

**ESSAYS ON ECONOMIC INSTRUMENTS FOR THE
CONTROL OF ENVIRONMENTAL EXTERNALITIES**

by

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M.Soc.Sc., M.Sc. (Tech.)

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ROLAND MAGNUSSON

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Abstract

This thesis consists of three essays on the use of economic instruments in environmental policy. The first essay analyses the case for interstate cooperation in environmental taxation while the second and the third essays study questions specific to the use of economic instruments in climate change mitigation.

The first essay analyses the incentives of national governments to cooperate in regulating pollutants that spill over jurisdictional boundaries. A well-established result within the literature that assumes perfect competition is that a country, which is small in the sense that it cannot affect world prices, has no incentive to depart from the cooperative choice of environmental regulation. By generalising the model presented by Oates and Schwab (1987, 1988) it is shown that this result does not hold for pollutants that have regional or global characteristics, as e.g. sulphur dioxide (SO_2) and carbon dioxide (CO_2) have.

The second essay demonstrates a methodology for analysing the progress and failure of projects in the CDM. It models the hazard of first issuance. Integrated over duration, the hazard of first issuance gives the time to market, defined as the duration between the start of the Global Stakeholder Process and the first issuance of Certified Emissions Reductions (CERs). It is shown that 50% of all projects which have started the Global Stakeholder Process fail to issue CERs, while the remainder has a median time to market of 4 years.

The third essay illustrates a paradox in which overlapping climate policy instruments may have the unintended consequence of accelerating rather than decelerating global warming. The insight follows from a dynamic model, where a quota obligation for power generated from renewables is introduced alongside a carbon budget. A dynamic model allows to study how the schedule at which the carbon budget is exhausted is affected by the quota obligation. The exhaustion schedule determines the global temperature response.

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Helsinki, November 9, 2017,

Roland Magnusson

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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Roland Magnusson. Efficiency of non-cooperative emission taxes in perfectly competitive markets. *Published in Finnish Economic Papers*, 23(2): 88-93, Autumn 2010.

II Roland Magnusson. Time to market in the CDM: variation over project characteristics and time. *Published in Climate Policy*, 15:2: 183-222, 2015.

III Roland Magnusson. Paradox of overlapping climate policy instruments. *Unpublished manuscript*, 2017.

Author's Contribution

Publication I: "Efficiency of non-cooperative emission taxes in perfectly competitive markets"

Roland Magnusson was the sole author.

Publication II: "Time to market in the CDM: variation over project characteristics and time"

Roland Magnusson was the sole author.

Publication III: "Paradox of overlapping climate policy instruments"

Roland Magnusson was the sole author.

1. Introduction

Since the industrial revolutions of the 18th and 19th centuries, environmental externalities have increased in prevalence, scale and scope. An environmental externality occurs when the actions of one individual affects the state of the environment, through a process which other individuals have no control over, but which affects their welfare.

The scope of the environmental externalities vary. While some externalities are very local, affecting only a handful people, such as the contamination of neighbouring lakes by Talvivaara nickel mine in northern Finland, others, such as the pollution of 80 per cent of shallow groundwaters in China to the extent of not being safe for human consumption, affects the livelihoods of hundreds of millions of individuals (Asian Development Bank, 2016; Talvivaara Mining Company, 2014). Climate change is an example of an externality with a global reach. A tonne of carbon dioxide released from Europe has the same effect as a tonne of carbon dioxide released from China. While the effects of climate change are not dependent on the source, the effects are not the same across regions. Some regions are expected to be affected more severely than others (Krusell & Smith, 2015).

Regulation of environmental externalities is a collective action problem. Currently, the main international forum for collective action on climate change mitigation is the United Nations Framework Convention on Climate Change (UNFCCC). Under the UNFCCC, two legal treaties co-exist, the Kyoto Protocol and the Paris Agreement. Publication I analyses the incentives for national governments to cooperate in regulating pollutants that spill over jurisdictional boundaries.

Traditionally, environmental externalities have been regulated by command-and-control policies, that is, standards that explicitly state the legally accepted range of environmental impairment by the regulated entities, with little or no flexibility. Gradually, since the 1970s, economic instruments have emerged

alongside, and in some cases replacing existing command-and-control policies. Economic instruments are defined here as policy instruments that leave some discretion for the regulated agents, typically but necessarily by establishing a market and a price for the externality or the activity that causes it. The idea of taxing the externality dates back to Pigou (1952). However, at the time of Arthur Pigou, it was not viewed as a practical approach for controlling pollution (Andersen, 1995).

The primary motivation for the use of economic instrument is efficiency. Efficiency is a difficult concept because of its many definitions. Pareto efficiency requires that marginal damage costs are set equal to marginal control costs (Adar & Griffin, 1976). However, for the regulation of most environmental externalities, Pareto efficiency is a naive objective, because both damage costs and control cost are typically unknown to the regulator. The emitters presumably know the control costs, but not the regulator. In most applications, the best the regulator can hope for is to realise a certain level of abatement, or environmental improvement, for the least cost. The least cost allocation is attained by the equalisation of marginal control costs across emitters through the establishment of a price on emissions. A price can established either through a tax, a subsidy or by allocating a fixed amount of tradable pollution allowances. With limited information, the level of abatement is a political decision. Moreover, with a tax or subsidy, the size of the abatement is not known ex-ante because the regulator does not know the control costs.

Emissions trading is a fairly new type of policy instrument, with the first applications in the US, as part of the Clear Air Act of 1977 and its amendment of 1990 (Hansjürgens, 2005). The appeal of emissions trading vis-à-vis taxes can be explained by the perceived flexibility of emissions trading, which allows heterogeneous economies, such as the EU Member States and, say, China to join a common scheme. The political realism in many parts of the world, including the EU, is that agreeing on emissions quotas is realistic whereas agreeing on uniform CO₂ taxes is not.

Current emissions trading schemes rely on one of two principles: cap-and-trade or baseline-and-credit. A cap-and-trade scheme puts a cap on emissions from included sectors and allows regulated entities to buy and sell emissions allowances. Initially, the allowances are either auctioned or distributed for free. The initial allocation has distributional effects but no effect on the equilibrium. In a baseline-and-credit scheme, credits are issued ex-post, based on the difference between monitored emissions and the baseline. The baseline is the counterfactual, the emissions in the business as usual case.

The leading examples of both types of schemes can be found within climate policy, which by design is a collective action problem. The EU Emissions Trading Scheme (EU ETS) is the leading example of a cap-and-trade scheme, whereas the Clean Development Mechanism (CDM), of the Kyoto protocol, is the leading example of a baseline-and-credit scheme. The EU ETS started off with a pilot phase in 2005-2007, and has since then expanded both in terms of its geographical coverage, sectoral coverage and gas coverage (Bragadóttir, Magnusson, Seppänen, & Sundén, 2016). Currently, The EU ETS covers approximately 42% of EU-28 emissions through a cap on emissions from large stationary sources and emissions from air traffic within the trading area (European Environment Agency, 2016). The cap is defined in terms of EU Emissions Allowances (EUAs), each of which give the right to emit one tonne of carbon dioxide equivalents (tCO₂e).

The CDM is one of three flexibility mechanisms under the Kyoto Protocol. Through the CDM, Annex I countries can meet part of their obligations under the Kyoto Protocol by reducing emissions in non-Annex I countries. Somewhat simplified, Annex I countries are developed countries, non-Annex I countries are developing countries. The rationale for the CDM is that the cost of reducing emissions in developing countries is, presumably, lower than the cost of reducing emissions in developed countries. Of past and current emissions trading schemes, no other scheme comes even close to the CDM, measured in terms of geographical coverage (117 host countries) sectoral coverage (energy, transport, agriculture, afforestation, reforestation, fugitive emissions, landfill gases, among others) (UNEP Risø, 2016). As such, the CDM serves as a benchmark and reference for mechanism developed under Article 6.4 of the Paris Agreement.

The CDM is a project based mechanism, in which individual projects that reduce emissions below the baseline are awarded Certified Emissions Reductions (CERs). A CDM project is said to be additional if it passes certain tests of whether the claimed emissions reductions are real. To evaluate additionality, the CDM makes use of third-party audits, once when a project applies for registration under the CDM and every time that a project applies for the issuance of CERs. The progress and failure of projects in the CDM is the topic of Publication II.

Figure 1 shows the development of the price of EUAs and CERs over 2005-2016. It shows large volatility in the market. The volatility can be attributed to the design features. At some point, EUAs and CERs were interchangeable, up to a given quantitative limit. The limit permitted by the current market

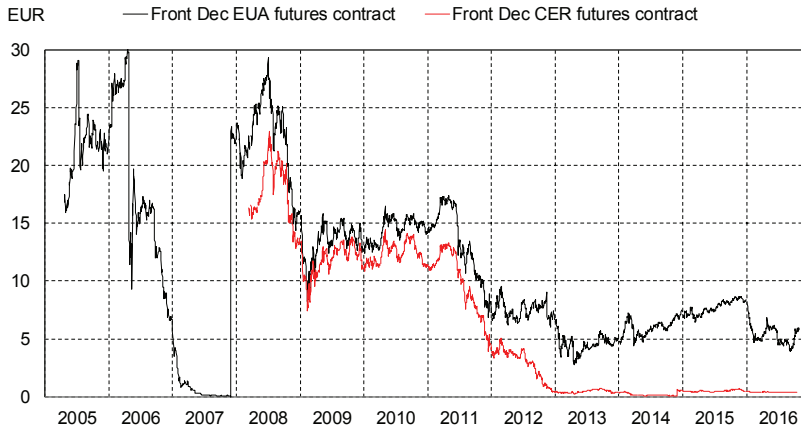


Figure 1. Price of EU Allowances (EUA) in the EU Emissions Trading Scheme and Certified Emission Reductions (CER) in the Clean Development Mechanism (CDM), based on end of day historical price data, from and with permission from the Intercontinental Exchange ICE.

framework has for all practical purposes been exhausted (Kossoy et al., 2015). In the period 2005-2007 the price of EUAs dropped to zero because banking between Phase 1 and 2 was not permitted. Between Phase 3 (2020-2030) and Phase 4 (2021-2030) there is unlimited banking. Currently, both the market for EUAs and the market for CERs are oversupplied. Publication II provides some explanation of the process that has led to the current situation in the market for CERs.

The introduction of new policy instruments combined with the reticence to remove existing ones has made the policy space of many sectors of the economy, in particular power generation, congested. In many countries, power generation is responsible for a significant share of greenhouse gas (GHG) emissions. From the perspective of global warming, there is just one externality, the release of GHG. Relying on Tinbergen (1952), one and only one policy instrument is needed to regulate it. In reality, however, climate policy is intertwined with other areas of policy, among others, security of supply, income distribution, regional development and trade. For decarbonising power generation, the EU Member States rely on a combination of a cap-and-trade scheme and schemes for the promotion of renewable energy sources (RES). The cap-and-trade scheme is union-wide whereas the RES subsidy schemes are national, with the exception of the Swedish-Norwegian tradable green electricity certificate scheme (Klessmann et al., 2014). Publication III analyses the interaction of overlapping climate policy instruments in a dynamic set-up. The dynamic set-up allows us to study time profile of emissions.

1.1 Non-cooperative emission taxes

Publication I deals with environmental federalism, the division of responsibility for environmental regulation between different levels of government. Within environmental federalism, an important question is the efficiency of non-cooperative environmental standards. A well-established result within the literature that assumes perfect competition is that a small country has no incentive to depart from the cooperative choice of environmental standards when there are no pollution spillovers between states. This has formally been shown by Oates and Schwab (1987, 1988). Assuming that trade policy is not banned, this result holds regardless of whether countries are large or small, in the sense of whether an individual country can influence world prices or not. However, if trade policy is banned, the government of a large country may use environmental policy to improve its terms of trade. The government of a small country, has no incentive to depart from the cooperative level of environmental regulation because it cannot influence the terms of trade and because failure to internalise the environmental externality reduces welfare.

By generalising the model presented by Oates and Schwab (1987, 1988), Publication I shows that the result that a small country has no incentive to depart from the cooperative choice of emissions taxes does not hold for pollutants that have regional or global characteristics, as e.g. sulphur dioxide (SO_2) and carbon dioxide (CO_2) have. A distinction is made between two types of regional pollutants, those that affect the level of pollution both in the source state and in neighbouring states and those that affect the level of pollution in neighbouring states only. An example of the former is waste water emissions that flow in the context of the Baltic Sea. An example of the latter is emissions of SO_2 that only affect neighbouring states.

In the absence of cooperation, national governments set the emissions tax equal to marginal social damage to domestic workers. The non-cooperative level of emission taxes is efficient for local pollutants but inefficiently low for regional and global pollutants. The source of the inefficiency is that without coordination, national governments only take into account costs and benefits that accrue to domestic consumers. In effect, the utility from more consumption accrue in full to domestic workers, whereas the disutility from more pollution is borne only partially by domestic consumers. An extreme case are regional pollutants, which affect the level of pollution in neighbouring states only. Without cooperation, the domestic government has no incentive to regulate them. Through cooperation, the pollution externality can be internalised

and the inefficiency eliminated. It follows that activities responsible for regional and global pollutants, such as fossil-fuel fired power generation and the associated release of CO₂ and SO₂, should be regulated at the federal level.

1.2 Time to market in the CDM

The contribution of Publication II is the demonstration of a methodology for analysing the progress and failure of projects in the CDM. Previous attempts at analysing it, among others, Ambrosi and Kossoy (2010), Koakutsu, Okubo, Takahashi, Torii, and Fukui (2011), Platonova-Oquab et al. (2012) and Cormier and Bellassen (2013), are biased because they fail to properly account for right-censored projects. The methodology relies on modelling the hazard of the first issuance of CERs. The hazard is allowed to vary both over time and over duration. Integrated over duration, the hazard of first issuance gives the time to market, which is defined as the duration between the first day of the Global Stakeholder Process (GSP), i.e. the date when the existence of the project becomes public knowledge, and the date of first issuance.

Publication II shows that between GSP start and request for registration 30% of all projects fail, while another 20% fail between request for registration and first issuance. Failure means that the project owner will not be able to recuperate any of the costs attributable to registration under the CDM. For the remaining 50%, the median time to market is 4 years, which does not include the time it takes to prepare the project documentation and the time it takes to negotiate a validation contract with an accredited third party. The considerable time to market created a honey trap for project developers. Initially, the supply of CERs was small and prices were high, which lured increasing number of projects to seek registration under the CDM. The flow of projects gained momentum for years before it became evident that there was not sufficient demand for CERs.

The data shows a great deal of variation in the hazard of first issuance. First, project types associated with a low degree of additionality have a high hazard of first issuance, whereas project types associated with a high degree of additionally have a low hazard of first issuance. It follows that the additional projects are least likely to issue CERs, whereas the non-additional projects are the most likely to issue CERs. Second, other things being equal, projects hosted by China have a very high hazard of first issuance, whereas projects hosted by Least Developed Countries exhibit a very low hazard of first issuance. This provides some explanation of why the number of CERs

awarded to Chinese projects is disproportionately large relative to the number of projects hosted by China. Third, the larger the scale of the project, the larger the hazard of first issuance. The small-scale methodologies contain a number of concessions compared with the large-scale methodologies. Other things being equal, these concessions should reduce the time to market. However, the data shows the opposite. Fourth, between 2008-2009 and 2010-2012, the hazard of first issuance was reduced while the hazard of the submission of a registration request was increased. This shows that the streamlined CDM procedures, requested by the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP) in Copenhagen in December 2009, were a mixed success.

1.3 Overlapping climate policy instruments

Publication III illustrates a paradox in which overlapping climate policy instruments may, in addition to increasing the cost of compliance, have the unintended consequence of accelerating rather than decelerating global warming. The insight follows from a dynamic model. In the model, quota obligation for renewables is introduced alongside a carbon budget. A dynamic model allows to study how the schedule at which the carbon budget is exhausted and released to the atmosphere is affected by a quota obligation. The release schedule determines the global temperature response.

The inefficiency is attributable to a reallocation of emissions, and consequently abatement, under the carbon budget. With a calibration for the EU-28 power generation sector, the quota obligation roughly doubles the costs of complying with the carbon budget. The acceleration of global warming is attributable to a front-loading of the exhaustion of the carbon budget. The introduction of a quota obligation suppresses the carbon price and induces a switch from low carbon intensity fossil fuels to high carbon intensity fossil fuels in generation to supply residual demand. Residual demand is defined as demand met by non-renewables. The fuel switches front-load the release of the carbon budget. A front-loaded release schedule translates into higher levels of cumulative CO₂ and a larger global temperature response. With a calibration for the EU-28 power generation sector, at its largest, the front-loading amounts to 5.5 GtCO₂ in 2035, which is equal to 5-6 years' worth of emissions from electricity generation in EU-28.

The model is set-up in the context of the EU's Winter Package, which reaffirms EU's commitment to a binding target for the share of RES of final energy

consumption by 2030 (European Commission, 2016). The literature that relates to Green Paradox, which was originally suggested by Sinn (2008), has analysed the situation where the first-best instrument is not available. In comparison, in the model of Publication III, the global warming externality is completely internalised by the carbon budget. A cap-and-trade scheme for CO₂ promotes RES in power generation by a pass-through of the carbon price on the the electricity price. It is shown that by suppressing the carbon price, the quota obligation undermines investments dependent on the carbon price. This creates a need for further market intervention in the form of additional support for RES. By promoting coal fired generation at the expense of gas fired generation, the quota obligation may bring forward the closure of gas-fired power stations, many of which currently serve to balance intermittent wind and solar power. This creates a need for further market intervention in the form of payments for reserve capacity.

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Publication I

Roland Magnusson. Efficiency of non-cooperative emission taxes in perfectly competitive markets. *Published in Finnish Economic Papers, 23(2): 88-93, Autumn 2010.*

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Efficiency of non-cooperative emission taxes in perfectly competitive markets

Roland Magnusson

Abstract

With the current efforts to regulate the emissions of greenhouse gases and other cross border pollutants, the question of environmental federalism is as important as ever. By generalising the model presented by Oates and Schwab (1987, 1988), we show that the well established result within environmental federalism, that the government of a small country has no incentive to depart from the cooperative choice of environmental standards, does not hold for pollutants that have regional or global characteristics, as e.g. sulphur dioxide and carbon dioxide has.

JEL Codes: H77, Q58

1 Introduction

With the current efforts to cut the emission of greenhouse gases, the question of environmental federalism - the division of responsibility for environmental regulation between different levels of government - deserves as much attention as ever. Current implementations vary. In the EU, for example, the price of emitting CO₂ has been harmonised for major stationary emitters. However, in other areas of environmental management, there are still large differences within the EU. One of these fields is the level of support to renewable electricity sources. Within this field, cooperation attempts at the EU level have been short-lived due to fierce opposition they have been met by some member states.

Within environmental federalism, an important question is the efficiency of non-cooperative environmental standards. A well established result within the literature is that, in perfectly competitive markets, a small state has no incentive to depart from the cooperative choice of environmental standards as long as pollution generated in one jurisdiction doesn't spill over into another. Two of the first ones to show this formally were Oates and Schwab (1987, 1988). Our objective is to extend their analysis by allowing for regional, e.g. SO₂, and global pollutants, e.g. CO₂. Most previous work, both within the strand that assumes perfect and within the strand that assumes imperfect competition, only consider local pollutants. Cross-border pollutants are, in our opinion, underrepresented. Thus, our aim is to contribute to the strand of literature that deals with them. We acknowledge that our assumption of perfect competition, inherited from Oates and Schwab, is a crude simplification, but we hope that our analysis will serve as a starting point for more elaborate analyses.

The paper is structured as follows. In Section 2, we review the main contributions within the field of environmental federalism. In Section 3, we outline the model and derive equilibrium conditions for the amount of capital employed and emissions generated by each state. In Section 4, we study some of the comparative statics of a unilateral emission tax increase. In Section 5 and 6, we derive the non-cooperative and cooperative choice of emission taxes, respectively. Section 7 concludes.

2 A brief literature review

Since the early papers of the 1970s and 1980s, among others Cumberland (1979, 1981) and Oates and Schwab (1987, 1988), the body of literature within environmental federalism has expanded along a number of different themes. Most importantly, with new insights on how to model imperfect competition, the literature has expanded to include markets where either producers or jurisdictions, or both, can affect prices.

A well established result within the strand that assumes perfect competition between the polluting firms is that a small country has no incentive to depart from the cooperative choice of environmental standards, assuming there are no pollution spillovers between states, see e.g. Rauscher (1994) or Ulph (1997). If trade policy is not banned, this result holds regardless of whether the countries are large or small, i.e. whether they can influence world prices or not. However, if trade policy is banned, the government of a large country may use

environmental policy to improve its terms of trade. The government of a small country, however, has no incentive to depart from the cooperative equilibrium, because by assumption it cannot influence the country's terms of trade, and failure to internalise environmental externalities is welfare reducing.

The results within the strand of literature that assumes less than perfect competition between the polluting firms are less conclusive. Early work within this strand relies on oligopoly models in the tradition of Brander and Krugman (1983) and Brander and Spencer (1985), and assumes that firms are immobile. Relying on the Cournot duopoly presented by Brander and Spencer (1985), Barrett (1994) shows that in the absence of trade policy, governments will bid down each others' environmental standards to shift profits toward domestic producers. However, if firms compete in prices rather than quantities, they will bid up each others' standards. More recent work, originating from Markusen et al. (1995), assumes that firms are mobile. As with immobile firms, the finding of Markusen et al. is that without cooperation, governments will either bid up or down each others' emission taxes. However, the determining factor is not whether firms play Cournot or Stackelberg, but the disutility of pollution. If the disutility of pollution is large enough, the states will increase their emission taxes until the polluting firms are driven out of business.

Subsequent research has made additional simplifications, especially regarding transportation costs while relaxing others, such as the number of countries (Rauscher 1995) and the number of firms (Greaker 2003, Hoel 1997, Ulph & Valentini 2001). With exception of Rauscher, the results are in line with Markusen et al. Of the above mention analyses, Rauscher is the only who allows for pollution spillovers. He reports that the opportunity cost, in terms of environmental damages, of undercutting foreign environmental regulations becomes infinitesimally small if pollution is perfectly global.

Within the non-competitive strand, Pflüger (2001) pursues an alternative strategy, but as most of the previous research, assumes that pollution is strictly local. Relying on the model of monopolistic competition by Dixit and Stiglitz (1977), Pflüger shows that choice of emissions tax by one state imposes a number externalities on the other, both positive and negative. Non-cooperative taxes are lower than cooperative taxes if the importance of emissions in production, relative to labour, is small in comparison to transport costs and the mark-up on average variable costs. However, in contrast with the oligopoly model by Markusen et al. (1995), in Pflüger the disutility of pollution is not among the parameters that separate the non-cooperative choice from the cooperative choice.

3 Model outline

Following Oates and Schwab (1987, 1988), we analyse the choice of emission taxes, τ^i , in an asymmetric general equilibrium model of a federal economy of small states. The states are small in the sense that they cannot influence the rate of return to capital, R , and thus treat it as exogenous. In the spirit of the original model, we assume that capital and goods are perfectly mobile. Labour, in contrast, is perfectly immobile. Thus, the supply of labour is fixed in each state.

Emissions, E^i , are generated as a by-product in the manufacturing of a homogeneous private good. Besides emissions, production requires capital, K^i , and labour, L^i . Following Oates and Schwab, we assume that the good is manufactured by perfectly competitive firms with technologies that may vary across states, but all of which exhibit constant returns to scale with regard to the three inputs.

The property of constant returns to scale and the assumption of a fixed supply of labour allow us to write the production functions in per worker terms, $F^i(K^i, L^i, E^i) = L^i f^i(k^i, e^i)$. By partial derivation of it with respect to K^i , L^i and E^i , we obtain the marginal products of capital, labour, and emissions as

$$F_{K^i}^i(\cdot) = f_{k^i}^i(\cdot), \quad (1)$$

$$F_{L^i}^i(\cdot) = f^i(\cdot) - k^i f_{k^i}^i(\cdot) - e^i f_{e^i}^i(\cdot), \text{ and} \quad (2)$$

$$F_{E^i}^i(\cdot) = f_{e^i}^i(\cdot), \quad (3)$$

respectively, where subscripts denote partial derivatives. We assume that the marginal products of $f^i(k^i, e^i)$ are positive but diminishing, and that $f_{k^i e^i}^i(\cdot) > 0$ and $f_{e^i k^i}^i(\cdot) > 0$, i.e. that capital and emissions are q-complements, using the definition by Seidman (1989).

As price takers, firms will employ capital up to the point where the marginal unit earns just enough to cover its cost. Thus, in equilibrium,

$$f_{k^i}^i(\cdot) = R, \text{ for all states } i, \quad (4)$$

by choosing the private good as the numéraire. As with capital, firms choose a level of emissions which equates the marginal product of emission with the tax rate. Thus, in equilibrium,

$$f_{e^i}^i(\cdot) = \tau^i, \text{ for all states } i, \quad (5)$$

We assume that within each state, workers are identical in both preferences and productive capacity, and that they are paid a wage equal to their marginal product. In addition to wages, workers receive tax income, $e^i \tau^i$, and exogenous income, b^i . For simplicity, we assume that all capital is owned by foreigners. With this simplification, we can write the budget constraint of the representative worker, resident of state i as

$$x^i = f^i(\cdot) - k^i f_{k^i}^i(\cdot) - e^i f_{e^i}^i(\cdot) + e^i \tau^i + b^i \quad (6)$$

where x^i is the consumption of the private good. Consumption of it increases utility $u^i = u^i(x^i, O^i)$, whereas exposure to pollution, O^i , reduces utility. We define the level of pollution as $O^i = O^i(e^1, \dots, e^i, \dots, e^n)$, where the sign of the partial derivatives depend on the type of pollutant. We examine four distinct types of pollutants, shown in Table 1.

Table 1. Types of pollutants.

Type of pollutant	Pollution function characteristics
Local	$O_{e^i}^i(\cdot) > 0$, $O_{e^j}^i(\cdot) = 0 \forall j \neq i$
Regional and partially transboundary	$O_{e^j}^i(\cdot) > 0 \forall i, j$
Regional and perfectly transboundary	$O_{e^i}^i(\cdot) = 0$, $O_{e^j}^i(\cdot) > 0 \exists j \neq i$
Global pollutant	$O_{e^i}^i(\cdot) = O_{e^j}^i(\cdot) > 0 \forall i, j$

We distinguish here between two types of regional pollutants, those that affect the level of pollution both in the source state and in neighbouring states, and those that affect neighbouring states only. An example of the former is wastewater emissions in context of the Baltic Sea. An example of the latter is emissions of SO_2 that only affect neighbouring states.

4 Comparative statics of an unilateral emission tax change

Total differentiation of the equilibrium conditions in Eq. 4 and Eq. 5 with respect to k^i , e^i and τ^i , yields the following system of equations

$$\begin{bmatrix} f_{k^i k^i}^i(\cdot) & f_{k^i e^i}^i(\cdot) \\ f_{e^i k^i}^i(\cdot) & f_{e^i e^i}^i(\cdot) \end{bmatrix} \begin{bmatrix} dk^i \\ de^i \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} d\tau^i. \quad (7)$$

From Cramer's rule, it follows that

$$\frac{dk^i}{d\tau^i} = \frac{-f_{k^i e^i}^i(\cdot)}{A} < 0 \text{ and that} \quad (8)$$

$$\frac{de^i}{d\tau^i} = \frac{-f_{k^i k^i}^i(\cdot)}{A} < 0, \quad (9)$$

because $A = f_{k^i k^i}^i(\cdot) f_{e^i e^i}^i(\cdot) - f_{k^i e^i}^i(\cdot) f_{e^i k^i}^i(\cdot) > 0$, as we show in the Appendix. Thus, increasing the tax rate reduces both the amount of capital employed and the amount emissions generated by a particular state.

5 Non-cooperative choice of emission taxes

Without coordination, national governments maximise the utility of the representative domestic consumer, u^i , subject to budget constraint in Eq. 6 and to the factor demands in Eq. 4 and Eq. 5. The Lagrangian for the non-cooperative maximisation problem can be written as

$$\begin{aligned} \Gamma \equiv & u^i(x^i, O^i) - \lambda[x^i - b^i - e^i \tau^i - f^i(\cdot) + k^i f_{k^i}^i(\cdot) + e^i f_{e^i}^i(\cdot)] \\ & - \gamma[f_{k^i}^i(\cdot) - R] - \eta[f_{e^i}^i(\cdot) - \tau^i] \end{aligned} \quad (10)$$

and the FOCs, with respect to x^i , e^i , k^i and τ^i , respectively, as

$$\lambda = u_{x^i}^i(\cdot), \quad (11)$$

$$\begin{aligned} u_{O^i}^i(\cdot) O_{e^i}^i(\cdot) + \lambda \tau^i - \lambda k^i f_{k^i e^i}^i(\cdot) - \lambda e^i f_{e^i e^i}^i(\cdot) \\ - \gamma f_{k^i e^i}^i(\cdot) - \eta f_{e^i e^i}^i(\cdot) = 0, \end{aligned} \quad (12)$$

$$- \lambda k^i f_{k^i k^i}^i(\cdot) - \lambda e^i f_{e^i k^i}^i(\cdot) - \gamma f_{k^i k^i}^i(\cdot) - \eta f_{e^i k^i}^i(\cdot) = 0, \text{ and} \quad (13)$$

$$\eta = -\lambda e^i. \quad (14)$$

By substituting Eq. 14 into Eq. 13, we obtain $\gamma = -\lambda k^i$. By substituting this and the expressions for the two other Lagrange multipliers into Eq. 12 yield

$$\tau^i = -\frac{u_{O^i}^i(\cdot) O_{e^i}^i(\cdot)}{u_{x^i}^i(\cdot)}. \quad (15)$$

Eq. 15 says that, without cooperation, national governments set a tax equal to marginal social damage to domestic workers. The damage is measured in terms of the willingness to sacrifice consumption in return for a decrease in the level of pollution.

6 Cooperative choice of emission taxes

Through cooperation, the welfare of neighbouring states is taken into consideration when deciding on the level of emission tax. Thus, the constraints are the same as in the non-cooperative case with one addition, the constraint of not reducing welfare abroad below a certain level. Here, this level is given

by \hat{u}^s . The additional constraint captures the effect of decisions in one state on the welfare in other states. With these changes, the Lagrangian for the cooperative maximisation problem can be written as

$$\begin{aligned} \Lambda \equiv & u^i(x^i, O^i) - \lambda[x^i - b^i - e^i\tau^i - f^i(\cdot) + k^i f_{k^i}^i(\cdot) + e^i f_{e^i}^i(\cdot)] \\ & - \gamma[f_{k^i}^i(\cdot) - R] - \eta[f_{e^i}^i(\cdot) - \tau^i] - \sum_{\substack{s=1 \\ s \neq i}}^n \xi^s [\hat{u}^s - u^s(x^s, O^s)] \end{aligned} \quad (16)$$

Since $\xi^s = -\partial\Lambda/\partial\hat{u}^s$, we can interpret ξ^s as the shadow prices, measured in units of u^i , that domestic consumers must pay to increase utility abroad. $\partial\Lambda/\partial\hat{u}^s \leq 0$ because the only way for domestic consumers to improve welfare abroad is by reducing emissions. Assuming that the domestic level of emissions is optimal, reducing them further cannot be welfare improving. It follows that $\xi^s \geq 0$.

The FOCs, with respect to x^i , e^i , k^i and τ^i , respectively, can be written as

$$\lambda = u_{x^i}^i(\cdot), \quad (17)$$

$$\begin{aligned} & u_{O^i}^i(\cdot)O_{e^i}^i(\cdot) + \lambda\tau^i - \lambda k^i f_{k^i e^i}^i(\cdot) - \lambda e^i f_{e^i e^i}^i(\cdot) \\ & - \gamma f_{k^i e^i}^i(\cdot) - \eta f_{e^i e^i}^i(\cdot) + \sum_{\substack{s=1 \\ s \neq i}}^n \xi^s u_{O^s}^s(x^s, O^s)O_{e^i}^s(\cdot) = 0, \end{aligned} \quad (18)$$

$$- \lambda k^i f_{k^i k^i}^i(\cdot) - \lambda e^i f_{e^i k^i}^i(\cdot) - \gamma f_{k^i k^i}^i(\cdot) - \eta f_{e^i k^i}^i(\cdot) = 0, \text{ and} \quad (19)$$

$$\eta = -\lambda e^i. \quad (20)$$

By performing the same substitutions as in the non-cooperative case, we obtain

$$\tau^i = -\frac{u_{O^i}^i(\cdot)O_{e^i}^i(\cdot)}{u_{x^i}^i(\cdot)} - \frac{\sum_{\substack{s=1 \\ s \neq i}}^n \xi^s u_{O^s}^s(x^s, O^s)O_{e^i}^s(\cdot)}{u_{x^i}^i(\cdot)} \quad (21)$$

The difference between the cooperative and non-cooperative tax level, Eq. 21 and Eq. 15, respectively, is

$$-\frac{\sum_{\substack{s=1 \\ s \neq i}}^n \xi^s u_{O^s}^s(x^s, O^s)O_{e^i}^s(\cdot)}{u_{x^i}^i(\cdot)}, \quad (22)$$

which represents the negative trans-state externality in our model, i.e. the effect of domestic emission on the level of pollution, and welfare, abroad. For regional and global pollutants, the term is larger than zero, because there is a state abroad for which $O_{e^i}^s(\cdot) > 0$. It follows, that for regional and global pollutants, the non-cooperative level of emission taxes is inefficiently low. For local pollutants, the term is zero, because $O_{e^i}^s(\cdot) = 0$ for all states s abroad. It

follows, that for local pollutants, the non-cooperative level of emission taxes is efficient.

Regional pollutants that are perfectly trans-boundary, e.g. emission of SO₂ that only affect neighbouring states, illustrates nicely the lack of incentives. The domestic government has no incentive to regulate them since the damage is borne entirely by neighbouring states. Thus, the domestic government chooses a zero tax rate. Obviously, this is inefficient.

7 Discussion and policy implications

The inefficiency arises because national governments, by assumption, care only for costs and benefits that accrue to domestic consumers; the utility from more consumption accrue in full to domestic workers, whereas the disutility from more pollution is borne only partially by domestic consumers. The only way to internalise the pollution externality, and remove the inefficiency, is by cooperation. Thus, our recommendation is that that the regulation of regional and global pollutants, or the activities that cause them, such as the use of fossil fuels in electricity generation and the associated generation of CO₂ and SO₂, should be coordinated at the federal level.

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Appendix

The per-worker profit of a firm producing in state i is given by $f^i(k^i, e^i) - Rk^i - \tau^i e^i$. The FOCs of the firm's problem are $f_{k^i}^i(\cdot) - R = 0$ and $f_{e^i}^i(\cdot) - \tau^i = 0$. The SOC is that the Hessian,

$$H = \begin{bmatrix} f_{k^i k^i}^i(\cdot) & f_{k^i e^i}^i(\cdot) \\ f_{e^i k^i}^i(\cdot) & f_{e^i e^i}^i(\cdot) \end{bmatrix} \quad (23)$$

is negative definite. For negative definiteness, the leading principal minors must alternate in sign, with the first leading principal minor being negative, i.e. $f_{k^i k^i}^i(\cdot) < 0$ and $f_{k^i k^i}^i(\cdot)f_{e^i e^i}^i(\cdot) - f_{k^i e^i}^i(\cdot)f_{e^i k^i}^i(\cdot) > 0$.

Publication II

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Time to market in the CDM: variation over project characteristics and time

Roland Magnusson

Abstract

Not only is the carbon market inundated with Certified Emissions Reductions (CERs) issued by successful projects, it is also littered with failed projects, that is, projects that either fail to be registered under the Clean Development Mechanism (CDM) or projects that have been successfully registered but fail to issue CERs. By relying on a novel application of survival analysis in the context of the CDM, this article shows that half of all projects that start the Global Stakeholder Process fail to issue CERs, while the other half have a median time to market of four years. Furthermore, it is shown that some of the best projects, in terms of being additional, are those that are least likely to make it to market, whereas some of the worst projects, in terms of not being additional, are the ones that are most likely to make it to market. This presents a fundamental challenge for the CDM and future offset schemes that rely on the same design as the CDM. In contrast with previous studies, it is shown that, when project characteristics are controlled for, not all durations measured along the CDM project cycle have increased over time.

Policy relevance: *This article develops a novel method for analysing durations measured along the CDM project cycle that avoids the biases of previous studies, and corrects for some misconceptions of what the delays faced by CDM projects are and how these delays have changed over time. Developing an understanding of the delays is important in order not to draw the wrong lessons from the CDM experience. As the leading example of an offset scheme, both in terms of geographical scope and sectoral coverage, and some would say institu-*

tional complexity, the CDM serves as a benchmark and reference for all future offset schemes, among others, for the New Market Mechanisms (NMMs) and the Chinese domestic offset programme. While the NMMs are still very much in development, China has announced that it will rely on the methodologies and procedures developed under the CDM for generating offsets for their regional carbon trading schemes.

Keywords: *Clean Development Mechanism (CDM), climate change, emissions trading schemes, Kyoto Protocol, policy instruments, UNFCCC*

1 Introduction

The Clean Development Mechanism (CDM) is one of three flexibility mechanisms under the Kyoto Protocol. Through the CDM, Annex I Parties can meet part of their obligations under the Kyoto Protocol by reducing emissions in non-Annex I Parties, where the cost of reducing emissions is presumably lower than in the Annex I countries.¹ The CDM has two objectives, to lower compliance costs for Annex I countries and to assist non-Annex I countries in achieving sustainable development (UNFCCC, 1998, p. 11).²

By the end of 2012, 190 states had ratified the Kyoto Protocol (one, Canada, had withdrawn from it). Of these, 38 states were classified as Annex I Parties and the rest as non-Annex I Parties. Of the 152 non-Annex I Parties, 105 states were host to a CDM project (UNEP Risø, 2013). By the same time, a total of 12,000 projects had applied for registration under the CDM, 5500 projects had been registered, and 2000 projects had issued a total of 1.2 billion Certified Emissions Reductions (CERs) (UNEP Risø, 2013).³

The CERs represent the reduction in GHG emissions achieved by the CDM projects. Annex I Parties can use CERs to meet part of their obligations under the Kyoto Protocol. Equivalently, companies within the EU can use CERs to meet part of their obligations under the EU Emissions Trading Scheme (EU ETS).

Between 2005 and 2012, the potential supply of CERs grew exponentially,

¹Annex I Parties are industrialized countries with binding targets under the Kyoto Protocol. Non-Annex I Parties are developing countries with no binding targets under the Kyoto Protocol (UNFCCC, 1998).

²Although not an explicit objective of the CDM, it is often argued that one way in which the CDM can contribute to sustainable development is through technology transfer (see e.g. Haites et al., 2006).

³Each CER corresponds to the reduction of one tonne CO₂ equivalent.

while demand, especially from companies within the EU ETS, declined as many of the companies gradually exhausted their quota for the use of CERs.⁴ In the face of decreasing demand and uncertainty about the continuation of the Kyoto Protocol beyond 2012, the price of CERs was close to zero at the end of 2012. At the eighth session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP 8) in December 2012 in Doha, the Parties to the Kyoto Protocol agreed on an amendment to the Protocol that establishes a second commitment period, running from 2013 to 2020. However, by the end of November 2013, only four Parties had ratified it, which casts some doubt over whether the amendment will ever become legally binding. Even if it does, it is not clear whether the pledges contained in it are ambitious enough to spur new demand for CERs.

Research about the CDM is nonetheless warranted, because the CDM is the leading example of an offset scheme, both in terms of geographical scope and sectoral coverage, and some would say institutional complexity. As such, it will serve as a benchmark and reference for all future offset schemes, among others, for the domestic offset scheme currently emerging in China.⁵ Research about the CDM is also warranted because of the CDM's potential role of acting as a bridge to a legally binding climate agreement, expected in 2020. With additional demand, the CDM could help to sustain momentum during negotiations for the agreement.

The CDM relies on the principle of baseline-and-credit. A central design element of a baseline-and-credit scheme is that the credits are issued *ex post* based on monitored emission reductions. As such, it is very different from a cap-and-trade scheme, such as the EU ETS. Compared with cap-and-trade schemes, baseline-and-credit schemes have the added complexity of establishing the baseline. The baseline is the counterfactual, i.e. the emissions in the absence of the additional revenue brought by the CDM.⁶ Any emission reductions below this baseline are said to be additional. To evaluate additionality, the CDM makes use of third-party audits, once when a project applies

⁴Actual supply is lower than potential supply because many CDM projects have extended their monitoring periods, and thus postponed issuance, in the hope of higher CERs prices in the future.

⁵In China, to reduce the cost of compliance, companies covered by the regional carbon-trading schemes are expected to be allowed to offset between 5 per cent and 8 per cent of their emissions with Chinese-issued carbon credits from emission reduction projects located in China (Chen, 2012).

⁶For grid-connected wind power, the baseline is the CO₂ emissions of the fossil fuel-based power generation that the wind power displaces (CDM EB, 2009, p. 8). If the wind power plants would have been built in any case, there is no displacement, the baseline is zero, and there is no reduction in emissions.

for registration under the CDM, and then every time a project applies for issuance of CERs. The CDM shares many common features with other offset schemes, among others, the Climate Action Reserve in the US and the Carbon Farming Initiative in Australia. The common features include, among others, methodologies for establishing the baseline and the use of third-party audits.

The third-party audits are carried out by independent entities, typically private firms, known as Designated Operational Entities (DOEs). The DOEs are contracted and paid by the project developers. The DOEs are accredited by the CDM Executive Board (EB), the main governing body of the CDM. The CDM EB operates under the guidance of the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol (CMP). Thus, in terms of governance, the CDM relies on a mix of private and public agents.

Over the years, the CDM has been criticized on many accounts. Two major subjects for criticism are the lack of additionality and transaction cost. The two are closely related, because assessing additionality incurs transaction costs, both in terms of monetary costs and non-monetary costs such as time. Without additionality, the CDM is merely a mechanism for income transfer from Annex I to non-Annex I countries (Burniaux, Chateau, Dellink, Duval, & Jamet, 2009). The question of additionality has been addressed by (among others) Michaelowa and Purohit (2007) and Schneider (2009), and more recently by Zhang and Wang (2011). All of them find some evidence of a lack of additionality, but the conclusiveness varies, which is not surprising given that assessing additionality is notoriously difficult, as already noted by Grubb, Vrolijk, Brack, and Forsyth (1999).

The question of monetary costs has been addressed by a number of sources. Among the first were Michaelowa, Stronzik, Eckermann, and Hunt (2003) and Michaelowa and Jotzo (2005).⁷ More recent research includes a technical report by the World Bank (2010).⁸ In contrast, the question of the delays caused by the approval processes and the more general question of how long it takes to bring CDM projects to the market has attracted very little research.

⁷Michaelowa et al. (2003) expresses the concern that small projects, in terms of their emission reduction potential, are at a disadvantage relative to large projects because many of the direct costs are independent of project size.

⁸In the World Bank carbon funds, the costs associated with preparation of a project amount to an average of \$200,000 per project. This cost includes the cost of due diligence to ensure compliance with the World Bank social and environmental safeguard, but excludes the cost of validation and periodic verifications. The World Bank experience shows an average validation cost of \$28,000 and an average verification cost of \$20,000, with little distinction between small- and large-scale projects. This is because prices for validation and verification are typically not based on the size of the project but on its complexity (World Bank, 2010).

The purpose of this article is to fill this gap.

There are three technical reports published by the World Bank and the Institute for Global Environmental Studies (IGES) (Ambrosi & Kossoy, 2010; Koakutsu, Okubo, Takahashi, Torii, & Fukui, 2011; Platonova-Oquab et al., 2012) that analyse the delays in bringing CERs to the market. However, because the three reports look at slightly different durations along the CDM project cycle they are not directly comparable.

The common finding of all three reports is that the durations have increased over time.⁹ Whether this is true or not is impossible to say, because all three reports suffer from the same sample selection bias. The bias arises as a result of how the sample that is taken to represent a certain year is chosen. The sample for a given year only includes those durations that are known to have ended during that year. As a result, projects with a short duration are systematically selected to represent early years, whereas projects with exceptionally long durations are systematically selected to represent later years. Given this systematic bias, it is no surprise that all three reports find that durations have increased over time.¹⁰

In addition, there is one very recent piece of research by Cormier and Bellassen (2013) that analyses the relative sizes of different risks that affect CER creation. The shortcoming of the analysis by Cormier and Bellassen is that it relies on an ambiguous approach to identifying the projects that are "bogged down", i.e. failed. Their analysis is likely to underestimate the durations because it incorrectly classifies projects with exceptionally long durations as failed.¹¹

⁹Ambrosi & Kossoy (2010, p. 42) report that, between 2005 and 2009, the time needed for the average project to move from GSP start to registration increased from 200 days to 600 days, and during the same period, the time needed for the average project to move from registration to first issuance increased from 100 days to 600 days. Koakutsu et al. (2011, p. 11) report that, between Q1 2006 and Q2 2011, the average number of days from registration to first issuance increased from 150 days to 870 days. Platonova-Oquab et al. (2012, p. 7) report that, between H1 2005 and H2 2011, the average time required for a project to move from GSP start to the submission of a request for registration increased from 270 days to 520 days.

¹⁰For example, for the time to market, the sample taken to represent year 2007 would include projects that began the GSP in the years 2004-2007, while the sample taken to represent the year 2012 would include projects that began the GSP in years 2005-2011, i.e. from a much larger range.

¹¹Cormier and Bellassen (2013) regress the projects' characteristics on validation duration. Only the successfully validated projects are included in the regression. Based on the regression results they estimate the expected validation duration of each project. Projects that have been in validation for longer than the expected duration plus twice the standard deviation of the residuals of the regression are classified as "bogged down", i.e. failed. The same is done for issuance.

This article will answer two questions. First, what is the distribution of the time to market across all projects that started the Global Stakeholder Process (GSP) in the period 2003-2012? Here, the time to market is defined as the duration between GSP start and first issuance. Second, how does the time to market depend on host country, the technology on which a project relies, the scale of the project, and time? While the second question is actually the determinant of the first, answering the first question in isolation from the second is warranted because no unbiased estimate of the distribution of the time to market has been presented, or indeed of any other duration measured along the CDM project cycle. Answering the first question in isolation from the second is also warranted because the answer to the second question is subject to the omitted variable bias, whereas the answer to the first question is not.

The answer to the second question is subject to omitted variable bias because not all of the variables that affect the time to market are included in the regression model on which the answer relies. If some of the omitted variables, e.g. the (unknown) efforts of some members of the CDM EB to promote certain project types, are correlated with variables included in the regression, then the effects of the included variables will be either over- or underestimated to compensate for the missing variables. When identifying causal effects, the omitted variable bias is a concern. When predicting how, for example, hydrofluorocarbons (HFCs) projects fare compared to hydro-power projects, the omitted variable bias is less of a concern.

Analysing how the time to market depends on host country is interesting because it shows how well different non-Annex I countries have managed to capitalize on the CDM projects they host. Analysing how the time to market depends on the expected emissions reductions of a project is interesting, because it may tell something about the small-scale methodologies. The small-scale methodologies were created to reduce transaction costs for projects below a certain threshold.¹² Analysing how the time to market depends on time is interesting because of the finding by the technical reports cited above that durations along the CDM project cycle have increased over time. The dependence on the time to market may also reveal something about the success of the streamlined CDM procedures, as required by CMP 5 in December 2009.

To answer these questions this article relies on survival analysis, which has

¹²With respect to DOE costs, the small-scale methodologies have not been very successful, based on the World Bank experience, which shows little difference between small-scale and large-scale projects (World Bank, 2010).

its origin in clinical studies. The study of the duration between GSP start and first issuance has remarkable similarities with the study of the duration between the onset of a cancer and death, for example. Cancer patients have different characteristics, as do CDM projects. Cases of cancer occur at different times, as do GSP starts. At any given point in time, some cancer patients will be right-censored, in the sense that death has not yet occurred. Analogously, at any given point in time, some CDM projects will be right-censored, in the sense that first issuance has not yet occurred. Cancer patients undergo different treatments that may or may not affect the hazard of death, as do CDM projects, in terms of changes to CDM procedures. The changes in the CDM procedures may, or may not, move a project closer to first issuance.

The one difference is that, whereas the duration between the onset of cancer and death is always finite, because death is inevitable, the time between GSP start and first issuance may be infinite. The duration between GSP start and first issuance is infinite if a project will never issue any CERs.

Modelling the time to market as such is not technically feasible because of censoring. The issue is how to deal with the right-censored project for which the time to market is not yet known. The solution is to model the hazard of first issuance, which is a function of duration, measured in days from GSP start. Integrated over duration, the hazard of first issuance gives the time to market. The hazard of first issuance is defined as the instantaneous probability that a CDM project issues the first CERs conditional on the fact that the project has not issued any CERs before.

Compared with previous studies, the advantage of modelling the hazard of first issuance is that there is no need to resort to sampling, as in the technical reports published by the World Bank and IGES cited above. Nor is there a need to explicitly identify the projects that are "bogged down" either at validation or at issuance as in Cormier and Bellassen (2013).

The rest of this article is structured as follows. Section 2 presents the background. Section 3 presents the analysis. Section 4 presents and discusses the results. Section 5 concludes.

2 Background

This section is divided into four subsections. The first presents the CDM project cycle. The second shows how the price of CERs has changed over time. The third discusses how the procedures and rules that govern the CDM have changed over time. The fourth describes the data.

2.1 CDM project cycle

The CDM project cycle is defined as the sequence of events that leads to the issuance of CERs, as shown in Figure 1. Within this sequence of events, the main duration that is studied is the time to market, which is defined as the duration between GSP start and first issuance.¹³ For comparison, outside the main narrative, the analysis looks at the duration between GSP start and request for registration.¹⁴

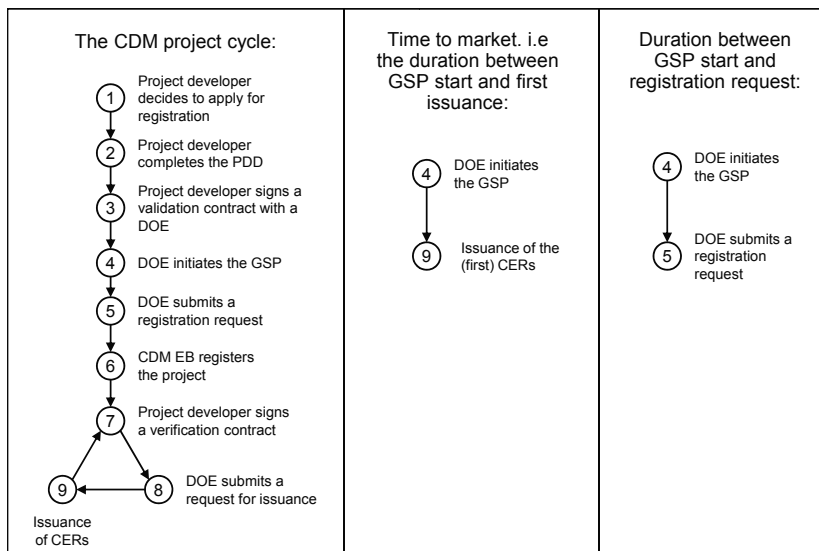


Figure 1. The CDM project cycle in terms of the events that lead to first issuance.

Table 1 shows the main agents involved in the CDM. The project developer initiates the project cycle by taking the decision to apply for registration (Event 1, Figure 1).¹⁵ Once the decision has been taken, the project developer must complete the project documentation using a standard format known as the Project Design Document (PDD) (Event 2). The PDD describes how the project meets the requirements of the CDM (CPD, 2012, p. 15).

¹³Because the time to market is measured from the start of the GSP, it excludes the time it takes to prepare the project documentation and the time it takes to negotiate and sign a validation contract with a DOE.

¹⁴Studying the duration between GSP start and registration would be more interesting than studying the duration between GSP start and registration request. However, due to a CDM rule change that allows backdating, registration dates for projects that submitted a request for registration before 11 December 2010 are not comparable with the registration dates of projects that did it on, or after, 11 December 2010 (CDM EB, 2011, p. 9).

¹⁵The project developer is typically a consultancy acting on behalf of the project owner.

Table 1. Main agents involved in the CDM

Agent	Composition	Role
CMP	Assembly of the parties to the Kyoto Protocol	Guidance of the CDM EB
CDM EB	10 members and 10 alternative members from Parties to the Kyoto Protocol	Issuance of CERs, registration of projects, approval of methodologies, accreditation of DOEs
UNFCCC Secretariat	UN professional staff	Supports to the CDM EB
DOEs	Private third-party auditors accredited by the CDM EB	Validation and verification
DNAs	Designated National Authorities of Parties to the Kyoto Protocol	The DNA of the host country issues a Letter of Approval (LoA)
Project developers	Private and public entities	Developing projects that qualify under the CDM

Notes: CMP, Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol; CDM EB, CDM Executive Board.

Source: Streck (2007) and CDM Policy Dialogue (CPD) (2012).

The CDM requires a third-party assessment of the project by a Designated Operational Entity (DOE). The assessment is done twice, first when the project applies for registration and second when the project applies for CERs. The first assessment is known as the validation and the second as the verification. The project developer chooses and signs a validation contract with a DOE (Event 3) (CPD, 2012, p. 16).

Once the validation contract is signed, the DOE initiates the GSP by making the PDD publicly available on the United Nations Framework Convention on Climate Change (UNFCCC) CDM website for a period of 30 days (Event 4) (CPD, 2012, p. 16). During this time parties affected by the proposed project activity may leave comments on it. The GSP start marks the time when the existence of the project becomes public knowledge. Consequently, the GSP start also marks the date when the project is recorded in the CDM project databases maintained by the United Nations Environment Programme (UNEP) Risø Centre and the IGES.¹⁶

If the DOE finds, as a result of the validation, that the project is in compliance with the requirements of the CDM, it submits a request for registration to the CDM EB (Event 5). If three members of the CDM EB request a review,

¹⁶Durations that begin before the GSP start cannot be studied because of this.

registration will be delayed and the project might be rejected. If no review is requested, the project is registered by the CDM EB (Event 6) (CPD, 2012, p. 17).

Once registered, the project is eligible for CER. The CERs are issued ex-post, based on monitored emissions reductions. The CDM rules require that the authenticity of the emission reduction is verified by a DOE (CPD, 2012, pp. 18-19). The process of verification is very similar to the process of validation. The project developer chooses and signs a verification contract with a DOE (Event 7). The DOE submits a request for issuance to the CDM EB (Event 8), and if no review is requested the CDM EB issues the CERs (Event 9) (CPD, 2012, pp. 21-24).

2.2 The price of CERs

CERs are traded both in spot and forward markets. Figure 2 shows the average monthly price of a front future contract with delivery in December. It shows that between January 2009 and July 2011, the price was relatively stable. After July 2011, the price gradually decreased to close to zero. The commonly held belief is that the price has dropped because of oversupply of credits from the CDM and the mechanism for Joint Implementation, CDM's sister scheme (see e.g. Jones, Brevik, & Melum, 2012).

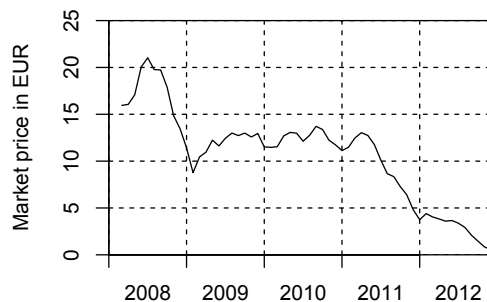


Figure 2. Average monthly price of a front future CER contract with delivery in December. *Source:* ICE Data, <http://data.theice.com> (with permission of ICE Data).

2.3 CDM procedures and rules

To facilitate analyses of how the hazard of first issuance has changed over time, time must be split into periods. The periods must be sufficiently long for the estimation to be reliable. Time is split into the following periods: Jan01-Dec07, Jan08-Dec09, and Jan10-Dec12. The split is very similar to that suggested by the World Bank (Platonova-Oquab et al., 2012).

Although the split is somewhat arbitrary, it serves the purpose of showing what the time to market was in the period that followed the CMP 5 in December 2009 in Copenhagen, compared with the period that preceded it. Jan08-Dec09 is chosen as the baseline, against which the hazard of first issuance in Jan10-Dec12 is compared. The period Jan01-Dec07 is excluded from the baseline because, before 2008, the regulation was driven by the need to kickstart the mechanism.

Between 2001 and 2007, regulation was driven by the need to improve market liquidity for CERs by pushing projects through the project cycle as fast as possible (Gillenwater & Seres, 2011, p. 189; Platonova-Oquab et al., p. 2). One of the policies aimed at increasing market liquidity was that of allowing projects to claim CERs retroactively, before the date of registration (Michaelowa et al., 2007, p. 11).¹⁷

In 2008, the focus of regulation was shifted towards increased scrutiny (Platonova-Oquab et al., p. 2). This shift was, at least partially, driven by concerns about the integrity of the mechanism expressed by, among others, Michaelowa and Purohit (2007) and Schneider (2009). The main concern was the lack of additionality.

In 2010, in response to a request from CMP 5, the CDM EB initiated a series of reforms to streamline and speed up the CDM procedures.¹⁸ One of the main drivers of these reforms was the widespread discontent among project developers over the delays in registration and issuance (see e.g. IETA, 2009). Studying the effect of these reforms is interesting, because in their 2010 annual report to the CMP, the CDM EB (2010, p. 6) says that the "main achievement during the reporting period was the streamlining of procedures". The International Emissions Trading Organisation (IETA, 2010) also took note of these reforms in their 2010 report, but noted that the reforms have not been in place long enough for the organization to make a judgement on them.

The hypothesis is, all other things being equal, that the streamlined procedures increased the hazard of first issuance as well as the hazard of request for registration, and thus reduced the duration of the CDM project cycle.

¹⁷This rule applied to projects that had started operation before 18 November 2004 and that had submitted a request for registration by 31 March 2007. Later projects may not claim CERs before the date of registration (COP, 2002, p. 2).

¹⁸One of the streamlined procedures is the two-tiered assessment of a request for registration, which replaced the earlier rule, according to which each request for registration had to pass through three independent checks, by the UNFCCC Secretariat, the Registration and Issuance Team, and the CDM EB. The new procedure was introduced in February 2010 at the 54th meeting of the CDM EB (CPD, 2012, p. 16).

2.4 The data

Due to the public nature of the CDM there is very good information available on every CDM project. The information is managed and made public by the UNFCCC. The UNEP Risø Centre and IGES both maintain readily accessible databases of this information (IGES, 2013; UNEP Risø, 2013).¹⁹ Each time a project starts the GSP, a new record of it is added to both databases. This article relies on the UNEP Risø database (with permission of UNEP Risø Centre), updated on 1 January 2013, because identifying and removing duplicates while preserving the date of the first GSP start is easier in the UNEP Risø data than in the IGES data.²⁰

The following information from the UNEP Risø database is utilized: host country, project type, whether a project relies on a small-scale methodology or not, expected yearly emission reduction in kilotonnes of carbon dioxide equivalent (ktCO₂e), issuance success²¹, date of first GSP start, date of request for registration, and date of first issuance.

Categories of host countries and project types below a certain threshold are merged. This threshold is set at either 10 or 25 projects that have issued CERs.²² The scale of the project is defined as the PDD estimate of the expected yearly emissions reduction adjusted with past issuance success of similar projects. Given the systematic tendency of some project types to under-deliver, the PDD estimate is adjusted with the average issuance success of projects of the same type. Nonetheless, the scale contains uncertainty. Actual issuance may be different.

¹⁹In addition to a range of static information, the UNEP Risø database records the dates of the following registration-related events: date of first GSP start, resubmission date, date of host LoA, date of registration request, start date of the request review period (if any), and date of registration. In addition, it records the following issuance-related events: date of crediting period start, date of first issuance, and end of most recent monitoring period.

²⁰The same project may need to complete the GSP more than once, e.g. because of material changes to the PDD after the first GSP has been completed. In this case, the DOE may require that the GSP is repeated, so that anyone who feels affected by the project may leave comments on the revised PDD. The time to market is measured from the start of the first GSP. Thus, in analysing the time to market, subsequent GSP starts are of no interest. Completing the GSP more than once is likely to add delay, which will show up in the time to market, which is measured from the start of the first GSP.

²¹Issuance success is defined as "CERs issued divided by the number of CERs expected in the PDD for the same period".

²²The threshold is defined in terms of projects that have issued CERs and not in terms of projects that have started the GSP because it is the number of projects that have issued CERs that determines the reliability of the estimation.

The following categorization is used for scale: less than 50 ktCO₂e per year, between 50 and 500 ktCO₂e per year, and above 500 ktCO₂e per year. Given that the categorization is somewhat arbitrary, two alternative definitions for scale are explored: one in which scale enters the regression as a continuous variable and another where scale is either small or large depending on whether the project relies on a small-scale or a large-scale methodology.

Table 2 presents some descriptive statistics. It shows the number of projects per category of host country, category of project type, and category of project scale. For each category it shows the number of projects that have started the GSP, the number of projects that have requested registration, and the number of projects that have issued CERs. For curiosity, the last column shows the number of CERs issued for each category by the end of December 2012. The table shows that China is the largest host country, followed by India. It also shows that China has been issued a disproportionately large number of CERs, disproportionate, that is, with respect to the number of projects to which China is host.

Table 2. Descriptive statistics per category of host country, project type, and scale of project, with threshold for merging categories set at 10 projects that have issued CERs.

Variable	Category	Number of projects that have			10 ⁶ CERs issued by end of 2012
		Started the GSP	Req. registration	Issued CERs	
Host	Host countries < 10 iss	787	357	78	31.8
	LDCs	123	56	10	0.3
	Argentina	68	35	13	9.4
	Brazil	628	290	134	78.3
	Chile	143	76	27	11.0
	China	4593	3297	1054	703.2
	Colombia	109	47	15	3.7
	Ecuador	49	21	11	1.4
	Honduras	45	27	11	0.8
	India	2795	1186	402	162.4
	Indonesia	214	114	27	7.5
	Israel	50	32	11	2.6
	Malaysia	223	138	29	4.1
	Mexico	295	172	55	18.4
	Peru	73	49	12	2.2
	South Africa	94	33	10	5.2
	South Korea	128	93	31	102.1

continued

Table 2. (continued)

Variable	Category	Number of projects that have			10 ⁶ CERs issued by end of 2012
		Started the GSP	Req. registration	Issued CERs	
	Thailand	220	97	22	2.0
	Vietnam	285	219	31	7.6
Type	Project types < 10 iss	432	192	37	14.9
	Biomass energy	1266	565	198	29.6
	Cement	92	32	12	2.7
	Coal bed/mine methane	139	73	29	17.8
	EE industry	276	93	33	2.1
	EE own generation	720	315	124	51.3
	EE supply side	172	46	12	2.0
	Fossil fuel switch	221	93	49	40.2
	Fugitive	87	29	10	16.7
	HFCs	24	23	19	472.3
	Hydro	2683	1774	613	122.7
	Landfill gas	511	311	104	33.2
	Methane avoidance	980	538	158	13.4
	N2O	112	96	50	236.7
	Solar	401	211	12	0.2
	Wind	2806	1948	523	98.4
Scale	< 50 ktCO ₂ e per yr	6130	3239	944	68.5
	50-500 ktCO ₂ e per yr	4465	2926	932	266.4
	> 500 ktCO ₂ e per yr	327	174	107	819.3

Table 3 shows a breakdown of project type for the five largest host countries. It shows that the most common project type in China is hydro. It also shows some interesting differences between China and India, including that biomass projects are much more common in India, both in relative as well as absolute terms.

Table 3. Breakdown of project type per host country for the five largest host countries, with threshold for merging categories set at 10 projects that have issued CERs.

Project type	Number of projects that have started the GSP				
	China	India	Brazil	Mexico	Vietnam
Project types with < 10 iss	59	151	26	7	3
Biomass energy	191	569	153	18	18
Cement	45	27	3	2	0

continued

Table 3. (continued)

Project type	Number of projects that have started the GSP				
	China	India	Brazil	Mexico	Vietnam
Coal bed/mine methane	131	3	0	1	0
EE industry	19	186	6	10	2
EE own generation	423	211	13	2	5
EE supply side	37	68	4	2	0
Fossil fuel switch	44	78	16	1	0
Fugitive	4	16	7	2	1
HFCs	11	9	0	2	0
Hydro	1603	286	147	14	216
Landfill gas	134	47	71	37	7
Methane avoidance	115	79	93	158	28
N ₂ O	50	9	5	3	0
Solar	160	136	1	0	0
Wind	1567	920	83	36	5
SUM	4593	2795	628	295	285

3 The analysis

This section is divided into four subsections. The first presents the concepts, the second discusses model choice, the third shows the analysis, which relies on the Kaplan-Meier (KM) estimator, and the fourth shows the analysis, which relies on the Cox Proportional Hazard (CPH) model.

3.1 Concepts

The starting point for analysing the time to market is the hazard of first issuance $h(d)$, and the decision of how to model it. $h(d)$ is the instantaneous probability that a CDM project issues the first CERs conditional on the fact that the project has not issued any CERs before. $h(d)$ is a function of duration days d from the start of the GSP.

Because $h(d)$ shows the instantaneous probability it is not very informative. A more informative measure is the survival function, $S(d)$, which gives the probability that a project has not issued any CERs as a function of duration

d .²³ As shown in Cameron and Trivedi (2005), p. 577), $S(d)$ is obtained by integrating $h(d)$ over duration,

$$S(d) = \exp\left(-\int_0^d h(u)du\right), \quad (1)$$

where $h(d)$ is recovered by differentiating $S(d)$ with respect to duration d ,

$$h(d) = \frac{d \ln S(d)}{dd}. \quad (2)$$

3.2 Model choice

The analysis relies on two estimators, the KM estimator and the CPH model. The KM estimator is used to answer the first question presented in Section 1, while the CPH model is used to answer the second. Both the KM estimator and the CPH model are chosen because of their generality. They are possibly the least restrictive models in their respective classes of nonparametric and parametric models for censored survival data. The disadvantage of the KM estimator is that it cannot accommodate covariates, hence the need for a second model, the CPH model, which can.

Although the KM estimator cannot accommodate covariates, what can be done using it (as in Appendix A) is to split the population of projects into subpopulations and estimate the probability distribution of the time to market separately for each. The disadvantage of this approach is that the probability distribution of small subpopulations cannot be estimated reliably, which makes comparisons of any but the largest subpopulations meaningless.

In terms of generality, the difference between the KM estimator and the CPH model is that the KM estimator makes no assumption of the functional form of hazard $h(d)$, while the CPH model assumes that the hazard, conditional on covariates \mathbf{x} , can be factored into two separate functions,

$$h(d|\mathbf{x}) = h_0(d)\phi(\mathbf{x}, \boldsymbol{\beta}) \quad (3)$$

where $h_0(d)$, which depends on d alone, can take any form, and $\phi(\mathbf{x}, \boldsymbol{\beta})$, which depends on \mathbf{x} alone, is assumed to take a parametric form. $h_0(d)$ is known as the baseline hazard. Usually, $\phi(\mathbf{x}, \boldsymbol{\beta}) = \exp(\mathbf{x}^T \boldsymbol{\beta})$, which is followed here (Cameron & Trivedi, 2005, p. 591).

The great advantage of this formulation is that the baseline hazard $h_0(d)$ can take any form. An alternative formulation would assume a specific functional

²³The term *survival* originates from clinical studies and refers to the state of the patient being alive, from which the exit is marked by the event of death. Here, *survival* refers to the state of non-issuance, from which the exit is marked by the event of first issuance.

form for $h_0(d)$, which would obviously be much more restrictive. The limitation imposed by this formulation is that the regression coefficients β must be constant over duration d . This is known as the proportionality assumption. It says that the hazard of one project must be proportional to the hazard of any other project.

A very convenient consequence of the proportionality assumption is that the ratio of two hazards, known as the hazard ratio, is constant over duration because the baseline hazards $h_0(d)$ cancel out. For this reason, the regression results of CPH models are usually presented in terms of hazard ratios. This convention is followed here. Because all the covariates used in the analysis are categorical, the hazard ratios are expressed in terms of the included category relative to the excluded category. A hazard ratio that is larger than one shows that a project from the included category has a larger hazard of first issuance than a project from the excluded category. Integrated over duration, this translates into a shorter time to market for a project from the included category.

3.3 The KM estimator

This subsection answers the question of the distribution of the time to market across all projects that started the GSP in 2003-2012. The answer relies on the KM estimator.

Without censoring, a natural candidate for the estimator of the hazard of first issuance $h(d)$ is the number of first issuances observed at d days from GSP start divided by the number of projects that were at risk of first issuance, i.e. projects that had not issued any CERs before d . The KM estimator extends this idea to censored data,

$$\hat{h}(d) = \frac{f_d}{r_{d-}} \quad (4)$$

where f_d is the number of first issuances observed at d and r_{d-} is the number of projects at risk of first issuance just before d . A project is said to be at risk of first issuance if it has not issued any CERs or has not been censored; e.g. a project that is censored at $d = 100$ days is not part of the risk set at $d- = 101$ days.

Estimating $\hat{h}(d)$ at each d , where at least one project is known to have issued the first CERs, produces a range of estimates of h at different d . Integrating these estimates over d gives the $S(d)$ shown in Figure 3.²⁴ For comparison, Figure 4 shows the probability that a project has not requested registration as

²⁴The estimation is done using the functions *Surv* and *survfit* in the package *survival* (version 2.37-4) written by Terry Therneau for *R*. The *R* version is 3.0.2.

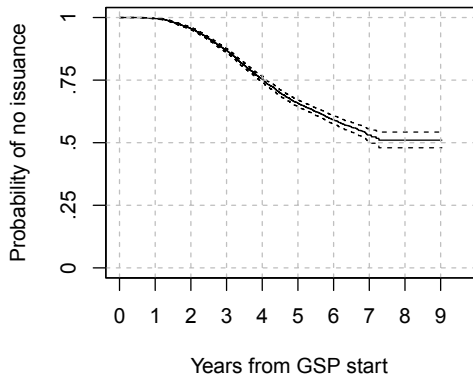


Figure 3. Time to market of all projects that started the GSP in 2003-2012. The solid line shows $S(d)$, the probability that a project from this population has not issued CERs as a function of days d from GSP start. The dotted lines demarcate the 95% confidence interval of $S(d)$.

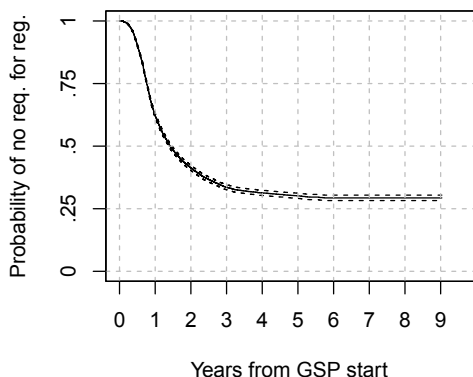


Figure 4. Time to request for registration of all projects that started the GSP in 2003-2012. The solid line shows the probability that a project from this population has not submitted a request for registration as a function of days d from GSP start.

a function of days d from GSP start. The process for producing it is identical to the process for producing Figure 3, with the hazard of first issuance replaced by the hazard of request for registration.

Two observations can be made based on Figures 3 and 4. First, between GSP start and request for registration, 30% of all projects fail, while another 20% fail between request for registration and first issuance. In other words, half of all CDM projects that start the GSP will never issue any CERs. Second, for the other 50% of all projects, the median time to market, defined as the duration between GSP start and first issuance, is four years.

3.4 CPH model

This subsection answers the question of how the time to market depends on host country, the technology on which a project relies, the scale of the project, and time. The answer relies on the CPH model. The specification of the model is developed in steps to highlight the choices made at each step. Table 4 shows the specifications that make up the narrative of this subsection.

Table 4. Outline of the alternative specifications of the CPH model.

Spec- ifica- tion	Hazard	Covariates				Inter- action terms	Threshold for splitting up durations	Threshold for merging categories
		Host coun- try	Pro- ject type	Sca- le	Ti- me			
1a	First iss.	x	x	x				25 projects
1b	First iss.	x	x	x			$m1 = 1\{d \geq 3 \text{ years}\}$	10 projects
2a	First iss.	x	x	x		x	$m1 = 1\{d \geq 3 \text{ years}\}$	25 projects
2b	First iss.	x	x	x		x	$m1 = 1\{d \geq 3 \text{ years}\}$	25 projects
3a	First iss.	x	x	x	x	x	$m1 = 1\{d \geq 3 \text{ years}\}$	25 projects
3b	First iss.	x	x	x	x	x	$m1 = 1\{d \geq 3 \text{ years}\}$	10 projects
3c	Reg. req.	x	x	x	x	x	$m2 = 1\{d \geq 250 \text{ days}\}$	25 projects

Notes: In Specification 2b, the scale of the project, defined as expected yearly emissions reduction, enters the regression directly as a continuous variable. In all other specifications, the scale enters the regression as a categorized variable.

3.4.1 Specifications 1a and 1b

The starting point for the analysis is Specification 1a, which has only constant covariates, i.e. covariates that do not vary over duration d or time t ,

$$h(d) = h_0(d) \exp(\mathbf{x}_{\text{chr}}^T \boldsymbol{\beta}_{\text{chr}}), \quad (5)$$

where \mathbf{x}_{chr} is a vector of dummies for project characteristics. \mathbf{x}_{chr} contains dummies for host country, project type, and scale. $\boldsymbol{\beta}_{\text{chr}}$ is a vector of regression coefficient.

Table 5 shows the estimation results for Specification 1a.²⁵ A regression cannot include dummies for all categories; one category must be omitted. The excluded categories are China for host country, hydro power for project type,

²⁵The estimation is done with functions *Surv* and *coxph* in the package *survival* (version 2.37-4).

and less than 50 ktCO₂e per year for the scale of the project.²⁶ The excluded categories are the reference against which the hazard ratios of the categories that are included in the regression are interpreted.

Table 5. Regression results for Specification 1a, where the dependent variable is the hazard of first issuance. One category of each independent variable is excluded from the regression.

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
Host	Host countries with < 25 iss	-0.79	0.09	0.46	0.00
	Brazil	-0.31	0.10	0.73	0.00
	Chile	-0.28	0.20	0.75	0.15
	India	-0.64	0.07	0.53	0.00
	Indonesia	-0.68	0.20	0.51	0.00
	Malaysia	-1.02	0.20	0.36	0.00
	Mexico	-0.86	0.15	0.42	0.00
	South Korea	-0.23	0.19	0.79	0.22
	Vietnam	-0.35	0.18	0.71	0.06
Type	Project types with < 25 iss	-0.42	0.11	0.65	0.00
	Biomass energy	-0.32	0.09	0.73	0.00
	Coal bed/mine methane	-0.59	0.19	0.55	0.00
	EE industry	-0.55	0.18	0.58	0.00
	EE own generation	-0.71	0.10	0.49	0.00
	Fossil fuel switch	-0.34	0.16	0.71	0.03
	Landfill gas	-0.04	0.11	0.96	0.72
	Methane avoidance	-0.15	0.11	0.86	0.15
	N ₂ O	0.55	0.15	1.73	0.00
	Wind	0.55	0.06	1.73	0.00
Scale	50-500 ktCO ₂ e per yr	0.34	0.05	1.40	0.00
	> 500 ktCO ₂ e per yr	1.22	0.11	3.40	0.00

Notes: The excluded categories are the reference relative to which the effects of the remaining categories are interpreted. The excluded categories are China (for host country), hydro power (for project type) and less than 50 ktCO₂e per year in expected emissions reduction (for project scale). Exp(coeff.) is the hazard ratio. The hazard ratio shows the hazard (of first issuance) of the included category relative to excluded category, e.g. the hazard of first issuance of a project hosted by India relative to a project hosted by China. The *p*-value shows the probability of the null hypothesis that the hazard ratio is equal to one, i.e. that a project hosted by India has the same hazard of first issuance as a project hosted by China.

In Specification 1a, the threshold for merging categories is 25 projects. Cate-

²⁶China is chosen as the excluded category for host country because it is the most common host country. Hydro is chosen as the excluded category for project type because hydro is the most common project type in China. The choice of excluded categories does not affect the results.

gories of host countries and project types with less than 25 projects are merged and relabelled as hosts with less than 25 issuances (iss) and types with less than 25 iss, respectively. For example, there are only 19 HFCs projects that have issued CERs. Thus, HFCs projects fall into the category of types with less than 25 iss. Without a threshold, the model would include dummies with extremely few observations, which would make estimation unreliable. Arguably, the choice of threshold is somewhat arbitrary.

For comparison, in Specification 1b, the threshold for merging categories is lowered from 25 to 10 projects. Table 6 shows the estimation results for Specification 1b. Lowering the threshold brings new dummies into the estimation, among others, a dummy for HFCs. However, the standard errors of the regression coefficients for the new dummies are much larger than for the original set of dummies due to the low number of observations.²⁷ Thus, the regression coefficients of the new dummies must either be very small or very large for them to be statistically significant.

Table 6. Regression results for Specification 1b, which is identical to Specification 1a but has threshold of 10 projects instead of 25 projects for merging categories.

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
Host	Host countries < 10 iss	-1.07	0.12	0.34	0.00
	LDCs	-1.00	0.32	0.37	0.00
	Argentina	-0.20	0.29	0.82	0.48
	Brazil	-0.30	0.10	0.74	0.00
	Chile	-0.27	0.20	0.76	0.17
	Colombia	-0.43	0.26	0.65	0.10
	Ecuador	0.04	0.30	1.04	0.89
	Honduras	-0.14	0.31	0.87	0.64
	India	-0.64	0.07	0.53	0.00
	Indonesia	-0.67	0.20	0.51	0.00
	Israel	-0.44	0.31	0.64	0.15
	Malaysia	-1.02	0.20	0.36	0.00
	Mexico	-0.93	0.15	0.40	0.00
	Peru	-0.46	0.29	0.63	0.11
	South Africa	-0.60	0.32	0.55	0.06
	South Korea	-0.26	0.19	0.77	0.18
	Thailand	-0.80	0.23	0.45	0.00
Vietnam	-0.34	0.18	0.71	0.06	
Type	Project types with < 10 iss	-0.49	0.17	0.61	0.00

continued

²⁷Lowering the threshold introduces 14 new dummies into the regression, most of which show a non-significant coefficient, i.e. a *p*-value > 0.05 for the null hypothesis that the coefficient is equal to zero.

Table 6. (continued)

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
	Biomass energy	-0.33	0.09	0.72	0.00
	Cement	-0.69	0.29	0.50	0.02
	Coal bed/mine methane	-0.57	0.19	0.56	0.00
	EE industry	-0.55	0.18	0.57	0.00
	EE own generation	-0.71	0.10	0.49	0.00
	EE supply side	-0.91	0.30	0.40	0.00
	Fossil fuel switch	-0.31	0.16	0.73	0.05
	Fugitive	-0.57	0.32	0.57	0.08
	HFCs	1.71	0.25	5.52	0.00
	Landfill gas	-0.04	0.11	0.96	0.70
	Methane avoidance	-0.13	0.11	0.88	0.22
	N2O	0.57	0.15	1.77	0.00
	Solar	-0.27	0.30	0.76	0.36
	Wind	0.56	0.06	1.75	0.00
Scale	50-500 ktCO ₂ e per yr	0.34	0.05	1.41	0.00
	More than 500 ktCO ₂ e per yr	1.13	0.12	3.10	0.00

Notes: The dependent variable is the hazard of first issuance. The excluded categories of the independent variables are China (for host country), hydro power (for project type), and less than 50 ktCO₂e per year in expected emissions reduction (for project scale). Dummies that are introduced as a result of lowering the threshold from 25 projects to 10 projects are shown in **red color**. The threshold is defined in terms of the number of projects that have issued CERs.

The regression results are presented in terms of the hazard ratio of the included category relative to the excluded category. The hazard ratio is equal to the exponent of the regression coefficient of the included category; e.g. for wind relative to hydro the hazard ratio is equal to the exponent of the regression coefficient for the dummy for the category of wind,

$$\frac{h_{wind}(d)}{h_{hydro}(d)} = \frac{h_0(d) \exp(\mathbf{x}_{-chr}^T \boldsymbol{\beta}_{-chr}) \exp(\beta_{wind} \cdot 1)}{h_0(d) \exp(\mathbf{x}_{-chr}^T \boldsymbol{\beta}_{-chr}) \exp(\beta_{wind} \cdot 0)} = \exp(\beta_{wind}), \quad (6)$$

where \mathbf{x}_{-chr} contains the same dummies as \mathbf{x}_{chr} expect for the dummy for the category of wind power. $h_0(d)$ and $\exp(\mathbf{x}_{-chr}^T \boldsymbol{\beta}_{-chr})$ cancel out as a consequence of the proportionality assumption. Specification 1a (Table 5) gives $\exp(\beta_{wind}) = 1.73$, which suggests that wind power projects move faster from GSP start to first issuance than hydro power projects.

However, Appendix B shows that Specification 1a does not satisfy the proportionality assumption; i.e. there are pairs of projects for which the hazard ratio is not constant over time. With respect to project type, this is not very

surprising.²⁸

3.4.2 Specifications 2a and 2b

To correct the violation of the proportionality assumption, interactions between the covariates and a dummy $m1 = 1\{d \geq d_{\text{thres}}\}$ for duration length are introduced in Specification 2a, which is defined as

$$h(d) = h_0(d) \exp(\mathbf{x}_{\text{chr}}^T \boldsymbol{\beta}_{\text{chr}} + (m1 \times \mathbf{x}_{\text{chr}})^T \boldsymbol{\gamma}_{\text{chr}}), \quad (7)$$

where $\mathbf{x}_{\text{chr}}^T \boldsymbol{\beta}_{\text{chr}}$ shows the main effects, and $(m1 \times \mathbf{x}_{\text{chr}})^T \boldsymbol{\gamma}_{\text{chr}}$ shows the interaction effects. Compared with Specification 1a, which only has constant covariates, the dummy $m1$ in Specification 2a varies over duration. Appendix B confirms that Specification 2a does not violate the proportionality assumption. The threshold d_{thres} is set at 3 years. The choice of threshold is guided by the test statistic.²⁹

The procedure for introducing the interactions is the simplest possible. Each duration that exceeds 3 years is split into two parts, [0 days, 3 years] and [3 years, d_{end}], where d_{end} is the end of the duration.³⁰ The dummy $m1$ (m for mature) has the value 0 for [0 days, 3 years] and the value 1 for [3 years, d_{end}].³¹ The procedure is illustrated in Figure 5. Dur. 1 is split into [0, 3 years] and [3 years, 4 years]. Dur. 2 is not split, because $d_{\text{end}} < 3$ years. Dur 3. is censored at the censoring date, which is 1 January 2013. However, because Dur. 3 is at least 6 years, it is split in [0, 3] and [3, 6+], where the plus sign indicates censoring.

Table 7 shows the estimation results for Specification 2a. The estimation is done using the same statistical package as the estimation of Specification 1a. Due to the interactions, the interpretation of results is not as straightforward as in Specification 1a. Given that dummy $m1$ is defined as $m1 = 1\{d \geq$

²⁸For example, landfill gas projects face more complex monitoring and verification requirements than hydro power projects, among others, because the methane content of the landfill gas must be monitored continuously. This is likely to add further delay to landfill gas projects, which will show up as differences in the shape of the hazard functions, and trigger a violation of the proportionality assumption.

²⁹A specification with a threshold much below 3 years does not correct the violation of the proportionality assumption. The same applies for a specification with a threshold much above 3 years.

³⁰For uncensored projects, i.e. projects that have issued CERs, d_{end} is the number of days between GSP start and first issuance. For censored projects, i.e. projects that have not (yet) issued CERs, d_{end} is the number of days between GSP start and the censoring date, which is 1 January 2013.

³¹The split is done using the function *survSplit* in the package *survival* (version 2.37-4).

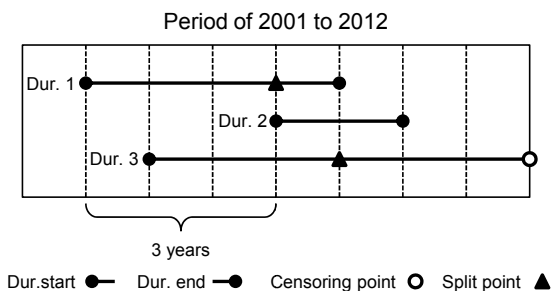


Figure 5. Procedure for introducing interactions between the covariates and a dummy for duration length in Specification 2a.

3 years}, the main effect shows the hazard ratio for d less than 3 years while the sum of the main effect and the interaction effect shows the hazard ratio for d of more than 3 years. For example, the hazard ratio of wind power relative to hydro power is $\exp(0.66) = 1.94$ for d less than 3 years and $\exp(0.66 - 0.13) = 1.70$ for d more than 3 years.³² For this particular effect, the qualitative result is the same as in Specification 1a. Wind power projects move faster from GSP start to first issuance than hydro power projects.

Table 7. Regression results for Specification 2a, where the dependent variable is the hazard of first issuance and one category of each independent variable is excluded from the regression.

Host	Host countries with < 25 iss	-0.49	0.13	0.61	0.00
	Brazil	0.37	0.13	1.45	0.00
	Chile	0.31	0.25	1.37	0.21
	India	-0.39	0.10	0.67	0.00
	Indonesia	-1.15	0.42	0.32	0.01
	Malaysia	-1.21	0.39	0.30	0.00
	Mexico	-0.36	0.23	0.70	0.12
	South Korea	-0.34	0.31	0.71	0.27
	Vietnam	-1.00	0.38	0.37	0.01
	Type	Project types with < 25 iss	-0.29	0.16	0.75
Biomass energy		0.21	0.12	1.23	0.09
Coal bed/mine methane		-0.82	0.36	0.44	0.02
EE industry		0.27	0.23	1.31	0.24
EE own generation		-0.52	0.16	0.59	0.00
Fossil fuel switch		0.03	0.21	1.03	0.88
Landfill gas		-0.05	0.18	0.96	0.80

continued

³²The intuition for why the hazard ratio changes over duration is that the hazard functions have a different shape.

Table 7. (continued)

	Methane avoidance	-0.16	0.17	0.85	0.33
	N2O	0.65	0.23	1.92	0.00
	Wind	0.66	0.10	1.94	0.00
Scale	50-500 ktCO ₂ e per yr	0.35	0.08	1.42	0.00
	> 500 ktCO ₂ e per yr	1.45	0.15	4.25	0.00
Interac-	<i>m1</i> :Hosts with < 25 iss	-0.58	0.17	0.56	0.00
tions for	<i>m1</i> :Brazil	-1.36	0.20	0.26	0.00
host	<i>m1</i> :Chile	-1.26	0.41	0.28	0.00
	<i>m1</i> :India	-0.48	0.14	0.62	0.00
	<i>m1</i> :Indonesia	0.60	0.48	1.83	0.21
	<i>m1</i> :Malaysia	0.17	0.46	1.19	0.71
	<i>m1</i> :Mexico	-0.91	0.31	0.40	0.00
	<i>m1</i> :South Korea	0.11	0.39	1.11	0.78
	<i>m1</i> :Vietnam	1.01	0.44	2.74	0.02
... and	<i>m1</i> :Types with < 25 iss	-0.20	0.23	0.82	0.38
project	<i>m1</i> :Biomass energy	-0.95	0.18	0.39	0.00
type	<i>m1</i> :Coal bed/mine methane	0.30	0.43	1.35	0.48
	<i>m1</i> :EE industry	-1.64	0.40	0.19	0.00
	<i>m1</i> :EE own generation	-0.32	0.20	0.72	0.11
	<i>m1</i> :Fossil fuel switch	-0.65	0.31	0.52	0.04
	<i>m1</i> :Landfill gas	0.01	0.23	1.01	0.96
	<i>m1</i> :Methane avoidance	0.06	0.22	1.06	0.80
	<i>m1</i> :N2O	-0.21	0.30	0.81	0.49
	<i>m1</i> :Wind	-0.13	0.13	0.88	0.34
... and	<i>m1</i> :50-500 ktCO ₂ e per yr	-0.02	0.11	0.98	0.85
size	<i>m1</i> :> 500 ktCO ₂ e per yr	-0.45	0.23	0.64	0.05

Notes: The excluded categories are the reference, relative to which the effects of the remaining categories are interpreted. The excluded categories are China (for host country), hydro power (for project type), and less than 50 ktCO₂e per year in expected emissions reduction (for project scale). Durations that exceed 3 years are split into two parts, $m1 = 1\{d \geq 3 \text{ years}\}$.

Scale is split, somewhat arbitrarily, into three categories: less than 50 ktCO₂e per year, between 50 and 500 ktCO₂e per year and above 500 ktCO₂e per year. For comparison, Specification 2b shows how the results change if expected yearly emissions reduction enters the regression as a continuous variable. The estimation results for Specification 2b are shown in Table 8. The qualitative result is the same: the larger the project, the larger the hazard of first issuance.

Table 8. Regression results for Specification 2b, which is same as Specification 2a expect that the scale, in terms of expected yearly emissions reductions in ktCO₂e, enters the regression directly.

Covar.	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	p-value
Host	Hosts with < 25 iss	-0.59	0.13	0.56	0.00
	Brazil	0.23	0.13	1.26	0.07
	Chile	0.22	0.25	1.25	0.38
	India	-0.60	0.09	0.55	0.00
	Indonesia	-1.23	0.42	0.29	0.00
	Malaysia	-1.29	0.39	0.28	0.00
	Mexico	-0.43	0.23	0.65	0.07
	South Korea	-0.49	0.31	0.61	0.11
	Vietnam	-1.10	0.38	0.33	0.00
Type	Types with < 25 iss	-0.22	0.16	0.81	0.18
	Biomass energy	0.24	0.12	1.27	0.05
	Coal bed/mine methane	-1.23	0.43	0.29	0.00
	EE industry	0.28	0.23	1.32	0.23
	EE own generation	-0.47	0.16	0.63	0.00
	Fossil fuel switch	0.39	0.21	1.47	0.06
	Landfill gas	0.00	0.18	1.00	0.99
	Methane avoidance	-0.25	0.17	0.78	0.13
	N2O	0.82	0.23	2.27	0.00
	Wind	0.75	0.09	2.12	0.00
Scale	Continuous (in ktCO ₂)	0.00040	0.00004	1.00040	0.00
Interac- tions for host	<i>m</i> 1:Hosts with < 25 iss	-0.56	0.17	0.57	0.00
	<i>m</i> 1:Brazil	-1.32	0.20	0.27	0.00
	<i>m</i> 1:Chile	-1.26	0.41	0.28	0.00
	<i>m</i> 1:India	-0.44	0.13	0.65	0.00
	<i>m</i> 1:Indonesia	0.61	0.48	1.85	0.20
	<i>m</i> 1:Malaysia	0.19	0.46	1.22	0.67
	<i>m</i> 1:Mexico	-0.92	0.31	0.40	0.00
	<i>m</i> 1:South Korea	0.09	0.39	1.09	0.81
	<i>m</i> 1:Vietnam	1.07	0.44	2.90	0.01
... project type	<i>m</i> 1:Types with < 25 iss	-0.22	0.22	0.80	0.33
	<i>m</i> 1:Biomass energy	-0.92	0.18	0.40	0.00
	<i>m</i> 1:Coal bed/mine meth.	0.76	0.49	2.13	0.12
	<i>m</i> 1:EE industry	-1.63	0.40	0.20	0.00
	<i>m</i> 1:EE own generation	-0.30	0.20	0.74	0.14
	<i>m</i> 1:Fossil fuel switch	-0.81	0.30	0.44	0.01
	<i>m</i> 1:Landfill gas	0.04	0.23	1.04	0.87
	<i>m</i> 1:Methane avoidance	0.10	0.22	1.10	0.65
	<i>m</i> 1:N2O	-0.18	0.30	0.84	0.55
	<i>m</i> 1:Wind	-0.12	0.13	0.89	0.35

continued

Table 8. (continued)

Covar.	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
... scale	<i>m1</i> :ktCO ₂ e per yr	0.00002	0.00007	1.00002	0.77

Notes: The dependent variable is the hazard of first issuance. With the exception of scale, the independent variables are categorical. The excluded categories are China (for host country) and hydro power (for project type). Durations that exceed 3 years are split into two parts, $m1 = 1\{d \geq 3 \text{ years}\}$.

A third variation of Specification 2a replaces the three categories for project scale with a dummy for large-scale methodology. The complete estimation results of this third variation are omitted to save space. The omitted results show that a project that applies a large-scale methodology has a hazard of first issuance of 1.92 for d less than 3 years and 1.28 for d more than 3 years compared with a project that applies a small-scale methodology.

3.4.3 Specifications 3a, 3b, and 3c

Finally, to quantify how the hazard of first issuance changes over time, dummies for period are introduced in Specification 3a, which is defined as

$$h(d) = h_0(d) \exp \left\{ \mathbf{x}_{\text{chr}}^T \boldsymbol{\beta}_{\text{chr}} + (m1 \times \mathbf{x}_{\text{chr}})^T \boldsymbol{\gamma}_{\text{chr}} + \mathbf{x}_{\text{per}}^T \boldsymbol{\beta}_{\text{per}} + (m1 \times \mathbf{x}_{\text{per}})^T \boldsymbol{\gamma}_{\text{per}} \right\}, \quad (8)$$

Time is split, somewhat arbitrarily, into three periods: Jan01-Dec07, Jan08-Dec09, and Jan10-Dec12. The dummy for the period Jan08-Dec09 is excluded from the regression. \mathbf{x}_{per} contains dummies for the remaining two, a dummy for Jan01-Dec07 and a dummy for Jan10-Dec12.

Compared with Specification 1a, which has only constant covariates, Specification 3a has variables that vary over both duration d and time t . Time is treated in an identical way to the other covariates. Thus, Specification 3a contains interactions between $m1 = 1\{d \geq 3 \text{ years}\}$ and the dummies \mathbf{x}_{per} . Appendix B confirms that Specification 3a does not violate the proportionality assumption.

The procedure for introducing the dummies for period is illustrated in Figure 6. The single duration that runs from 2006 to 2012+ is split in three points in time, twice where the period changes and once where the duration exceeds the threshold of 3 years.³³

Table 9 shows the estimation results for Specification 3a. The inclusion of time provides for some new insights. The estimates show that in Jan10-Dec12

³³The split is done using a custom piece of R code.

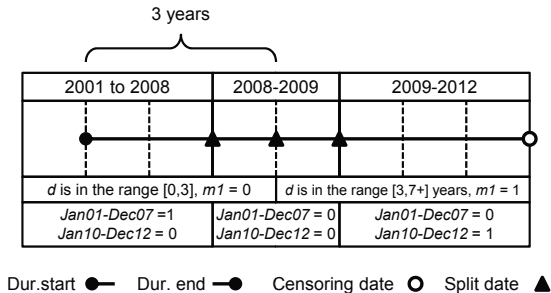


Figure 6. Procedure for introducing the dummies for period in Specification 3a.

the hazard of first issuance was $\exp(-0.80) = 0.45$ for d less than 3 years and $\exp(-0.80 + 0.43) = 0.70$ for d more than 3 years, compared with the period Jan08-Dec09. The main effect (Jan10-Dec12) shows the hazard ratio for d less than 3 years, while the sum of the main effect (Jan10-Dec12) and the interaction effect ($m1:Jan10-Dec12$) shows the hazard ratio for d more than 3 years.³⁴

Table 9. Regression results for Specification 3a, where the dependent variable is the hazard of first issuance, and one category of each independent variable is excluded from the regression.

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	p-value
Host	Hosts with < 25 iss	-1.10	0.13	0.33	0.00
	Brazil	-0.41	0.14	0.66	0.00
	Chile	-0.39	0.26	0.68	0.13
	India	-0.80	0.10	0.45	0.00
	Indonesia	-1.34	0.42	0.26	0.00
	Malaysia	-1.55	0.39	0.21	0.00
	Mexico	-1.11	0.24	0.33	0.00
	South Korea	-0.90	0.31	0.41	0.00
	Vietnam	-1.04	0.39	0.35	0.01
Type	Types with < 25 iss	-0.25	0.16	0.78	0.13
	Biomass energy	0.06	0.12	1.06	0.63

continued

³⁴Table 9 shows that the coefficient is positive (2.48) for the dummy Jan01-Dec07 but negative (-2.15) for the interaction $m1:Jan01-Dec07$. Taking the exponent of the coefficient for Jan01-Dec07 shows that a project with a duration (between GSP start and first issuance) of less than 3 years had a hazard (of first issuance) of 11.97 in Jan01-Dec07 relative to a similar project in Jan08-Dec09. Taking the exponents of the sum of coefficients for Jan01-Dec07 and $m1:Jan01-Dec07$ shows that a project with a duration of more than 3 years had a hazard of 1.39 in Jan01-Dec07 compared with a similar project in Jan08-Dec09. The intuition is that, between Jan01-Dec07 and Jan08-Dec09, delays increased a lot and, as a result, the share of projects that issued CERs within 3 years of GSP start dropped dramatically.

Table 9. (continued)

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
	Coal bed/mine methane	-0.95	0.36	0.39	0.01
	EE industry	0.05	0.23	1.06	0.81
	EE own generation	-0.52	0.16	0.59	0.00
	Fossil fuel switch	-0.15	0.21	0.86	0.48
	Landfill gas	-0.51	0.18	0.60	0.00
	Methane avoidance	-0.19	0.17	0.82	0.25
	N ₂ O	0.63	0.23	1.87	0.01
	Wind	0.80	0.09	2.22	0.00
Scale	50-500 ktCO ₂ e per yr	0.33	0.08	1.39	0.00
	> 500 ktCO ₂ e per yr	1.43	0.15	4.17	0.00
Period	Jan01-Dec07	2.48	0.10	11.97	0.00
	Jan10-Dec12	-0.80	0.08	0.45	0.00
Interac- tions for host	<i>m</i> 1:Hosts with < 25 iss	-0.01	0.18	0.99	0.93
	<i>m</i> 1:Brazil	-0.63	0.21	0.53	0.00
	<i>m</i> 1:Chile	-0.60	0.41	0.55	0.15
	<i>m</i> 1:India	-0.11	0.14	0.90	0.44
	<i>m</i> 1:Indonesia	0.78	0.48	2.19	0.10
	<i>m</i> 1:Malaysia	0.50	0.46	1.65	0.27
	<i>m</i> 1:Mexico	-0.21	0.31	0.81	0.50
	<i>m</i> 1:South Korea	0.64	0.39	1.90	0.10
	<i>m</i> 1:Vietnam	1.04	0.44	2.84	0.02
... and project type	<i>m</i> 1:Types with < 25 iss	-0.25	0.23	0.78	0.27
	<i>m</i> 1:Biomass energy	-0.81	0.18	0.45	0.00
	<i>m</i> 1:Coal bed/mine methane	0.41	0.43	1.51	0.33
	<i>m</i> 1:EE industry	-1.44	0.40	0.24	0.00
	<i>m</i> 1:EE own generation	-0.32	0.21	0.72	0.12
	<i>m</i> 1:Fossil fuel switch	-0.48	0.31	0.62	0.13
	<i>m</i> 1:Landfill gas	0.46	0.23	1.58	0.05
	<i>m</i> 1:Methane avoidance	0.09	0.22	1.09	0.69
	<i>m</i> 1:N ₂ O	-0.17	0.31	0.85	0.58
	<i>m</i> 1:Wind	-0.26	0.13	0.77	0.05
... and size	<i>m</i> 1:50-500 ktCO ₂ e per yr	0.00	0.11	1.00	0.99
	<i>m</i> 1:> 500 ktCO ₂ e per yr	-0.43	0.23	0.65	0.06
... and pe- riod	<i>m</i> 1:Jan01-Dec07	-2.15	0.73	0.12	0.00
	<i>m</i> 1:Jan10-Dec12	0.43	0.15	1.54	0.01

Notes: The excluded categories are the reference, relative to which the effects of the remaining categories are interpreted. The excluded categories are China (for host country), hydro power (for project type), less than 50 ktCO₂e per year in expected emissions reduction (for project scale), and Jan08-Dec09 (for period). Durations that exceed 3 years are split into two parts, $m1 = 1\{d \geq 3 \text{ years}\}$.

Thus, in the period Jan10-Dec12, first issuance was less likely than in the period that preceded it, regardless of how many days or years a project had spent in the CDM project cycle. Given the somewhat artificial split of time, Section 4 presents two variations of Specification 3a, one in which the split point between the second and third period is shifted 6 months forward in time and another where it is shifted 12 months forward.

Specification 3a relies on the same threshold for merging categories as Specification 1a. For comparison, in Specification 3b the threshold for merging categories is lowered from 25 projects to 10. Table 10 shows the estimation results for Specification 3b. As in moving from Specification 1a to Specification 1b, lowering the threshold brings new dummies into the estimation.

Table 10. Regression results for Specification 3b, which is identical to Specification 3a but has a threshold of 10 projects instead of 25 projects for merging categories.

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	p-value
Host	Hosts with < 10 iss	-1.42	0.19	0.24	0.00
	LDCs	-2.02	0.71	0.13	0.00
	Argentina	-0.68	0.42	0.51	0.10
	Brazil	-0.39	0.14	0.67	0.00
	Chile	-0.36	0.26	0.70	0.17
	Colombia	-0.51	0.38	0.60	0.19
	Ecuador	-0.13	0.36	0.88	0.72
	Honduras	-1.10	0.42	0.33	0.01
	India	-0.82	0.10	0.44	0.00
	Indonesia	-1.32	0.42	0.27	0.00
	Israel	-0.03	0.39	0.97	0.94
	Malaysia	-1.54	0.39	0.21	0.00
	Mexico	-1.11	0.24	0.33	0.00
	Peru	-0.81	0.45	0.45	0.08
	South Africa	-1.02	0.46	0.36	0.03
	South Korea	-0.98	0.31	0.38	0.00
	Thailand	-1.00	0.37	0.37	0.01
Vietnam	-0.95	0.39	0.39	0.01	
Type	Types with < 10 iss	-0.32	0.28	0.72	0.25
	Biomass energy	0.08	0.13	1.08	0.52
	Cement	-0.20	0.36	0.82	0.57
	Coal bed/mine methane	-0.87	0.36	0.42	0.02
	EE industry	0.07	0.23	1.08	0.75
	EE own generation	-0.48	0.16	0.62	0.00
	EE supply side	-0.32	0.39	0.73	0.41
	Fossil fuel switch	-0.08	0.22	0.92	0.71
	Fugitive	-0.52	0.47	0.60	0.27

continued

Table 10. (continued)

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
	HFCs	0.83	0.30	2.29	0.01
	Landfill gas	-0.50	0.18	0.61	0.01
	Methane avoidance	-0.18	0.17	0.84	0.30
	N2O	0.69	0.23	1.99	0.00
	Solar	-0.03	0.30	0.97	0.93
	Wind	0.84	0.10	2.32	0.00
Scale	50-500 ktCO ₂ e per yr	0.30	0.08	1.35	0.00
	> 500 ktCO ₂ e per yr	1.25	0.17	3.49	0.00
Period	Jan01-Dec07	2.47	0.10	11.81	0.00
	Jan10-Dec12	-0.79	0.08	0.45	0.00
Interac- tions for host	<i>m1</i> :Hosts with < 10 iss	0.03	0.25	1.03	0.91
	<i>m1</i>:LDCs	1.11	0.80	3.03	0.17
	<i>m1</i>:Argentina	0.49	0.57	1.63	0.40
	<i>m1</i> :Brazil	-0.63	0.21	0.53	0.00
	<i>m1</i> :Chile	-0.61	0.41	0.54	0.14
	<i>m1</i>:Colombia	-0.13	0.53	0.88	0.81
	<i>m1</i>:Ecuador	-0.77	0.68	0.46	0.26
	<i>m1</i>:Honduras	0.44	0.62	1.55	0.48
	<i>m1</i> :India	-0.06	0.14	0.94	0.68
	<i>m1</i> :Indonesia	0.80	0.48	2.22	0.10
	<i>m1</i>:Israel	-1.02	0.64	0.36	0.11
	<i>m1</i> :Malaysia	0.52	0.46	1.69	0.26
	<i>m1</i> :Mexico	-0.21	0.31	0.81	0.50
	<i>m1</i>:Peru	0.07	0.59	1.07	0.91
	<i>m1</i>:South Africa	-0.01	0.65	0.99	0.99
	<i>m1</i> :South Korea	0.66	0.39	1.94	0.09
	<i>m1</i>:Thailand	0.09	0.47	1.09	0.86
	<i>m1</i> :Vietnam	0.95	0.44	2.59	0.03
... and project type	<i>m1</i> :Types with < 10 iss	0.00	0.36	1.00	0.99
	<i>m1</i> :Biomass energy	-0.88	0.18	0.42	0.00
	<i>m1</i>:Cement	-1.25	0.62	0.29	0.04
	<i>m1</i> :Coal bed/mine methane	0.32	0.43	1.38	0.46
	<i>m1</i> :EE industry	-1.50	0.40	0.22	0.00
	<i>m1</i> :EE own generation	-0.38	0.21	0.68	0.06
	<i>m1</i>:EE supply side	-0.91	0.60	0.40	0.13
	<i>m1</i> :Fossil fuel switch	-0.58	0.32	0.56	0.07
	<i>m1</i>:Fugitive	-0.34	0.65	0.71	0.60
	<i>m1</i>:HFCs	0.00	0.78	1.00	1.00
	<i>m1</i> :Landfill gas	0.41	0.23	1.51	0.07
	<i>m1</i> :Methane avoidance	0.06	0.22	1.06	0.80
	<i>m1</i> :N2O	-0.25	0.31	0.78	0.42

continued

Table 10. (continued)

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
	<i>m1</i> :Solar			<i>omitted from the regression</i>	
	<i>m1</i> :Wind	-0.31	0.13	0.73	0.02
... and size	<i>m1</i> :50-500 ktCO ₂ e per yr	0.05	0.11	1.06	0.61
	<i>m1</i> :> 500 ktCO ₂ e per yr	-0.22	0.24	0.80	0.37
... and period	<i>m1</i> :Jan01-Dec07	-2.17	0.73	0.11	0.00
	<i>m1</i> :Jan10-Dec12	0.40	0.16	1.49	0.01

Notes: The dependent variable is the hazard of first issuance. The excluded categories are China (for host country), hydro power (for project type), less than 50 ktCO₂e per year in expected emissions reduction (for project scale), and Jan08-Dec09 (for period). Durations that exceed 3 years are split into two parts, $m1 = 1\{d \geq 3 \text{ years}\}$. Dummies that are introduced as a result of lowering the threshold from 25 projects to 10 projects are shown in **red color**. To make sure the model converges, the interaction *m1*:Solar is omitted. In the data, there is not a single solar project with a time to market of less than 3 years.

Specification 3c is identical to Specification 3a, except the hazard of first issuance is replaced by the hazard of request for registration. Table 11 shows the estimation results for Specification 3c.³⁵ Interestingly, it shows that, compared with Jan08-Dec09, in Jan10-Dec12 the hazard of requesting registration was $\exp(0.86) = 2.37$ for d less than 250 days $\exp(0.86 - 0.68) = 1.20$ for d more than 3 years. Thus, in the period Jan10-Dec12, request for registration was more likely than in the period that preceded it.

Table 11. Regression results for Specification 3c, which is identical to Specification 3a but the dependent variable is the hazard of requesting registration instead of the hazard of first issuance.

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
Host	Hosts with < 25 iss	-0.67	0.08	0.51	0.00
	Brazil	-1.21	0.13	0.30	0.00
	Chile	-0.60	0.21	0.55	0.00
	India	-1.17	0.07	0.31	0.00
	Indonesia	-0.40	0.18	0.67	0.03
	Malaysia	-0.29	0.18	0.75	0.10
	Mexico	0.26	0.11	1.30	0.02
	South Korea	-0.05	0.16	0.95	0.74
	Vietnam	-0.32	0.17	0.72	0.06

continued

³⁵Because the typical duration from GSP start to request for registration is much shorter than the duration from GSP start to first issuance, the threshold d_{thres} is set at 250 days in Specification 3c.

Table 11. (continued)

Covariate	Dummy	Coeff.	SE of coeff.	Exp(coeff.)	<i>p</i> -value
Type	Types with < 25 iss	0.65	0.09	1.92	0.00
	Biomass energy	0.38	0.09	1.47	0.00
	Coal bed/mine methane	-0.83	0.28	0.44	0.00
	EE industry	0.12	0.19	1.13	0.53
	EE own generation	-0.37	0.13	0.69	0.00
	Fossil fuel switch	0.20	0.19	1.22	0.29
	Landfill gas	0.35	0.12	1.41	0.00
	Methane avoidance	0.19	0.11	1.21	0.07
	N2O	0.96	0.16	2.62	0.00
Wind	1.01	0.07	2.74	0.00	
Scale	50-500 ktCO ₂ e per yr	-0.02	0.06	0.98	0.72
	> 500 ktCO ₂ e per yr	-0.07	0.14	0.93	0.60
Period	Jan01-Dec07	1.74	0.08	5.71	0.00
	Jan10-Dec12	0.86	0.07	2.37	0.00
Interac- tions for host	<i>m2</i> :Hosts < 25 iss	0.07	0.09	1.07	0.45
	<i>m2</i> :Brazil	0.47	0.15	1.60	0.00
	<i>m2</i> :Chile	0.12	0.25	1.13	0.64
	<i>m2</i> :India	0.29	0.09	1.34	0.00
	<i>m2</i> :Indonesia	0.08	0.21	1.08	0.71
	<i>m2</i> :Malaysia	0.12	0.21	1.13	0.56
	<i>m2</i> :Mexico	-1.29	0.17	0.28	0.00
	<i>m2</i> :South Korea	-0.04	0.22	0.96	0.85
<i>m2</i> :Vietnam	0.54	0.19	1.71	0.00	
... and project type	<i>m2</i> :Types < 25 iss	-0.99	0.11	0.37	0.00
	<i>m2</i> :Biomass energy	-0.91	0.11	0.40	0.00
	<i>m2</i> :Coal bed/mine methane	0.26	0.31	1.29	0.41
	<i>m2</i> :EE industry	-0.89	0.23	0.41	0.00
	<i>m2</i> :EE own generation	-0.49	0.14	0.61	0.00
	<i>m2</i> :Fossil fuel switch	-0.86	0.23	0.42	0.00
	<i>m2</i> :Landfill gas	-0.41	0.14	0.67	0.00
	<i>m2</i> :Methane avoidance	-0.43	0.12	0.65	0.00
	<i>m2</i> :N2O	0.02	0.22	1.02	0.92
<i>m2</i> :Wind	-0.57	0.08	0.57	0.00	
... and size	<i>m2</i> :50-500 ktCO ₂ e per yr	0.14	0.07	1.15	0.03
	<i>m2</i> :> 500 ktCO ₂ e per yr	0.20	0.17	1.22	0.25
... and pe- riod	<i>m2</i> :Jan01-Dec07	-1.05	0.10	0.35	0.00
	<i>m2</i> :Jan10-Dec12	-0.68	0.08	0.51	0.00

Notes: One category of each independent variable is excluded from the regression. The excluded categories are China (for host country), hydro power (for project type), less than 50 ktCO₂e per year in expected emissions reduction (for project scale), and Jan08-Dec09 (for period). Durations that exceed 250 days are split into two parts, $m_2 = 1\{d \geq 250 \text{ days}\}$. As the typical duration from GSP start to request for registration is much shorter than the duration from GSP start to first issuance, the threshold d_{thres} is set at 250 days.

4 Results

This section presents and discusses the results. It is split into five subsections. The first discusses the robustness of the results over different specifications. The remaining subsections discuss specific results, with respect to host country, project type, scale, and time.

4.1 Robustness

A comparison of the regression results shows that lowering the threshold for merging categories brings new dummies into the regression, in moving from Specification 1a (Table 5) to Specification 1b (Table 6) and from Specification 3a (Table 9) to Specification 3b (Table 10). Lowering the threshold has a negligible effect on the coefficient of the existing dummies, but changes the coefficients of the "residual" categories that contain the projects that fall below the threshold.

Introducing interactions between the covariates and a dummy for duration length, in moving from Specification 1a (Table 5) to Specification 2a (Table 7), changes the structure of the results. In Specification 1a there is one hazard ratio for each category, but in Specification 2a there are two hazard ratios for each category, one for duration less than 3 years and one for duration more than 3 years. In this sense, Specification 2a gives a more detailed picture. In addition, Specification 2a satisfies the proportionality assumption, whereas Specification 1a does not. Not satisfying the proportionality assumption makes the results of Specification 1a susceptible to bias.

As a consequence of introducing period dummies, in moving from Specification 2a (Table 7) to Specification 3a (Table 9), all coefficients change, some more, others less. With a few exceptions (Brazil, Chile, and landfill gas), the qualitative results are unchanged. The reason why the coefficients change is that the distribution (of the project mass) over time varies across categories; e.g. 17% of projects hosted by Brazil started the GSP before 2006, while only 1% of the projects hosted by China did so. In Specification 2a, part of this variation is captured by host-country dummies. In Specification 3a, this variation is captured by period dummies. In this sense, Specification 3a is less prone to omitted variable bias and gives a more accurate picture than Specification 2a.

4.2 Host country

To satisfy the proportionality assumption, Specifications 2a (Table 7) and 3a (Table 9) include interactions between a dummy $m1$, for duration exceeding 3 years, and the covariates. In the presence of interactions, interpreting the results is not as straightforward as in Specification 1a (Table 5) with no interactions.

For example, what is the hazard ratio of a project hosted by India relative to a similar project hosted by China? Specification 1a shows a hazard ratio of 0.53. In Specifications 2a and 3a there are two types of effects: main effects and interactions effects. Given that $m1 = 1\{d \geq 3 \text{ years}\}$, the main effect shows the hazard ratio for d less than 3 years while the sum of the main effect and the interaction effect shows the hazard ratio for d more than 3 years. The difference between Specification 2a and Specification 3a is that Specification 3a controls for time. Specification 3a shows a hazard ratio of $\exp(-0.80) = 0.45$ for d less than 3 years and hazard ratio of $\exp(-0.80 - 0.11) = 0.40$ for d more than 3 years. Integrated over duration, a hazard ratio of less than 1.0 shows that a project hosted by India faces a longer time to market than an identical project by China.

Table 12 shows these hazard ratios for d less than 3 years and d more than 3 years for all host countries, including India. Table 12 relies on Specification 3b, because this Specification contains a more rich set of host countries than Specification 3a. A number of observations can be made based on Table 12. First, in terms of the hazard of first issuance, no country outperforms China. Second, no statistically significant deviation is observed for Argentina, Colombia, Ecuador, Peru, and Vietnam. Whether this is because of the large standard errors or because these countries are on par with China is impossible to say. Third, the remaining host countries underperform China. This follows from the observation that they have a hazard ratio less than 1.0, either for d less than 3 years or d more than 3 years, or both.

Table 12. Effect of host country on the hazard of first issuance, based on Specification 3b, where the excluded category is China (for host country).

Dummy for host country	Duration $d < 3$ years		Duration $d \geq 3$ years	
	Hazard ratio	p -value	Hazard ratio	p -value
Host countries < 10 iss	0.24	0.00	0.25	0.00
LDCs	0.13	0.00	0.40	0.01
Argentina	0.51	0.10	0.82	0.62

continued

Table 12. (continued)

Dummy for host country	Duration $d < 3$ years		Duration $d \geq 3$ years	
	Hazard ratio	p -value	Hazard ratio	p -value
Brazil	0.67	0.00	0.36	0.00
Chile	0.70	0.17	0.38	0.00
Colombia	0.60	0.19	0.53	0.08
Ecuador	0.88	0.72	0.41	0.12
Honduras	0.33	0.01	0.51	0.15
India	0.44	0.00	0.42	0.00
Indonesia	0.27	0.00	0.59	0.02
Israel	0.97	0.94	0.35	0.04
Malaysia	0.21	0.00	0.36	0.00
Mexico	0.33	0.00	0.27	0.00
Peru	0.45	0.08	0.48	0.05
South Africa	0.36	0.03	0.36	0.02
South Korea	0.38	0.00	0.73	0.18
Thailand	0.37	0.01	0.40	0.00
Vietnam	0.39	0.01	1.00	0.99

Notes: The hazard ratios are expressed relative to the excluded category. The p -value shows the probability of the null hypothesis that the hazard ratio is equal to one, i.e. that there is no difference between a project from the included category and one from the excluded category.

The fact that the Least Developed Countries (LDCs), a subgroup of 49 countries, some of which are host to only one CDM project, show a very low hazard of first issuance is noteworthy. Integrated over duration, this translates into a very long time to market and high share of failed projects. Why are projects hosted by LDCs at a disadvantage? Compared with China, projects hosted by LDCs are likely to face additional hurdles, both along the CDM project cycle and along the process of constructing and operating the underlying project. Obtaining a Letter of Approval (LoA) from the government of an LDC that may not have the processes in place for issuing LoAs may take more time than obtaining an LoA from the government of China. Poor infrastructure may also slow down construction, which will, given that CERs are issued *ex post* based on monitored emissions reductions, show up as additional delay in the time to market.

Table 12 shows that a project hosted by India has approximately half the hazard of first issuance as that of an identical project hosted by China. This provides some explanation of why the number of CERs issued to Chinese projects is disproportionately large relative to the number of projects to which China is host.

4.3 Project type

Table 13 shows a similar comparison for project type. A number of observations can be made based on it. First, in terms of the hazard of first issuance, the destruction of HFCs, decomposition of N₂O, and wind power outperform hydro power. Second, no statistically significant deviation is observed for the (prevention of) fugitive emissions, methane emissions, and solar power. Third, the remaining project types underperform hydro power.

Table 13. Effect of project type on the hazard of first issuance, based on Specification 3b, where the excluded category is hydro power (for project type).

Dummy for project type	Duration $d < 3$ years		Duration $d \geq 3$ years	
	Hazard ratio	p -value	Hazard ratio	p -value
Types < 10 iss	0.72	0.25	0.72	0.14
Biomass energy	1.08	0.52	0.45	0.00
Cement	0.82	0.57	0.23	0.00
Coal bed/mine methane	0.42	0.02	0.58	0.02
EE industry	1.08	0.75	0.24	0.00
EE own generation	0.62	0.00	0.42	0.00
EE supply side	0.73	0.41	0.29	0.01
Fossil fuel switch	0.92	0.71	0.52	0.00
Fugitive	0.60	0.27	0.43	0.06
HFCs	2.29	0.01	2.29	0.25
Landfill gas	0.61	0.01	0.92	0.55
Methane avoidance	0.84	0.30	0.89	0.39
N ₂ O	1.99	0.00	1.56	0.03
Solar	0.97	0.93	0.97	0.93
Wind	2.32	0.00	1.69	0.00

Notes: The hazard ratios are expressed relative to the excluded category. The p -value shows the probability of the null hypothesis that the hazard ratio is equal to one, i.e. that there is no difference between a project from the included category and one from the excluded category, e.g. that methane avoidance projects are on par with hydro power projects.

An interesting observation that has been made in previous studies is that the contribution of the CER revenue to the economic viability of a project depends very much on project type. Au Yong (2009) and Giger (2012) define the contribution of the CER revenue to the economic viability of a project as the difference between the Internal Rate of Return (IRR) with and without CER revenue.

According to Giger (2012), wind and hydro power projects lie at the low end of the spectrum, with an IRR difference in the range of three to four

percentage points, while coal bed/mine methane, landfill gas, and methane avoidance projects lie at the high end, with an IRR difference in the range of 10 to 30 percentage points. Interestingly, Table 13 shows that project types at the low end of the IRR difference spectrum exhibit a large hazard of first issuance, while projects at the high end of the IRR difference spectrum exhibit a low hazard of first issuance. This presents a challenge for the additionality of projects in the market, because it shows that projects that do not rely on the CER revenue for economic viability are the projects most likely to make it to market.

Another noteworthy observation is that the highly contentious HFCs projects have a very high hazard of first issuance. Schneider (2011) found that HCFC-22 plants produced less HFC-23 during periods when no emission credits could be claimed compared with periods during which HFC-23 destruction could be credited under the CDM, which suggests that the claimed emission reductions may not be additional.

4.3.1 Scale of the project

Regardless of how scale is defined, with expected yearly emission reduction entering the regression as a categorical variable (Specifications 2a, 3a and 3b), as a continuous variable (Specification 2b), or as a dummy for large-scale methodology, the result is the same - the larger the scale, the larger the hazard of first issuance.

The small-scale methodologies contain a number of concessions when compared with large-scale methodologies, such as allowing the same DOE to perform both the validation and the verification. Other things being equal, these concessions should reduce the time to market. However, here, the finding is the opposite. A likely explanation is that, because there is more at stake in large-scale projects in terms of potential CER revenue, more effort is put into pushing large projects through the CDM project cycle. The result shows that the concessions have not been able to counterbalance the effect of this additional effort.

Specifications 3a and 3b shows that projects that are expected to reduce emission by more than 500 ktCO₂e have a hazard between three and four times as large as projects that are expected to reduce emission by less than 50 ktCO₂e per year. This observation is noteworthy in the context of claims that very large projects are unlikely to be additional. The argument goes that large-infrastructure projects are typically part of strategic long-term plans of governments (see e.g. Carbon Market Watch, 2011). As such, they are not

driven solely by financial considerations, which make it unlikely that their implementation depends on CER revenue.³⁶

4.4 Time

Table 14 shows how, based on Specification 3a, the hazard of first issuance has changed over time when project characteristics are controlled for. In Specification 3a, time is split into three periods: Jan01-Dec07, Jan08-Dec09, Jan10-Dec12. Arguably, the split is somewhat artificial, but it serves the purpose of showing what the hazard was in the period that followed the request by CMP 5 in December 2009 to streamline and speed up CDM procedures, compared with the period that preceded it. The hypothesis is that the hazard of first issuance is larger in Jan10-Dec12 than in Jan08-Dec09.

Table 14. Effect of time on the hazard of first issuance, based on Specification 3a and two variations of Specification 3a.

Speci- fica- tion	Time split	Dummy for period	$d < 3$ years		$d \geq 3$ years	
			Hazard ratio	p -value	Hazard ratio	p -value
3a	Jan01-Dec07, Jan08-Dec09, Jan10-Dec12	Jan01-Dec07	11.97	0.00	1.39	0.64
3a	Jan01-Dec07, Jan08-Dec09, Jan10-Dec12	Jan10-Dec12	0.45	0.00	0.69	0.00
Vari- ation of 3a	Jan01-Dec07, Jan08-May10, Jun10-Dec12	Jan01-Dec07	13.64	0.00	1.52	0.56
Vari- ation of 3a	Jan01-Dec07, Jan08-May10, Jun10-Dec12	Jun10-Dec12	0.53	0.00	0.74	0.00
Vari- ation of 3a	Jan01-Dec07, Jan08-Dec10, Jan11-Dec12	Jan01-Dec07	17.23	0.00	2.00	0.33

continued

³⁶An example of a group of such projects, according to Lazarus and Chandler (2011), comprises high-efficiency coal power plants in China. Such plants may claim CERs if the project developer can demonstrate that in the absence of the CDM, a less-efficient coal power plant would have been built, which would result in more emissions.

Table 14. (continued)

Speci- fica- tion	Time split	Dummy for period	$d < 3$ years		$d \geq 3$ years	
			Hazard	p -value	Hazard	p -value
			ratio		ratio	
Vari- ation of 3a	Jan01-Dec07, Jan08-Dec10, Jan11-Dec12	Jan11-Dec12	0.83	0.02	1.13	0.13

Notes: The dummy for the period that begins with Jan08 is excluded from the regression. Thus, the hazard ratios of the remaining dummies are interpreted relative to that period. The p -value shows the probability of the null hypothesis that the hazard ratio is one, i.e. that the hazard of first issuance is the same in the included and excluded periods.

Somewhat surprisingly, the estimates show that in Jan10-Dec12 the hazard of first issuance was approximately only half what it was in Jan08-Dec09, proving the hypothesis wrong. Given that the changes envisaged by CMP 5 were implemented gradually by the CDM EB during 2010, Table 14 shows how the result changes if the split point between the second and third period is moved 6 and 12 months forward in time. The conclusion remains unchanged, with the hazard of first issuance being smaller in the third period than in the second.

For comparison, Table 15 shows how the hazard of request for registration has changed over time. Surprisingly, it shows that in Jan10-Dec12 the hazard of request for registration was much higher than in Jan08-Dec09.

Table 15. Effect of time on the hazard of submitting a registration request, based on Specification 3c.

Dummy for period	Duration $d < 250$ days		Duration $d \geq 250$ days	
	Hazard ratio	p -value	Hazard ratio	p -value
Jan01-Dec07	5.71	0.00	2.00	0.00
Jan10-Dec12	2.37	0.00	1.20	0.00

Notes: The dummy for the period Jan08-Dec09 is excluded from the regression. Thus, the hazard ratios of the remaining dummies are interpreted relative to the period Jan08-Dec09. The p -value shows the probability of the null hypothesis that the hazard ratio is one, i.e. that the hazard of requesting registration is the same in the included and excluded periods.

Summa summarum, when project characteristics are controlled for, the duration between GSP start and request for registration has reduced over time, whereas the duration between GSP start and first issuance has increased over time. To the extent that these changes can be attributed to the streamlined

CDM procedures, they show that the procedures have had a mixed success. However, attributing the change solely to the streamlined CDM procedures would be a gross overstatement. There are a plethora of omitted variables, not least the CER price, which has also changed over time.

5 Conclusions

This article answers two questions. First, what is the distribution of the time to market across all projects that started the Global Stakeholder Process (GSP) in 2003-2012? Second, how does the time to market depend on host country, the technology on which a project relies, the scale of the project, and time?

The answer to the first questions shows that not only is the carbon market littered with successful projects and Certified Emissions Reductions (CERs) issued by them, it is further littered with failed projects, that is, projects that either fail to be registered under the Clean Development Mechanism (CDM) or projects that have been successfully registered but that fail to issue any CERs. This conclusion is based on the finding that between GSP start and request for registration 30% of all projects fail, while another 20% fail between request for registration and first issuance. For an individual project, a failure means that it will not be able to recuperate any of the costs due to the CDM, including the cost of preparing the Project Design Document and the cost of validation. A project may fail to issue CERs for a number of reasons. These may be related to the CDM project cycle or the underlying project; e.g. a registered project may fail to generate CERs because of a missing grid connection.

For the other 50% of all projects, the median time to market is four years. Is four years a long time or not? It is definitely longer than what was expected at the outset of the CDM. For example, the World Bank's Carbon Finance Unit put the time to market (as defined here) at 1.5-3.5 years (World Bank, 2003). The considerable delay in bringing CDM projects to market has created a honey trap for project developers. The high initial prices for CERs lured more and more projects to seek registration under the CDM, and, because of the delay, the flow of projects gained momentum for years. As large volumes entered the market, it became clear that there was not sufficient demand, and the price for CERs dropped close to zero.

The answer to the second question shows that some of the best projects, in terms of being additional, are those that are least likely to make it to market, whereas some of the worst projects, in terms of not being additional, are

those that are most likely to make it to market. This presents a fundamental challenge for the CDM. The answer to this question also shows that, in contrast to what has been reported previously, not all durations measured along the CDM project cycle have increased over time.

A topic not covered by this article is how the hazard of first issuance of certain project types, e.g. HFCs destruction projects, has changed over time. This would make an interesting topic for future research. The methodology is provided in this article.³⁷

³⁷The complete *R* code for all of the estimations presented in this article is available on request.

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Appendix A

In this appendix, the probability distribution of the time to market, in terms of the survival function $S(d)$, is estimated separately for a number of selected subpopulations using the KM estimator. $S(d)$ gives the probability that a project has not issued any CERs as a function of duration d from GSP start.

The subpopulations are Chinese wind power (Figure 7), Chinese hydro power (Figure 8), Chinese biomass energy (Figure 9) and Chinese HFCs destruction projects (Figure 10). The subpopulations were chosen to illustrate the effect of the size of the subpopulation (in terms of the number of projects that have issued CERs) on the accuracy of the estimate of $S(d)$. The estimates show, as might be expected, that the accuracy of the estimate of $S(d)$ deteriorates as the size of the subpopulation decreases.

Differences among survival functions can also be tested using a log-rank test. For the null hypothesis that Chinese hydro and wind power projects have the same $S(d)$, a log-rank test gives the probability $p = 0.000$. The testing is done with the function *survdif* in the package *survival* (version 2.37-4) in the open-source software *R* (version 3.0.2, <http://www.r-project.org/>).

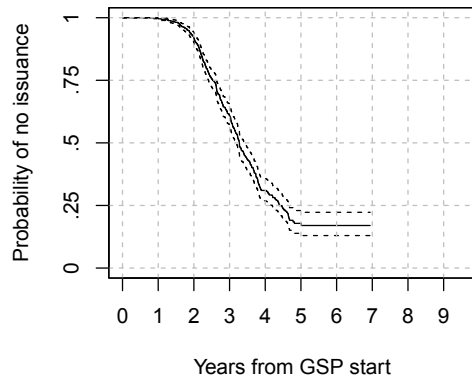


Figure 7. Time to market of Chinese wind power projects, of which a total of 1603 had started the GSP and 455 had issued CERs by the end of 2012. The solid line shows $S(d)$, the probability that the project has not issued any CERs as a function of days d from GSP start. The dotted lines demarcate the 95% confidence interval of $S(d)$.

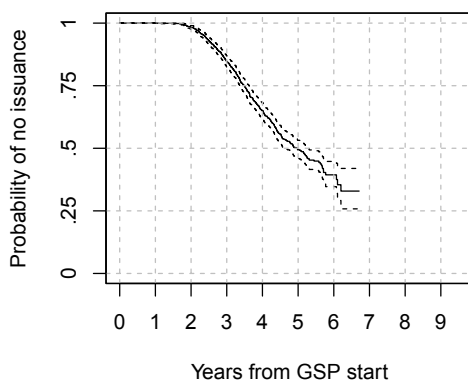


Figure 8. Time to market of Chinese hydro power projects, of which a total of 1576 had started the GSP and 378 had issued CERs by the end of 2012.

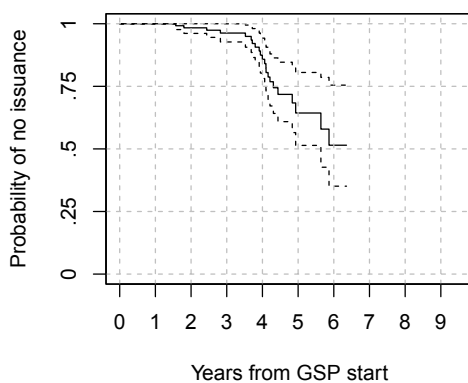


Figure 9. Time to market of Chinese biomass energy projects, of which a total of 191 had started the GSP and 22 had issued CERs by the end of 2012.

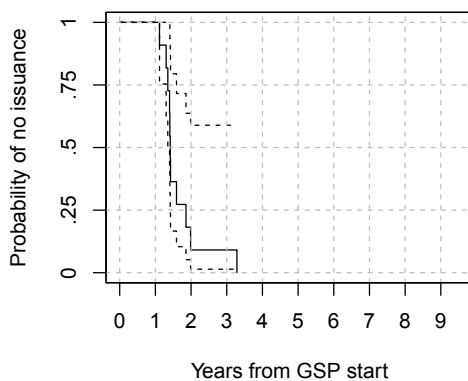


Figure 10. Time to market of Chinese HFCs destruction projects, of which a total of 11 had started the GSP and 11 had issued CERs by the end of 2012.

Appendix B

This appendix presents the results of a test of the proportionality assumption suggested by Grambsch and Therneau (1994) for Specification 1a, Specification 2a, and Specification 3a. The testing is done with function *cox.zph* in the package *survival* (version 2.37-4) in the open-source software *R* (version 3.0.2).

Table 16 shows the results of the per-variable tests and a global chi-square test. The results are shown in terms of the p -value of the null hypothesis that the proportionality assumption holds. If the p -value is small, the proportionality assumption is violated.

Table 16. Results of the test suggested by Grambsch and Therneau (1994).

Covariate	Dummy	p -value		
		Specif. 1a	Specif. 2a	Specif. 3a
Host	Hosts with < 25 iss	0.03	0.74	0.73
	Brazil	0.00	0.02	0.19
	Chile	0.02	0.86	0.74
	India	0.00	0.02	0.19
	Indonesia	0.62	0.87	0.81
	Malaysia	0.76	0.87	0.89
	Mexico	0.01	0.19	0.40
	South Korea	0.85	0.97	0.68
	Vietnam	0.45	0.73	0.65
Type	Types with < 25 iss	0.05	0.47	0.60
	Biomass energy	0.00	0.08	0.19
	Coal bed/mine methane	0.56	0.79	0.73
	EE industry	0.00	0.81	0.92
	EE own generation	0.44	0.59	0.64
	Fossil fuel switch	0.02	0.71	0.84
	Landfill gas	0.59	0.77	0.53
	Methane avoidance	0.57	0.25	0.43
	N2O	0.99	0.78	0.81
Wind	0.10	0.96	0.85	
Scale	50-500 ktCO ₂ e per yr	0.69	0.90	0.85
	> 500 ktCO ₂ e per yr	0.08	0.62	0.73
Period	Jan01-Dec07			0.12
	Jan10-Dec12			0.89
Interactions for host	$m1$:Hosts countries < 25 iss		0.33	0.54
	$m1$:Brazil		0.02	0.06
	$m1$:Chile		0.46	0.64
	$m1$:India		0.02	0.09

continued

Table 16. (continued)

Covariate	Dummy	<i>p</i> -value		
		Specif. 1a	Specif. 2a	Specif. 3a
	<i>m1</i> :Indonesia		0.67	0.62
	<i>m1</i> :Malaysia		0.82	0.85
	<i>m1</i> :Mexico		0.14	0.21
	<i>m1</i> :South Korea		0.87	0.63
	<i>m1</i> :Vietnam		0.33	0.29
... and project type	<i>m1</i> :Types < 25 iss		0.68	0.62
	<i>m1</i> :Biomass energy		0.20	0.31
	<i>m1</i> :Coal bed/mine methane		0.82	0.79
	<i>m1</i> :EE industry		0.63	0.76
	<i>m1</i> :EE own generation		0.28	0.31
	<i>m1</i> :Fossil fuel switch		0.76	0.71
	<i>m1</i> :Landfill gas		0.34	0.25
	<i>m1</i> :Methane avoidance		0.15	0.23
	<i>m1</i> :N2O		0.35	0.39
	<i>m1</i> :Wind		0.17	0.22
... and size	<i>m1</i> :50-500 ktCO ₂ e per yr		0.57	0.56
	<i>m1</i> :> 500 ktCO ₂ e per yr		0.67	0.74
... and pe- riod	<i>m1</i> :Jan01-Dec07			0.70
	<i>m1</i> :Jan10-Dec12			0.62
Global		0.00	0.21	0.56

Publication III

Roland Magnusson. Paradox of overlapping climate policy instruments.
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Paradox of overlapping climate policy instruments

Abstract

This paper illustrates a paradox in which overlapping climate policy instruments have the unintended consequence of accelerating global warming. The insight follows from a dynamic model, where a quota obligation for renewables is introduced alongside a carbon budget. It is shown that the quota obligation suppresses the carbon price, and induces a switch from low carbon intensity fossil fuels to high carbon intensity fossil fuels in generation to supply demand not met with renewables. These fuel switches front-load the schedule at which the carbon budget is exhausted and released to the atmosphere. Front loading the release schedule brings emissions forward in time and accelerates global warming. The amount of front-loading depends on the calibration of the model. With a calibration for the EU-28 power generation sector, at its largest, the front-loading amounts to 5.5 GtCO₂ in 2035, which is equal to 5-6 years' worth of emissions from electricity generation in EU-28.

1 Introduction

In the aftermath of COP 21, the question of instrument choice is as topical as ever, as the signatories of the Paris Agreement must decide how to transform contributions into policies.¹ The current policy paradigm to control global

¹COP21 refers to the 21st yearly session of the Conference of the Parties (COP) to the 1992 United Nations Framework Convention on Climate Change (UNFCCC) held in Paris. The agreement adopted at the conference is commonly referred to as the

warming is to rely on multiple instruments. The EU, among others, relies on a combination of a cap-and-trade scheme for greenhouse gases (GHG), subsidy schemes for the explicit promotion of renewable energy sources (RES) and energy efficiency standards. The EU Emissions Trading Schemes (EU ETS) covers approximately 42% of EU-28 emissions through a cap on emissions from large stationary sources, electricity generation in particular, and emissions from air traffic within the trading area (EEA, 2016).² National and supranational schemes that rely on quota obligations, such as the Swedish-Norwegian tradable green electricity certificate scheme, typically set an explicit target of increasing generation or generation capital by a given date.³

This paper combines elements from the literature pioneered by Tinbergen (1952), on the relation between the number of policy instruments and the number of policy targets, and the literature pioneered by Sinn (2008) on the relation between climate policies and the temporal incentives to extract fossil fuel deposits. Recent work with close relevance is Böhringer and Rosendahl (2010, 2011), which demonstrate that the introduction of a quota obligation for renewables alongside a cap-and-trade scheme for CO₂ promotes power generation by the most polluting fossil fuels. Other recent work include Kopsakangas-Savolainen and Svento (2013) and Liski and Vehviläinen (2015), which study the subsidised entry of wind power to the Nordic electricity market, and Lecuyer and Vogt-Schilb (2014) and Amigues, Le Kama, and Moreaux (2015), which study the transition from non-renewable to renewable energy sources.

A gap in the literature is how overlapping instruments interact in a dynamic set-up. To fill this gap, this paper studies how the a combination of a carbon budget and a quota obligation drives de-carbonisation in a dynamic set-up, which gives specific consideration to the time paths of the endogenous variables.⁴ For comparison, Lecuyer and Vogt-Schilb (2014) study how the transition is driven by just a carbon budget, Amigues et al. (2015) how the Paris Agreement.

²Excluding land use, land use changes and forestry (LULUCF), GHG emissions from the EU-28 in 2014 were approximately 4.27 GtCO₂e, of which 1.79 GtCO₂e were covered by the EU ETS. Emissions from electricity generation were approximately 1.05 GtCO₂e (EEA, 2016; Eurostat, 2016).

³The Swedish-Norwegian tradable green electricity certificate scheme (TGC) has an explicit target of increasing power generation from renewables by a total of 28.4 TWh between 2012 and 2020 (Swedish Energy Agency, 2016).

⁴This paper studies policy instrument overlap, i.e. interaction of policies targeted at the same sectors. The question of policies targeted at non-ETS sectors, such as road transport that fall under the Effort Sharing Regulation in the EU, is an entirely different albeit interesting question.

transition is driven by a declining stock of the non-renewable resource. This paper follows the practice of Lecuyer and Vogt-Schilb (2014) and Amigues et al. (2015) and assumes that generation is subject to capacity constraints and convex adjustment costs.⁵ In this set-up, it is shown that a quota obligation alongside a carbon budget is not just inefficient but may have the unintended consequence of accelerating rather than decelerating global warming.⁶

The inefficiency is attributable to a reallocation of emissions, and consequently abatement, within the carbon budget.⁷ With a calibration for the EU-28 power generation sector, the quota obligation roughly doubles the costs of complying with the carbon budget.⁸

The acceleration of global warming is attributable to a front-loading of the exhaustion of the carbon budget. The introduction of a quota obligation suppresses the carbon price, induces a switch from low carbon intensity fossil fuels to high carbon intensity fossil fuels in generation to supply residual demand, defined as demand met by non-renewables. As a consequence, the release of carbon budget is brought forward in time. Front-loading the release of the carbon budget leads to a higher level of cumulative CO₂ and a larger global temperature response.⁹ The amount of front-loading depends on the calibration of the model. It is shown that with a calibration for the EU-28 power generation sector, at its largest, the front-loading amounts to 5.5 GtCO₂ in 2035, which is equal to 5-6 years' worth of emissions from electricity generation in EU-28.

The result that a quota obligation may bring forward the release of carbon budget resembles the Green Paradox, proposed by Sinn (2008). In both the

⁵Lecuyer and Vogt-Schilb (2014) assume that initial generation capital has a carbon intensity equal to the current average thermal production mix in the EU and show that it is replaced by new gas fired generation in the mid-term and renewables in the long-term. Amigues et al. (2015) assume that initially generation relies on oil and show how oil is gradually replaced with a renewable resource.

⁶It is important to note that this result has no bearing on the desirability of quota obligations as stand-alone instruments, the study of which is not part of this paper.

⁷Aggregate emissions are unchanged unless the quota obligation, as a stand-alone instrument, is strict enough to push emissions below the carbon budget (Böhringer & Rosendahl, 2011).

⁸If there are other market failures in addition to global warming, such as energy security, the situation is different, see e.g. Fischer and Preonas (2010). In the model of this paper there are no other market failures.

⁹The schedule at which the carbon budget is released determines the global temperature response, albeit with a delay of 25-50 years. According to Hansen et al. (2005), it takes 25-50 years for the Earth's surface temperature to reach 60 percent of its equilibrium response to increased concentrations of greenhouse gases in the atmosphere.

Green Paradox and the paradox identified in this paper, the introduction of new policies accelerates global warming, albeit in this paper there is no strategic behaviour by the owners of fossil deposits.¹⁰ Within the literature pioneered by Sinn (2008), van der Ploeg and Withagen (2012, p. 358) show that with convex production costs of the renewable backstop, a backstop subsidy always accelerates the extraction of fossil fuel resources in regime where (i) global warming externalities are not internalised, (ii) fossil fuel reserves are fully exhausted in finite time, and (iii) in which there is an initial phase where only fossil fuel is used. The result by van der Ploeg and Withagen (2012) arises in a set-up where the first-best instrument, a CO₂ tax is not feasible, and governments resort to a second-best instrument, a renewable backstop subsidy.¹¹ In comparison, the paradox identified in this paper arises in a set-up where the GHG externality is fully internalised, by the carbon budget.

The set-up of this paper is believed to reflect the current situation of the EU where the perceived inability of the EU ETS to de-carbonise the economy is used as argument for subsidising RES.¹² The result that a quota obligation brings emissions forward in time may provide some explanation for the *Energiewende paradox*. In Germany, aggregate emissions are increasing despite power generation from renewables increasing both in relative as well as absolute terms (Graichen & Redl, 2014).¹³

The model of this paper is an optimal control problem with the interception of two targets. The first target is that RES generation must equal or exceed the quota obligation by time $t = \hat{T}$, where \hat{T} is fixed and equal to 2030. $\hat{T} = 2030$ has been chosen to match the EU 2030 target.¹⁴ Starting from $t = T$, where T is free, the economy is in steady state. The second target is that at T , RES

¹⁰The Green Paradox states that a gradual greening of economic policies exerts a stronger downward pressure on future fossil fuel prices than current fossil fuel prices and acts as an announced expropriation, which provokes deposit-owners to accelerate extraction (Sinn, 2009).

¹¹In the set-up of van der Ploeg and Withagen (2012, p. 358), the first-best instrument is CO₂ tax that increases at a rate equal to a Hotelling term minus a term that depends on marginal global warming damages.

¹²RES subsidies typically fall into one of three categories: investment subsidies, feed-in-tariffs and tradable green certificates (TGC).

¹³Between 2009 and 2013, emissions from German power supply has steadily increased as a consequence of a switch from gas to lignite and gas to hard coal (Graichen & Redl, 2014). The fuel switches have been driven by (i) an increase in the spread between the gas price and the hard coal price, and (ii) a decrease in the carbon price.

¹⁴The EU has adopted a binding target of increasing the share of RES to at least 27% of EU energy consumption by 2030 through the policy framework for climate and energy for 2020-2030 (European Commission, 2014).

generation capital must be sufficient to supply all electricity.¹⁵ To to solve the model, this paper relies on the rich literature that deals with multiple intercept problems, specifically on Bryson and Ho (1975), Stengel (1994) and Chachuat (2007). In comparison with current megamodels, e.g. those used to generate the EU Reference Scenario 2016, the model of this paper is very simple.¹⁶ The model of this paper is made as realistic as possible in its particular context while allowing it to be solved analytically, to the extent of decomposing the effect of a more ambitious quota obligation on emissions and cumulative CO₂ released to the atmosphere.

For simplicity, in the model, it is assumed that there just one sector, one quota, no end date for the carbon budget and no constraints on how big a share of the budget may be exhausted in a given year. In comparison, the EU ETS covers all stationary sources above a certain threshold, not just power utilities. Also flights within the European Economic Area are included in the EU ETS. Allowances for these sectors are either auctioned or allocated for free, depending on whether a sector is perceived to be at risk of carbon leakage or not.¹⁷ The EU ETS consists of a series of linked trading periods. The current rules allow for unlimited banking. Borrowing within a trading period is allowed. Borrowing is however constrained by the availability of future vintages.¹⁸ The rules allow operators to use allowances from year $y+1$ to meet compliance obligations in year y . Alternatively, operators can also borrow by using part of the accumulated surplus.¹⁹ The Market Stability Reserve (MSR), due to become operational in January 2019 will further facilitate borrowing, and as a consequence move the EU ETS a step closer to the model of this paper.²⁰

¹⁵At at T , the carbon budget may or may not have been exhausted.

¹⁶For a description of the models used to generate the EU Reference Scenario 2016 see Capros et al. (2016).

¹⁷The power sector is free to trade emission allowances with other ETS sectors, but not with the aviation sector. Airlines can buy allowances from stationary sources but not vice versa.

¹⁸For each year, a yearly allocation is established. The free allowances are allocated by the end of February, the rest is auctioned evenly throughout the year. Operators surrender allowances once a year. Surrendering of allowances for a given year takes place by end of April the following year (European Parliament and Council, 2003).

¹⁹By the end of 2015, the surplus was 1.83 GtCO₂e, which is equal roughly to one year's worth of emissions from the EU ETS (Sandbag, 2016).

²⁰The reserve will have an initial size equal to the back-loaded allowances from Phase 3 of the EU ETS (2013-2020). Allowances will be automatically released from the reserve if the number of allowances in the market falls below a certain minimum threshold (European Parliament and Council, 2015). Most importantly, the release is not dependent on the price, only on the number of allowances in circulation.

The remainder of this paper is structured as follows. The model is presented in Section 2. Analytical and numerical results are derived in Sections 3 and 4, respectively. Section 5 concludes. The derivation of necessary conditions to the social planner’s problem and longer proofs are given in the appendices.

2 Necessary conditions for the optimal control

Here, the model is presented and the necessary conditions for social planner’s choice of the optimal control are derived. The social planner’s objective is to minimise the total discounted cost C of supplying electricity by the choice of the controls $\mathbf{u}(i, t) = [y(i, t) \quad q(i, t)]$, where $y(i, t)$ is investments in generation capital, $q(i, t)$ is generation, i is an index for technology and t is time.²¹ The state variables to the control problem are $[k(i, t) \quad b(t)]$, where $k(i, t)$ is generation capital, which is technology specific and does not depreciate, and $b(t)$ is the remaining carbon budget at time t .²² Table 1 shows the interdependencies between the control variables and the state variables.

Table 1. Interdependencies between the state and the control variables

Type	Var.	Description	Interdependencies	Initial value
State	$k(i, t)$	Generation capital	$\dot{k}(\text{RES}, t) = y(i, t)$	$k(\text{RES}, 0) = 0$
State	$b(t)$	Carbon budget	$\dot{b}(t) = -\sum_{i \in I} \epsilon(i)q(i, t)$	$b(0) = \Theta$
Control	$y(i, t)$	Investment	.	.
Control	$q(i, t)$	Generation	$0 \leq q(i, t) \leq k(i, t)$.

For simplicity, it is assumed that demand for electricity is fixed and equal to Ω . Electricity can be generated by combustion of GHG emitting fossil fuels or by a renewable energy source (RES). The generation technologies are indexed by $i \in I = \{1, \dots, m, \text{RES}\}$.²³ The set I is finite and $\epsilon(i)$ is strictly positive for fossil fuels and zero for RES.²⁴ The following properties of the model drive de-carbonisation of power generation,

- i generation from renewables has a zero cost of operation whereas fossil fuels do not,

²¹The social planner only considers the costs of supplying electricity. Other components of social welfare, such as social damages from GHG, are not included in the cost function.

²² $\mathbf{u}(i, t)$ and $\mathbf{x}(i, t)$ are column vectors.

²³It is assumed that there are no pair of technologies (i, j) that have the same carbon intensity, $\epsilon(i) \neq \epsilon(j)$. This assumption is required for the analytical results.

²⁴Lignite is more carbon intensive than hard coal. As a consequence, a kWh generated by the combustion of lignite reduces the carbon budget more than a kWh generated by the combustion of hard coal.

- ii a carbon budget of b , which has an initial size equal to Θ , and
- iii a quota obligation, which requires that electricity generated from RES $q(i, t)$, and consequently generation capital, $k(i, t)$, where $i = \text{RES}$, is equal or larger to a fixed target equal to Φ at $t = \hat{T}$.

Even without (ii) and (iii), all power generation will eventually be de-carbonised. In the presence of (i)-(iii), the transition path is different than in the presence of just (i). A situation where the carbon budget is not exhausted is perfectly conceivable, as is the situation in which the carbon leads to more RES based generation at $t = \hat{T}$ than required by the quota obligation. The situation in which the entire carbon budget is exhausted before \hat{T} is also perfectly conceivable.²⁵

The strategy of complying with the quota obligation is to solve for the optimal control in parts. First, the optimal control, and associated cost C_1 , is solved for $[0, \hat{T}]$. Second, the optimal control, and associated cost C_2 , is solved for $[\hat{T}, T]$. The total cost C is equal to the sum of C_1 and C_2 . By this strategy, the quota obligation can be taken as a state inequality constraint over the optimisation over the first period. The first period is linked to the second period by the terminal cost, which is equal to future costs given an optimal choice of the controls in the second period. At the end of the second period, at $t = T$, the economy is in steady state. In the steady state, by necessity, all power is supplied by renewables, investments in RES are zero, generation with fossil fuels is zero and emissions are zero.²⁶ Since the cost after T is zero, the time after T is omitted from the optimisation.

2.1 Optimal control over the first period

The objective over the first period $[0, \hat{T}]$ is to minimise

$$C_1 = \int_0^{\hat{T}} e^{-rt} \sum_{i \in I} c_i(\mathbf{u}(i, t)) dt + C_2^*, \quad i \in I = \{1, \dots, m, \text{RES}\}, \quad (1)$$

²⁵Whether or not the carbon budget will be exhausted by T or not depends on the choice of parameter values. A generous carbon budget, a low cost of increasing RES generation capacity and high costs of fossil fuels work in favour of leaving a part of the carbon budget unused.

²⁶In the limit $t \rightarrow \infty$ it must be that $k(\text{RES}, t) \rightarrow \Omega$. If not not, the carbon budget will be violated. In principle, with $q(i, t) \rightarrow 0$ for $i \in I \setminus \text{RES}$, T could be infinite. However, for simplicity, it is assumed that T is finite. While not modelled explicitly, because of the lumpiness of capital, supplying very small amounts of fossil fuel based electricity is not feasible.

by the choice of the controls $\mathbf{u}(i, t) = \begin{bmatrix} y(i, t) & q(i, t) \end{bmatrix} \in U$, where U is the control region, which takes the form of a hypercube, such that

$$y(i, t) \in [0, \bar{y}(i)], \quad (2)$$

$$q(i, t) \in [0, k(i)], \forall i \in I, \quad (3)$$

and $c_i(\cdot)$ is a technology specific cost function, which is a function of the controls only. The necessary conditions for the optimal control are derived for a very general case of the cost function $c_i(\cdot)$, for which the following hold true,

i fossil fuel fired generation capital is in abundance and does not depreciate, which is equivalent to assuming that that generation capital can be increased without cost, $dc_i(\mathbf{u})/dy(i, t) = 0$ for $i \in I/RES$,²⁷

ii marginal investment costs in RES generation capital are positive and strictly increasing, which reflects a competitive industry with increasing marginal costs, $dc_i(\mathbf{u})/dy(i, t) > 0$ and $d^2c_i(\mathbf{u})/dy(i, t)^2 > 0$ for $i = RES$,

iii generation with fossil fuels has a strictly positive cost of operation, $dc_i(\mathbf{u})/dq(i, t) > 0$ for $i \in I/RES$,

iv generation with RES has a zero cost of operation, $dc_i(\mathbf{u})/dq(i, t) = 0$ for $i = RES$.

The minimisation of Eq. 1 must obey a number of constraints. First, the equations of motion of the state variables,

$$\dot{\mathbf{x}}(i, t) = \mathbf{f}(t, \mathbf{u}(t)), \forall i \in I, \text{ where} \quad (4)$$

$$\dot{\mathbf{x}}(i, t) = \begin{bmatrix} \dot{k}(i, t) \\ \dot{b}(t) \end{bmatrix}, \text{ and} \quad (5)$$

$$\mathbf{f}(t, \mathbf{u}(t)) = \begin{bmatrix} y(i, t) \\ -\sum_{i \in I} \epsilon(i)q(i, t) \end{bmatrix}. \quad (6)$$

Second, the initial values of the state variables,

$$k(i, 0) = k_0(i) \geq 0, i \in I \setminus RES, \quad (7)$$

$$k(i, 0) = 0, i = RES, \quad (8)$$

$$b(0) = \Theta > 0. \quad (9)$$

²⁷Assuming otherwise, e.g. assuming an initial stock which must be maintained or which depreciates, adds another level of complexity which does not allow for any meaningful analytical results.

Third, the terminal constraints on the state variables,

$$\psi(\hat{T}, \mathbf{x}(i, \hat{T})) = \Phi - k(i, \hat{T}) \leq 0, i = \text{RES}, \quad (10)$$

$$\kappa(\hat{T}, \mathbf{x}(i, \hat{T})) = -b(\hat{T}) \leq 0. \quad (11)$$

which state that the quota obligation and the carbon budget, both of which are treated as politically determined exogenous constraints, may not be violated. Fourth, the complementary slackness conditions of the terminal constraints,

$$\xi\psi(\hat{T}, \mathbf{x}(i, \hat{T})) = 0, \xi \geq 0, i = \text{RES}, \quad (12)$$

$$\nu\kappa(\hat{T}, \mathbf{x}(i, \hat{T})) = 0, \nu \geq 0, \quad (13)$$

from which it follows that that if the quota obligation of Eq. 10 is not binding, that $\xi = 0$. Fifth, inequality constraints, each of which explicitly depend on the controls,

$$\mathbf{g}(t, \mathbf{x}(i, t), \mathbf{u}(i, t)) = \begin{bmatrix} -y(i, t) \\ y(i, t) - \bar{y}(i) \\ -q(i, t) \\ q(i, t) - k(i, t) \\ \Omega - \sum_{i \in I} q(i, t) \end{bmatrix} \leq \mathbf{0}, \forall i \in I, \quad (14)$$

where $q(i, t) - k(i, t) \leq 0$ requires that generation may not exceed generation capital and $\Omega - \sum_{i \in I} q(i, t) \leq 0$ that aggregate generation must equal or exceed demand, which are physical requirements of the power system.

By adjointment of the equations of motion by the adjoint variable $\boldsymbol{\lambda}(i, t)$ and the inequality constraints by the Lagrange multiplier $\boldsymbol{\sigma}(i, t) \geq 0$, the Lagrangian reads

$$L_1(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma}) = e^{-rt} \sum_{i \in I} c_i(\mathbf{u}(i, t)) + \boldsymbol{\lambda}^T \mathbf{f}(t, \mathbf{u}) + \boldsymbol{\sigma}^T \mathbf{g}(t, \mathbf{x}, \mathbf{u}), \quad (15)$$

where

$$\boldsymbol{\lambda}(i, t) = \begin{bmatrix} \lambda_k(i, t) \\ \lambda_b(t) \end{bmatrix}, \text{ and} \quad (16)$$

$$\boldsymbol{\sigma}(i, t) = \left[\sigma_{\underline{y}}(i, t) \quad \sigma_{\bar{y}}(i, t) \quad \sigma_q(i, t) \quad \sigma_{\bar{q}}(i, t) \quad \sigma_{cap}(i, t) \quad \sigma_{gen}(t) \right]^T. \quad (17)$$

Table 2 gives an outline of the elements of the adjoint variable $\boldsymbol{\lambda}(i, t)$ and the elements of the Lagrange multiplier $\boldsymbol{\sigma}(i, t)$, both of which are expressed in present-value terms, i.e. discounted to $t = 0$.

$\lambda_k(i, \hat{T})$ and $\lambda_b(\hat{T})$ give the change in future costs at \hat{T} in response to a tiny perturbation of respective state variable at \hat{T} (Chachuat, 2007, p. 124-125),

$$\lambda_k(i, \hat{T}) = \frac{\partial C_2^*}{\partial k(i, t)}, \quad i \in I, \quad (18)$$

$$\lambda_b(\hat{T}) = \frac{\partial C_2^*}{\partial b(t)}. \quad (19)$$

It follows that $\lambda_k(i, t)$ and $\lambda_b(t)$ are both negative. $\lambda_k(i, t) \leq 0$ because an additional unit of RES generation capital reduces the need for investments and as a consequence either has no effect or reduces costs. $\lambda_b(t) \leq 0$ because an increase of the carbon budget either has no effect or decreases costs.

It shown in Appendix A that the necessary conditions with respect to the marginal value of generation capital read

$$\lambda_k(i, \hat{T}^-) = \lambda_k(i, \hat{T}^+), \quad i \in I \setminus \text{RES}, \quad (20)$$

$$\lambda_k(i, \hat{T}^-) = \lambda_k(i, \hat{T}^+) - \xi, \quad i = \text{RES}, \quad (21)$$

$$\lambda_k(i, t) + \sigma_{\bar{y}}(i, t) - \sigma_{\bar{y}}(i, t) = -e^{-rt} \frac{\partial c_i(\mathbf{u})}{\partial y(i, t)}, \quad i \in I, \quad (22)$$

$$\sigma_{gen}(t) + \sigma_q(i, t) = e^{-rt} \frac{\partial c_i(\mathbf{u})}{\partial q(i, t)} - \epsilon(i) \lambda_b(t) + \dot{\lambda}_k(i, t), \quad i \in I, \quad (23)$$

where \hat{T}^- denotes the time just before \hat{T} and \hat{T}^+ just after \hat{T} . Eq. 20 states that the marginal value of fossil fuel fired generation capital is continuous at \hat{T} . Eq. 21 states that the marginal value of RES generation capital may be discontinuous at \hat{T} if the quota obligation in Eq. 10 is binding, because if the quota obligation is binding, ξ is either zero or strictly positive. Eq. 22 states that for an interior point solution for investments, the marginal value of generation capital must equal investment costs, while Eq. 23 states that for an interior point solution for generation, the marginal value of the generation requirement, interpreted as the electricity price, must equal the sum of the fuel cost, the carbon cost and the opportunity cost of capital.

Further, it is shown in Appendix A that the necessary conditions with respect to the marginal value of the remaining carbon budget, $\lambda_b(t)$, interpreted as the carbon price, read

$$\dot{\lambda}_b(t) = 0, \quad (24)$$

$$\lambda_b(\hat{T}^-) = \lambda_b(\hat{T}^+) - \nu. \quad (25)$$

Eq. 24 and 25 state that the present value of the carbon price is constant, except at \hat{T} , at which there may be a discontinuity, a increase in the carbon

Table 2. Elements of $\lambda(i, t)$ and $\sigma(i, t)$.

Element	Description	Constraint	Comp. slackness condition
$\lambda_k(i, t)$	Change of $k(i, t)$ over time	$\dot{k}(i, t) = y(i, t)$.
$\lambda_b(t)$	Change of $b(t)$ over time	$\dot{b}(t) = -\sum_{i \in I} \epsilon(i)q(i, t)$.
$\sigma_{\underline{y}}(i, t) \geq 0$	Boundary of control region	$-y(i, t) \leq 0$	$\sigma_{\underline{y}}(i, t)y(i, t) = 0$
$\sigma_{\bar{y}}(i, t) \geq 0$	Boundary of control region	$y(i, t) - \bar{y}(i, t) \leq 0$	$\sigma_{\bar{y}}(i, t)(y(i, t) - \bar{y}(i, t)) = 0$
$\sigma_{\underline{q}}(i, t) \geq 0$	Boundary of control region	$-q(i, t) \leq 0$	$\sigma_{\underline{q}}(i, t)q(i, t) = 0$
$\sigma_{cap}(i, t) \geq 0$	Capacity constraint	$q(i, t) - k(i, t) \leq 0$	$\sigma_{cap}(i, t)(q(i, t) - k(i, t)) = 0$
$\sigma_{gen}(t) \geq 0$	Generation requirement	$\Omega - \sum_{i \in I} q(i, t) \leq 0$	$\sigma_{gen}(t)(\Omega - \sum_{i \in I} q(i, t)) = 0$

price.²⁸ It follows from the complementary slackness condition of Eq. 13 that if the carbon budget has not been exhausted by \hat{T} , that $\nu = 0$, and that there is no increase. If $b(\hat{T}) = 0$, then $\nu \geq 0$, and there may or may not be a increase.

2.2 Optimal over control the second period

The objective over the second period $[\hat{T}, T]$ is to minimise

$$C_2 = \int_{\hat{T}}^T e^{-rt} \sum_{i \in I} c_i(\mathbf{u}(i, t)) dt, \quad (26)$$

$$i \in I = \{1, \dots, m, \text{RES}\}$$

by choice of the controls $\mathbf{u}(i, t) = [y(i, t) \quad q(i, t)] \in U$. There is no terminal cost for the optimisation over the second period. T is endogenous. T is not part of the control set, but is determined by the investments in RES generation capital such that

$$k(\text{RES}, T) = \int_0^T y(\text{RES}, t) dv = \Omega, \quad (27)$$

where Ω is the demand for electricity. The minimisation over the second period is subject to the same equations of motion of the state variables and the same

²⁸A increase in the carbon price represents a reduction in the level of ambition given that $\lambda_b(0) \leq 0$.

inequality constraints as the minimisation over the first period, but subject to different initial values of the state variables, which read

$$k(i, \hat{T}^+) = k(i, \hat{T}^-), \quad i \in I, \quad (28)$$

$$b(\hat{T}^+) = b(\hat{T}^-), \quad (29)$$

and a different terminal constraint, which reads

$$\eta(T, \mathbf{x}(i, T)) = -b(T) \leq 0, \quad (30)$$

and a different complementary slackness condition of the terminal constraint, which reads

$$\gamma \eta(T, \mathbf{x}(i, T)) = 0. \quad (31)$$

It is shown in Appendix B that the necessary conditions for the optimal control over the second period are the same as the necessary conditions for the optimal control over the first period, except for the traversal conditions, which read

$$\lambda_k(i, T^-) = 0, \quad i \in I, \quad (32)$$

$$\lambda_b(T^-) = -\gamma. \quad (33)$$

Eq. 32 states that at the steady state, at T , the marginal value of generation capital is zero for all technologies including RES. Eq. 33 states that the carbon price is equal to $-\gamma$ at T . It follows from Eq. 24 and Eq. 31 that if the carbon budget has not been exhausted by T , i.e. $b(T) > 0$, then $\gamma = 0$, and the carbon price $\lambda_b(t)$ is zero over both periods. If, however, the carbon budget is exhausted by T , i.e. $b(T) = 0$, then $\gamma \geq 0$, and the carbon price may be zero or negative.

3 Analytical results

Next, the analytical results are derived. The main analytical result is that tightening the quota obligation unambiguously suppresses the carbon price and postpones switches from high carbon intensity fuels to low carbon intensity fuels in generation to supply residual demand. Residual demand is defined as demand met by non-renewables. For this section, the following restrictions are adopted.

- [i] Total investment costs are quadratic, which is analogous to assuming that marginal investment costs are linear,

$$\frac{\partial c_{\text{RES}}(\mathbf{u}(i, t))}{\partial y(\text{RES}, t)} = \beta y(\text{RES}, t). \quad (34)$$

ii Fuel costs may vary across fuels i but not over time t ,

$$\frac{\partial c_i(\mathbf{u}(i, t))}{\partial q(i, t)} = \alpha(i). \quad (35)$$

iii $\xi > 0$, from which it follows that $k(\text{RES}, \hat{T}) = \Phi$ by Eq. 12. The corner-point equilibrium where $\xi = 0$ is non-interesting because in it the carbon budget alone leads to a level of RES generation, which exceeds the quota obligation.

iv $b(\hat{T}) > 0$, from which it follows that $\nu = 0$ by Eq. 13. By a similar argument, the corner-point equilibrium where $b(\hat{T}) = 0$ is non-interesting because the steady state is reached before the requirement of the quota obligation is to be met.

v $b(T) = 0$, from which it follows that $\gamma \geq 0$ by Eq. 31. The case where $b(T) > 0$ is non-interesting because it entails a zero carbon price over the whole transition.

(i) and (ii) are restrictions on the cost function $c_i(\mathbf{u}(i, t))$, whereas (iii)-(v) are restrictions that rule out non-interesting cases. The cost parameters $\alpha(i)$ and β are independent of time. That $\alpha(i)$ is constant reflects the assumption that the carbon budget covers only a small share of world emissions, and consequently world fossil fuel consumption. This assumption reflects the EU ETS. As a consequence of (ii), changes in the demand for fossil fuels within the carbon budget has no effect on fuel prices.²⁹ Another way to think about the assumption that $\alpha(i)$ is constant is that fossil fuel fired generation is constrained by the size of the carbon budget but not by the size of fossil fuel deposits.

Lemma 1 *A quota obligation Φ cannot reduce the total discounted cost of supplying electricity C . It can only increase it.*

Proof *The quota obligation is a constraint to the optimisation problem. Any eligible control in the presence of the quota obligation can be attained in the absence of the quota obligation.*

Lemma 2 *The marginal value of the carbon budget, interpreted as the carbon price, follows Hotelling's rule. In present value terms, i.e. discounted to $t = 0$, the carbon price is constant.³⁰*

$$\lambda_b(t) = \lambda_b(0) \quad (36)$$

²⁹In 2015, the EU-28 accounted for 6.8 per cent of world consumption of coal and 11.5 per cent of world consumption of natural gas (BP, 2016).

³⁰It follows that in current value terms, i.e. compounded to t , the carbon price equals $e^{rt}\lambda(0)$.

Proof Eq. 24 states that the change of the present value of the carbon price is zero.

Lemma 3 Investments in RES are increased up to the point where marginal investment costs in RES equal the marginal value of RES capital,

$$\frac{\partial c_{\text{RES}}(\mathbf{u})}{\partial y(\text{RES}, t)} = -e^{rt} \lambda_k(\text{RES}, t), \quad (37)$$

where $e^{rt} \lambda_k(\text{RES}, t)$ is the marginal value of RES capital at t in current value terms.

Proof Eq. 22 states that $\lambda_k(i, t) + \sigma_{\underline{y}}(i, t) - \sigma_{\bar{y}}(i, t) = -e^{-rt} \partial c_i(\mathbf{u}) / \partial y(i, t)$. With a zero cost of operation for RES and a non-zero cost of operation for fossil fuels, investments in RES are necessarily strictly positive over $[0, T]$, from which it follows, by the complementary slackness condition, that $\sigma_{\underline{y}}(\text{RES}, t) = 0$. It is assumed that the upper boundary $\bar{y}(\text{RES})$ is large enough as not to limit the level of investments. Then, $\sigma_{\bar{y}}(\text{RES}, t) = 0$. Substitution of $\sigma_{\underline{y}}(\text{RES}, t) = 0$ and $\sigma_{\bar{y}}(\text{RES}, t) = 0$ into Eq. 22 give Eq. 37.

Lemma 4 For all fossil fuel fired generation technologies, the marginal value of increasing generation capital $\lambda_k(i, t)$ is zero,

$$\lambda_k(i, t) = 0, \quad \forall i \in I \setminus \text{RES}. \quad (38)$$

Proof Substitution of $\partial c_i(\mathbf{u}) / \partial y(i, t) = 0$ for $i \in I \setminus \text{RES}$ into Eq. 22, gives Eq. 38 for $y(i, t) \in [0, \bar{y}(i)]$.

Lemma 5 If generation $q(i, t)$ with technology i is strictly positive, the following must hold,

$$\sigma_{\text{gen}}(t) = e^{-rt} \alpha(i) - \epsilon(i) \lambda_b(0) + \dot{\lambda}_k(i, t). \quad (39)$$

whereas if it is zero, the following must hold,

$$\sigma_{\text{gen}}(t) \leq e^{-rt} \alpha(i) - \epsilon(i) \lambda_b(0) + \dot{\lambda}_k(i, t), \quad (40)$$

Proof Eq. 22 states that $\sigma_{\text{gen}}(t) + \sigma_q(i, t) = e^{-rt} \partial c_i(\mathbf{u}) / \partial q(i, t) - \epsilon(i) \lambda_b(t) + \dot{\lambda}_k(i, t)$. By substitution of $\partial c_i(\mathbf{u}(i, t)) / \partial q(i, t) = \alpha(i)$ from Eq. 35 and $\lambda_b(t) = \lambda_b(0)$ from Eq. 36, Eq. 23 reads

$$\sigma_{\text{gen}}(t) + \sigma_q(i, t) = e^{-rt} \alpha(i) - \epsilon(i) \lambda_b(0) + \dot{\lambda}_k(i, t), \quad (41)$$

where $\sigma_q(i, t) \geq 0$. Eq. 39 and 40 follow from the complementary slackness condition $\sigma_q(i, t) q(i, t) = 0$. If generation is strictly positive it holds that $\sigma_q(i, t) = 0$.

Eq. 39 states that the marginal cost of increasing generation, interpreted as the electricity price, must be equal across all technologies with non-zero generation. The marginal cost of increasing generation is the sum of the fuel cost, the carbon cost and the change in the marginal value of increasing generation capital, all of which are expressed in present value terms, i.e. discounted to $t = 0$.

Lemma 6 *At every point over the transition, demand is met by RES and a single fossil fuel. First, all available RES capital is used. Second, the remainder is met with the fossil fuel with the lowest cost of combustion.*

Proof Eq. 40 states that generation is dispatched in order of increasing costs. Because $\lambda_k(i, t) = 0$ for fossil fuels, the sum of the fuel cost and the carbon cost alone determine which fossil fuel is combusted to meet residual demand.

Lemma 7 *For every exogenous assignment of fossil fuel prices $\alpha(i)$, $i \in I/\text{RES}$, and endogenous carbon price $\lambda_b(0)$, there is an ordered subset*

$$S \equiv \{1, \dots, n\} \subset I/\text{RES}, \quad (42)$$

and a fuel switch schedule,³¹

$$\hat{S} \equiv \{\hat{t}_0, \hat{t}_1, \dots, \hat{t}_n\}, \quad (43)$$

which shows what fossil fuels are used over the transition and in what order to supply residual demand. For two consecutive elements in S , it must be that $\epsilon(i) > \epsilon(i+1)$ and that $\alpha(i+1) > \alpha(i)$.

Proof A fuel i is in S if and only if it is the least fossil cost fuel, $\min_i \{e^{-rt}\alpha(i) - \epsilon(i)\lambda_b(0)\}$ where $i \in I/\text{RES}$ at some t . For a high carbon intensity fuel to be part of S it must be cheaper than the low carbon intensity fuel

Lemma 8 *There is a one-to-one correspondence, a bijection, between the carbon price $\lambda_b(0)$ and the fuel switch times \hat{t}_i . An increase of the carbon price $\lambda_b(0) < 0$, i.e. a reduction in the level of ambition, is accompanied by a postponement of \hat{t}_i .*

Proof *The carbon cost increases at the rate of interest. As a consequence, high carbon intensity fuels lose their competitiveness quicker than low carbon intensity fuels. At the time of a switch from one fossil fuel to another, from*

³¹ \hat{t}_i shows the time when the use of fuel i ends and the use of fuel $i+1$ begins. $\hat{t}_0 < 0$ shows the time when the combustion of fuel $i = 1$ begins. At $\hat{t}_n \equiv T$ the use of the least carbon intensive fossil fuels ends, after which all electricity is supplied by RES.

fuel i to fuel $i + 1$, which occurs at \hat{t}_i , the cost of combustion of fuel i and $i + 1$ must be equal,

$$e^{-r\hat{t}_i}\alpha(i) - \epsilon(i)\lambda_b(0) = e^{-r\hat{t}_i}\alpha(i + 1) - \epsilon(i + 1)\lambda_b(0), \quad (44)$$

which is equivalent to

$$-e^{r\hat{t}_i}\lambda_b(0) = \underbrace{\frac{\alpha(i + 1) - \alpha(i)}{\epsilon(i) - \epsilon(i + 1)}}_{>0}. \quad (45)$$

Figure 1 illustrates the case of $S = \{1, 2, 3\}$ for which it must hold, by Lemma 7, that $\epsilon(1) > \epsilon(2) > \epsilon(3)$ and $\alpha(1) < \alpha(2) < \alpha(3)$. At $t = 0$, residual demand is met by fuel $i = 1$, between \hat{t}_1 and \hat{t}_2 residual demand is met by fuel $i = 2$. From \hat{t}_2 onwards residual demand is met by fuel $i = 3$. Lemma 8 shows that \hat{t}_i pins down the carbon price.

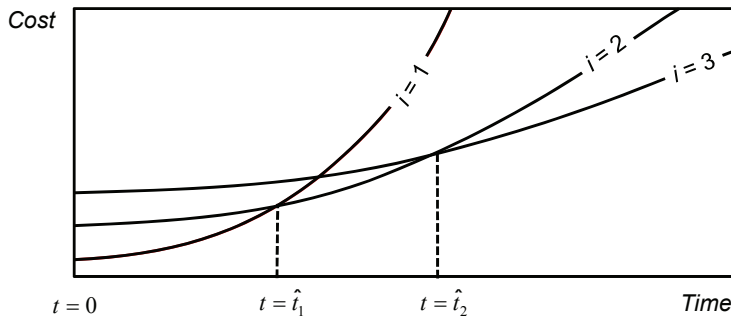


Figure 1. Change in the cost of combustion over time of three fossil fuels $i \in S = 1, 2, 3$.

It follows from Eq. 39 that over the transition, between $t = 0$ and $t = T$, the change in the marginal value of a unit of RES capital must equal the cost of generating one unit of output with the least cost fossil fuel,

$$\dot{\lambda}_k(\text{RES}, t) = \min_{i \in S} \{e^{-rt}\alpha(i) - \epsilon(i)\lambda_b(0)\}. \quad (46)$$

The marginal value of RES capital between $t = 0$ and $t = \hat{T}$ is found by integrating both sides of Eq. 46 from t to \hat{T}

$$\int_t^{\hat{T}} \frac{\partial \lambda_k(\text{RES}, s)}{\partial s} ds = \int_t^{\hat{T}} \min_{i \in S} \{e^{-rs}\alpha(i) - \epsilon(i)\lambda_b(0)\} ds, \quad (47)$$

which is equivalent to

$$\lambda_k(\text{RES}, \hat{T}) - \lambda_k(\text{RES}, t)|_{t \leq \hat{T}} = \int_t^{\hat{T}} \min_{i \in S} \{e^{-rs}\alpha(i) - \epsilon(i)\lambda_b(0)\} ds, \quad (48)$$

which reads by substitution of $\lambda_k(\text{RES}, \hat{T}^-) = \lambda_k(\text{RES}, \hat{T}^+) - \xi$ from Eq. 21,

$$\lambda_k(\text{RES}, t)|_{t \leq \hat{T}} = - \int_t^{\hat{T}} \min_{i \in S} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds + \lambda_k(\text{RES}, \hat{T}^+) - \xi. \quad (49)$$

By analogy, the marginal value of RES capital between $t = \hat{T}$ and $t = T$ is found by integrating both sides of Eq. 46 from t to T ,

$$\int_t^T \frac{\partial \lambda_k(\text{RES}, s)}{\partial s} ds = \int_t^T \min_{i \in S} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds, \quad (50)$$

which is equivalent to

$$\lambda_k(\text{RES}, T) - \lambda_k(\text{RES}, t)|_{t > \hat{T}} = \int_t^T \min_{i \in S} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds, \quad (51)$$

which reads by substitution of $\lambda_k(\text{RES}, T) = 0$ from Eq. 32,

$$\lambda_k(\text{RES}, t)|_{t > \hat{T}} = \int_t^T \min_{i \in S} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds. \quad (52)$$

Lemma 9 *The marginal value of RES capital at $t \in [0, T]$ can be written as a sum of integrals over the fuel switch schedule $\hat{S} \equiv \{\hat{t}_1, \dots, \hat{t}_n\}$, where $\hat{t}_n \equiv T$,*

$$\lambda_k(\text{RES}, t) = -\pi(t) - \mathbf{1}\{t < \hat{T}\} \xi, \text{ where} \quad (53)$$

$$\begin{aligned} \pi(t) &= \int_t^T \min_{i \in S} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds \\ &= \sum_{\substack{i=\min_{j \in S} \\ \{j|t \leq \hat{t}_j\}-1}}^{n-1} \int_{\max\{t, \hat{t}_i\}}^{\hat{t}_{i+1}} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds \geq 0, \end{aligned} \quad (54)$$

where $\pi(t)$ is the discounted sum of the fuel cost and the carbon cost of the generation that an additional unit of RES capital at t replaces over the remaining transition from t to T .

Proof *With the help of an indicator function $\mathbf{1}\{t < \hat{T}\}$, Eq. 49 and Eq. 52 can be written as Eq 53.*

The Lagrange multiplier ξ in Eq. 53 be interpreted as an investment subsidy. The investment subsidy accelerates investment in RES capital between t and \hat{T} to satisfy the quota obligation Φ at \hat{T} . The present value of the investment subsidy ξ is constant.

Proposition 1 *A increase of the quota obligation Φ , increases the Lagrange multiplier ξ , accelerates RES deployment over $[0, \hat{T}]$, increases the strictly negative carbon price $\lambda_b(0)$ making it less ambitious, and postpones all fossil fuel switches \hat{t}_i .³²*

³²The carbon price is negative because the model is set up as a cost minimisation problem.

Proof See Appendix C.

Proposition 1 states that tightening the quota obligation Φ has two opposite sign effects on the rate at which the carbon budget is exhausted and released to the atmosphere. These effects are illustrated in Figure 2. The first effect reduces the rate of exhaustion and is attributable to the accelerated deployment of RES over $[0, \hat{T}]$ and the consequent reduction in residual demand. The second effect increases the rate of exhaustion and is attributable to the postponement of fuel switches from low carbon intensity fuels to high carbon intensity fuels in generation to supply residual demand. The first effect is gradual as a result of quadratic investment costs. The second effect is instantaneous as a result of an abundant supply of fossil fuel fired generation capital.

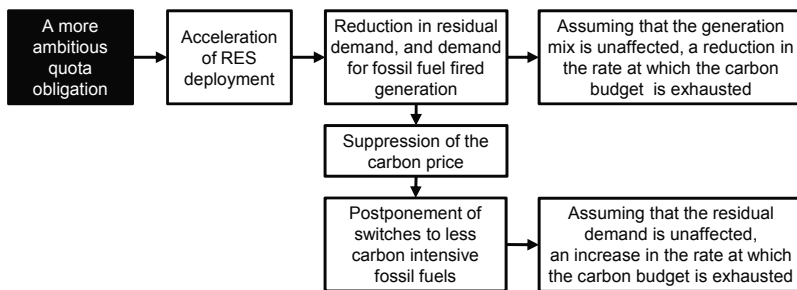


Figure 2. Effects of tightening the quota obligation

Proposition 2 *The net effect of tightening the quota obligation Φ on cumulative CO_2 released to the atmosphere by time t is ambiguous and equal to*

$$\frac{dCO_2(t)}{d\Phi} = \underbrace{\sum_{i=0}^{m-1} -\epsilon(i) \int_{\max\{0, \hat{t}_i\}}^{\min\{t, \hat{t}_{i+1}\}} \frac{dk(\text{RES}, w)}{d\Phi} dw}_{<0} + \underbrace{\sum_{i=1}^{m-1} (\epsilon(i) - \epsilon(i+1))(\Omega - k(\text{RES}, \hat{t}_i)) \frac{d\hat{t}_i}{d\Phi}}_{>0}, \quad (55)$$

where $m = \max\{j | \hat{t}_j < t\}$ is the fuel that is used to meet residual demand at t . All fuel switches up to and including \hat{t}_m take place before t . The first set of terms represent the effect attributable to the reduction in residual demand and the second set of terms the effect attributable to the postponement of fuel switches.

Proof See Appendix C.

The relative magnitude of the two opposite sign effects determine how the path of exhaustion is affected by a more ambitious quota obligation. By

assumption, the carbon budget will eventually be depleted.³³ Front-loading the release schedule accelerates global warming, while back-loading the release schedule decelerates global warming.

4 Numerical results

Next, to quantify the two opposite-sign effects identified in the previous section, a numerical minimisation of the total discounted cost of supplying electricity is performed with a choice of parameter values that reflect the EU-28 power generation sector. Table 3 shows the parametrisation.

The optimisation is done for two scenarios. The climate policy of Scenario 1 relies on the carbon budget only. The climate policy of Scenario 2 relies on the combination of a carbon budget and a quota obligation. Scenario 1 represents the counterfactual, that of relying solely on the EU ETS, while Scenario 2 represents the current situation in the EU of relying on a combination of instruments. In Scenario 2, the level of RES investments over $[0, \hat{T}]$ are higher, the carbon price is less ambitious, i.e. higher, and the switch from lignite to hard coal and from hard coal to gas in generation to supply residual demand occurs later than in Scenario 1. The release of the carbon budget in Scenario 2 is more front-loaded than in Scenario 1. The cumulative level of CO₂ in Scenario 2 is higher and as a consequence the average global temperature response is larger in Scenario 2.

4.1 Power supply in EU-28

Table 4 shows the split of electricity generation in EU-28 across generation technologies. It shows three things. First, generation with GHG emitting fuels have been relatively stable between 1990-2014. Generation with GHG emitting fuels in 2014 is taken to represent initial residual demand. Second, the current fuel mix in this category is dominated by three fuels, *lignite*, *other bituminous coal* and *natural gas*. *Other bituminous coal* is taken to be representative of the aggregate *hard coal*. Jointly these three fuels account for more than 90% of generation with GHG emitting fuels. To simplify the analysis, while preserving a maximum amount of realism, it assumed that there are three GHG emitting fuels, *lignite*, *hard coal*, and *natural gas*, and one representative RES technology. Third, after exclusion of hydro, the increase in generation from RES over 1990-2014 can almost entirely be attributed to wind, solar and

³³Non-depletion of the carbon budget would entail a zero carbon price

Table 3. Choice of parameters for the numerical optimisation problem.

Parameter	Value	Source
Discount rate	$r = 0.05$.
CO ₂ emission factors in gCO ₂ /kWh	1035 for lignite, 875 for hard coal (other bituminous coal), 400 for natural gas	Implied carbon emission factors from electricity generation from IEA (2015, p. 35)
Demand for electricity	1383 TWh/a	Equal to EU-28 generation from CO ₂ emitting sources from Eurostat (2016)
Initial level of emissions from electricity generation	1.05 GtCO ₂ /a (in 2014)	Generation from Eurostat (2016), emission factors from IEA (2015, p. 35)
Size of the carbon budget	23 GtCO ₂ , assuming a linear reduction from the initial level in 2014 of 1.74 pp/a between 2015-2020 and 2.2 pp/a from 2021 onwards	Linear reduction factors for 2015-2030 as per the proposal of the European Commission (2015) to revise the EU ETS
Size of the quota obligation	Requirement is to increase generation from RES by 800 TWh/a between 2015 and 2030	Based on the projection by Held et al. (2014)
Cost parameter β	See Table 5	See Table 5
Fossil fuel cost in EUR per generated MWh	13.57 of lignite, 20 of hard coal, 47 of natural gas	VGB (2015), the cost of lignite includes only the variable cost

biofuels.³⁴

The cost parameter β , which determines the rate at which marginal investment costs of RES increase as function of investment is calibrated by comparing unit capital cost for 2012 from IEA (2014b) with the deployment statistics from EWEA (2013) and EPIA (2013). The comparison is done for wind and solar photovoltaics (PV). Biofuels are excluded because the model assumes that RES has no fuel costs. The calibration is done by asking the question what value of β generates the observed capital costs for 2012 given the deployment realisation of 2012. Table 5 shows the estimated value β for onshore wind, offshore wind, rooftop PV and utility-scale PV. Rooftop PV is chosen

³⁴Hydro power is excluded because the availability of hydro power is precipitation dependent, which varies from year to year.

Table 4. Electricity generation in EU-28 across generation technologies in TWh. Aggregated from Eurostat (2016).

Year	1990	1995	2000	2005	2010	2011	2012	2013	2014
GHG emitting fuels	1473	1480	1642	1832	1738	1683	1616	1499	1383
.. Solid fuels	1019	946	934	961	830	851	902	872	809
.... Anthracite	0	0	0	18	10	18	17	11	13
.... Cooking coal	53	59	38	37	16	19	24	5	9
.... Other bituminous coal	599	539	531	539	463	454	498	507	447
.... Sub-bituminous coal	8	11	6	6	3	6	5	4	5
.... Lignite/brown coal	338	320	344	341	314	334	338	324	316
.... Peat	5	8	6	7	9	8	7	6	6
.... Brown coal briquettes	2	1	1	3	2	2	2	3	3
.... Oil shale and oil sands	15	8	8	9	11	11	10	11	10
.. Crude oil and petroleum	224	230	181	143	87	74	74	61	57
.. Natural gas and derived gases	224	294	513	704	798	734	615	540	490
Renewables	327	382	448	495	710	706	799	886	931
.. Hydro	309	353	386	347	407	340	366	402	406
.. Wind	1	4	22	70	149	180	206	235	253
.. Solar	0	0	0	1	23	47	71	85	98
.. Biofuels	12	18	27	58	107	115	130	139	147
.. Municipal waste (renewable)	2	4	7	12	17	18	19	19	19
.. Tide, wave, ocean	1	1	1	0	0	0	0	0	0
.. Geothermal	3	3	5	5	6	6	6	6	6
Nuclear	795	881	945	998	917	907	882	877	876
Waste (non-renewable)	5	9	12	14	19	20	20	21	23
Other	0	1	1	10	4	4	5	4	5
Total gross electricity production	2595	2743	3035	3325	3364	3296	3297	3262	3191

as the representative RES technology because it has a lower β than offshore wind and utility-scale PV. Onshore wind is excluded because of the natural limitations to significant further expansion of its use in Europe.

Table 5. Capital cost of wind power and solar photovoltaics (PV) in Europe in 2012.

Parameter	Unit	Onshore wind	Offshore wind	Rooftop solar	Utility scale PV
Capital cost ^a	$\frac{\text{MEUR}}{\text{MW}}$	1.79	5.18	3.25	2.49
Load factor adjusted capital cost ^b	$\frac{\text{MEUR}}{\text{MW}}$	6.3	10.6	21.1	14.9
Load factor adjusted capital cost ^b	$\frac{\text{MEUR}}{\text{TWh/a}}$	723	1211	2405	1701
Capacity deployment ^c	MW	10729	1166	11954	4718
Load factor adjusted capacity deployment ^b	$\frac{\text{TWh}}{\text{a}}$	20.7	3.9	12.6	5.4
Estimate of β^d	$\frac{\text{MEUR}}{\text{TWh/a}} / \frac{\text{TWh}}{\text{a}}$	34.9	311.9	191.4	316.6

^a IEA (2014b) model assumption of capital costs in Europe in 2012.

^b Adjusted with estimates of load factors in 2012 in Europe from IEA (2014b), e.g. 0.22 for onshore wind has. The load factor states the ratio of actual output to rated output.

^c Wind deployment figures from EWEA (2013), solar from EPIA (2013).

^d Calculated based on Eq. 34 as the ratio between load factor adjusted capital cost and load factor adjusted capacity deployment.

4.2 The carbon budget and the quota obligation

The size of the carbon budget is set by assuming a linear reduction factor of 1.74 pp/a between 2015-2020, 2.2 pp/a between 2021-2030, and 2.2 pp/a from 2031 onwards. The linear reduction factors for 2015-2030 are as per the proposal of the European Commission to revise the EU ETS and are expressed relative to the quantity of allowances issued in 2010 (European Commission, 2015).

The size of the quota obligation is set to require a 800 TWh/a increase in RES generation between 2015 and 2030, based on Held et al. (2014). According to Held et al. (2014), to meet the EU 2020 target electricity generation from RES must increase by 500 TWh/a between 2010-2020 in net terms and by an additional additional 350-650 TWh/a between 2020-2030 in net terms, to meet the EU 2030 target. The variance of the latter is attributable to different assumption of the improvement in energy efficiency.³⁵

A quota obligation of 800 TWh/a is compatible with the revised Renewable Energy Directive, released by the European Commission as part of the Winter

³⁵For comparison, over the same periods, total energy generation from RES, including heat, cooling and transport, must increase by 1,000 TWh/a and by 1,300-1,700, respectively. Held et al. (2014) assume a least-cost allocation between sectors.

Package (European Commission, 2016). A central objective of the directive is that by 2030 half of European electricity should be from RES. This is equivalent to a quota obligation of 665 TWh/a for 2030 (cf. last column of Table 4). While the decision of how to promote RES is left to each Member States, the Directive lays down general principles that Member States should follow in designing support schemes for RES.

4.3 Scenario 2 compared with Scenario 1

Figure 3a shows that the quota obligation of Scenario 2 accelerates RES deployment between 2015 and 2030. Figure 3b shows that residual demand is reduced along the whole transition in Scenario 2 as a consequence. With more RES capital there is less demand for fossil fuel fired generation.

Figure 4a and 4b show the undiscounted investment and fuel costs in trillion EUR (TEUR) per year. The total cost is the sum of the investment costs and fuels costs. For Scenario 1, the total cost is the sum of the areas under the dotted lines. For Scenario 2, the total cost is the sum of the areas under the solid lines. The discounted total cost of Scenario 2 is roughly double that of Scenario 1.

Figure 5a and 5b show that the quota obligation of Scenario 2 suppresses the carbon price. The carbon price is negative because the model is set up as a cost minimisation problem. The quota obligation suppresses the carbon price from minus EUR 47 to minus EUR 21 per tCO₂ in present value terms. Eq. 45 states that at the time of a fuel switch, the value of the CO₂ reduction must equal the increase in fuel cost. It follows that at the time of a switch from hard coal to natural gas, the carbon price must be EUR 56.8.³⁶ In Scenario 1 this switch occurs in 2018, in Scenario 3 the switch takes place in 2035. Discounted to 2015, the increase in fuel cost equals approximately EUR 47 in Scenario 1 and EUR 21 in Scenario 2, which matches the carbon prices generated by the numerical optimisation.

Why does not the carbon price of Scenario 2 match the price of future contracts for EU Emissions Allowances (EUA)? In December 2016, EUA future contracts were traded for EUR 5 to EUR 7 depending on the year. The main fundamental for the current price is the accumulated surplus of EUAs and the market's disbelief about the measures suggested by the European Commission to address it. The model of this paper does not factor in the

³⁶Based on the CO₂ emission factors and fuels costs in Table 3 switching from hard coal to natural gas reduces CO₂ by 0.475 tCO₂ per MWh and increases fuel costs by EUR 27 per MWh.

market's scepticism.

Figure 6a and 6b show, in line with Proposition 1, that a suppression of the carbon price postpones the switch from lignite to hard coal and from hard coal to natural gas. In Scenario 1, the carbon price is too ambitious for lignite to be competitive against hard coal and natural gas at any point over the transition. In both Scenario 1 and Scenario 2 the carbon budget is exhausted. The carbon budget is equal to the hatched areas in Figure 6a and 6b weighted by the carbon intensities of each fuel.

Figure 7a and 7b show that the cumulative level of CO₂ released to the atmosphere is higher in Scenario 2 compared with Scenario 1. Figure 7b shows the net effect of the quota obligation on the cumulative CO₂ released to the atmosphere by time t . It is a quantification of Proposition 2. It shows that the net effect is a front-loading of the release schedule. At its largest, in 2035, the front-loading amounts to approximately 5.5 GtCO₂, which is equal to 5-6 years' worth of emissions from electricity generation from EU-28 (with the level of emissions in 2014).

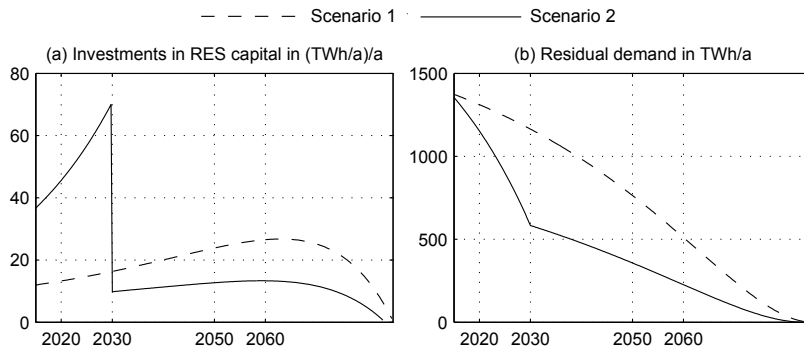


Figure 3. (a) shows RES deployment, (b) shows residual demand.

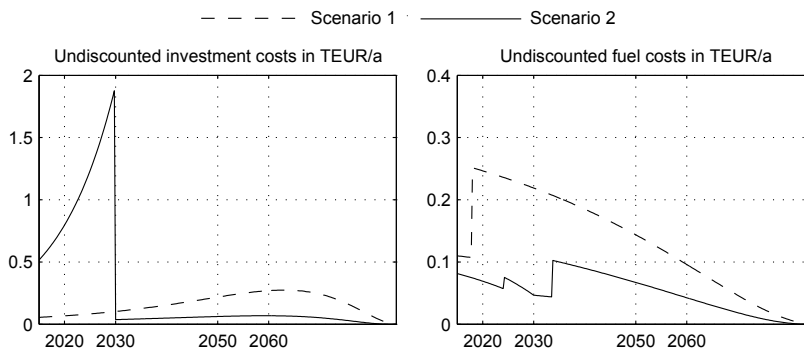


Figure 4. (a) shows cumulative undiscounted investment costs, (b) shows fuel costs per year.

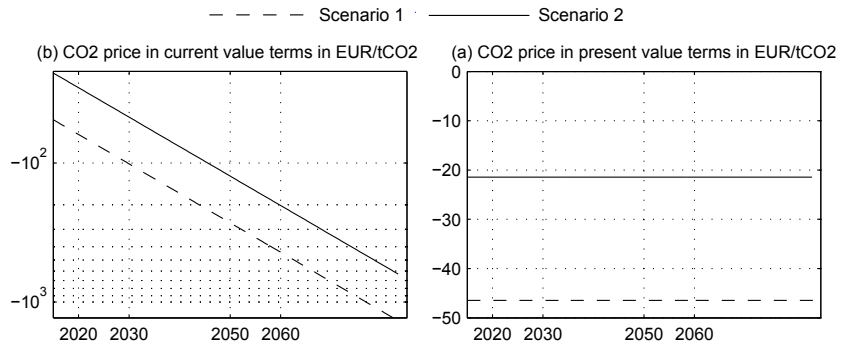


Figure 5. (a) shows the carbon price in current value terms, (2) shows the same in present value terms (discounted to 2015).

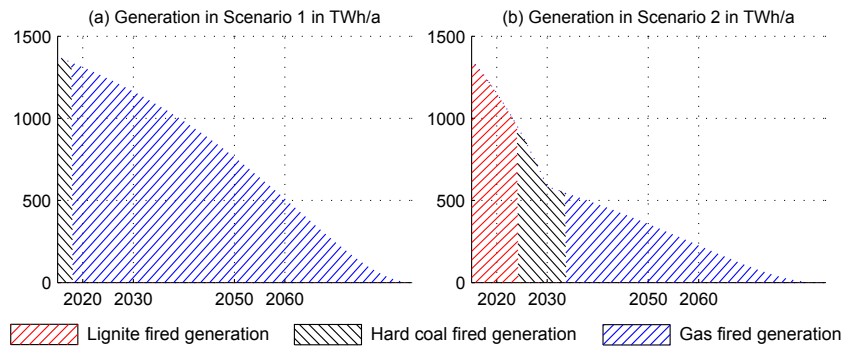


Figure 6. (a) shows generation in Scenario 1 in TWh/a with GHG emitting fuels for supplying residual demand, (b) shows the same in Scenario 2.

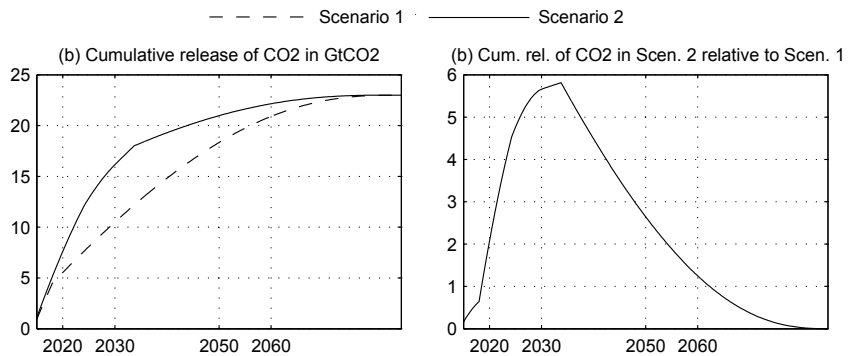


Figure 7. (a) shows cumulative release of CO₂ to the atmosphere in GtCO₂ in Scenario 1 and in Scenario 2, (b) shows cumulative release of CO₂ in Scenario 2 relative to Scenario 1 in GtCO₂.

5 Conclusions

Previous research has established that the introduction of a quota obligation alongside a carbon budget increases the costs of compliance as a consequence

of reallocation of abatement within the carbon budget. This paper illustrates the existence of a mechanism through which the quota obligation not only increases costs but may in addition accelerate rather than decelerate global warming. The dynamic model of this paper provides this new insight. Static models cannot predict the schedule at which the carbon budget is exhausted and released to the atmosphere.

It is shown that a quota obligation accelerates the deployment of RES, suppresses the carbon price, and postpones the fuel switches to less carbon intensive fuels in generation to meet residual demand. However, as the quota obligation simultaneously reduces residual demand, the net effect of a quota obligation can either be an acceleration or a deceleration of global warming. Calibration of the model for the EU-28 power generation sector shows an acceleration of global warming.

The paper has three contributions to the topical discussion of diluting cap-and-trade schemes for CO₂. First, the instrument overlap accelerates the deployment of RES, and by doing so, it suppresses the carbon price. A cap-and-trade scheme for CO₂ promotes RES in power generation by a pass-through of the carbon price into the electricity price. A higher price of electricity benefits RES producers. By suppressing the carbon price, the quota obligation dilutes this effect and creates a need for further policy intervention, which is likely to further suppress the carbon price. This observation is supported by CERA (2011), which show that achieving the 20 percent energy efficiency target as well as the 20 percent renewables target of the EU's 2020 climate and energy package will deliver CO₂ emission reductions in excess of the abatement required under the cap for Phase 2 and Phase 3 of the EU ETS.

Second, it demonstrates a process by which coal fired generation may take precedence over gas fired generation. This may provide some explanation for the *Energiewende paradox*, reported by Graichen and Redl (2014). The paradox is that in Germany emissions are increasing despite RES based power generation increasing both in relative as well as absolute terms. The reason for the emissions increase is a switch from gas to lignite and gas to hard coal. Germany is not the only country that has recently experienced a coal renaissance IEA (2014a).

Third, it illustrates a paradox. The paradox is that relying on multiple instruments not only increases costs but has the potential to accelerate global warming, as a consequence of front-loading emissions. Scenarios that keep global warming either within the 1.5 degree target or the 2.0 degree target of the Paris agreement call for very significant early reduction by the power

generation sector (Rogelj et al., 2015). Overlapping instruments may have the opposite effect.

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Appendix A: Necessary conditions for optimal control over the first period

The Lagrangian for the optimal control over $[0, \hat{T}]$ is given by Eq. 15 as

$$L_1(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma}) = e^{-rt} \sum_{i \in I} c_i(\mathbf{u}(i, t)) + \boldsymbol{\lambda}^T \mathbf{f}(t, \mathbf{u}) + \boldsymbol{\sigma}^T \mathbf{g}(t, \mathbf{x}, \mathbf{u}), \quad (56)$$

The quadruple $(\mathbf{x}^*, \mathbf{u}^*, \boldsymbol{\lambda}^*, \boldsymbol{\sigma}^*)$ over $[0, \hat{T}]$ must satisfy the following equations (Chachuat, 2007, p. 150). First,

$$\dot{\mathbf{x}}(i, t)^T = \frac{\partial L(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma})}{\partial \boldsymbol{\lambda}(i, t)} = \mathbf{f}(t, \mathbf{u})^T = \begin{bmatrix} y(i, t) \\ -\sum_{i \in I} \epsilon(i) q(i, t) \end{bmatrix}^T, \quad (57)$$

second,

$$\begin{aligned} \dot{\boldsymbol{\lambda}}(i, t)^T &= \begin{bmatrix} \dot{\lambda}_k(i, t) \\ \dot{\lambda}_b(t) \end{bmatrix}^T = -\frac{\partial L(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma})}{\partial \mathbf{x}(i, t)} = -\boldsymbol{\sigma}_{1 \times 5}^T(i, t) \frac{\partial \mathbf{g}(t, \mathbf{x}, \mathbf{u})}{\partial \mathbf{x}_{5 \times 2}(i, t)} \\ &= -\begin{bmatrix} \sigma_{\underline{y}}(i, t) \\ \sigma_{\bar{y}}(i, t) \\ \sigma_q(i, t) \\ \sigma_{cap}(i, t) \\ \sigma_{gen}(t) \end{bmatrix}^T \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -1 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \sigma_{cap}(i, t) \\ 0 \end{bmatrix}^T, \end{aligned} \quad (58)$$

and third,

$$\begin{aligned} \mathbf{0} &= \frac{\partial L(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma})}{\partial \mathbf{u}(i, t)} \\ &= e^{-rt} \frac{\partial c_i(\mathbf{u}(i, t))}{\partial \mathbf{u}(i, t)} + \boldsymbol{\lambda}^T(i, t) \frac{\partial \mathbf{f}(t, \mathbf{u})}{\partial \mathbf{u}(i, t)} + \boldsymbol{\sigma}^T(i, t) \frac{\partial \mathbf{g}(t, \mathbf{x}, \mathbf{u})}{\partial \mathbf{u}(i, t)} \\ &= e^{-rt} \begin{bmatrix} \frac{\partial c_i(\mathbf{u})}{\partial y(i, t)} \\ \frac{\partial c_i(\mathbf{u})}{\partial q(i, t)} \end{bmatrix}^T + \begin{bmatrix} \lambda_k(i, t) \\ \lambda_b(t) \end{bmatrix}^T \begin{bmatrix} 1 & 0 \\ 0 & -\epsilon(i) \end{bmatrix} \\ &\quad + \begin{bmatrix} \sigma_{\underline{y}}(i, t) \\ \sigma_{\bar{y}}(i, t) \\ \sigma_q(i, t) \\ \sigma_{cap}(i, t) \\ \sigma_{gen}(t) \end{bmatrix}^T \begin{bmatrix} -1 & 0 \\ 1 & 0 \\ 0 & -1 \\ 0 & 1 \\ 0 & -1 \end{bmatrix} \\ &= e^{-rt} \begin{bmatrix} \frac{\partial c_i(\mathbf{u})}{\partial y(i, t)} \\ \frac{\partial c_i(\mathbf{u})}{\partial q(i, t)} \end{bmatrix}^T + \begin{bmatrix} \lambda_k(i, t) \\ -\epsilon(i) \lambda_b(t) \end{bmatrix}^T \\ &\quad + \begin{bmatrix} -\sigma_{\underline{y}}(i, t) + \sigma_{\bar{y}}(i, t) \\ -\sigma_q(i, t) + \sigma_{cap}(i, t) - \sigma_{gen}(t) \end{bmatrix}^T. \end{aligned} \quad (59)$$

Rearranging, Eq. 58 and 59 read

$$\dot{\lambda}_b(t) = 0, \quad (60)$$

$$\lambda_k(i, t) + \sigma_y(i, t) - \sigma_{\bar{y}}(i, t) = -e^{-rt} \frac{\partial c_i(\mathbf{u})}{\partial y(i, t)}, \quad (61)$$

$$\sigma_{gen}(t) + \sigma_{\bar{q}}(i, t) = e^{-rt} \frac{\partial c_i(\mathbf{u})}{\partial q(i, t)} - \epsilon(i) \lambda_b(t) + \dot{\lambda}_k(i, t), \quad (62)$$

for all generation technologies $i \in I = \{1, \dots, n, \text{RES}\}$.

In addition, the following transversal conditions must hold (Chachuat, 2007, p. 127, 151),³⁷

$$\lambda_k(i, \hat{T}^-) = \frac{\partial \Gamma}{\partial k(i, t)} = \frac{\partial C_2^*}{\partial k(i, t)} = \lambda_k(i, \hat{T}^+), \quad i \in I \setminus \text{RES}, \quad (63)$$

$$\lambda_k(i, \hat{T}^-) = \frac{\partial \Gamma}{\partial k(i, t)} = \frac{\partial C_2^*}{\partial k(i, t)} + \frac{\partial \xi \psi(\hat{T}, \mathbf{x})}{\partial k(i, t)} = \lambda_k(i, \hat{T}^+) - \xi, \quad i = \text{RES}, \quad (64)$$

$$\lambda_b(\hat{T}^-) = \frac{\partial \Gamma}{\partial b(t)} = \frac{\partial C_2^*}{\partial b(t)} + \frac{\partial \nu \kappa(\hat{T}, \mathbf{x})}{\partial b(t)} = \lambda_b(\hat{T}^+) - \nu, \quad (65)$$

in which

$$\Gamma = C_2^* + \xi \psi(\hat{T}, \mathbf{x}) + \nu \kappa(\hat{T}, \mathbf{x}), \quad (66)$$

and C_2^* is the terminal cost over the optimisation over the first period.

³⁷ \hat{T}^- denotes the time just before \hat{T} and \hat{T}^+ denotes the time just after \hat{T} .

Appendix B: Necessary conditions for optimal control over the second period

By analogy with the first period, the Lagrangian for the optimal control over $[\hat{T}, T]$ reads

$$L_2(t, \mathbf{x}, \mathbf{u}, \boldsymbol{\lambda}, \boldsymbol{\sigma}) = e^{-rt} \sum_{i \in I} c_i(\mathbf{u}(i, t)) + \boldsymbol{\lambda}^T \mathbf{f}(t, \mathbf{u}) + \boldsymbol{\sigma}^T \mathbf{g}(t, \mathbf{x}, \mathbf{u}). \quad (67)$$

The necessary conditions are the same as over $[0, \hat{T}]$ except for the transversal conditions which read

$$\lambda_k(i, T^-) = \frac{\partial \Gamma}{\partial k(i, t)} = 0, \quad i \in I \setminus \text{RES} \quad (68)$$

$$\lambda_k(i, T^-) = \frac{\partial \Gamma}{\partial k(i, t)} = 0, \quad i = \text{RES}, \quad (69)$$

$$\lambda_b(T^-) = \frac{\partial \Gamma}{\partial b(t)} = \frac{\partial \nu \kappa(T, \mathbf{x})}{\partial b(t)} = -\gamma, \quad (70)$$

where

$$\Gamma = \gamma \eta(T, \mathbf{x}) = \gamma \eta(T, \mathbf{x}). \quad (71)$$

Eq. 71 has no terminal cost because the terminal cost is zero over the optimisation over the second period.

Appendix C: Direct and indirect effects of a change of the quota obligation

In this appendix it is shown that $d\lambda_b(t)/d\Phi > 0$ and that $d\xi/d\Phi > 0$.

The quota obligation and RES investments over $[0, \hat{T}]$

At \hat{T} , RES capital $k(\text{RES}, \hat{T})$ must equal the quota obligation Φ . By substitution of $\partial c_{\text{RES}}(\mathbf{u}(i, t))/\partial y(\text{RES}, t) = \beta y(\text{RES}, t)$ from Eq. 34 and $\lambda_k(\text{RES}, t) = -\pi(t) - \mathbb{1}\{t < \hat{T}\}\xi$ from Eq. 53, Eq. 37 reads

$$y(\text{RES}, t) = \frac{1}{\beta} e^{rt} \{\pi(t) + \mathbb{1}\{t < \hat{T}\}\xi\}. \quad (72)$$

The accumulated stock of RES generation capital at \hat{T} is given by the integral of $y(\text{RES}, t)$ over $[0, \hat{T}]$ and must equal Φ ,

$$k(\text{RES}, \hat{T}) = \frac{1}{\beta} \int_0^{\hat{T}} e^{rv} \{\pi(v) + \xi\} dv = \Phi, \quad (73)$$

of which the total derivative with respect to the size of the quota obligation is

$$\frac{dk(\text{RES}, \hat{T})}{d\Phi} = \frac{1}{\beta} \int_0^{\hat{T}} e^{rv} \left\{ \frac{d\pi(v)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} dv = 1, \quad (74)$$

based on which it is explicitly assumed that

$$\frac{dy(\text{RES}, v)}{d\Phi} = \frac{1}{\beta} e^{rt} \left\{ \frac{d\pi(v)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} > 0, \quad (75)$$

at all $0 < v < \hat{T}$, i.e. it is assumed that increasing the quota accelerates investments in RES throughout $[0, \hat{T}]$. That it would decelerate investments at any point along $[0, \hat{T}]$ is thus ruled out.

The steady state and RES investments over $[\hat{T}, T]$

Per definition, at T , RES generation capital is equal to the total demand for electricity Ω . The stock of RES generation capital at T is given by the integral of $y(t)$ over $[0, T]$,

$$\begin{aligned} k(\text{RES}, T) &= \frac{1}{\beta} \int_0^T e^{rv} \left\{ \pi(v) + \mathbb{1}\{t < \hat{T}\}\xi \right\} dv \\ &= \frac{1}{\beta} \int_0^{\hat{T}} e^{rv} \{\pi(v) + \xi\} dv + \frac{1}{\beta} \int_{\hat{T}}^T e^{rv} \pi(v) dv \\ &= \Phi + \frac{1}{\beta} \int_{\hat{T}}^T e^{rv} \pi(v) dv = \Omega, \end{aligned} \quad (76)$$

of which the total derivative with respect to the size of the quota obligation is

$$\frac{dk(\text{RES}, T)}{d\Phi} = 1 + \frac{1}{\beta} \int_{\hat{T}}^T e^{rv} \frac{d\pi(v)}{d\Phi} dv = 0, \quad (77)$$

which is equivalent to

$$\frac{1}{\beta} \int_{\hat{T}}^T e^{rv} \frac{d\pi(v)}{d\Phi} dv = -1, \quad (78)$$

based on which it is explicitly assumed that

$$\frac{dy(\text{RES}, v)}{d\Phi} = \frac{1}{\beta} e^{rt} \frac{d\pi(v)}{d\Phi} < 0 \quad (79)$$

for all $\hat{T} < v < T$, i.e. it is assumed that increasing the quota decelerates investments in RES throughout $[\hat{T}, T]$. That it would accelerate investments at any point along $[\hat{T}, T]$ is thus ruled out. It follows from Eq. 78 and Eq. 79 that

$$\frac{1}{\beta} \int_{\hat{T}}^t e^{rv} \frac{d\pi(v)}{d\Phi} dv < -1 \quad (80)$$

for all $\hat{T} < v < T$.

The carbon budget and the price of CO₂

At T , the cumulative amount of CO₂ released to the atmosphere must equal the size of the carbon budget Θ . For the subsequent analysis, the following notation is adapted. At \hat{T} residual demand is met by generation technology m , which has a carbon intensity of $\epsilon(m)$. Thus, fuel switches from $i - 1$ to i , where $i \leq m$, occur before \hat{T} .

$$\begin{aligned} CO2(T) &= \sum_{i=0}^{m-1} \epsilon(i) \int_{\max\{0, \hat{t}_i\}}^{\min\{\hat{T}, \hat{t}_{i+1}\}} \left[\Omega - \frac{1}{\beta} \int_0^w e^{rv} \{\pi(v) + \xi\} dv \right] dw \\ &+ \sum_{i=m-1}^{n-1} \epsilon(i) \int_{\max\{\hat{T}, \hat{t}_i\}}^{\hat{t}_{i+1}} \left[\Omega - \left(\Phi + \frac{1}{\beta} \int_{\hat{T}}^w e^{rv} \pi(v) dv \right) \right] dw = \Theta \end{aligned} \quad (81)$$

of which the total derivative with respect to the size of the quota obligation is

$$\begin{aligned} \frac{dCO2(T)}{d\Phi} &= \frac{\partial CO2(T)}{\partial \Phi} + \frac{\partial CO2(T)}{\partial T} \frac{dT}{d\Phi} + \frac{\partial CO2(T)}{\partial \pi(v)} \frac{d\pi(v)}{d\Phi} \\ &+ \frac{\partial CO2(T)}{\partial \xi} \frac{d\xi}{d\Phi} + \sum_{i=1}^n \frac{\partial CO2(T)}{d\hat{t}_i} \frac{d\hat{t}_i}{d\Phi} = 0, \end{aligned} \quad (82)$$

where

$$\frac{\partial CO_2(T)}{\partial \Phi} = - \sum_{i=m-1}^{n-1} \epsilon(i) \int_{\max\{\hat{T}, \hat{t}_i\}}^{\hat{t}_{i+1}} 1 dw, \quad (83)$$

$$\frac{\partial CO_2(T)}{\partial T} = \epsilon(n) [\Omega - k(\text{RES}, T)] dw = 0, \quad (84)$$

$$\begin{aligned} \frac{\partial CO_2(T)}{\partial \pi(v)} \frac{d\pi(v)}{d\Phi} &= - \sum_{i=0}^{m-1} \epsilon(i) \int_{\max\{0, \hat{t}_i\}}^{\min\{\hat{T}, \hat{t}_{i+1}\}} \left[\frac{1}{\beta} \int_0^w e^{rv} \frac{d\pi(v)}{d\Phi} dv \right] dw \\ &\quad - \sum_{i=m-1}^{n-1} \epsilon(i) \int_{\max\{\hat{T}, \hat{t}_i\}}^{\hat{t}_{i+1}} \left[\frac{1}{\beta} \int_{\hat{T}}^w e^{rv} \frac{d\pi(v)}{d\Phi} dv \right] dw, \end{aligned} \quad (85)$$

$$\frac{\partial CO_2(T)}{\partial \xi} \frac{d\xi}{d\Phi} = - \sum_{i=0}^{m-1} \epsilon(i) \int_{\max\{0, \hat{t}_i\}}^{\min\{\hat{T}, \hat{t}_{i+1}\}} \left[\frac{1}{\beta} \int_0^w e^{rv} \frac{d\xi}{d\Phi} dv \right] dw, \quad (86)$$

$$\sum_{i=1}^n \frac{\partial CO_2(T)}{d\hat{t}_i} \frac{d\hat{t}_i}{d\Phi} = \sum_{i=1}^n (\epsilon(1) - \epsilon(i+1)) (\Omega - k(\text{RES}, \hat{t}_i)) \frac{d\hat{t}_i}{d\Phi}. \quad (87)$$

By rearranging terms, Eq. 82 reads

$$\begin{aligned} & - \sum_{i=0}^{m-1} \epsilon(i) \int_{\max\{0, \hat{t}_i\}}^{\min\{\hat{T}, \hat{t}_{i+1}\}} \left[\frac{1}{\beta} \int_0^w e^{rv} \left\{ \frac{d\pi(v)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} dv \right] dw \\ & \quad - \sum_{i=m-1}^{n-1} \epsilon(i) \int_{\max\{\hat{T}, \hat{t}_i\}}^{\hat{t}_{i+1}} \left[1 + \frac{1}{\beta} \int_{\hat{T}}^w e^{rv} \frac{d\pi(v)}{d\Phi} dv \right] dw \\ & \quad + \sum_{i=1}^n (\epsilon(1) - \epsilon(i+1)) (\Omega - k(\text{RES}, \hat{t}_i)) \frac{d\hat{t}_i}{d\Phi} = 0, \end{aligned} \quad (88)$$

where

$$k(\text{RES}, \hat{t}_i) = \frac{1}{\beta} \int_0^{\hat{t}_i} e^{rv} \{ \pi(v) + \mathbf{1}\{v < \hat{T}\} \xi \}, dv. \quad (89)$$

The first term in Eq. 88 is negative because, by Eq. 75,

$$\frac{1}{\beta} e^{rt} \left\{ \frac{d\pi(v)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} > 0 \quad (90)$$

for all $0 < v < \hat{T}$. The second term in Eq. 88 is negative because, by Eq. 80,

$$\frac{1}{\beta} \int_{\hat{T}}^t e^{rv} \frac{d\pi(v)}{d\Phi} dv < -1 \quad (91)$$

for all $\hat{T} < t < T$. Lemma 8 states that there is bijection between the carbon price and the fossil fuel switch times \hat{t}_i . As a consequence, $d\hat{t}_i/d\Phi$ must have the same sign for all \hat{t}_i , and this sign must be positive for Eq. 88 to equal zero.

To sum up, in response to a tightening of the quota obligation, all fossil fuel switches are postponed,

$$\frac{d\hat{t}_i}{d\Phi} > 0, \forall i \in S, \quad (92)$$

and the carbon price is increased,

$$\frac{d\lambda_b(t)}{d\Phi} > 0. \quad (93)$$

The cost saving and size of the investment subsidy

Eq. 54 states that discounted sum of fuel and CO₂ costs of the generation that an additional unit of RES capital at t replaces over the remaining transition $[t, T]$ can be written as

$$\pi(t) = \sum_{\substack{i=\min_{j \in S} \\ \{j|t \leq \hat{t}_j\}-1}}^{n-1} \int_{\max\{t, \hat{t}_i\}}^{\hat{t}_{i+1}} \{e^{-rs} \alpha(i) - \epsilon(i) \lambda_b(0)\} ds \quad (94)$$

of which the total derivative with respect to the carbon price is

$$\frac{d\pi(t)}{d\lambda_b(0)} = - \sum_{\substack{i=\min_{j \in S} \\ \{j|t \leq \hat{t}_j\}-1}}^{n-1} \int_{\max\{t, \hat{t}_i\}}^{\hat{t}_{i+1}} \epsilon(i) ds < 0, \quad (95)$$

the time derivative of which is zero,

$$\frac{d}{dt} \frac{d\pi(t)}{d\lambda_b(0)} = 0. \quad (96)$$

Eq. 74 requires that

$$\frac{1}{\beta} \int_0^{\hat{T}} e^{rv} \left\{ \frac{d\pi(v)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} dv = 1, \quad (97)$$

which is equivalent to

$$\frac{1}{\beta} \int_0^{\hat{T}} e^{rv} \left\{ \frac{d\pi(v)}{d\lambda_b(0)} \frac{d\lambda_b(0)}{d\Phi} + \frac{d\xi}{d\Phi} \right\} dv = 1 \quad (98)$$

where $d\lambda_b(0)/d\Phi > 0$ by Eq. 93 and $d\pi(v)/d\lambda_b(0) < 0$ by Eq. 95. As a consequence, the term $d\xi/d\Phi$ must be strictly positive.