and a mark-up on the fare for public transport, the regulator can achieve the socially optimal outcome. This is a key result, and we highlight its importance by analyzing several long-run equilibrium outcomes from partial instrument use. We consider three economic instruments and one technical instrument and show that their use *will* result in insufficient regulation. Further, such a strategy can be costly and can result in unintended consequences. Finally, we conduct comparative statics for different cost parameters and discuss the long-run equilibriums concerning transport choice and regulation. Specifically, we note the importance of the congestion costs faced by the commuters.

There is an extensive literature focusing on externalities from transport. The diversity of these externalities includes congestion (Newbery, 1990; Vickrey, 1969; Walters, 1961), road wear (Newbery, 1988a), global emissions (I. W. Parry, Walls, & Harrington, 2007), local emissions

(Calthrop & Proost, 1998; I. W. Parry et al., 2007; Verhoef, 1994), noise (Swärdh & Genell, 2020) and accidents (Newbery, 1988b; Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010).

Further, there have been numerous contributions focusing on instruments to internalize negative externalities from road transport Many of these have used theoretical and simulation models (Beaudoin et al., 2018; De Borger & Wouters, 1998; Diamond, 1973; Johansson-Stenman, 2006; Johansson, 1997; Newbery, 1990; I. W. Parry & Small, 2005; I. W. H. Parry, 2002; Rouwendal & Verhoef, 2006; Tsekeris & Voß, 2009; Wangsness, Proost, & Rødseth, 2020). There are also several empirical papers examining the effect of different instruments (Beaudoin & Lawell, 2018; Gallego, Montero, & Salas, 2013; Knittel & Sandler, 2018; Small, Winston, & Yan, 2005).

The paper contributes to the literature on the regulation of negative externalities from road transport. Using four categories of externalities, we focus on the difference in the long-run private and socially optimal outcomes on the transport choice of commuters. Our approach allows us to examine the effect of the different externalities on the equilibrium outcomes. Further, we examine key insights from economics regarding the regulation of negative externalities and discuss important economic principles for achieving a socially optimal outcome. To the best of our knowledge, there are no other papers using a similar setup to analyze this problem of regulation. The inclusion of electric cars also enables us to highlight the trade-off in the regulation of local and global negative externalities. Since there is a discussion of whether electric cars can be part of the solution to the problem of global (Jochem, Doll, & Fichtner, 2016) and local pollution (Timmers & Achten, 2016) from transport, this is a highly relevant addition to the analysis. We also examine partial instrument use and conduct comparative statics for different cost parameters. Using formal analyses, we obtain results that allow us to underscore the important point of coherent and differentiated regulation. A deviation from this strategy leads to costly, inadequate, and, in some cases, counterproductive regulation of negative externalities from road transport.

The remainder of the paper is organized as follows: The model is presented in section 2, along with accompanying assumptions. In section 3, we apply the model and derive the equilibrium conditions for both the private and socially optimal solutions. We stress key economic principles for the use of economic instruments to internalize the negative externalities from transport. Further, we perform comparative statics to show the effects on transport choice in the long-run private and socially optimal equilibrium outcomes. In section 4, we analyze the outcomes when the regulator pursues a strategy of partial use of instruments and discuss the implications of this strategy. We look at three economic instruments and one technical instrument. Summary and concluding remarks are provided in section 5.

2. The model[3]

We analyze the long-run private and socially optimal equilibrium conditions for the transport choice of the commuters. We examine the equilibrium condition without regulation and then look at the effects of internalizing the negative externalities from road transport[4]. Further, we consider important economic principles for regulators who seek to minimize the social costs from externalities. The use of first-best pricing instruments entails that the instruments must be differentiated with respect to geography, time of the day and distance (Anas & Lindsey, 2011). To simplify, the trips studied in our model are taken during rush hour; hence, off-peak periods are not considered. Moreover, we focus on a densely populated urban area. The trip is identical for all commuters. They can choose between a fossil car $(\mathrm{x_f})$, an electric car $(\mathrm{x_e})$ or public transport $\left(\mathrm{x_p}\right)$, and there is a fixed number of trips taken $(\bar{\mathrm{x}})$. This is well-used assumption that can be relaxed. The purpose of the trip is deemed essential to secure an economic outcome. We assume that all commuters have a fixed utility for the trip $(\bar{\mathrm{u}})$ but not necessarily the same utility. To ensure that the trip is made, for all commuters, the utility is always of greater order than the minimized cost of making the trip. Hence, since both the utility and the number of commuters is fixed, we analyze the problem of transport choice as a cost-minimization problem.

The user costs for the different transport modes are composed of two parts. For private transport, these costs consist of imputed costs and congestion costs. Public transport consists of imputed costs and crowding costs. The imputed costs are made up of costs related to fuel, time consumption of travel, comfort of transport, vehicle maintenance, parking, and the car price. The imputed unit costs are assumed to be highest for public transport and lowest for fossil cars, i.e., $\mathrm{c_f} < \mathrm{c_e} < \mathrm{c_p}$. The high imputed costs from using public transport are due to the relative discomfort and lack of flexibility of using public transport. In particular, the use of public

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[3] The nomenclature used in the model is summarized in Appendix A

[4] Goods transport is not included in the model. For goods transport, the same choices are not relevant, i.e., switching from a truck to using public transport. For a discussion on a separate system for the transport industry, we refer to other contributions (Pinchasik & Hovi, 2017).

transport entails time costs that include waiting on the platform and being forced to plan according to inconvenient timetables. Previous research points to perceived benefits for commuters in which private rather than public transport is used. A car can be perceived as a symbol of freedom, independence and status (Steg, 2003, 2005); it may also provide psychosocial benefits (feelings of autonomy, protection and self-esteem) (Ellaway, Macintyre, Hiscock, & Kearns, 2003). Further, the imputed costs are assumed to be higher for electric cars than for fossil cars. Although fuel is cheaper, electric car owners face a higher annuity for the car price. In addition, there might be concerns regarding the range and the possibility of charging an electric car. The focus of the model is to analyze the long-term equilibrium under the condition of no regulations and with the inclusion of externalities. Hence, in the basic model, it is assumed that there are no governmental subsidies for electric cars.

Apart from imputed costs, car users also face congestion costs that are denoted as $\mathrm{g}(\mathrm{x_f} + \mathrm{x_e})$. The congestion cost function is increasing in the number of cars. With an increase in the number of cars, the road traffic speed decreases, increasing travel time; hence, the congestion costs increase (Newbery, 1990). With more cars on the road, all cars face these congestion costs. Public transport at least partly uses designated lanes. In the model, we assume that public transport uses a separate lane from private transport; hence, public transport users do not face congestion costs. However, commuters using public transport face crowding aboard the public transport service. This crowding cost is the discomfort of using a crowded and undersized public transport service plus the time cost of not being able to enter a completely full bus and of having to wait for the next. The crowding costs on public transport are denoted as $\mathrm{m}(\mathrm{x_p}, \bar{\mathrm{y}})$ and are assumed to increase in the number of passengers. With more passengers boarding, crowding and passenger discomfort increase as well (Kraus, 1991). If the number of trips taken by public transport is below a certain capacity threshold ($\mathrm{x_p} < \bar{y}$), then the cost of using public transport is $\mathrm{c_p}$. However, if the threshold is exceeded, then the crowding cost is also present. We will focus on the scenario in which the capacity threshold is exceeded $(\mathrm{x_p} \geq \bar{y})$. This cost increases in additional passengers, i.e., $\mathrm{m}'_{\mathrm{x_p}}(\mathrm{x_p}, \bar{\mathrm{y}}) > 0$ and is reduced if the capacity is expanded, i.e., $\mathrm{m}'_{\bar{\mathrm{y}}}(\mathrm{x_p}, \bar{\mathrm{y}}) < 0$.

We include four categories of negative externalities. The first is the congestion externalities for cars. An extra car on the road increases the congestion costs for all other cars. This externality is equal for both car types. The second is the crowding externality aboard the public transport service. When an additional passenger boards, it increases the crowding for all the other passengers. The third is CO_2 emissions from fossil cars. The cost function for CO_2 emissions is denoted as e per commuter and increases linearly in the number of commuters using fossil cars. For simplicity, the use of public transport does not cause CO_2 emissions in the model. A bus seats many passengers, and the marginal effect on CO_2 emissions from one more commuter using the bus can be assumed to be rather small (Proost & Van Dender, 2011) Hence, we simplify and set the effect equal to zero.

Finally, we have the other local negative externalities. These are bundled in the pollution cost function $h(x_f + \alpha x_e)$. This externality inflicts costs on the inhabitants of the urban area at large and is not assumed to be directed towards the commuters causing the externality. The pollution cost function is increasing in the number of cars. Even though there are no CO_2 emissions from the use of electrical cars, these cars still cause local pollution through non-exhaust sources, such as the wear of tires, brakes and road surfaces, as well as the whirling up of particulates through road dust (Timmers & Achten, 2016). As a local externality, this pollution is considered for a fossil car by assuming a damage intensity that is normalized to one and of which an electric car has a share. The share is denoted α, where $0 < \alpha < 1$. Such a relationship can be derived from Rødseth et al. (2019). It was assumed that the use of public transport does not cause CO_2 emissions. This same assumption is made for local externalities as well. Assuming only crowding externalities for public transport is a simplification (I. W. Parry & Small, 2009). However, we look at the marginal effect of an additional commuter using public transport, and therefore, we simplify by assuming the marginal effect for local externalities is equal to zero.

3. Model applications and analyses

3.1. Private solution

We begin the analysis with a scenario in which a representative commuter makes a choice regarding the transport mode. Since the utility and the number of commuters in our model are fixed, the problem facing the commuter is a cost minimization problem. The focus in this section is to analyze the long-term equilibrium condition for transport choice under the condition that regulation is absent and that externalities are not internalized. Hence, we do not consider the short-term adjustments of how a commuter with a fossil car will adapt to the introduction of different instruments. Even though externalities are not included here, crowding and congestion costs are included, since these are costs faced by the commuters. The optimization problem reads as follows:

$$\min\{c_f + g(x_f + x_e), c_e + g(x_f + x_e), c_p + m(x_p, \bar{y})\}$$

In equilibrium, the commuter must be indifferent between the different transport alternatives. Further, a condition for equilibrium is a binding constraint of a fixed number of trips. This can be expresses as follows:

$$x_f + x_e + x_p = \bar{x}$$

The equilibrium condition then reads as follows:

$$c_f + g(x_f + x_e) = c_e + g(x_f + x_e) = c_p + m(x_p, \bar{y}) \quad (1)$$

The imputed unit costs are fixed for all transport modes. Hence, the congestion and crowding costs are instrumental for the adjustments to obtain an equilibrium solution.

We can start out by comparing the indifference conditions for the two car types:

$$c_f + g(x_f + x_e) = c_e + g(x_f + x_e) \quad (2)$$

Since congestion costs are equal for both car types, we have that the condition in (2) can only hold if the imputed costs are equal. By assumption, $c_f < c_e$. Hence, the result in (2) cannot hold, and no commuters will choose electric cars. Note that this corner solution is contingent upon the simplified functional forms. However, the result is interesting in that in a situation with no regulation (including the absence of governmental subsidies) and no externalities internalized, there are no clear incentives to switch from a fossil car to an electric car.

We can compare the indifference conditions for fossil cars and public transport:

$$c_f + g(x_f) = c_p + m(x_p, \bar{y}) \quad (3)$$

Since we have assumed that $c_f < c_p$, the congestion costs for fossil cars must be larger than the crowding costs for public transport for the condition in (3) to hold. Both congestion and crowding costs are determined by the number of commuters using the two transport modes. Hence, they are instrumental for obtaining a long-run equilibrium. Under the assumptions of the model, with two equations and two unknowns and a fixed number of trips, there exists an equilibrium solution that determines the distribution of the commuters' transport choice.

3.1.1. Socially optimal solution

The objective for the regulator is to ensure that the commuters make their essential work trip and to minimize the social costs stemming from the negative externalities. In this section, we analyze the long-run equilibrium when the negative externalities from transport are considered. As previously mentioned, we study the scenario in which the capacity threshold is exceeded for public transport. Hence, crowding costs and externalities are present. The regulator can invest in expanded capacity for public transport. This investment benefits all users of the public transport service since it reduces crowding. The cost of expansion is expressed by the investment function $\mathrm{i}(\bar{\mathrm{y}})$. The costs increase in additional expanded capacity, i.e., $\mathrm{i}'(\bar{\mathrm{y}}) > 0$. The optimization problem reads as follows:

$$\begin{aligned}\min \mathrm{SC} = &\big(\mathrm{c_f} + \mathrm{e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e})\big)\mathrm{x_f} + \big(\mathrm{c_e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e})\big)\mathrm{x_e} + \Big(\mathrm{c_p} + \mathrm{m}\big(\mathrm{x_p}, \bar{\mathrm{y}}\big)\Big)\mathrm{x_p} + \mathrm{i}(\bar{\mathrm{y}}) \\ &+ \mathrm{h}(\mathrm{x_f} + \alpha\mathrm{x_e})\end{aligned}$$

subject to the constraint of a fixed number of trips, which is assumed to be binding:

$$\mathrm{x_f} + \mathrm{x_e} + \mathrm{x_p} \leq \bar{\mathrm{x}} \tag{λ}$$

The first-order conditions are the following:

$$\frac{\partial \mathrm{SC}}{\partial \mathrm{x_f}} = \mathrm{c_f} + \mathrm{e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) + \mathrm{g}'(\mathrm{x_f} + \mathrm{x_e})(\mathrm{x_f} + \mathrm{x_e}) + \mathrm{h}'(\mathrm{x_f} + \alpha\mathrm{x_e}) - \lambda = 0 \tag{4}$$

$$\frac{\partial \mathrm{SC}}{\partial \mathrm{x_e}} = \mathrm{c_e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) + \mathrm{g}'(\mathrm{x_f} + \mathrm{x_e})(\mathrm{x_f} + \mathrm{x_e}) + \alpha\mathrm{h}'(\mathrm{x_f} + \alpha\mathrm{x_e}) - \lambda = 0 \tag{5}$$

$$\frac{\partial \mathrm{SC}}{\partial \mathrm{x_p}} = \mathrm{c_p} + \mathrm{m}\big(\mathrm{x_p}, \bar{\mathrm{y}}\big) + \mathrm{m}'_{\mathrm{x_p}}\big(\mathrm{x_p}, \bar{\mathrm{y}}\big)\mathrm{x_p} - \lambda = 0 \tag{6}$$

$$\frac{\partial \mathrm{SC}}{\partial \bar{\mathrm{y}}} = \mathrm{m}'_{\bar{\mathrm{y}}}\big(\mathrm{x_p}, \bar{\mathrm{y}}\big)\mathrm{x_p} + \mathrm{i}'(\bar{\mathrm{y}}) = 0 \tag{7}$$

We begin with the first-order condition from (7). This can be rearranged to obtain the following:

$$i'(\bar{y}) = -m'_{\bar{y}}(x_p, \bar{y})x_p \tag{8}$$

The condition in (8) states that investments take place until the marginal investment costs are equal to the marginal benefits of decreasing crowding by capacity expansion. If the crowding is too high, i.e., if $i'(\bar{y}) < -m'_{\bar{y}}(x_p, \bar{y})x_p$, the regulator increases the investment to obtain the condition in (8). The reduced crowding reduces the crowding cost $m(x_p, \bar{y})$.

The investment costs are not included in the first-order conditions in (4)–(6). This cost is assumed to be covered by all commuters as a one-time payment. Hence, it does not affect the marginal decisions made by the commuters and can be considered a "head tax". In our model, all commuters are willing to make this payment because the utility of making the essential work trip $(\bar{u})$ is assumed to be of a higher order than the sum of transport costs and the "head tax".

We combine (4)–(6) to obtain the equilibrium conditions:

$$\begin{aligned} c_f + e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) \\ = c_e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + \alpha h'(x_f + \alpha x_e) \\ = c_p + m(x_p, \bar{y}) + m'_{x_p}(x_p, \bar{y})x_p \end{aligned} \tag{9}$$

First, we compare the indifference conditions for fossil and electric cars:

$$\begin{aligned} c_f + e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) \\ = c_e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + \alpha h'(x_f + \alpha x_e) \end{aligned} \tag{10}$$

If we compare (10) with (2), we can see that there could be electric cars in the socially optimal solution. For the condition in (10) to hold, we must have that $c_e > c_f + e$, since $0 < \alpha < 1$. This is to ensure that unlike what we did in section 3.1., we do not obtain a corner solution. Since congestion costs are equal for both car types, the congestion externalities, denoted by $g'(x_f + x_e)(x_f + x_e)$, are equal as well. However, for electric cars, due to a lower damage intensity, the effect from the other local externalities is smaller. Finally, only the use of fossil cars causes CO_2 emissions, with a marginal effect denoted as e. Hence, compared to the private solution, the socially optimal solution contains increased costs for both car types, but fossil cars have the largest cost increase. This means that in the socially optimal solution, there will be a decrease in the number of trips taken by fossil cars, and a part of this reduction should be absorbed by electric cars.

Next, we compare the indifference conditions for fossil cars and public transport:

$$\begin{aligned} c_f + e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) \\ = c_p + m(x_p, \bar{y}) + m'_{x_p}(x_p, \bar{y})x_p \end{aligned} \tag{11}$$

Compared to the private solution in (3), the socially optimal solution now includes an additional cost of using public transport, namely, the externality cost denoted as $m'_{x_p}(x_p, \bar{y})x_p$. This stems from the crowding externality imposed by an additional passenger on the other passengers.

With the condition in (8), we showed that the regulator invests to expand the public transport capacity until the point at which the marginal investment costs equal the marginal benefit of increased capacity. There is the question of why the regulator would be interested in making this investment. First, it will reduce the crowding aboard public transport. Second, of the transport modes considered, public transport contributes to the lowest number of externalities per trip. Hence, it would be in the interest of the regulator to incentivize this type of travel. Finally, if more commuters choose public transport, this reduces the congestion costs for private transport and, thus, reduces social costs.

The question is whether there exists a solution in which all three transport alternatives are present. From the equilibrium condition in (9), and the constraint of a fixed number of trips, we have three equations and three unknowns. Under the assumptions of the model, an equilibrium may exist. The inclusion of negative externalities socially increases the costs for all three transport modes. Note that to avoid a corner solution in condition (10), we must have that $c_e > c_f + e$. Further, if the cost increase for fossil cars is larger than that for public transport, i.e., $e + g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) > m'_{x_p}(x_p, \bar{y})x_p$, then the use of public transport increases at the expense of fossil cars. Hence, in the socially optimal equilibrium, there should be a decrease in the use of fossil cars compared with that in the private solution in section 3.1. Further, our results suggest that commuters will switch to both electric cars and public transport in the new long-run equilibrium.

The regulator can internalize the negative externalities analyzed in this section. This will require coherent regulation and the use of targeted instruments that consider the differentiated effects of the various externalities. More precisely, the use of four economic instruments in a "sandwich" arrangement targeting specific externalities directly can achieve the socially optimal outcome. The first instrument is a congestion tax, which will be equal for both car types and can be denoted as $\tau = g'(x_f + x_e)(x_f + x_e)$. The second instrument is a carbon tax, which is levied only on fossil cars and can be expressed as $\kappa = e$. Third, we have a local pollution tax. To obtain an optimal outcome, this tax must be differentiated for the two car types: it will be $\rho = h'(x_f + \alpha x_e)$ for a fossil car and $\alpha\rho$ for an electric car. The final instrument is a mark-up on the public transport fare. This instrument internalizes the crowding externality aboard the public transport service and can be denoted by $\upsilon = m'_{x_p}(x_p, \bar{y})x_p$[5].

In this section, we have shown how the use of economic principles with the direct pricing of negative externalities can bring about socially optimal outcomes. In practice, however, efficient pricing instruments can be difficult to introduce (Anas & Lindsey, 2011). It is beyond the scope of this paper to examine the obstacles and the political economics of the implementation of efficient instruments. Our objective is to analyze the effect of externalities on the socially optimal transport choice and to discuss the internalization of these externalities by using important principles from the economics of regulation.

While it is in the interest of the regulator to invest in the expansion of public transport capacity, it is also sound to charge commuters a mark-up on the public transport fare. This result may appear somewhat counterintuitive. With more passengers aboard the public transport service, this increases crowding and hence the discomfort for the other passengers (Kraus, 1991). Crowding can create feelings of anxiety and stress, concerns about safety, and a feeling of an invasion of privacy (Tirachini, Hensher, & Rose, 2013). If the users of public transport impose an externality on the other passengers, it is not unreasonable that the users should be charged for this. When an externality is present, the marginal social cost of using public transport increases, which can justify a mark-up on the fare (Jara-Diaz & Gschwender, 2005; Pedersen,

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[5] We have focused on the scenario in which a certain capacity threshold for public transport is exceeded. In this case, crowding costs (and externalities) are present. However, if the threshold is not exceeded ($x_p < \bar{y}$), then the cost of using public transport consists only of the imputed unit costs. Then, in equilibrium, the other transport alternatives must adjust to this fixed cost. Since there is no crowding, the regulator does not need to introduce a mark-up on the fare, and we obtain that $\upsilon = 0$.

2003). Further, if the revenues from the increased fare are used to improve the public transport service, this benefits the users of public transport as well.

If it is desirable to make commuters switch to public transport, then presumably, it could be reasonable to subsidize public transport fares. There are basically two main justifications for this. First, it has been argued that public transport operates under conditions of economics of scale. The marginal social cost of supplying a trip with public transport is then lower than the average cost. An increase in route density or service frequency will decrease the users' waiting or access costs for public transport services (Mohring, 1972). However, if crowding externalities are considered, more passengers aboard the public transport service can also increase the social cost of traveling (Jara-Diaz & Gschwender, 2005). Second, cheaper fares can incentivize people to switch from private to public transport. This will then reduce the externalities from car use (I. W. Parry & Small, 2009). However, subsidizing fares could also have disadvantages. The funding of subsidies will entail distorting taxes (Newbery, 1990), and for shorter trips, people could switch from walking and bicycling to public transport (Van Goeverden, Rietveld, Koelemeijer, & Peeters, 2006). Finally, public transport contributes to externalities such as congestion and pollution, in addition to crowding aboard the public transport service (I. W. Parry & Small, 2009).

3.2. Comparative statics

In this section, we investigate the effects of changes in various cost parameters on long-run equilibrium outcomes of transport choice. We can then compare different outcomes with the private and socially optimal long-run equilibrium conditions. Since we focus more on imputed costs later in the paper, we will not visit them here. Instead, we focus on the remaining cost elements derived in sections 3.1. and 3.1.1.[6] The mathematical derivations can be found in the Appendix.

3.2.1. Effects in the private solution

In the private solution, there are only fossil cars and public transport. Denoting the variable χ, which expresses a general notation for the parameters of a cost increase ($\gamma, \delta, \mu, \eta, \varphi$ and ω),

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[6] The comparative statics is carried out with a multiplicative increase in costs. The analyses have also been conducted with additive cost increases that yielded the same qualitative results.

we have $\frac{dx_p}{d\chi} = -\frac{dx_f}{d\chi}$. From the equilibrium condition in (1), there are two types of costs to be examined, congestion costs and crowding costs.

With an increase in congestion costs denoted as γ, we obtain the following: $\frac{dx_f}{d\gamma} < 0, \frac{dx_p}{d\gamma} > 0$.

Compared with the equilibrium in the private solution, the condition in which there is an increase in congestion costs is characterized by a decrease in the number of commuters using fossil cars and an increase in the number of commuters using public transport. The result is a decrease in congestion, CO_2-emissions, and local pollution, while the crowding aboard public transport is increased.

The increase in crowding costs is denoted δ. We then obtain the following: $\frac{dx_f}{d\delta} > 0, \frac{dx_p}{d\delta} < 0$.

With an increase in crowding costs, the share of commuters using fossil cars is larger than that in the private equilibrium condition. With more trips taken by fossil cars, there will be an increase in congestion, CO_2 emissions and local pollution. There will also be a reduction in crowding on public transport.

3.2.2. Effects in the socially optimal solution

In the socially optimal solution, we have that $\frac{dx_p}{d\chi} = -\left(\frac{dx_f}{d\chi} + \frac{dx_e}{d\chi}\right)$. Further, from (9), there are four cost categories under consideration for the comparative statics: congestion costs, costs of CO_2 emissions, local pollution costs, and crowding costs aboard public transport.

The increase in congestion costs is denoted as μ, and we obtain the following solution: $\frac{dx_p}{d\mu} > 0, \frac{dx_e}{d\mu} < 0, \frac{dx_f}{d\mu} > 0$ and $\frac{dx_e}{d\mu} + \frac{dx_f}{d\mu} < 0$.

Since congestion costs (and externalities) are equal for both car types, the indifference condition between these can be written as follows:

$$(1-\alpha)h'(x_f + \alpha x_e) = c_e - c_f - e \tag{12}$$

Due to the equilibrating cost mechanism, the congestion costs increase in part spills over to public transport, which experiences an increase in its use, and car transport decreases. The latter would, *ceteris paribus*, lead to less local pollution. This would distort the indifference condition between fossil and electric cars that necessitates that local pollution stays constant, implying that $x_f + \alpha x_e$ remains constant (see condition (12)). With a decrease in car transport, constant local pollution can only come about if the number of fossil cars increases and the number of electric cars (that are less pollutive) decreases more. Compared with the equilibrium condition in (9), the new equilibrium is characterized by lower congestion together with higher CO_2 emissions and crowding, while local pollution remains constant.

The cost increase from CO_2 emissions is denoted by η, and we obtain $\frac{dx_p}{d\eta} < 0, \frac{dx_e}{d\eta} > 0, \frac{dx_f}{d\eta} < 0$ and $\frac{dx_e}{d\eta} + \frac{dx_f}{d\eta} > 0$.

Further, the indifference condition between the two car types must hold with equality:

$$(1 - \alpha)h'(x_f + \alpha x_e) = c_e - c_f - \eta e \tag{13}$$

A differentiation of (13) shows that local pollution must decrease.

With an increase in costs from CO_2 emissions, fossil car use becomes socially more expensive than both the use of electric cars and the use of public transport. To secure a decrease in fossil car use, a decrease in local pollution costs *and* a preservation of the indifference condition between electric cars and public transport, we must have an increase in electric car use (which are less pollutive) slightly greater than the decrease in the use of fossil car. In addition, there will be a slight decrease in public transport use. Then, compared to the socially optimal outcome in section 3.1.1, the new equilibrium is characterized by decreased CO_2 emissions, local pollution, and crowding, while there is a slight increase in congestion.

The results above might seem counterintuitive since increased costs from CO_2 emissions result in a decrease in public transport use. This paradox is contingent upon assumptions made in the model. The commuters' willingness to pay to make the trip exceeds the costs of transport, and the number of trips is constant, even after the cost increase. Further, we saw from the equilibrium condition in (10) that we must have that $c_e > c_f + e$ to ensure that we do not obtain a corner solution for either car type.

The increase in local pollution costs is denoted φ, and we obtain the following solution: $\frac{dx_p}{d\varphi} = 0, \frac{dx_e}{d\varphi} > 0, \frac{dx_f}{d\varphi} < 0$ and $\frac{dx_e}{d\varphi} + \frac{dx_f}{d\varphi} = 0$.

The indifference condition between fossil and electric cars is as follows:

$$c_f + e + \varphi h'(x_f + \alpha x_e) = c_e + \alpha\varphi h'(x_f + \alpha x_e) \tag{14}$$

A differentiation of (14) shows that local pollution must be lower after the increase in local pollution costs.

An increase in local pollution costs makes private transport socially more costly than public transport, but the increase is largest for fossil cars. Further, the cost increase also makes the use of fossil cars socially more costly than electric cars, as seen from (14). Hence, a decrease in total car use will increase these distortions. However, a decrease in fossil cars coupled with an equivalent increase in electric cars will resolve both of these issues. First, local pollution will decrease since electric cars are less pollutive. This will close the cost cap between fossil and electric cars. Second, reduced local pollution will result in an asymmetric cost increase for private versus public transport. Hence, the increase in local pollution costs is nullified in its entirety by the increase in electric cars. The marginal cost of using private versus public transport remains the same, although the composition of the car fleet is altered. In the new equilibrium, CO_2 emissions and local pollution are decreased, while congestion and crowding remain unaltered.

For crowding costs, the cost increase is denoted ω, and we obtain the following solution: $\frac{dx_p}{d\omega} < 0, \frac{dx_e}{d\omega} > 0, \frac{dx_f}{d\omega} < 0$ and $\frac{dx_e}{d\omega} + \frac{dx_f}{d\omega} > 0$.

We have the following indifference condition for the two car types:

$$(1 - \alpha)h'(x_f + \alpha x_e) = c_e - c_f - e \tag{15}$$

The equilibrating mechanisms ensure that an increase in crowding costs spills over to private transport, with increased car use and decreased use of public transport. An increase in car use, would, *ceteris paribus*, result in more local pollution, distorting thereby between the two car types, the indifference condition, which states that local pollution stays constant (see condition (15)). An increase in car use and a condition of constant local pollution can only hold if there is a decrease in fossil cars and a larger increase in electric cars (which are less pollutive). Hence, compared with the socially optimal condition in section 3.1.1, the new equilibrium is characterized by lower CO_2 emissions and decreased crowding, while there is an increase in congestion.

The results from the comparative statics are summarized in Table 1. The results under the labels "Private solution" and "Socially optimal solution" denote the outcomes in the new equilibria compared to the initial equilibrium conditions in the private and socially optimal solutions, respectively. Increases are denoted as +, decreases are denoted as -, and non-applicable results are denoted as N/A.

Table 1. Results from comparative statics

	Private solution			Socially optimal solution		
	x_f	x_e	x_p	x_f	x_e	x_p
Congestion costs	-	N/A	+	+	-	+
Costs of CO_2-emissions	N/A	N/A	N/A	-	+	-
Local pollution costs	N/A	N/A	N/A	-	+	0
Crowding costs	+	N/A	-	-	+	-

4. Comparisons of partial instrument use

In section 3.1.1., we derived the socially optimal transport choice. Further, we discussed how the regulator could achieve this solution through coherent regulation by using a "sandwich" of targeted economic instruments. In practice, however, it is more common to apply a strategy of partial instrument use. In the following sections, we explore examples of such a strategy and examine its implications. The equilibrium outcomes are compared with the preceding private solution, as well as the socially optimal outcome from section 3.1.1. We focus on four alternatives, including three economic instruments and one technical instrument: a tax on fossil cars; a subsidy for electric cars; a congestion tax for both car types; and finally, a rule that allows electric cars into the bus lane.

4.1 A tax levied on the use of fossil cars

In this section, we examine the scenario in which the regulator implements a tax on the use of fossil cars. This is a well-established strategy and can take many forms (fuel tax, toll payment, emission tax, etc.). Here, we do not focus on one specific type of tax but instead concentrate on the equilibrium outcome when the regulator increases user costs for fossil cars. The optimization problem reads as follows:

$$\min\{c_f + g(x_f + x_e) + t, c_e + g(x_f + x_e), c_p + m(x_p, \bar{y})\}$$

The equilibrium condition, contingent on the restriction of a fixed number of trips, reads as follows:

$$c_f + g(x_f + x_e) + t = c_e + g(x_f + x_e) = c_p + m(x_p, \bar{y}) \tag{16}$$

First, we compare the indifference conditions for the two car types:

$$c_f + g(x_f + x_e) + t = c_e + g(x_f + x_e) \tag{17}$$

We have not defined the level of the fossil car tax, but this is of course of critical importance. If the tax is set too low, the result would be a reduction in fossil cars and an increase in the use of public transport but not necessarily any use of electric cars in equilibrium. We would then still have a corner solution for electric cars. Conversely, if the tax is set high enough, then one could obtain the corner solution in which the commuters use only public transport and electric cars. In the following discussion, we assume that the tax is set at a sufficiently high level to incentivize the use of electric cars. From (17), this means that the tax must be equal to $c_e - c_f$. This is a knife-edge solution in which the shares of fossil and electric cars are indeterminate.

If we compare the indifference conditions for fossil cars and public transport, we obtain the following:

$$c_f + g(x_f + x_e) + t = c_p + m(x_p, \bar{y}) \tag{18}$$

We have a constraint of a fixed number of commuters. Taking the implicit differential with respect to tax (t) and recognizing that $\frac{\mathrm{d}x_f}{\mathrm{dt}} + \frac{\mathrm{d}x_e}{\mathrm{dt}} = -\frac{\mathrm{d}x_p}{\mathrm{dt}}$, we obtain the following:

$$\frac{\mathrm{dx_p}}{\mathrm{dt}} = \frac{1}{\mathrm{g}'(\,\mathrm{x_f} + \mathrm{x_e}) + \mathrm{m}'_{\mathrm{x_p}}(\mathrm{x_p}, \bar{\mathrm{y}})} > 0 \tag{19}$$

Consequently, we also have $\frac{\mathrm{d}x_f}{\mathrm{dt}} + \frac{\mathrm{d}x_e}{\mathrm{dt}} < 0$.

The implementation of the tax on fossil cars then leads to an increase in the use of public transport and a decrease in car use. This results in a new equilibrium with less congestion, less local pollution, and less CO_2 emissions. The magnitude of these reductions depends on the composition of fossil and electric cars in the new equilibrium. On the other hand, the crowding on public transport will increase. In a sense, the emission tax is therefore in part shifted over to public transport.

We can compare the equilibrium outcome in this section with the socially optimal outcome. The tax is levied on fossil cars, and we obtain a reduction in fossil car use (even if no new electric cars enter, the fossil car use cannot increase). The reduced use of cars also reduces CO_2 emissions, congestion, and local pollution. The increased use of public transport leads to more crowding. Contrary to the socially optimal solution, in this situation, only fossil cars are regulated. This means that there are no separate regulation mechanisms that increase costs for electric cars and public transport, internalizing the externalities from their use. The exact outcome depends on the composition of the different transport alternatives in the new equilibrium.

4.2. A subsidy provided for use of electric cars

In this scenario, electric cars receive remuneration in the form of a subsidy. The reasoning behind such a policy could be that the regulator wants to reduce CO_2 emissions. This can be done in different ways (free public parking, subsidized fuel, reduced toll fees, etc.). The optimization problem reads as follows:

$$\min\{\mathrm{c_f} + \ \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}), \mathrm{c_e} + \ \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) - \mathrm{s}, \mathrm{c_p} + \mathrm{m}(\mathrm{x_p}, \bar{\mathrm{y}})\}$$

With the constraint of a fixed number of trips, we obtain the following equilibrium condition:

$$\mathrm{c_f} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) = \mathrm{c_e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) - \mathrm{s} = \mathrm{c_p} + \mathrm{m}(\mathrm{x_p}, \bar{\mathrm{y}}) \tag{20}$$

We start out by comparing the indifference conditions for both car types:

$$\mathrm{c_f} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) = \mathrm{c_e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) - \mathrm{s} \tag{21}$$

We can see from (21) that for commuters to be indifferent between fossil and electric cars, the subsidy must cover the cost difference $\mathrm{c_e} - \mathrm{c_f}$. This was the equivalent size of the tax in the previous section. Again, this is a knife-edge solution in which the shares of fossil and electric cars are indeterminate. If the subsidy is set at a lower level, commuters would strictly prefer fossil cars over electric cars, and we would obtain a corner solution. A sufficiently high subsidy could be introduced that displaced fossil cars entirely (and even public transport); however, this is not considered to be a desired outcome. In the following, we assume that the subsidy is set at a level such that commuters are indifferent between a fossil and electric car.

For the indifference conditions for electric cars and public transport, we obtain the following:

$$\mathrm{c_e} + \mathrm{g}(\mathrm{x_f} + \mathrm{x_e}) - \mathrm{s} = \mathrm{c_p} + \mathrm{m}(\mathrm{x_p}, \bar{\mathrm{y}}) \tag{22}$$

With the constraint of a fixed number of commuters, we take the implicit differential with respect to the subsidy (s). Recognizing that, $\frac{\mathrm{d}x_f}{\mathrm{ds}} + \frac{\mathrm{d}x_e}{\mathrm{ds}} = -\frac{\mathrm{d}x_p}{\mathrm{d}s}$, we obtain the following result:

$$\frac{\mathrm{dx_p}}{\mathrm{ds}} = -\frac{1}{\mathrm{g}'(\mathrm{x_f} + \mathrm{x_e}) + \mathrm{m}'_{\mathrm{x_p}}(\mathrm{x_p}, \bar{\mathrm{y}})} < 0 \tag{23}$$

Consequently, we also have the following: $\frac{\mathrm{d}x_f}{\mathrm{ds}} + \frac{\mathrm{d}x_e}{\mathrm{ds}} > 0$.

A subsidy for electric cars results in a decrease in public transport use and an increase in total car use. From (21), the subsidy unambiguously lowers the cost of electric car use compared to that for fossil cars. Since total car use increases, a reduction in fossil cars must be less than the increase in electric cars. This results in more congestion, more local pollution and less $\mathrm{CO_2}$

emissions and crowding in this situation than in the case before the introduction of the subsidy. The magnitude of these changes depends on the composition of fossil and electric cars in the new equilibrium.

The use of subsidies for electric cars alone is not able to achieve the socially optimal outcome. If commuters switch from fossil to electric cars, then CO_2 emissions decrease unambiguously. However, congestion does not decrease. Since the use of public transport decreases, congestion will increase, while crowding will decrease. An electric car causes fewer local negative externalities than a fossil car, but if commuters also switch from public transport to electric cars, the total effect is not clear-cut. When electric car use is subsidized, it incentivizes the discharge of externalities from electric cars. A target for CO_2 emission reductions can then conflict with the effective regulation of other externalities from car use. This can be especially problematic in urban areas in which congestion is considered the costliest externality in peak periods (Small, Verhoef, & Lindsey, 2007). Further, subsidies entail a cost to be covered elsewhere in the economy.

Although electric cars do not emit CO_2 on the road, the size of the environmental benefit from switching to electric cars depends on whether fossil or renewable sources are used in electricity generation (Jochem et al., 2016). Further, since an electric car takes up the same amount of space as a fossil car, electric cars are not a solution to the congestion problem. In a study from the US, Holland, Mansur, Muller & Yates (2016) argue that if only greenhouse gases are included in emission calculations, then compared to gasoline vehicles, electric cars provide a clear environmental benefit. However, if local pollution is accounted for, the results can be quite different. In areas with low population density and power generation based on coal firing, the damage from gasoline vehicles can be relatively low, while the environmental benefit from electric cars can be negative. In Norway, electricity generation comes almost exclusively from renewable sources. A generous support scheme ensured that Norway had the highest market share of electric vehicle sales in 2019 (IEA, 2020a). Electric cars receive substantial tax exemptions, prompting the argument that incentivizing electric cars is a costly way of reducing CO_2 emissions (Bjertnæs, 2016). Cheaper electric cars may also incentivize people to use an electric car rather than public transport (Holtsmark, 2012). The support scheme may also create incentives for the procurement of heavier electric cars, which contribute considerably to local negative externalities, such as noise and the emission of particulate matter (Holtsmark, 2020). Timmers & Achten (2016) show a positive correlation between weight and non-exhaust emissions for electric cars. They argue that future policy initiatives should focus on incentives for manufacturers and consumers to switch to lighter vehicles.

4.3. A congestion tax for both car types

In this section, we examine the situation in which a uniform congestion tax is introduced for both car types. Since congestion is considered to be the costliest externality in urban areas in peak periods (Small et al., 2007), this instrument can be appealing for regulators. The optimization problem reads as follows:

$$\min\{c_f + g(x_f + x_e) + q, c_e + g(x_f + x_e) + q, c_p + m(x_p, \bar{y})\}$$

We obtain the following equilibrium condition, with the constraint of a fixed number of trips:

$$c_f + g(x_f + x_e) + q = c_e + g(x_f + x_e) + q = c_p + m(x_p, \bar{y}) \tag{24}$$

First, we observe the indifference conditions for the two car types:

$$c_f + g(x_f + x_e) + q = c_e + g(x_f + x_e) + q \tag{25}$$

The use of a congestion tax for both car types is an efficient way of handling congestion when the congestion tax is set at an effective level. However, if the level of the tax is too low, then congestion will be underpriced. We can see from (25) that the level of the congestion tax does not affect the distribution of commuters between the two car alternatives. If the congestion tax is equal for fossil and electric cars, there is no incentive for electric cars (assuming no governmental subsidies). Hence, we obtain the same solution as we did in the private solution, i.e., a corner solution with no electric cars in the new equilibrium.

We can now compare the indifference conditions for fossil cars and public transport:

$$c_f + g(x_f) + q = c_p + m(x_p, \bar{y}) \tag{26}$$

With no electric cars in equilibrium and a fixed number of trips, we have that $\frac{dx_f}{dq} = -\frac{dx_p}{dq}$. Taking the implicit differential with respect to q, we obtain the following:

$$\frac{\mathrm{d}x_p}{\mathrm{dq}} = \frac{1}{\mathrm{g}'(\mathrm{x_f}) + \mathrm{m}'(\mathrm{x_p}, \bar{\mathrm{y}})} > 0 \tag{27}$$

Consequently, we also have the following: $\frac{\mathrm{dx_f}}{\mathrm{dq}} < 0$.

The use of a congestion tax results in a decrease in fossil car use and an increase in the use of public transport. The same result was shown in section 3.2.1. This leads to congestion, local pollution and CO_2 emissions that are less than those in the case before the introduction of the congestion tax. However, the crowding aboard public transport will increase. The magnitude of these changes depends on the composition of fossil cars and public transport in the new equilibrium. Note that from (26), the congestion could be taxed so high that we obtain a corner solution in which the commuters only use public transport. However, this is not considered to be a realistic solution.

Although a fossil and an electric car cause the same amount of congestion, this is not the case for the other externalities. With only a congestion tax, the other externalities are not internalized. Unlike the socially optimal solution, this equilibrium solution includes no electric cars. Whether there are too many fossil cars in equilibrium compared to the number of fossil cars in the socially optimal outcome depends on the level of the congestion tax. If it is set equal to the marginal externality cost of congestion, it is an effective instrument for this externality. However, the overall taxation is then too low, and there are too many fossil cars in the new equilibrium. Furthermore, there are no regulations on public transport use to internalize the crowding externality.

Although congestion pricing alone is insufficient for an overall internalization of negative externalities from transport, it can be an efficient component in this regulation. However, since congestion pricing entails charging people for something that used to be free, it has not been unproblematic to implement (Small, 1992). Nevertheless, there are some notable examples where this instrument type has been introduced: Singapore (Chin, 2005), London (Leape, 2006; Litman, 2005), Stockholm (Börjesson, Eliasson, Hugosson, & Brundell-Freij, 2012), Norway (Ramjerdi, Minken, & Østmoe, 2004) and Milan (Anas & Lindsey, 2011).

The results show that uniform congestion pricing alone does not incentivize the use of electric cars over fossil cars. This incentivization could, however, be done with differentiated congestion taxes. In Norway, electric cars cannot be charged more than 50 percent of the congestion tax for fossil cars. However, since electric cars cause the same amount of congestion as a fossil car, a differentiated tax for congestion goes against the principle of effective congestion pricing.

4.4. Electric cars allowed into the bus lane

In the preceding sections, we have looked at economic instruments. A regulator can also use technical instruments (technology standards, emission-free zones, etc.). Here, we examine the scenario in which electric cars are allowed into the bus lane. This was one of the instruments introduced in Norway to stimulate the use of electric cars to reduce CO_2 emissions. For simplicity, when electric cars are allowed into the bus lane, we assume that all electric car users choose this option. Hence, there is one congestion cost for fossil cars and another for electric cars. Further, electric cars cause congestion for other electric cars and public transport, but not the other way around[7]. The total congestion costs are additive, i.e., $g(x_f) + g(x_e)$. The optimization problem reads as follows:

$$\min\{c_f + g(x_f), c_e + g(x_e), c_p + g(x_e) + m(x_p, \bar{y})\}$$

With the binding constraint of a fixed number of trips, we obtain the following:

$$c_f + g(x_f) = c_e + g(x_e) = c_p + g(x_e) + m(x_p, \bar{y}) \tag{28}$$

We begin by comparing the indifference conditions for fossil and electric cars:

$$c_f + g(x_f) = c_e + g(x_e) \tag{29}$$

When electric cars drive in the bus lane, their congestion costs are unaffected by the number of fossil cars. Likewise, the congestion costs for fossil cars are solely determined by the number of fossil cars. With identical functional forms for the congestion costs, the equilibrium condition in (29) holds if $g(x_f) > g(x_e)$. In the private solution in section 3.1., we obtained the corner

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[7] A similar assumption is made in (Strøm & Vislie, 2008).

solution that there would be no electric cars. From (29), however, we have that if electric cars are allowed into the bus lane, then in equilibrium, commuters will choose *both* fossil and electric cars and that most of the car users prefer fossil cars.

We can also compare the indifference conditions for electric cars and public transport:

$$c_e + g(x_e) = c_p + g(x_e) + m(x_p, \bar{y}) \tag{30}$$

We can see from (30) that now there is an additional cost for public transport when electric cars create congestion in the bus lane. We have assumed that $c_e < c_p$. For the equality in (30) to hold, we must have the following: $c_e = c_p + m(x_p, \bar{y})$. Obviously, this cannot hold. Hence, we obtain a corner solution in which commuters choose either fossil or electric cars in the new equilibrium. This is a very strong assumption since there are always some commuters who cannot or will not choose private transport. Further, the corner solution is a result of the functional forms used. However, the result shows that when facing congestion costs from cars, public transport loses an important advantage over private transport.

When electric cars are allowed into the bus lane, this results in a displacement of public transport in favor of private transport. With a fixed number of commuters, this displacement results in congestion, local pollution, and crowding greater than those in the case before the implementation of the technical instrument. The magnitude of these reductions depends on the composition of fossil and electric cars in the new equilibrium. Whether CO_2 emissions increase or decrease depends upon the distribution of commuters between the two car types. However, since congestion costs for fossil cars now only depend on other fossil cars, our results suggest that there could be an increase in CO_2 emissions as well.

A comparison with the outcome in section 3.1.1., shows that allowing electric cars in the bus lane is not an effective instrument for reducing the externalities from road transport. In section 4.2., we discussed the implications of subsidizing electric car use and showed that this could be a costly way of reducing CO_2 emissions. At the same time, it incentivized externalities from electric car use. In this section, we find that if electric cars are allowed into the bus lane, not only will they inflict congestion costs on public transport and displace this alternative, but fossil cars will also benefit, since the fossil cars will face lower congestion costs.

5. Summary and concluding remarks

In this paper, we examine the problem of transport choice for commuters in a congested urban area. We analyze the long-run equilibrium conditions under the situation in which the negative externalities are not internalized. Then, we move from the private to the socially optimal solution, in which the externalities are internalized, and examine this new equilibrium. The commuters use either a fossil car, an electric car or public transport. Each mode of transport is responsible for a different composition of negative externalities. We discuss how the regulator can achieve an optimal internalization of the externalities, stressing the use of economic principles for efficient regulation. This is highlighted by analyzing outcomes from partial instrument use and by conducting comparative statics, allowing us to compare different long-run outcomes.

The regulator can optimally internalize the externalities with four economic instruments: a CO_2 tax for fossil cars, a differentiated local pollution tax for both car types, a uniform congestion tax for both car types, and a mark-up on the public transport fare to account for crowding aboard the public transport service. Further, we show the results when the regulator strays from this strategy of coherent and targeted regulation.

We study four examples in which the regulator uses a strategy of partial instrument use. Three economic instruments are considered: a tax on fossil cars, a subsidy for electric cars, and a congestion tax for both car types. Finally, we look at a technical instrument under which electric cars are allowed into the bus lane. We analyze the long-run equilibriums from these regulation choices and show that compared to the socially optimal outcome, each outcome results in insufficient regulation. A strategy of partial regulation can also cause unintended consequences. The subsidization of electric car use may seem to be an appealing way to reduce CO_2 emissions, but it can be both costly and come into conflict with the regulation of other externalities. Further, allowing electric cars into the bus lane not only creates congestion for public transport but also can incentivize the use of fossil cars by reducing their congestion costs as well.

Our results are derived from a stylized model using simplified functional forms and in which several assumptions have been made. There are a fixed number of trips taken. Further, all commuters have a fixed utility for the trip (but not necessarily the same utility). Since the trip is deemed essential, to secure an economic outcome, utility is always of greater order than the minimized cost of making the trip. This means that for all commuters, it is not an alternative to opt out of making the trip. In addition, we have partly abstracted away from some types of negative externalities from public transport use. Further, in our analysis, we have discussed the economic principles of regulation to achieve a socially optimal outcome. In practice, however, there could be political and public constraints restricting the regulators' choice of instruments. Concerns about equity, technology and privacy are recurring objections.

However, with the potentially large social costs stemming from transport-related externalities, the discussion of effective regulation is clearly important. Our results highlight the significance of transport choice to the contribution of negative externalities and discuss important economic principles for effective regulation. These principles entail the implementation of coherent regulation and the use of a "sandwich" of economic instruments. The implemented instruments should be derived such that they both target in a direct way the externalities and are differentiated to account for different damage intensities from different vehicle types.

Appendix

A. Functional forms and expressions used in the model

Symbol	**Description**
$\bar{u}$	Individual utility of travel (fixed)
$\bar{x}$	Total number of trips (fixed)
x_f	Total number of trips by fossil cars
x_e	Total number of trips by electric cars
x_p	Total number of trips by public transport
$\bar{y}$	Capacity limit for public transport
c_f	Imputed unit cost of a fossil car
c_e	Imputed unit cost of an electric car
c_p	Imputed unit cost of public transport
$g(x_f + x_e)(x_f + x_e)$	Total congestion costs from car use, with $g'(x_f + x_e) > 0$ and $g''(x_f + x_e) \geq 0$
$g(x_f + x_e)$	Average congestion costs
$g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e)$	Marginal congestion costs,
$h(x_f + \alpha x_e)$	Local pollution cost, with $h'(x_f + \alpha x_e) > 0$ and $h''(x_f + \alpha x_e) \geq 0$
α	Damage intensity for an electric car, with $0 < \alpha < 1$
e	Marginal CO_2 emission from fossil car use
$m(x_p, \bar{y})$	Crowding cost function for public transport, with $m'_{x_p}(x_p, \bar{y}) > 0, m'_{\bar{y}}(x_p, \bar{y}) < 0$ and $m''_{x_p}(x_p, \bar{y}) \geq 0$
$i(\bar{y})$	Investment function for public transport capacity, with$i'(\bar{y}) > 0$
t	Tax on fossil car use
s	Subsidy provided for electric car use
q	Congestion tax for both car types

B. Private solution – effects of increased congestion costs

With a multiplicative increase in congestion costs denoted by γ, the equilibrium condition reads as follows:

$$c_f + \gamma g(x_f) = c_p + m(x_p, \bar{y}) \tag{B.I.}$$

By derivation of B.I. of γ, we obtain the following:

$$\frac{dx_f}{d\gamma} = -\frac{g(x_f)}{\gamma g'(x_f) + m'(x_p, \bar{y})} < 0 \tag{B.II.}$$

Hence, $\frac{dx_f}{d\gamma} < 0$, and $\frac{dx_p}{d\gamma} > 0$.

C. Private solution – effects of increased crowding costs

We denote the cost increase δ and obtain the following equilibrium condition:

$$c_f + g(x_f) = c_p + \delta m(x_p, \bar{y}) \tag{C.I.}$$

By derivation of C.I. of δ, we obtain the following:

$$\frac{dx_f}{d\delta} = \frac{m(x_p, \bar{y})}{g'(x_f) + \delta m'(x_p, \bar{y})} > 0 \tag{C.II.}$$

Hence, $\frac{dx_f}{d\delta} > 0$, and $\frac{dx_p}{d\delta} < 0$.

D. Socially optimal solution – effects of increased congestion costs

The increase in congestion costs is denoted by μ. The equilibrium condition is then as follows:

$$\begin{aligned} c_f + e + \mu g(x_f + x_e) + \mu g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) \\ = c_e + \mu g(x_f + x_e) + \mu g'(x_f + x_e)(x_f + x_e) + \alpha h'(x_f + \alpha x_e) \\ = c_p + m(x_p, \bar{y}) + m'_{x_p}(x_p, \bar{y})x_p \end{aligned} \tag{D.I.}$$

Denoting $Z = (2\mu g' + \mu g''(x_f + x_e) + h'' + 2m' + m''_{x_p} x_p)$, the condition in D.I. can be written on matrix form as follows:

$$\begin{bmatrix}(1-\alpha)^2h'' & (1-\alpha)h'' \\ (1-\alpha)h'' & Z\end{bmatrix}\begin{bmatrix}dx_e \\ dx_p\end{bmatrix} = \begin{bmatrix}0 \\ \big(g(x_f+x_e)+g'(x_f+x_e)(x_f+x_e)\big)\end{bmatrix} \qquad \text{D.II.}$$

By using Cramer's rule and the condition of a fixed number of trips, we obtain the following:

$$\frac{dx_e}{d\mu} = -\frac{\big(g(x_f+x_e)+g'(x_f+x_e)(x_f+x_e)\big)}{(1-\alpha)(Z-h'')} < 0 \qquad \text{D.III.}$$

$$\frac{dx_p}{d\mu} = \frac{(1-\alpha)\big(g(x_f+x_e)+g'(x_f+x_e)(x_f+x_e)\big)}{(1-\alpha)(Z-h'')} > 0 \qquad \text{D.IV.}$$

$$\frac{dx_f}{d\mu} = \frac{\alpha\big(g(x_f+x_e)+g'(x_f+x_e)(x_f+x_e)\big)}{(1-\alpha)(Z-h'')} > 0 \qquad \text{D.V.}$$

Hence, $\frac{dx_p}{d\mu} > 0, \frac{dx_e}{d\mu} < 0, \frac{dx_f}{d\mu} > 0$, and $\frac{dx_e}{d\mu} + \frac{dx_f}{d\mu} < 0$.

E. Socially optimal solution – effects of increased costs of CO2 emissions

With the cost increase denoted η, the equilibrium condition reads as follows:

$$\begin{aligned} c_f + \eta e + g(x_f+x_e) + g'(x_f+x_e)(x_f+x_e) + h'(x_f+\alpha x_e) & \\ = c_e + g(x_f+x_e) + g'(x_f+x_e)(x_f+x_e) + \alpha h'(x_f+\alpha x_e) & \\ = c_p + m(x_p,\bar{y}) + m'_{x_p}(x_p,\bar{y})x_p & \end{aligned} \qquad \text{E.I.}$$

Denoting $Z = (2g' + g''(x_f+x_e) + h'' + 2m' + m''_{x_p}x_p)$, the condition in E.I. can be written on matrix form as follows:

$$\begin{bmatrix}(1-\alpha)^2h'' & (1-\alpha)h'' \\ (1-\alpha)h'' & Z\end{bmatrix}\begin{bmatrix}dx_e \\ dx_p\end{bmatrix} = \begin{bmatrix}e \\ e\end{bmatrix} \qquad \text{E.II.}$$

With the use of Cramer's rule, we obtain the following:

$$\frac{dx_e}{d\eta} = \frac{e(Z-(1-\alpha)h'')}{(1-\alpha)^2h''(Z-h'')} > 0 \qquad \text{E.III.}$$

$$\frac{\mathrm{dx_p}}{\mathrm{d\eta}} = -\frac{\alpha(1-\alpha)h''e}{(1-\alpha)^2 h''(Z-h'')} < 0 \qquad \text{E.IV.}$$

$$\frac{\mathrm{dx_f}}{\mathrm{d\eta}} = -\frac{e(Z-(1-\alpha^2)h'')}{(1-\alpha)^2 h''(Z-h'')} < 0 \qquad \text{E.V.}$$

Hence, $\frac{dx_p}{d\eta} < 0, \frac{dx_e}{d\eta} > 0, \frac{dx_f}{d\eta} < 0$ and $\frac{dx_e}{d\eta} + \frac{dx_f}{d\eta} > 0$

F. Socially optimal solution – effects of increased local pollution costs

The increase in local pollution costs is denoted by φ. The equilibrium condition then reads as follows:

$$\begin{aligned} c_f + e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + \varphi h'(x_f + \alpha x_e) \qquad \text{F.I.} \\ = c_e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + \alpha\varphi h'(x_f + \alpha x_e) \\ = c_p + m(x_p, \bar{y}) + m'_{x_p}(x_p, \bar{y})x_p \end{aligned}$$

Denoting $Z = (2g' + g''(x_f + x_e) + \varphi h'' + 2m' + m''_{x_p}x_p)$, the condition in F.I. can be written on matrix form as:

$$\begin{bmatrix} (1-\alpha)^2\,\varphi h'' & (1-\alpha)\varphi h'' \\ (1-\alpha)\varphi h'' & Z \end{bmatrix} \begin{bmatrix} dx_e \\ dx_p \end{bmatrix} = \begin{bmatrix} (1-\alpha)h' \\ h' \end{bmatrix} \qquad \text{F.II.}$$

By using Cramer’s rule, we obtain the following results:

$$\frac{dx_e}{d\varphi} = \frac{h'}{(1-\alpha)\varphi h''} > 0 \qquad \text{F.III.}$$

$$\frac{dx_p}{d\varphi} = \frac{(1-\alpha)^2\,\varphi h''h' - (1-\alpha)\varphi h''(1-\alpha)h'}{(1-\alpha)^2\varphi h''(Z-\varphi h'')} = 0 \qquad \text{F.IV.}$$

$$\frac{dx_f}{d\varphi} = -\frac{h'}{(1-\alpha)\varphi h''} < 0 \qquad \text{F.V.}$$

Hence, $\frac{dx_p}{d\varphi} = 0, \frac{dx_e}{d\varphi} > 0, \frac{dx_f}{d\varphi} < 0$ and $\frac{dx_e}{d\varphi} + \frac{dx_f}{d\varphi} = 0.$

G. Socially optimal solution – effects of increased crowding costs

The increase in crowding costs is denoted ω, and the equilibrium condition reads as follows:

$$\begin{aligned} c_f + e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + h'(x_f + \alpha x_e) \\ = c_e + g(x_f + x_e) + g'(x_f + x_e)(x_f + x_e) + \alpha h'(x_f + \alpha x_e) \\ = c_p + \omega m(x_p, \bar{y}) + \omega m'_{x_p}(x_p, \bar{y}) x_p \end{aligned} \qquad \text{G.I.}$$

Denoting $Z = (2g' + g''(x_f + x_e) + h'' + 2\omega m' + \omega m''_{x_p} x_p)$, the condition in G.I. can be written on matrix form as follows:

$$\begin{bmatrix} (1-\alpha)^2 h'' & (1-\alpha)h'' \\ (1-\alpha)h'' & Z \end{bmatrix} \begin{bmatrix} dx_e \\ dx_p \end{bmatrix} = \begin{bmatrix} 0 \\ -(m + m'x_p) \end{bmatrix} \qquad \text{G.II.}$$

With the use of Cramer's rule, we obtain the following results:

$$\frac{dx_e}{d\omega} = \frac{(m + m'x_p)}{(1-\alpha)(Z - h'')} > 0 \qquad \text{G.III.}$$

$$\frac{dx_p}{d\omega} = -\frac{(1-\alpha)(m + m'x_p)}{(1-\alpha)(Z - h'')} < 0 \qquad \text{G.IV.}$$

$$\frac{dx_f}{d\omega} = -\frac{\alpha(m + m'x_p)}{(1-\alpha)(Z - h'')} < 0 \qquad \text{G.V.}$$

Hence, $\frac{dx_p}{d\omega} < 0, \frac{dx_e}{d\omega} > 0, \frac{dx_f}{d\omega} < 0$ and $\frac{dx_e}{d\omega} + \frac{dx_f}{d\omega} > 0.$

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