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Research Report

Essays on the Integration of New Energy Sources into Existing Energy Systems

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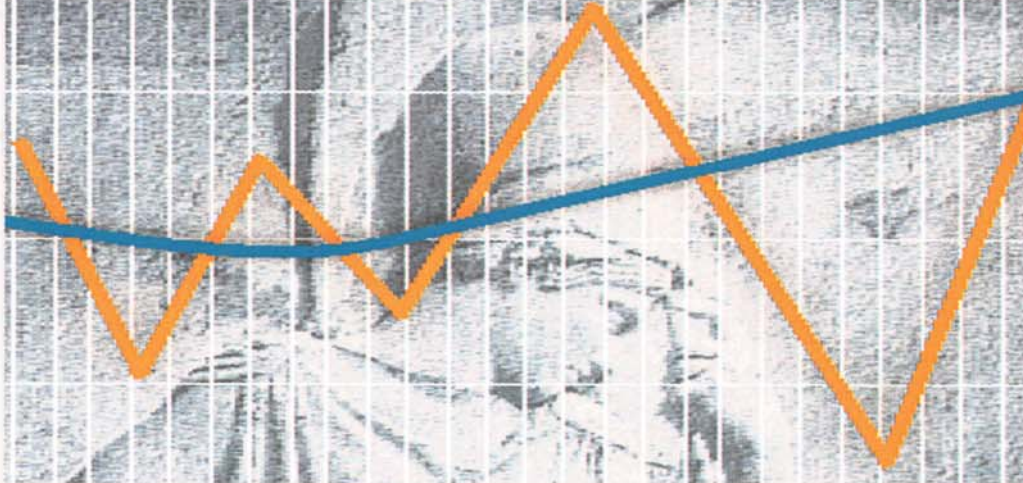
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ifo Beiträge zur Wirtschaftsforschung

Essays on the Integration of New Energy Sources into Existing Energy Systems

Luise Röpke

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Leibniz-Institut für Wirtschaftsforschung
an der Universität München e.V.

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Preface

The last decades have witnessed a tremendous increase in the use of alternative energy sources in industrialized countries. The importance of renewable as well as unconventional fossil energies in systems that formerly were almost exclusively based on conventional, mostly fossil, energy sources grows significantly. The integration process that comes along with this development faces challenges on different levels. Out of this, three aspects regarding the consequences of introducing new energy sources into existing fossil fuel markets are analyzed in the present thesis. This is done by using two theoretical dynamic models and a more applied analysis of the German electricity market.

To introduce the topic, Figure 1 gives an overview on the development of how the renewable energies contribute to energy supply. For selected regions, their share of total primary energy supply from 1990 to 2011 is illustrated. It reveals that although the contribution of renewable energies remained fairly constant on a global level, in the industrialized countries, it increased over the last years. Particularly in some European countries, it increased tremendously - with Germany being an especially impressive example. Looking at the absolute levels of 'green' energy contribution paints a similar picture. For example, from 1990 to 2011, renewable energy supply in the OECD increased from 268 Mtoe (million tons of oil equivalent) to 433 Mtoe (OECD 2013a). In Germany, it even increased from 5.3 Mtoe in 1990 to 33.8 Mtoe in 2011 (OECD 2013a). These stylized facts show unambiguously that renewable energy supply increased more than proportionally to total energy supply. The same pattern can be seen for unconventional fossil fuels. For instance, in the United States, natural gas production by hydraulic fracturing of shale gas (fracking) increased more than sixfold from 2007 to 2011 (EIA 2013) - from a share of almost 7% to almost 35% of total U.S. natural gas production during that time frame (EIA 2013; OECD 2013b).

This alternative energy 'boom' is not surprising. Indeed, several aspects of the conventional energy markets go some distance toward explaining the enthusiasm Western policymakers show for endorsing or even promoting renewable, and partly also unconventional, energy sources. Two general motives for this can be identified; these are energy-political considerations on the one hand and increasing awareness of problems related to the emission of anthropogenic greenhouse gases on the other. Moreover, these aspects point out to the basic trade-off inherent to the usage of fossil fuels between their essentiality as a production factor and their negative climate effects. In face of this dilemma, alternative energy sources, especially renewables which this thesis focuses on, seem to bring relief to this conflict as shall be elucidated in the following.

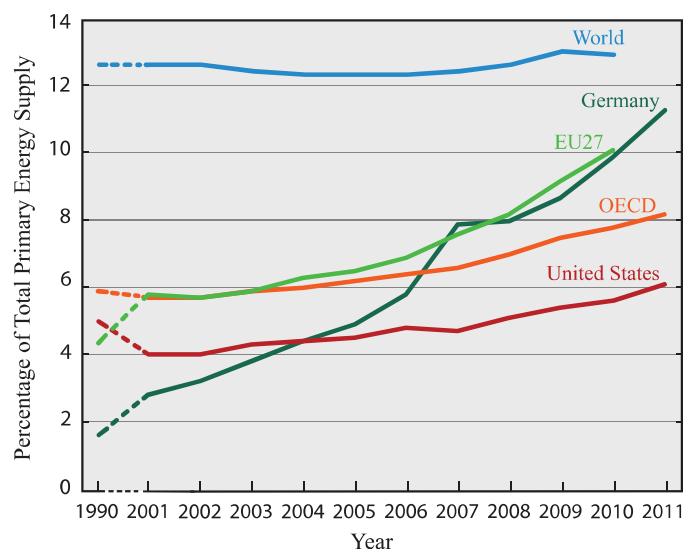


Figure 1: Contribution of renewable energies to energy supply for selected countries as percentage of total primary energy supply

Source: OECD (2013a)

Note: Renewable energy includes the “primary energy equivalent of hydro (excluding pumped storage), geothermal, solar, wind, tide and wave. It also includes energy derived from solid biofuels, biogasoline, biodiesels, other liquid biofuels, biogases, and the renewable fraction of municipal waste” (OECD 2013a, p. 116).

In regard to energy-political considerations, the scarcity of conventional energy sources is a key aspect for the increasing attractiveness and use of alternative energy sources. Since energy is an essential production factor, alternative, substitutable energies can work as a source of long-term growth (see, e.g., Dasgupta and Heal 1974). Closely related in its effects are increasing and highly volatile prices of fossil energies during the last few years (IEA 2013). This price behavior is beneficial for the development of alternative energy sources.¹ In addition, new energy sources can decrease the (economic) dependency of Western states on imported oil and gas. This is because the sources of renewable energy are much more widespread compared to fossil fuels. To some extent, this is also true for unconventional fossil fuels, a prime example being the fracking boom in the United States (see, e.g., Westphal 2013).

Due to their potentially neutral climate balance, renewables are in favor of unconventional fossil resources in the light of increasing awareness of climate-related problems. Today, nearly all scientists agree as to the climate change-inducing effects of anthropogenic carbon emissions and there is increasing pressure for immediate action to reduce harmful greenhouse gas emissions. Figure 2 illustrates atmospheric CO₂ concentration as well as global average temperature changes since the beginning of the last century until today together with trend extrapolations up to 2100 for the IPCC A1FI and A2 scenarios (Houghton et al. 2001). The projections of the

¹ For example, Jaakkola (2012) analyzes the strategically interrelating decisions of oil-importing countries to conduct R&D in the area of renewable energies together with the supply side’s oil pricing decision. One effect he finds is that higher fossil fuel prices induce higher research intensity in the area of renewable energies.

A1FI scenario can be viewed as ‘business as usual,’ whereas the A2 scenario includes a higher increase in world population and, consequently, a less increasing world GDP.²

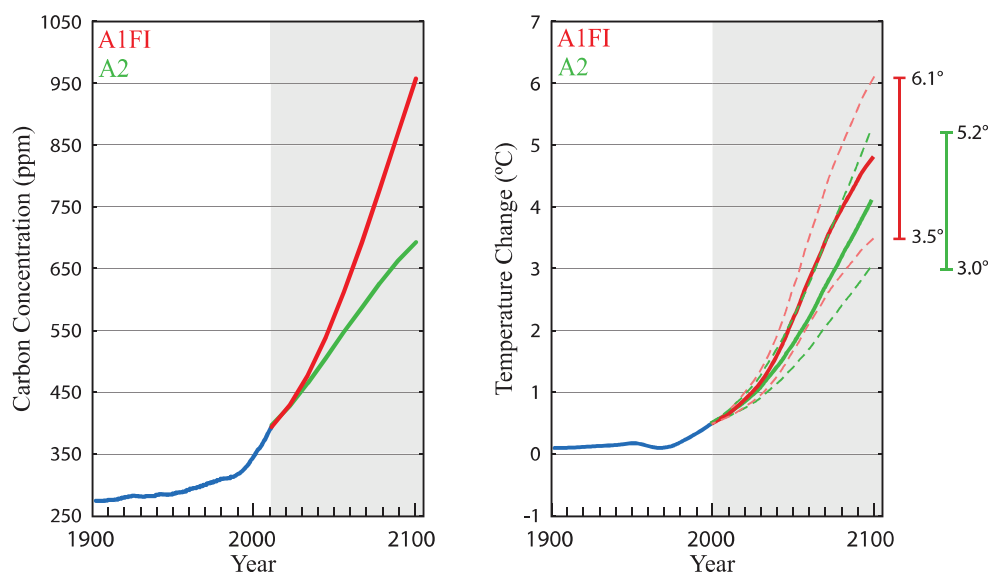


Figure 2: Measured and projected CO₂ concentration and global average temperature change since industrialization from 1900 to 2100 for IPCC A1FI and A2 scenarios

Source: Houghton et al. (2001)

Note: Red line: A1FI scenario; Green line: A2 scenario

The left graph of Figure 2 shows the concentration of atmospheric CO₂ from the beginning of the last century together with projections up until 2100, revealing a startling increase in the last several decades. The 390 ppm concentration in 2011 is the highest ever measured (see, e.g., Lüthi et al. 2008). In none of the scenarios does a slowing down, not to mention a reversal of this trend, look likely. However, there is high uncertainty in the forecasts. This also applies to predicted global temperatures, as can be seen on the right-hand side of Figure 2. Illustrating the changes in global temperature compared to the beginning of the last century, an increase of almost 1°C (by 0.85°C from 1880 to 2012; see Stocker et al. 2013) can be observed. Due to the inertia of the climate system, this increase will continue in response to the already accumulated carbon concentration (Stern 2007). The projections for the year 2100 are based on the IPCC A1FI and A2 scenarios (Houghton et al. 2001). Although characterized by high uncertainty as illustrated by the dashed lines which show the estimation ranges of the scenarios, they clearly predict a continuing raise in temperature.

Modeling climate change itself is difficult enough; predicting its social consequences is even more challenging.³ Stern (2007) tries to quantify and evaluate these costs and benefits of adaptation and mitigation of climate change. He estimates that for the Business-as-usual (BAU) scenario which resembles the A1FI scenario presented in Figure 2, the adaptation costs of climate change amount up to 5-20% of global GDP per year, “now and forever” (Stern 2007, p. vi).

² The A1FI scenario resembles the BAU (Business-as-usual) scenario of the Stern report (Stern 2007).

³ For an overview of the consequences expected to accompany increases of the average global temperature compared to pre-industrial times, see Stern (2007) and Parry et al. (2007).

In the BAU scenario, temperature is about to rise by 5°C (see Figure 2) by a chance of 50% at the end of the century.⁴ At the same time, Stern (2007) estimates mitigation costs of restricting CO₂ concentration to 550 ppm at about 1% of global GDP per year. A concentration of 550 ppm resembles to a temperature increase of about 3°C compared to pre-industrial levels. A restriction of CO₂ concentration to 550 ppm can be interpreted as an ambitious, but not unrealistic minimum target since “anything higher would substantially increase the risks of very harmful impacts while reducing the expected costs of mitigation by comparatively little” (Stern 2007, p. xvii).⁵

In order to constrain damages from climate change to a manageable amount, at the international climate conference in Cancun in 2010, the so-called two-degree target, i.e. the target of keeping the global temperature from going any higher than 2°C compared to pre-industrial levels, has been officially determined by the community of states. Taking another look at Figure 2 shows that reaching the 2°C target is an even more ambitious undertaking.⁶ Schellnhuber et al. (2009) point out that industrialized countries have to reduce their greenhouse gas emissions by up to 90% in order to reach the 2°C target.

In light of the above, policymakers’ attention to the development and use of renewable energy sources is a rational response. Indeed, most progress on the alternative energy front has been politically induced (see, e.g., IEA 2013). About half of the feed-in tariffs and quotas for renewable energies that are worldwide enacted were introduced within the last five years (REN21 2013).⁷ However, the actual policies adopted in the different countries are as diverse as the energy sources themselves. For example, in the United States, there is a special focus on the development of hydraulic fracturing, whereas most European countries are concerned with the development of renewable energies.

Moreover, due to the complexity of energy markets, the actual impact of an instrument might be very different from its intended one. A famous example of this, and one analyzed in detail in Chapters 1 and 2 of this thesis, is the so-called green paradox which occurs in the context of exhaustible resource markets - markets, that are substantially responsible for global anthropogenic carbon emissions. Basically, a green paradox occurs as “good intentions do not always

⁴ Stern (2007) points out that exceeding these 5°C “would take humans into unknown territory” (Stern 2007, p. iv).

⁵ Some further insight into the discussion of evaluating the risks from climate change can be found in a current paper of Stern (2013).

⁶ Reaching an emissions path such that carbon concentration does not exceed 450 ppm corresponds to a probability of about 20 to 70% to remain below the 2°C target (van Vuuren et al. 2010).

⁷ Two common instruments employed in the development of renewable energies are feed-in tariffs and emission trading schemes. A famous example of a feed-in system can be found in Germany. The EEG (the German Renewable Energies Act) guarantees fixed tariffs for feeding-in renewably produced electricity (§§16-22 EEG) as well as feed-in priority (§5 EEG) and aims at satisfying 80% of electricity demand with renewables by 2050. The costs to the net operator arising from the gratification of renewables feed-in - minus the revenues from selling them - are charged to the consumers (see, e.g., Sensfuß and Ragwitz 2008; BMWi and BMU 2010). An example of an emissions trading scheme is the EU ETS, which is the world’s largest emissions trading scheme. The EU ETS’s cap is set such that overall emissions will be 21% lower in 2020 compared to 2005. It covers 45% of the European Union’s CO₂ emissions, emitted by some 11,000 power and manufacturing plants, as well as those produced by intra-European flights (Ellerman et al. 2010).

breed good deeds” (Sinn 2008, p. 380). Or, more specifically in the context of this dissertation, a policy measure intended to slow down resource extraction and to reduce welfare damage from anthropogenic carbon emissions induces the exact opposite effect - increased resource extraction or possibly even worse welfare. These adverse effects can occur because, for example, policy-makers neglect to take into consideration the supply side response to their market intervention.⁸

Furthermore, designing an appropriate energy policy will almost necessarily involve certain trade-offs between different energy-political goals. The energy-political triangle as shown in Figure 3 is the ‘classic’ way of illustrating the three targets that must be combined when designing an appropriate energy policy: supply security, environmental sustainability, and economic efficiency. Supply security involves achieving a secure and continuous supply of energy. In case of electricity, for example, this is achieving a continuous and secure grid-bounded electricity supply. Environmental sustainability means avoiding a negative environmental impact (e.g. land use or particulate matter), as well as the emission of greenhouse gases, from energy use. Economic efficiency is the achievement of energy that is both efficient and inexpensive. Aspects of the energy-political triangle are discussed in detail in Chapter 3 of this thesis. There, the difficulty of integrating all three targets in one instrument is illustrated on the concrete example of subsidizing green energies in the German electricity market.

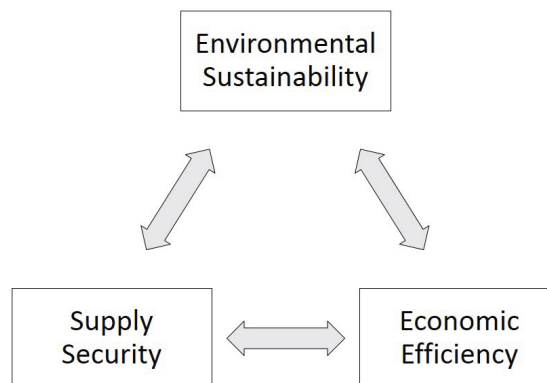


Figure 3: The energy-political triangle

The three chapters of this thesis address the above-described problems of integrating new energy sources into existing systems. In the following, a preview of what will be covered in these chapters is provided.

Chapter 1 deals with the integration of a renewable, but capacity-constrained, backstop technology into a market that is dominated by exhaustible and fossil energy sources.⁹ The presented model covers two important features. First, it encompasses three different resources that, second, differ with regard to their extraction and production costs as well as in their climate impact.

⁸ Examples for different channels through which a green paradox can arise are presented in Chapters 1 and 2.

⁹ Chapter 1 is a joint work with Ngo Van Long and Marc Gronwald. The paper has been published in a working paper version as Gronwald, M., N. V. Long, and L. Röpke (2013). Simultaneous Supplies of Dirty and Green Fuels with Capacity Constraint: Is There a Green Paradox? *CESifo Working Paper No. 4360*. In order to include it in this thesis, I made some minor changes in wording and added some further explanations where necessary and appropriate.

One of these resources is assumed to be ‘green’ and capacity constrained. These two features distinguish this paper from the majority of recent work on climate policies. In this approach, a situation is modeled where the economy faces a binding capacity constraint on renewable resource use. This is strongly supported by stylized evidence. The model is illustrated with the example of an oil market that is supplied by conventional, unconventional, and renewable fuels which can be used as perfect substitutes and are listed in order of increasing extraction and production costs. The biofuel substitute is assumed to have zero carbon emissions and unconventional fuels have higher emissions than conventional fuels. By considering two dirty exhaustible resources, the model reflects the heterogeneity of energy sources with respect to cost structure and carbon content. Using these heterogeneous deposits and energy sources in a resource-extraction framework, Chapter 1 studies possible unintended consequences of alternative climate policies, thus extending the scope of theory of the green paradox. The analytical investigation is complemented by a numerical analysis of the welfare effects of the different policies. The policies under consideration are taxation of the dirty resources and promotion of the green resource via subsidies or capacity-increasing measures. Evolution of the stock of atmospheric carbon is modeled under alternative assumptions about its accumulation in the atmosphere. Using specific functional forms of climate damage, based on different specifications of a green paradox, the overall welfare effect of the various policy scenarios compared to a base case without policy intervention is numerically evaluated regarding the net present value of the respectively resulting climate damages. Based on the concrete oil market example, the numerical analysis involves oil market features allowing for an investigation of the use of conventional and unconventional oils, as well as biofuels.

A key feature of the model is a capacity constraint on the green backstop resource, inducing simultaneous use of the expensive backstop resource and the cheaper exhaustible resources over some period of time. Moreover, by determining an upper price floor on energy, the capacity constraint makes policy instruments effective that would otherwise be neutral or even harmful from a climate perspective. The key findings of this paper are that, compared to a baseline scenario with no policy intervention, (1) expanding the capacity of the renewable energy sector without enacting additional policy measures can decrease social welfare, (2) both the capacity expansion and the subsidy of green energy lead to increases in short-term emissions, and (3) none of the analyzed policy measures shortens the duration of extracting exhaustible resources. Indeed, the welfare analysis implies that a tax on the high-cost exhaustible resource has the best welfare effects. Subsidizing the green energy or taxing the low-cost exhaustible resource also appear to be useful instruments. All three measures reduce, directly or indirectly, the production costs of the green substitute without crowding out exhaustible resources. Finally, the model is not restricted to the oil market but can cope with many empirically relevant problems of transforming the energy sector. Further application possibilities are provided in a separate section of the chapter.

The approach presented in Chapter 1 is a first step toward analyzing complex supply decisions in energy markets, one that is especially focused on the integration of capacity-constrained (green) backstop technologies. However, to better understand the extraction and production decisions of energy suppliers and evaluate the resulting implications for climate and climate policy, a closer look at the substitute itself is needed. This is done in Chapter 2 of the thesis which entails an analysis of the effects of increasing flexibility between exhaustible and renewable resource use on resource extraction, climate, as well as climate policy.

Chapter 1 analyzes an energy market in which energy sources are perfect substitutes; Chapter 2 investigates a more complex and thus more realistic situation.¹⁰ The effects of increasing substitutability, both exogenously and endogenously, measured in terms of elasticity of substitution between exhaustible and renewable energy sources that are used to produce a composite, intermediate energy good, are evaluated. The special focus of this chapter is on short-term effects of increasing flexibility of input factor use on extraction decisions of resource owners. Thereby, elasticity of substitution can be viewed as a measure of technological flexibility, allowing insight into the impact of integrating renewable energies into industry structures dominated by exhaustible resources. It is assumed that even though at present substitutability is limited, it could increase over time. This assumption can be based on stylized evidence, for example derived from the Brazilian biofuel sector. Therefore, the thesis is that, over time, a society becomes more flexible in its use of different energy inputs. When exhaustible resources become scarcer, technological progress permits increasing elasticity of substitution between fossil fuels and renewable energies. However, the hypothesis is that exhaustible and renewable energy sources will never be perfect substitutes.¹¹

The effects of this increased flexibility are analyzed, both analytically and numerically, on the extraction path of resources, as well as on the timing of production and pollution and are compared with the standard constant elasticity of substitution case. Moreover, the impacts of three policy scenarios on the analyzed energy market are evaluated: (1) an optimally chosen policy (here, a carbon tax) that fully internalizes the negative externality from carbon emissions; (2) a *laissez-faire* policy, that is no policy at all; and (3) a non-optimal policy of an exogenously determined carbon tax rate. The model reveals two flexibility effects as well as one politically induced intertemporal arbitrage effect which influence the extraction decision of resource owners. The intertemporal arbitrage effect is the standard arbitrage effect usually found in the green paradox literature: The resource owner anticipates the effects of a tax on its future revenues and adjusts his extraction plans. If the growth rate of the tax is lower than the discount rate, the speed of extraction can be reduced by a carbon tax. The flexibility effects reflect that resource owners anticipate future decreases in the value of the resource stock due to increasing input substitutability. The effect is called ‘exogenous’ when a resource owner cannot influence the speed

¹⁰ Chapter 2 is based on a joint work with Karen Pittel.

¹¹ This means that elasticity of substitution is assumed to converge toward unity. Otherwise, with elasticity of substitution exceeding unity, we are back in the standard backstop world, which is more theoretical and less plausible; see Chapter 2.

of flexibility increase (exogenously increasing elasticity of substitution) and otherwise is called an ‘endogenous’ effect (endogenously increasing elasticity of substitution). The first induces faster extraction; the latter tends to counteract the first effect.

The results have several important implications for the design of policy measures intended to slow down resource extraction. Specifically, a policy measure that induces flexibility-increasing technological progress must take into consideration the supply-side effects that result from the anticipation of increasing flexibility. The model shows that for a policy to be effective, not only must flexibility effects be taken into account, the specific type of flexibility effect is also very important. Therefore, a policymaker has to consider whether the exogenous flexibility effect on the targeted market where the actual extraction decision is independent of elasticity of substitution is complemented by an endogenous flexibility effect in which the resource owner can influence the speed of elasticity increase by its supply decision. This clearly shows the importance of carefully evaluating the structures of the considered markets before designing an energy-political instrument which directly leads to the topic of Chapter 3.

The model presented in Chapter 3 is of more practical nature compared to the theoretical ones presented in Chapters 1 and 2.¹² By applying it to the German electricity market, its utility is illustrated. In Germany, the development of renewable energies is considered an appropriate way to reduce the country’s CO₂ emissions, and to that end, several measures were taken to promote the development of renewable energies. The instruments used were highly effective with the consequence that there has been a tremendous increase in electricity capacity from renewable energies, initiating a transition process in the electricity market.

The effects of this transformation are analyzed in Chapter 3 by means of the energy-political triangle, with a special focus on the question of how the development of renewable energies will affect security of electricity supply. The transformation changes the supply structure of the electricity market from its current centralized form to one that is decentralized. Without an appropriate adaption of the electricity grid, technical supply - in terms of frequency and duration of power outages - will be less secure. Chapter 3 analyzes the welfare effects of maintaining the current level of supply security given the large-scale integration of green power into the energy system and quantifies the effects of the resulting trade-off. The benefits of maintaining the current level of supply security are calculated as the avoided damages of a decreasing quality of supply security that would occur in case of a ceteris paribus development of renewable energies without grid adaptation. The damages result from welfare losses arising from an increasing amount of power outages for electricity consumers. The resulting value of lost load is evaluated with a production function approach for firms and by evaluating the labor-leisure choice of

¹² Chapter 3 was published as Röpke, L. (2013). The Development of Renewable Energies and Supply Security: A Trade-Off Analysis. *Energy Policy* 61, 1011-1021. In this thesis, I use the more detailed working paper version: Röpke, L. (2012). The Development of Renewable Energies and Supply Security: A Trade-Off Analysis. *Ifo Working Paper No. 151*. Where necessary and appropriate, I made some minor changes and added some further explanations.

households. The investment costs of the associated grid expansion of the distribution grid are calculated based on BET et al. (2011).

The net present value shows that the costs of maintaining a constant supply security level far exceed the welfare gains of doing so. After comparing the benefits of supply security with the costs of its provision, as illustrated in the energy-political triangle, conclusions are drawn regarding the climate targets and the effects on electricity prices. When looking at climate goals, the efficiency of the instrument is controversial since it induces different marginal abatement costs not only for different green energies but ones that are also different from those in the European emissions trading system. Moreover, the mitigation effect on CO₂ emissions is doubtful because of interrelations between the European emissions trading system (EU ETS) and the German renewable energies subsidy scheme (EEG). Considering the price target, society suffers, not only in the matter of efficiency, but also because higher costs of electricity mean possibly not to meet distributive goals.

It thus appears that the energy-political triangle characterizes well what is happening in the German electricity market. However, the results of German energy policy shouldn't be dismissed simply as the 'natural' outcome of a triple trade-off between different energy-political goals. To the contrary, the results are the consequence of a deliberately chosen energy-political strategy. Moreover, the present analysis implies that the conflict between development of renewable energies and supply security is at least to some extent based on an imprecise differentiation between the climate instruments and the climate goals. Their neglect of the dynamics of the energy-political triangle, not only in regard to the climate goals themselves, but also in regard to negative net present value and price effects, indicate that the instruments the German government employed to reach its renewable energy development goals were not appropriately evaluated before being implemented. The consequences of this inefficient instrument choice on the transition process are reflected in the follow-up costs derived in the last chapter.

Essays on the Integration of New Energy Sources into Existing Energy Systems

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CHAPTER 1

Simultaneous Supplies of Dirty and Green Fuels with Capacity Constraint: Is there a Green Paradox?

1.1 Introduction

Scientific evaluation of the consequences of climate change points out the importance of decarbonizing the global economy. An important step toward this is a slowing down of fossil fuel extraction. This shall be achieved by different policy measures like carbon taxes or emission trading schemes. In addition, the production of green energy has become more and more important: The replacement of coal-fired power plants by wind turbines and solar power stations, as well as the use of biofuels as substitutes for fossil fuels in the transport sector. In many parts of the world and especially in the industrialized countries, various policy measures have been introduced in order to push this ‘green’ development. The inevitable consequence of an integration of renewable energy sources into existing, conventional energy systems is a complete reconstruction of the entire energy sector.

This reconstruction is not a simple matter. Investment projects in the development of green energies are not only large scaled and complex ventures, but also of a very long-term nature; and there are various challenges that need to be met. This can be observed on fuel markets. For example, in the field of fuel development, increasing the usage of biofuels is beset by many problems of food security and sustainability, as well as technological constraints. In short, the decarbonization process is limited in many respects and green energy cannot be used to the extent many would wish. In consequence, conventional fuels continue to be predominant. However, despite the above-mentioned problems and the fact that biofuels are not competitive in terms of their production costs, we observe that they are used simultaneously with conventional fuel types.

These two features - implementation difficulties and simultaneous use of resources with different marginal production costs - are also apparent in the context of renewable-source electricity. Transforming existing electricity transmission networks is extremely expensive, as is the provision of sufficient storage facilities for renewable-source electricity. But again, even though green electricity is considerably more expensive than conventional sources - the prime costs for producing wind and solar power being much greater than those for producing conventional thermal electricity - both types of electricity are being generated and used simultaneously.

Although these two facts - green energy is capacity-constrained and it is used simultaneously with conventional energy - are obvious, they are not adequately considered in the evaluation of climate policies regarding their consequences for the resource extraction paths and the respective climate consequences. The aim of this work is to remedy this by using an extended Hotelling resource extraction model with a capacity-constrained backstop technology in order to analyze the effects of green policies.¹ The effects of different policy measures on emission paths as well as their welfare consequences are studied both analytically and numerically. Our model is formulated to correspond to the concrete oil market example, and our numerical analysis involves oil market features allowing for an investigation of the use of conventional oil, unconventional oils, and biofuels. In consequence, this model is able to capture many empirically relevant problems of the transformation of the energy sector.

Our paper is related to two streams of literature. The first of these is the so-called green paradox literature, which deals with the effects of green policies on the extraction decisions of carbon resource owners. Referring to earlier analyses of firms' extraction decisions in anticipation of future tax changes (e.g. Long and Sinn 1985), Sinn's (2008) seminal paper sparked enormous research efforts (see, e.g., Gerlagh 2011; Hoel 2011; Grafton et al. 2012; van der Ploeg and Withagen 2012a; 2012b). Sinn (2008) considers a situation in which owners of carbon resources are confronted with green policies that are expected to become stricter over time. He shows that this can provide exhaustible resource owners with an incentive to accelerate rather than postpone the extraction of the carbon resource. Thus, a well-intended but poorly designed climate policy can have detrimental effects for the climate. In the spirit of Sinn (2008), Sinclair (1992; 1994) point out that a carbon tax should start at a high level and fall over time, contrary to the usual policy prescription (see, e.g., Nordhaus 2007). Also in line with Sinn's argument, using a two-country model with country heterogeneity, Hoel (2011) finds that lowering the costs of producing a substitute for carbon resources or imposing carbon taxes can have undesirable consequences since those policy measures can speed up the use of the carbon resource producing a green paradox result.² The green paradox literature is vast, but, to our knowledge, an explicit consideration of the possibility of green paradox outcomes is rare in a framework with capacity-constrained green resources, which would be clearly more realistic. This is somewhat surprising as there is a literature on the order of resource extraction showing that this kind of constraints can have substantial effects on the optimal order of exploitations of deposits – and thereby on climate and climate policy.³

¹ This is in contrast to the standard backstop literature. There, it is assumed that at a point in time (e.g. when a certain threshold price is reached), a backstop technology becomes available in unlimited amounts, from then on being the only energy source used.

² In an earlier paper with multiple countries, Hoel (2008) shows that if clean energy can be supplied at constant and positive marginal costs and without a capacity constraint, a policy of committing to subsidize the production of the clean energy will induce market participants to expect a lower price for fossil fuels in the future, leading to higher extraction rates, resulting in the fossil fuel stock being exhausted sooner and hence producing a green paradox outcome. Thus, in the Hoel (2008) model, subsidizing clean energy increases carbon emissions (assuming that the subsidy is not accompanied by other policy measures).

³ For example, Chakravorty, Tidball, and Moreaux (2008) consider the optimal order of exploitations if non-renewable deposits have different carbon contents. They impose overall capacity constraints on extractions, but do not address the issue of a green paradox.

Indeed, it is this very order of extraction literature that provides the second motivation for this paper. This stream of literature has its origin in Herfindahl (1967). The original finding that resources with different constant marginal extraction costs are extracted in strict order from low- to high-cost, the so-called Herfindahl rule, has been repeatedly called into question. For example, Kemp and Long (1980) and Amigues et al. (1998) show in general equilibrium settings that when the inexhaustible substitute can be supplied only in constrained amounts, the extraction order deviates from the standard Herfindahl path. The contribution that is most relevant to this paper is from Holland (2003) who finds similar results using a partial equilibrium model. Holland argues, in line with the resource literature, that resource owners base their extraction decision not only on marginal extraction costs, but also on the scarcity rent of their resources. Then, the crucial feature of the model is that some extraction capacities are limited, which has important implications for the optimal order of resource extraction. In such a situation, energy from the inexhaustible resource may be used parallel to and even strictly before some exhaustible resource stocks that have lower marginal costs. The resulting extraction patterns are similar to the ones we actually observe.

Based on a reinterpretation of Holland's (2003) model, we evaluate whether results obtained by Sinn (2008) and Hoel (2008; 2011) also hold in our model with two exhaustible resources and one capacity-constrained green backstop. We model the backstop technology in line with Dasgupta and Heal (1974, p. 8), as a "perfectly durable commodity," which provides energy at constant rate. We analyze different scenarios, such as different taxation schemes on exhaustible resources or a marginal expansion of the green capacity for their green paradox effects. Based on this, we find conditions under which a green paradox outcome arises.

The analysis employs the notions of a 'weak green paradox' and a 'strong green paradox' introduced by Gerlagh (2011) as well as an 'overall green paradox' effect. The first refers to a short-term increase of anthropogenic emissions due to a policy measure, the overall green paradox effect refers to an overall increase; finally, the strong green paradox refers to overall increased social damages compared to a baseline scenario.

Our analytical results are complemented by a numerical welfare analysis, in which we investigate the situation where various deposits have different carbon contents. We formulate alternative explicit climate damage functions, and analyze and compare specific accumulation behavior of the anthropogenic carbon in the atmosphere. For the purpose of illustration, we introduce the example of an oil market with exhaustible resources being conventional and unconventional oil and a capacity-constrained green backstop technology. Based on the different specifications of a green paradox as previously introduced, we numerically evaluate the overall welfare effect by looking at the social consequences of the considered policy scenarios compared to a base case without policy intervention. While the strong green paradox is the most important effect for the analysis, the other green paradox effects are also worth analyzing since they provide additional insight into market behavior that has an impact on the short- and medium-term effects of climate policy.

The remainder of the paper is organized as follows. In the next section, we derive a model of substitute production under a capacity constraint based on Holland (2003). Sections 1.3 and 1.4 present a policy analysis with an implicit determination of the endogenous variables and the comparative static analysis of the different policy scenarios both analytically and numerically and a welfare analysis, respectively. Section 1.5 discusses the policy relevance of this paper. Section 1.6 offers some concluding remarks.

1.2 A Model of Substitute Production under Capacity Constraint

Assume that there are two deposits of fossil fuels, S_1 and S_2 . The constant per unit extraction costs for these deposits are c_1 and c_2 , respectively. There are no capacity constraints on the amount of extraction at any given point of time t , i.e. no upper bounds on $q_1(t)$ and $q_2(t)$. The cumulative extraction constraints are

$$\int_0^{\infty} q_i(t) dt \leq S_i \text{ for } i = 1, 2.$$

There is a clean energy good that is a perfect substitute for the fossil fuels. Let $q_3(t)$ be the amount of clean energy produced at time t . Assume there is a capacity constraint on clean energy production: $q_3(t) \leq \bar{q}_3$. This means that at each point of time, the amount of green energy that can be produced is exogenously determined by the capacity constraint. Let c_3 be constant unit costs of production of the clean energy.

Let $Q(t) = q_1(t) + q_2(t) + q_3(t)$ denote the aggregate supply of energy from the three resources at time t , where some of these $q_i(t)$, $i = 1, 2, 3$, may be zero. The utility of consuming $Q(t)$ is $U(Q)$, where $U(\cdot)$ is a strictly concave and increasing function and $U'(0)$ can be finite or infinite. Moreover, assume $c_1 < c_2 < c_3 < U'(0)$.

Total welfare is

$$\int_0^{\infty} e^{-rt} \left[U[Q(t)] - \sum_{i=1}^3 c_i q_i(t) - C[V(t)] \right] dt$$

where $V(t)$ is the volume of CO_2 in the atmosphere at time t and $C(V)$ is the damage cost function with $C'(V) > 0$ and $C''(V) \geq 0$.

We assume that CO_2 emissions are proportional to the consumption of fossil fuels $q_1(t)$ and $q_2(t)$ and can be expressed as

$$\varepsilon_1(t) = \eta_1 q_1(t) \text{ and } \varepsilon_2(t) = \eta_2 q_2(t),$$

where η_1 and η_2 are positive coefficients.

Our first task is to characterize the equilibrium in the perfect competition situation. Consumers' demand is represented by the condition $p = U'(Q) \equiv \phi(Q)$, where $\phi(Q)$ is strictly decreasing. Inverting this function, we obtain the demand function

$$Q = D(p), D'(p) < 0.$$

Resource supply follows a Hotelling-like extraction path, maximizing the value of resource stocks such that the resource rent increases at the rate of interest. The extraction order of the exhaustible resource stocks is based on the Herfindahl rule: The low-cost resource stock is strictly exhausted before the high-cost resource stock is extracted. Since the renewable resource owners do not have to optimize intertemporally, their supply behavior is different from that of the exhaustible resource owners as it will be explained later. In the following, we assume that the parameters of the models satisfy two conditions that ensure that the high-cost renewable energy will be produced simultaneously with extraction of the lowest-cost deposit, and well before the lower-cost stock S_2 enters into production. These conditions were first identified by Holland (2003). We impose these conditions as described in the introduction to this paper and based on that, the resulting extraction phases and prices can be outlined.

1.2.1 Extraction Capacity and Cost Reversal

Based on Holland (2003), two conditions are imposed to ensure that both a binding capacity constraint of the renewable energy as well as a cost reversal can be illustrated in the model. By 'cost reversal,' we mean that the higher-cost renewable resource is produced well before the intermediate-cost exhaustible resource begins to be extracted. In specifying the capacity constraint, we describe the real-world situation where even though in theory we have enough renewable energy resources, only a limited amount of that energy is practically available due to technological and economic constraints. To sharpen the consequences of this situation, we focus in the following analysis on the case where the capacity constraint is binding when green energy is produced. Then, at price $p = c_3$, the market demand $D(c_3)$ for energy exceeds the capacity output of the clean energy sector \bar{q}_3 . This is stated in the following condition.

$$\text{Condition 1: } D(c_3) > \bar{q}_3$$

So, when $p(t)$ reaches c_3 , market demand must be met from both the clean energy sector and fossil fuel extraction.

Since the demand curve is downward sloping, Condition 1 implies that there exists a value $\bar{p} > c_3$ such that $D(\bar{p}) = \bar{q}_3$. Therefore, for all p in the range of c_3 and \bar{p} , the clean resource will always be produced at maximum capacity. The equilibrium price of energy can never exceed \bar{p} , even when $U'(0) = \infty$.⁴

⁴ We will not consider the alternative case of $D(c_3) \leq \bar{q}_3$. In this case, at price $p = c_3$, market demand $D(c_3)$ is lower than (or equals) capacity output \bar{q}_3 . In case of $D(c_3) < \bar{q}_3$, the capacity constraint $q_3 \leq \bar{q}_3$ is never

The second condition states that the size of the high-cost exhaustible resource must be sufficiently scarce such that the cost reversal of resource use described in the introduction can be illustrated with the present model. An analytical derivation of this condition can be found in Appendix A (“A razor’s edge case”).

$$\text{Condition 2: } S_2 < S_2^{\max} \equiv \int_0^x D [c_2 + (c_3 - c_2) e^{r\tau}] d\tau - \frac{\bar{q}_3}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right]$$

where we define x by

$$x \equiv \frac{1}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right].$$

From condition 2, we can show that if the size of deposit 2 is smaller than the threshold value S_2^{\max} , the equilibrium time path of extraction is continuous and production of green energy starts strictly before extraction of the high-cost resource deposit S_2 begins (Holland 2003).⁵

1.2.2 Four Phases of Resource Utilization and the Price Path

Based on Conditions 1 and 2, the equilibrium path of the energy price is continuous and the resource use pattern can be described as follows (see also Holland 2003, Figure 1.1).

Phase 1: Energy is supplied only by extraction from the low-cost deposit. This phase begins at time 0 and ends at an endogenously determined time $t_3 > 0$, such that the equilibrium price at time t_3 is equal to c_3 . During this phase, the net price of the low-cost resource, $p(t) - c_1$, rises at a rate equal to the interest rate r .

Phase 2: Energy is simultaneously supplied by both extraction from the low-cost resource deposit S_1 and the (more costly) renewable energy running at its capacity level \bar{q}_3 . This phase begins at time t_3 and ends at an endogenously determined time $T > t_3$. (In a limiting case, when Condition 2 holds with equality, we have $T = t_3$, meaning that Phase 2 degenerates to a single point.) The low-cost resource stock S_1 is entirely exhausted at time T . During this phase, the net price of the low-cost exhaustible resource, $p(t) - c_1$, also rises at a rate equal to the interest rate r .

binding and for $D(c_3) = \bar{q}_3$, the capacity constraint is exactly binding. In the razor’s edge case defined by $D(c_3) = \bar{q}_3$ and shown in Appendix A, Holland (2003) finds that when the price just reaches c_3 , the supply of renewable energy can be anything between zero and \bar{q}_3 and from then on the price will remain at c_3 forever. Then, we can assume to be back in the standard backstop technology world: Before the price reaches c_3 , the only supply is from the exhaustible resource deposits since the efficient level of supply of the renewable is $q_3(t) = 0$ when $p(t) < c_3$.

⁵ The intuition is if S_2 is sufficiently scarce, the price path is sufficiently high to reach the capacity-induced choke price before the low-cost deposit is exhausted. While Condition 1 can be understood as a necessary, Condition 2 can be understood as a sufficient condition for cost reversal. The analyzed situations resulting from the stated conditions must be viewed as extreme cases. The model could also be designed to allow a smooth increase in the production of green energy until the constraint is reached (which would be in accordance to actual observations on, for example, the German electricity market). Determining such a ‘dynamic capacity increase’ would allow differentiating between constraints on existing production and natural capacity restrictions. Modeling such a differentiation would allow us to show a smooth and increasing use of green energy while maintaining the constrained situation. For simplicity and to sharpen our results, we believe it is useful to retain the strong assumptions.

Phase 3: Energy is simultaneously supplied by both extraction from the high-cost resource deposit S_2 and the (more costly) renewable energy running at its capacity level \bar{q}_3 . This phase begins at time T and ends at an endogenously determined time \bar{T} . At time \bar{T} , the stock S_2 is completely exhausted. During this phase the net price of the higher-cost exhaustible resource, $p(t) - c_2$, rises at a rate equal to the interest rate r . At time \bar{T} , the energy price reaches \bar{p} (where \bar{p} is defined by $D(\bar{p}) = \bar{q}_3$).

Phase 4: The only source of energy is green energy, available at capacity level \bar{q}_3 . The price is constant at \bar{p} . This phase begins at time \bar{T} and continues for ever (because the time horizon is infinite).

Note that from time t_3 on, where $p(t_3) = c_3$, the clean energy sector will supply \bar{q}_3 without any intertemporal considerations, and due to Condition 1, there will not be enough energy to meet the demand $D(c_3)$. The shortfall, or residual demand, is met by extraction from the lowest-cost deposit available such that at t_3 ,

$$\bar{q}_3 + q_1(t_3) = D(c_3).$$

Or, in other words, only the residual demand must be met by the exhaustible resource, indicating that the existence of a constrained renewable resource reduces the scarcity problem of the exhaustible resources.⁶

Holland (2003) does not explicitly specify how the length of various phases depends on parameters such as $c_1, c_2, c_3, \bar{q}_3, S_1$, and S_2 . In order to obtain insightful comparative static results, this will be done in the following.

1.3 Policy Scenario Analysis

In the sections below, we develop explicit expressions for determining the length of the various phases. Based on these, we investigate the conditions under which energy policy measures to reduce climate change damages due to exhaustible resource use are effective when a capacity-constrained renewable energy source is available. Is it still true that a subsidy on renewable energy will harm the environment (Section 1.3.2.1)? Does a marginal expansion of the capacity help or hurt the mitigation efforts (Section 1.3.2.2)? Moreover, what are the effects of different ways of taxing exhaustible resource use (Sections 1.3.2.3 and 1.3.2.4)?

⁶ The reason deposit 2 is not extracted during the time interval $[t_3, T)$ is that any attempt to move extraction from S_2 to that interval to replace the high-cost clean energy would require curtailing consumption during the phase $[T, \bar{T})$, which implies costs in terms of foregoing consumption smoothing.

1.3.1 Implicit Determination of the Endogenous Variables

Define y to be the length of Phase 3, i.e. the phase during which deposit 2 is extracted. Then $y \equiv \bar{T} - T$. Since total demand must equal total supply during $[T, \bar{T})$ and deposit 2 must be exhausted during this interval, we can solve for y from the following equation

$$\int_T^{\bar{T}} D[p(t)]dt = S_2 + (\bar{T} - T) \bar{q}_3. \quad (1.1)$$

Since $q_2(t) > 0$ over the time interval $[T, \bar{T})$, the Hotelling rule applied to deposit 2 must hold with equality such that

$$p(t) = c_2 + (\bar{p} - c_2) e^{r(t-T-y)} \quad (1.2)$$

with $t - \bar{T} = t - T - (\bar{T} - T)$.⁷ Inserting this into (1.1), together with $\tau \equiv t - T$, and noting that \bar{p} and \bar{q}_3 are related through the equation $\bar{q}_3 = D(\bar{p})$, then y is the solution of the following equation

$$0 = F(S_2, \bar{p}, c_2) = \int_0^y D[c_2 + (\bar{p} - c_2) e^{r(\tau-y)}] d\tau - yD(\bar{p}) - S_2 \quad (1.3)$$

where $S_2 < S_2^{\max}$ as stated in Condition 2.

Remark: It is clear that an increase in S_2 will increase y . The proof is as follows. Keeping \bar{p} and c_2 constant, and differentiating the previous equation totally, we obtain

$$\left\{ [D(c_2) - D(\bar{p})] - r(\bar{p} - c_2) \int_0^y (e^{r(\tau-y)}) D' [c_2 + (\bar{p} - c_2) e^{r(\tau-y)}] d\tau \right\} dy = dS_2.$$

Thus

$$\frac{\partial y}{\partial S_2} > 0. \quad (1.4)$$

Having solved for y , we can determine the price at time T , when the high-cost deposit begins being extracted, as

$$p(T) = c_2 + (\bar{p} - c_2) e^{-ry} \equiv p_2. \quad (1.5)$$

Next, we can determine the length of the time interval $[t_3, T)$ over which energy demand is met by both extraction from the lowest-cost deposit and via production of renewable energy at capacity level. We denote this length by $z \equiv T - t_3$. Then, since $p(t_3) = c_3$, the Hotelling rule gives

$$z = \frac{1}{r} \ln \left[\frac{p(T) - c_1}{c_3 - c_1} \right].$$

Substituting for $p(T)$, we obtain

$$0 = G(y, c_1, c_2, c_3, \bar{p}) = (c_3 - c_1) e^{rz} - (c_2 - c_1) - (\bar{p} - c_2) e^{-ry}. \quad (1.6)$$

⁷ As it is described analogously in Appendix A, $p(t)$ can be derived from the condition $(p(t) - c_2)e^{-rt} = (p(T) - c_2)e^{-rT} = (p(\bar{T}) - c_2)e^{-r\bar{T}}$.

It is easy to see that

$$\frac{\partial z}{\partial y} < 0. \quad (1.7)$$

From (1.4) and (1.7), we conclude that an increase in S_2 will reduce z . Specifically, as S_2 approaches S_2^{\max} , z approaches zero. Moreover, analogously to the determination of y in (1.1), over the period from 0 to T , the total demand for energy must equal total supply that comes from deposit 1 and from renewable energy produced at capacity after time t_3 . Since we know that because deposit 1 is extracted over the interval $[0, T)$, T must satisfy the following equation

$$\int_0^T D[p(t)] dt = S_1 + (T - t_3) \bar{q}_3, \quad (1.8)$$

the Hotelling rule applies to this deposit over that period such that

$$p(t) = c_1 + (c_2 - c_1) e^{r(t-T)} + (\bar{p} - c_2) e^{r(t-T-y)}. \quad (1.9)$$

Finally, from inserting (1.9) into (1.8), the following equation determines T as

$$0 = H(y, z, T, c_1, c_2, \bar{p}) = \int_0^T D \left[c_1 + (c_2 + (\bar{p} - c_2) e^{-ry} - c_1) e^{r(t-T)} \right] dt - S_1 - zD(\bar{p}). \quad (1.10)$$

1.3.2 Comparative Statics

In this section, different policy scenarios aimed at reducing anthropogenic carbon emissions are analyzed with regard to their effects on resource extraction. In addition, we differentiate between the notions of a weak green paradox (as introduced by Gerlagh 2011) and an overall green paradox. A weak green paradox is said to arise when an apparently green-oriented policy results in a short-run increase in emissions. In our analysis, a weak green paradox can be identified as a decrease of $p(0)$, which indicates higher initial resource extraction and (or) a decrease in T . An overall green paradox occurs when the overall extraction duration of both resources (which is represented by \bar{T} in our paper) decreases due to the policy measure. Moreover, later in the welfare analysis, we introduce the concept of a strong green paradox (see Gerlagh 2011), which occurs when the conducted climate policy is socially harmful, e.g. when the present value of the stream of climate damages increases due to greater accumulated emissions at all times up to the time of exhaustion.

To assess the possibility of a green paradox, we apply the implicit function theorem to the system of Equations (1.3), (1.6), and (1.10) to determine the response of the endogenous variables (y, z, T) as well as of the price path to changes in the exogenous parameters c_1, c_2, c_3 , and \bar{p} . The changes in the exogenous parameters are assumed to result from four different policy measures, which are two taxes on the exhaustible resources, subsidization of the renewable resource, and an exogenous increase in capacity, intended to slow down carbon extraction.

1.3.2.1 Effect of a Subsidy for Renewable Energy

In the first part of our comparative static analysis, we investigate how subsidizing clean energy affects the extraction of the exhaustible resources. From the literature, we know that a subsidy can have detrimental effects on the environment if the clean energy is available at constant cost without capacity constraint (see, e.g., Hoel 2008). But does a green paradox also arise in the presence of a capacity-constrained green energy source or can this capacity-constrained source reduce pressure on exhaustible resource use? Examples of such subsidy systems include the renewable energy feed-in tariffs in Germany and Sweden or, analogously, an exemption of biofuels from taxation. In the following, subsidization of green energy is modeled as a decrease of the constant marginal production cost, c_3 . The effect of a change in c_3 on the endogenous variables (y, z, T) can be computed from the following matrix equation

$$\begin{bmatrix} F_y & F_z & F_T \\ G_y & G_z & G_T \\ H_y & H_z & H_T \end{bmatrix} \begin{bmatrix} dy \\ dz \\ dT \end{bmatrix} = \begin{bmatrix} -F_{c_3} \\ -G_{c_3} \\ -H_{c_3} \end{bmatrix} dc_3 \quad (1.11)$$

where

$$\begin{aligned} F_y &= -r(\bar{p} - c_2) \int_0^y D'[p(\tau)] e^{r(\tau-y)} d\tau > 0 \\ G_y &= r(\bar{p} - c_2) e^{-ry} > 0 \\ G_z &= r(c_3 - c_1) e^{rz} > 0 \\ G_{c_3} &= e^{rz} > 0 \\ H_y &= \int_0^T D'[p(t)] [-r(\bar{p} - c_2) e^{-ry} e^{r(t-T)}] dt > 0 \\ H_z &= -D(\bar{p}) < 0 \\ H_T &= D[p(T)] + \int_0^T D'[p(t)] [-r e^{r(t-T)}] (c_2 + (\bar{p} - c_2) e^{-ry} - c_1) dt > 0 \end{aligned}$$

and

$$F_z, F_T, F_{c_3}, G_T, H_{c_3} = 0.$$

Let J denote the determinant of the 3×3 matrix on the left-hand side of (1.11). Calculation shows that

$$J = F_y G_z H_T > 0. \quad (1.12)$$

Then, using Cramer's rule, we obtain the effect of an increase in c_3 on the variables $y, z,$ and T :

$$\frac{dy}{dc_3} = 0 \quad (1.13)$$

$$\frac{dz}{dc_3} = \frac{-e^{rz}}{J} [F_y H_T] < 0 \quad (1.14)$$

$$\frac{dT}{dc_3} = \frac{e^{rz}}{J} [F_y H_z] < 0. \quad (1.15)$$

Thus, we see from (1.13)-(1.15) that an increase in the clean energy producer's unit cost, c_3 , has no effect on the length of time over which deposit 2 is extracted ($dy/dc_3 = 0$), but will shorten the life of the low-cost deposit 1 ($dT/dc_3 < 0$) and will also shorten the interval of time over which both q_1 and q_3 are positive ($dz/dc_3 < 0$). The initial price $p(0)$ will be higher, as can be derived from Equation (1.9):

$$\frac{dp(0)}{dc_3} = -r \left(c_2 + (\bar{p} - c_2) e^{-ry} - c_1 \right) e^{-rT} \frac{dT}{dc_3} > 0. \quad (1.16)$$

Since \bar{p} and y are not affected by the increase in c_3 , we can deduce that the price at which the high-cost deposit begins to be extracted will be unaffected, see (1.5):

$$\frac{dp_2}{dc_3} = 0.$$

The effect of an increase in c_3 on t_3 (i.e. on the time interval over which all energy is supplied from deposit 1 alone) can also be computed. Since $t_3 + z = T$,

$$\frac{dt_3}{dc_3} = \frac{dT}{dc_3} - \frac{dz}{dc_3} = \frac{e^{rz} F_y}{J} [H_z + H_T] > 0. \quad (1.17)$$

The analytical results are summarized in Proposition 1.

Proposition 1: Subsidizing the clean energy product results in a lower initial price of energy. This leads to a faster extraction of the lowest-cost exhaustible resource during the initial phase $[0, t_3)$. However, this phase itself is shortened (t_3 is brought closer to time 0), and thus clean energy production will begin earlier. This effect allows deposit 1 to be extracted over a longer period. Therefore, in total and contrary to Hoel's (2008) model where subsidization of clean energy (a fall in c_3) results in earlier exhaustion of the exhaustible resource, subsidizing clean energy lengthens the life of the aggregate resource stock (i.e. it results in an increase of $y + T$ in our model). Thus, there is a weak green paradox effect, but no overall green paradox effect.

This first result can be understood as follows (see also the illustrated price path in Section 1.4.2): Subsidizing renewable energy is equivalent to decreasing c_3 . From $dy/dc_3 = 0$ (see (1.13)), we know that subsidizing the renewable backstop has no effect on how long it will take to exhaust S_2 . For illustration purposes, let T^* denote the time of exhaustion of S_1 when the renewable technology is subsidized. Let the equilibrium price path that results from the subsidy be denoted by $\tilde{p}(t)$. From the invariance of y , it follows that $\tilde{p}(T^*) = p(T)$. This in turn ensures that the aggregated supply of energy over the length of time y equals the demand.

Moreover, from (1.15) follows that subsidization of the renewable resource increases the time span of extraction of S_1 by $(T^* - T)$. This means that the resource stock S_1 is available for longer and the price level $p(T) = \tilde{p}(T^*)$ is reached later.

Additionally, an intuitive explanation of the effect of a green-energy subsidy on extraction of q_1 at the production start date of the renewable energy and, therefore, on z is as follows. If

the price path were not affected, subsidizing the backstop would lead to earlier production of the renewable energy, implying that, given the unchanged time path of price, the supply of energy is greater than demand. Since this situation would be a disequilibrium, the price path must change. In consequence, $p(0)$ declines to $p^*(0)$, as indicated by (1.16) (see also Section 1.4.2, Figure 1.1). This decrease moderates the decline in t_3 , restoring the balance between supply and demand; still, the analytical results show that $t_3^* < t_3$ (see (1.17)).

These considerations show that two opposed effects work on T and z . (1) Due to the decrease of c_3 , t_3 decreases (see (1.17)), which increases T since, as q_3 is available earlier, it can help to serve the demand during extraction of the low-cost exhaustible resource sooner. This effect tends to increase z . (2) To equalize demand and supply at t_3 , $p(0)$ decreases, as explained previously (see (1.16)). This second effect works in a direction opposite to the first effect and tends to postpone t_3 and also to shorten z . Moreover, due to a lower initial price level, the demand for energy increases and is satisfied by an increase in q_1 in period $[0, t_3)$. Which of the two effects dominates depends on their relative strength, which has been analyzed analytically. From $dT/dc_3 < 0$ and $dz/dc_3 < 0$ (see (1.15) and (1.14)), we find that the first effect is stronger than the second. This means that the exhaustible resource saving effect (of the subsidy on renewable energy) on S_1 dominates the demand increasing effect of the price decrease (the effect of $dT/dc_3 + dy/dc_3$ is unambiguous).

Therefore, when the capacity-constrained renewable backstop is subsidized, there is no overall green paradox effect in the long run, but there is a weak green paradox effect, i.e. a near term increase of extraction in time interval $[0, t_3)$.

1.3.2.2 Effect of an Increase in Capacity

We now investigate the effect of an increase in capacity \bar{q}_3 , which could occur due to a technological innovation such as, for example, the repowering of wind mills or a change from first-generation to second-generation biofuels. An increase in capacity is equivalent to a decrease in the capacity-induced choke price (\bar{p}).

The general case

The effect of a change in \bar{q}_3 on the endogenous variables (y, z, T) , which is identical to a change in \bar{p} since $D(\bar{p}) = \bar{q}_3$, can be computed, analogously to the previous section, from the following matrix equation as

$$\begin{bmatrix} F_y & F_z & F_T \\ G_y & G_z & G_T \\ H_y & H_z & H_T \end{bmatrix} \begin{bmatrix} dy \\ dz \\ dT \end{bmatrix} = \begin{bmatrix} -F_{\bar{p}} \\ -G_{\bar{p}} \\ -H_{\bar{p}} \end{bmatrix} d\bar{p}$$

where

$$\begin{aligned} F_{\bar{p}} &= -yD'(\bar{p}) + \int_0^y D'[p(\tau)] e^{r(\tau-y)} d\tau \geq 0 \\ G_{\bar{p}} &= -e^{-ry} < 0 \\ H_{\bar{p}} &= -zD'(\bar{p}) + \int_0^T D'[p(t)] e^{r(t-T-y)} dt \geq 0 \end{aligned}$$

and the determinant J has been defined in (1.12).

The comparative static results are ambiguous:

$$\begin{aligned} \frac{dy}{d\bar{p}} &= \frac{-F_{\bar{p}}}{J} [G_z H_T] \text{ has the sign of } -F_{\bar{p}} \\ \frac{dz}{d\bar{p}} &= \frac{1}{J} \{F_{\bar{p}} G_y H_T - G_{\bar{p}} F_y H_T\} \geq 0 \\ \frac{dT}{d\bar{p}} &= \frac{1}{J} \{F_y [e^{-ry} D(\bar{p}) - H_{\bar{p}} G_z] - F_{\bar{p}} [-D(\bar{p}) G_y - H_y G_z]\} \geq 0. \end{aligned}$$

The effect on the life of the aggregate resource stock is also ambiguous:

$$\frac{d(T+y)}{d\bar{p}} = \frac{1}{J} \{F_y [e^{-ry} D(\bar{p}) - H_{\bar{p}} G_z] - F_{\bar{p}} [G_z H_T - D(\bar{p}) G_y - H_y G_z]\} \geq 0. \quad (1.18)$$

However, using (1.9), the effects on the price path are unambiguous. First, an increase in capacity (a fall in \bar{p}) necessarily leads to a lower initial price:

$$\frac{dp(0)}{d\bar{p}} > 0. \quad (1.19)$$

Second, a fall in \bar{p} lowers the price at which deposit S_2 begins to be exploited:

$$\frac{dp(T)}{d\bar{p}} > 0. \quad (1.20)$$

Proposition 2: An increase in the capacity of the clean energy sector has an ambiguous effect on the life of the aggregate resource stock, and it lowers the scarcity rent of both exhaustible resources.

To obtain clearer results, let us consider the case of linear demand.

The special case of linear demand

In the following, we assume that demand is linear with the functional form

$$D[p(t)] = A - p(t). \quad (1.21)$$

Then, taking into account (1.21), (1.3) becomes

$$\int_0^y \left[A - \left(c_2 + (\bar{p} - c_2) e^{r(\tau-y)} \right) \right] d\tau = y(A - \bar{p}) + S_2.$$

Differentiating totally, we obtain after rearranging

$$\frac{dy}{d\bar{p}} = -\frac{S_2}{(1 - e^{-ry})(\bar{p} - c_2)^2} < 0. \quad (1.22)$$

Thus, an expansion in capacity \bar{q}_3 , which leads to a fall in \bar{p} , lengthens the life of deposit 2. Moreover, from (1.6) and (1.22), we can derive the effect of an increase in \bar{p} on z as

$$\frac{dz}{d\bar{p}} = \frac{1}{r} \left(\frac{1}{c_2 - c_1 + (\bar{p} - c_2) e^{-ry}} \right) \left[e^{-ry} - r(\bar{p} - c_2) e^{-ry} \frac{dy}{d\bar{p}} \right] > 0. \quad (1.23)$$

A fall in \bar{p} shortens the phase during which both q_1 and q_3 are supplied to the market. To find the effect of an increase in \bar{p} on T , insert the linear demand function (1.21) into (1.10), leading to

$$\int_0^T \left[A - c_1 - \left(c_2 + (\bar{p} - c_2) e^{-ry} - c_1 \right) e^{r(t-T)} \right] dt = S_1 + z(A - \bar{p}),$$

where y and z are both functions of \bar{p} , with derivatives given by (1.22) and (1.23). Rearranging terms and totally differentiating leads to

$$\begin{aligned} & \left[A - c_1 - \left(c_2 + (\bar{p} - c_2) e^{-ry} - c_1 \right) e^{-rT} \right] \frac{dT}{d\bar{p}} \\ &= \left\{ -\left(\frac{1 - e^{-rT}}{r} \right) r(\bar{p} - c_2) e^{-ry} \frac{dy}{d\bar{p}} + (A - \bar{p}) \frac{dz}{d\bar{p}} + \left(\frac{1 - e^{-rT}}{r} \right) e^{-ry} \right\} - z. \end{aligned} \quad (1.24)$$

Consider the right-hand side (RHS) of (1.24). The sum of the terms inside the curly brackets {...} is positive. However, because z is positive, the sign of the RHS seems ambiguous. On the left-hand side, the expression inside the square brackets [...] is ambiguous, though it is positive if A is sufficiently large.

The effect of an increase in \bar{p} on the life of the aggregate resource stock, $y + T$, is also ambiguous. The results shown in (1.22), (1.23), and (1.24) can be summarized in the following proposition.

Proposition 3: Under linear demand, an increase in the capacity of the clean energy sector (i.e. a decrease in \bar{p}) will lengthen the life of deposit 2, shorten the interval of simultaneous supply of q_1 and q_3 , and has an ambiguous effect on the life of deposit 1 and the life of the aggregate resource stock. In the special case where A is large and z is small (i.e. S_2 approaches S_2^{\max} from below), an increase in capacity will shorten the life of deposit 1:

$$\frac{dT}{d\bar{p}} > 0. \quad (1.25)$$

An increase in the capacity of the renewable resource increases the extraction duration of the second exhaustible resource: $dy/d\bar{p} < 0$ (see (1.22)). This indicates that a capacity expansion of the renewable resource sector permits the stock of higher-cost resource S_2 to be spread over a longer period. In contrast, if z is small and A is large, we can state that $dT/d\bar{p} > 0$ (see (1.25)), and the effect of a capacity increase on the extraction duration of the low-cost stock S_1 is negative. This case is especially plausible since we know that a capacity expansion reduces the energy price at the exhaustion point of S_1 (see (1.20)), which indicates a faster extraction of q_1 . Additionally, analogous to the subsidy scenario, the capacity increase induces a reduction in the initial energy price, which also accelerates exhaustion (see (1.19)).

Moreover, increased capacity shortens the period of parallel supply of q_1 and q_3 : $dz/d\bar{p} > 0$ (see (1.23)). Therefore, the capacity increase cannot reduce the demand for S_1 and, consequently, weakening the capacity constraints leads to at least a weak green paradox with regard to the cheaper exhaustible resource. This holds irrespective of the effect on t_3 , which is ambiguous. Nevertheless, it is not clear whether there will be an overall green paradox: $(d(T + y)/d\bar{p})$ is ambiguous and further evaluation is needed.

1.3.2.3 Effect of a Tax on the Low-Cost Exhaustible Resource

The effects of different tax schemes on exhaustible resources are evaluated in the present and next section. We first consider a tax on the low-cost exhaustible resource that causes an increase in the (tax-inclusive) constant marginal extraction costs of deposit 1.⁸ The effect of taxing the low-cost resource on the endogenous variables (y, z, T) as well as on the price path, analogously to the previous sections modeled as a marginal increase in the extraction costs c_1 , can be computed from the following matrix equation

$$\begin{bmatrix} F_y & F_z & F_T \\ G_y & G_z & G_T \\ H_y & H_z & H_T \end{bmatrix} \begin{bmatrix} dy \\ dz \\ dT \end{bmatrix} = \begin{bmatrix} -F_{c_1} \\ -G_{c_1} \\ -H_{c_1} \end{bmatrix} dc_1$$

where

$$\begin{aligned} F_{c_1} &= 0 \\ G_{c_1} &= 1 - e^{rz} < 0 \\ H_{c_1} &= \int_0^T D'[p(t)] (1 - e^{r(t-T)}) dt < 0 \end{aligned}$$

and J has been determined in (1.12).

⁸ Many authors, including Sinn (2008) or Sinclair (1992; 1994), show that a credible commitment to a tax rate that is high today but decreases over time is the best strategy for slowing down extraction of fossil fuels. We examine this situation here with the simplification that we assume a tax on the low-cost resource but not on the high-cost resource.

In contrast to the calculations in Section 1.3.2.1, the results are unambiguous. First, the tax on deposit 1 does not change the length of the extraction period for deposit 2:

$$\frac{dy}{dc_1} = 0. \quad (1.26)$$

This result in turn implies that the price at which extraction of deposit 2 begins is unaffected from changes in c_1 ; see (1.5). Second, the tax lengthens the interval over which q_1 and q_3 are simultaneously supplied:

$$\frac{dz}{dc_1} = \frac{1}{J} [F_y(-G_{c_1})H_T] > 0. \quad (1.27)$$

Then, extraction of the low-cost deposit will be spread out over a longer period:

$$\frac{dT}{dc_1} = \frac{1}{J} [F_y G_z(-H_{c_1}) - F_y(-G_{c_1})H_z] > 0. \quad (1.28)$$

Moreover, from (1.9), the initial price of the extracted resource will be raised, though by a smaller amount than the increase in tax:

$$1 > \frac{dp(0)}{dc_1} = 1 - e^{-rT} > 0. \quad (1.29)$$

Only the effect on the time at which the renewable energy is made available, t_3 , is ambiguous:

$$\frac{dt_3}{dc_1} = \frac{dT}{dc_1} - \frac{dz}{dc_1} = \frac{1}{J} [F_y G_z(-H_{c_1}) + F_y G_{c_1} H_z] - \frac{1}{J} [F_y(-G_{c_1})H_T] \geq 0. \quad (1.30)$$

But since the exhaustion time for the cheaper resource, T , is delayed, the ambiguous sign of (1.30) is of no consequence with regard to the green paradox.⁹ The results are summarized in Proposition 4.

Proposition 4: While a tax on the low-cost resource has no effect on the extraction duration of the high-cost resource, it does result in a higher initial price of energy. Moreover, the overall period of extraction from the cheaper resource is lengthened, leading to slower extraction of the cheaper exhaustible resource during the initial phase $[0, t_3)$ due to an increase in both T and $p(0)$. Thus, there is neither a weak nor an overall green paradox. (The ambiguous effect on the interval $[0, t_3)$ is of no consequence for the green paradox results.)

This result can be understood as follows (see also the price path of this scenario illustrated Figure 1.1 of Section 1.4.2): A tax on the cheaper exhaustible resource is equivalent to an increase in c_1 . From $dy/dc_1 = 0$ (see (1.26)), we know that a tax on the low-cost resource has no effect on how long it will take to exhaust S_2 . Parallel to the case of subsidizing the renewable resource, from the invariance of y it follows that p_2 is unchanged, see (1.5). Moreover, $dT/dc_1 > 0$ (see (1.28)) implies that the tax increases the time span of extraction of S_1 (by $(T^* - T)$, if we follow the previous notation). Together with $p^*(0) > p(0)$ (see (1.29)), this

⁹ Thus, our result for the multi-resource case supports Sinn's (2008) and Sinclair's (1992;1994) proposition that a tax to slow down resource extraction should be initially high and decreases over time.

means that the price level p_2 (at which the second deposit begins to be exploited) is reached later and the exhaustible resource S_1 is available longer. The price path during $[0, T)$ is flatter and the price level is higher such that extraction of S_1 is spread over a longer period of time. Therefore, the old and the new price path during the extraction of S_1 must intersect. Nevertheless, the effect on t_3 is not clear. Even though we know from $dz/dc_1 > 0$ (see (1.27)) that the time span of simultaneous use of q_1 and q_3 increases, we do not know whether the production of clean energy will begin earlier or later, as the sign of dt_3/dc_1 (see (1.30)) is ambiguous. In conclusion, the imposition of a constant unit tax on the low-cost exhaustible resource gives rise to neither a weak green paradox (since $dp(0)/dc_1 > 0$) nor an overall green paradox (since $dT/dc_1 + dy/dc_1 > 0$).

1.3.2.4 Effect of a Tax on the Extraction of the High-Cost Exhaustible Resource

We now examine how a tax on c_2 affects the endogenous variables.¹⁰ This can be computed from the following matrix equation

$$\begin{bmatrix} F_y & F_z & F_T \\ G_y & G_z & G_T \\ H_y & H_z & H_T \end{bmatrix} \begin{bmatrix} dy \\ dz \\ dT \end{bmatrix} = \begin{bmatrix} -F_{c_2} \\ -G_{c_2} \\ -H_{c_2} \end{bmatrix} dc_2$$

where

$$\begin{aligned} F_{c_2} &= \int_0^y D'[p(t)] (1 - e^{r(\tau-y)}) dt < 0 \\ G_{c_2} &= -(1 - e^{-ry}) < 0 \\ H_{c_2} &= \int_0^T D'[p(t)] (1 - e^{-ry}) e^{r(t-T)} dt < 0 \end{aligned}$$

and J has been determined in (1.12).

The general case

Even though the signs of the above partial derivatives are unambiguous, some results of the comparative statics are ambiguous. The tax on the high-cost exhaustible resource will lead to a lengthening of its extraction period:

$$\frac{dy}{dc_2} = \frac{1}{J} [-F_{c_2} G_z H_T] > 0. \quad (1.31)$$

However, the effect on the period of simultaneous use of green energy and the low-cost resource is not clear:

$$\frac{dz}{dc_2} = \frac{1}{J} [F_y (-G_{c_2}) H_T - (-F_{c_2}) G_y H_T] \geq 0,$$

¹⁰ Increasing taxes on fossil fuels is common practice throughout the world, not only for fiscal reasons, but due to growing awareness of the consequences of climate change and the exhaustibility of fossil fuels. However, according to Sinn (2008) and others, this practice may cause detrimental green paradox effects.

and the effect on the period of exploitation of the low-cost deposit is also ambiguous:

$$\frac{dT}{dc_2} = \frac{1}{J} [F_y G_z (-H_{c_2}) + (-F_{c_2}) G_y H_z - (-F_{c_2}) G_z H_y - F_y (-G_{c_2}) H_z] \geq 0.$$

We summarize the results in Proposition 5.

Proposition 5: A tax on the high-cost exhaustible resource deposit lengthens the exploitation period of this deposit, but has an ambiguous effect on the life of the lower-cost resource and of the aggregate resource stock.

Therefore, to obtain sharper results, we consider the case of linear demand in the following.

The special case of linear demand

In case of a linear demand function as formulated in (1.21), the partial derivatives have the following signs:

$$\frac{dz}{dc_2} > 0 \quad (1.32)$$

$$\frac{dT}{dc_2} > 0 \quad (1.33)$$

$$\frac{dp(0)}{dc_2} > 0 \quad (1.34)$$

$$\frac{dt_3}{dc_2} < 0. \quad (1.35)$$

From (1.31)-(1.35), we can now state Proposition 6.

Proposition 6: Under linear demand, a tax on the high-cost resource extraction (an increase of c_2) will lengthen the life of both deposits 1 and 2, lengthen the interval of simultaneous supply of q_1 and q_3 , and therefore increase the life of the aggregate resource stock.

The effects can be understood as follows: A change in the marginal extraction costs has no effect on the price ceiling determined by $D(\bar{p}) = \bar{q}_3$. Therefore, when \bar{p} and \bar{q}_3 are given, a longer (slower) extraction of deposit 2, as indicated by $dy/dc_2 > 0$ (see (1.31)), is possible only when demand is reduced during the considered time span. This can be reached by an overall price level increase. From

$$\frac{dp(T)}{dc_2} > 0, \quad (1.36)$$

we know that, following the previous notation, $p(T^*) > p(T)$. This means that extraction from the high-cost deposit starts from a higher price level and $q_2(t)$ already starts lower. Therefore, to have S_2 exhausted at $\bar{T}^* > \bar{T}$, the price path is flatter such that $y^* > y$. The changes in the depletion path of deposit 1 which are a flatter price path and a longer extraction period ($dT/dc_2 > 0$; see (1.33)) with a higher initial price ($dp(0)/dc_2 > 0$; see (1.34)) can be explained analogously. This means that S_1 is more valuable to the resource owner (higher price and higher

scarcity rent). Moreover, even though the tax on the high-cost resource postpones production of green energy ($dt_3/dc_2 > 0$; see (1.35)), the length of simultaneous production of q_1 and q_3 increases ($dz/dc_2 > 0$; see (1.32)). In the end, neither a weak nor an overall green paradox is found.

In the following section, the comparative static policy analysis is complemented by a numerical analysis, which allows us to link the theoretical model to a concrete example of the fossil fuel market and derive precise results, which are missing from the analytical part. Moreover, we conduct a welfare analysis to discover the social consequences of the different scenarios. In this context, we introduce two different explicit damage functions as well as a situation where the various deposits have different carbon contents. This allows us to draw further conclusions regarding the strong green paradox effect defined by Gerlagh (2011).

1.4 Numerical Analysis

In the following, we provide a numerical illustration of the previous model. For illustration purposes, we use the concrete example of an oil market. The parameter values are chosen to reflect, in a stylized manner, real-world relations for the different oil market parameters. Our numerical exercise allows not only the derivation of unambiguous results, but also a concrete illustration of the relevant effects. We derive the accumulation paths of anthropogenic carbon in the atmosphere and compare their resulting consequences for social welfare. In addition to the situation of zero decay, we also evaluate the situation of a positive depreciation of anthropogenic carbon. The analysis begins by describing the stylized oil market example in Section 1.4.1. The numerical results are derived in Section 1.4.2, followed by a welfare analysis in Section 1.4.3.

1.4.1 The Oil Market Example

The parameters are chosen so as to reflect, in a stylized manner, the relations between marginal extraction costs for conventional oil, unconventional oil, and advanced biofuel (see, e.g., IEA 2012). To do so, we set $c_1 = 0.75$, $c_2 = 1.75$, and $c_3 = 4$. This reflects the cost structure observed in oil markets: Biofuel has the highest, unconventional oil has medium, and conventional oil the lowest production costs. Moreover, we continue to assume the case of linear demand, $D[p(t)] = A - p(t)$ (see (1.21)), and that $\bar{p} > c_3$. We choose $A = 20$, $\bar{p} = 15$, $r = 0.01$. Then $\bar{q}_3 = A - \bar{p} = 5$. To compute the pollution stock, we specify the stock sizes S_1 and S_2 . Let us assume that $S_1 = 700$ and $S_2 = 900$, which reflects the fact that there is more unconventional than conventional oil available. First, we need to make sure that $S_2 < S_2^{\max}$. This means that we first have to compute the value S_2^{\max} from our specifications of the cost parameters c_1 , c_2 , and c_3 and of capacity \bar{q}_3 (which is equal to $A - \bar{p}$). From Condition 2 with S_2^{\max} equals approximately 1249, it follows that $S_2 = 900$ does indeed satisfy the condition $S_2 < S_2^{\max}$.¹¹

¹¹ This condition is fulfilled throughout the following numerical analysis.

1.4.2 Derivation of Numerical Results

We now show how numerical results can be derived for the base case.¹² We first calculate the length of Phase 3, which is $y \equiv \bar{T} - T = 144.30$. Second, we solve for the length of Phase 2, $z \equiv T - t_3$, which is the time interval over which the lowest-cost deposit and the renewable energy are available simultaneously. From (1.6) follows that $z = 23.96$. Next, we solve for T (the time at which deposit 1 is exhausted) from (1.10) such that we have $T = 51.18$. Moreover, the length of Phase 1, t_3 , and the total length of Phases 1-3, \bar{T} , can be calculated as $t_3 = T - z = 27.22$ and $\bar{T} = T + y = 195.48$.

From (1.9), the equilibrium price at time t (for $0 \leq t \leq T$) is $p(t) = 0.75 + e^{0.01(t-51.18)} + 13.25e^{0.01(t-195.48)}$; specifically, $p(0) = 3.23$, $p(T) = 4.88$, and, as expected, $p(t_3) = 4 = c_3$. Moreover, from (1.2), the equilibrium price path for $T \leq t \leq \bar{T}$ is $p(t) = 1.75 + 13.25e^{0.01(t-195.48)}$. Finally, we have $p(\bar{T}) = 15$.

Table 1.1 presents the results of the numerical analysis for the different policy scenarios and the base case in the chosen numerical example. This allows a comparison of the effects of the respective policy measures on extraction speed and duration of fossil fuel extraction. In our first policy scenario, there is a subsidy on the green energy at the rate 1 per unit (e.g. one Euro per kilowatt-hour). Consequently, the (marginal) production costs of the green energy decrease from 4 to 3 per unit. In an alternative policy scenario, there is a capacity expansion from 5 to 6; therefore, \bar{p} decreases from 15 to 14. In a third policy scenario, the tax on the low-cost exhaustible resource increases from 0 to 1, such that the (marginal) production cost of the green energy increases from 0.75 to 1.75 per unit. Finally, in the fourth scenario, the tax on the high-cost exhaustible resource is increased from 0 to 1; therefore, the (marginal) production cost of the green energy increases from 1.75 to 2.75 per unit.

	base scenario	subsidy on green energy ¹	capacity increase of green energy ²	tax on low cost resource ³	tax on high cost resource ⁴
y	144.30	144.30	151.49	144.30	151.49
z	23.96	60.73	12.78	33.00	36.74
T	51.18	64.95	47.61	54.62	56.42
t_3	27.22	4.23	34.83	21.61	19.68
\bar{T}	195.48	209.26	199.10	198.92	207.94
$p(0)$	3.23	2.91	3.04	3.56	3.42
$p(T)$	4.88	4.88	4.44	4.88	5.44

Table 1.1: Numerical results for the different policy scenarios

Notes: ¹ Green energy production costs decrease to: $c_3^* = c_3 - 1$; ² Maximum capacity increases to: $\bar{q}_3^* = \bar{q}_3 + 1$; ³ Extraction costs of S_1 increase to: $c_1^* = c_1 + 1$; ⁴ Extraction costs of S_2 increase to: $c_2^* = c_2 + 1$

¹² The results of the different policy scenarios can be derived analogously.

Recall from Proposition 3 that an increase in capacity will increase y , may reduce T , and the effect on \bar{T} is ambiguous (see (1.18)). Our numerical results show that an increase in the capacity of the green substitute indeed decreases T but does not reduce \bar{T} indicating that there is no overall green paradox. This is because numerically we find $d\bar{T}/d\bar{p} < 0$.¹³ Moreover, we find that $dt_3/d\bar{p} < 0$. The reason for the positive effect on t_3 is that $p(0)$ is lower than before; therefore, it takes longer for $p(t)$ to reach c_3 . However, with $dy/d\bar{p} < 0$, it also takes longer to exhaust the aggregate resource stock than is the case in the base scenario.

With regard to the effect of a tax on the low-cost resource on t_3 , the numerical analysis shows that $dt_3/dc_2 > 0$ (Table 1.1, fifth column). Analogous to the previous explanation, the slight increase in t_3 is mostly explained by the increase in $p(0)$ that flattens the price path. This can be summarized in Proposition 7.

Proposition 7: In our numerical simulation, a capacity increase of the green energy substitute leads to earlier production of green energy (t_3 decreases) and does not produce an overall green paradox effect since it induces an increase of \bar{T} .

Figure 1.1 illustrates how the different policy measures of the chosen numerical example affect the price paths. In the figure, the price paths of the different policy scenarios shown in dashed lines are compared with the base case price path in solid lines. The upper left graph named ‘a) Subsidy and base scenario’ illustrates the effect of subsidizing the renewable energy good on the price path compared to the base case, the upper right graph named ‘b) Capacity and base scenario’ describes a capacity increase of the renewable energy good compared to the base case, the lower left graph, ‘c) Tax 1 and base scenario,’ shows the effects of a tax on the low-cost and the lower right graph ‘d) Tax 2 and base scenario’ those of a tax on the high-cost exhaustible resource on the price path compared to the base case. The policy measures reduce the price level for most time periods; for the subsidy and capacity scenario, this even refers to the total duration of exhaustible resources extraction. However, we know from Table 1.1 that this does not necessarily lead to a decrease in the overall extraction duration of the exhaustible resources.

¹³ The price path behavior is remarkable in the case of a capacity increase of green energy (see section b) of Figure 1.1). First, the capacity increase reduces the capacity-constrained choke price. Second, the increase in capacity can overcompensate the higher demand resulting from the lower price path such that the overall extraction duration of the exhaustible resources increases (see also Table 1.1) even though an overall higher demand needs to be satisfied.

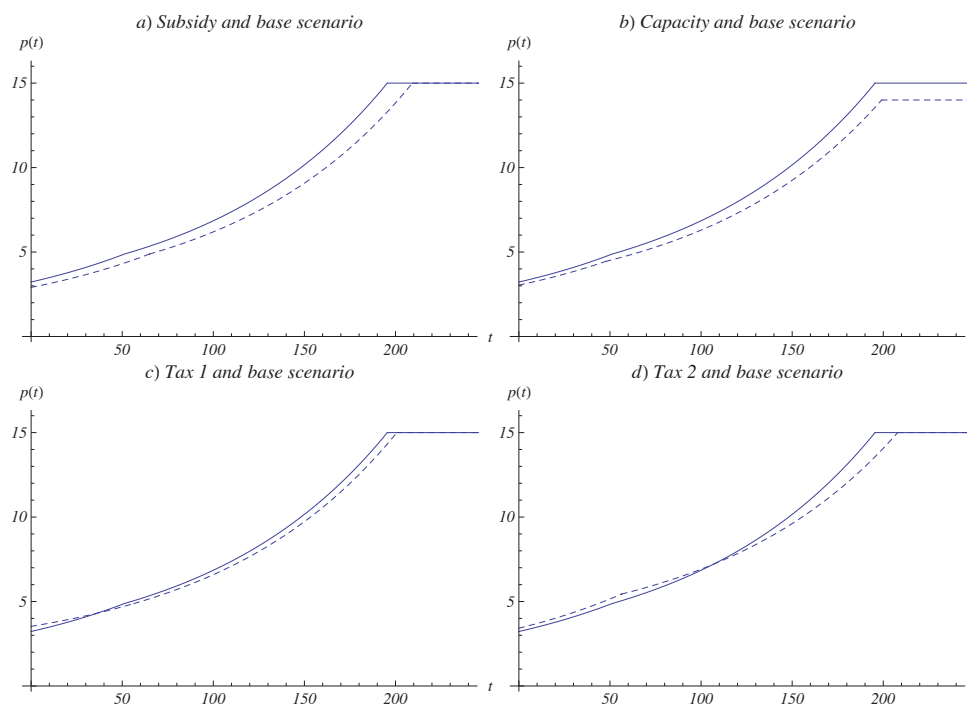


Figure 1.1: Price paths of the policy scenarios compared with the base scenario

Note: The price paths of the different policy scenarios are shown in dashed lines, the price path of the base scenario in solid lines.

In the following, the emission paths and the resulting welfare effects in terms of damages from accumulated anthropogenic carbon pollution in the atmosphere will be determined. We calculate accumulated emissions in the situation where the various deposits have different carbon contents, evaluate the welfare effects for both a zero and positive decay rate for the atmospheric carbon, and compare the effects of various policies on the social cost, under two alternative specifications of a damage function. This permits us to derive explicit social consequences resulting from carbon use under the analyzed policy scenarios, allowing for both flow and stock damages.

1.4.3 Welfare Analysis

We complement our analytical and numerical investigation by a welfare analysis that evaluates the effects of the different policies, using specific functional forms to model social damage from anthropogenic carbon emissions. Thereby, the evolution of the stock of atmospheric carbon is modeled under alternative assumptions about the accumulation of anthropogenic carbon in the atmosphere. First, the decay rate of atmospheric carbon is assumed to be zero. Second, the zero depreciation rate assumption is relaxed and a more realistic model is introduced in which the atmospheric carbon stock partially decays from the atmosphere over time. The latter is modeled based on considerations of Archer (2005) and others (see, e.g., Socolow and Lam 2007) who analyze the accumulated stock of emissions in the atmosphere. We study both the cases of linear and convex social damage functions, and compare the present value damages of the different policy scenarios. Accumulated damages depend not only on the speed of extraction. A faster

accumulating emissions stock brings higher damages closer to the present. Therefore, modeling a positive decay rate allows to gain further insight into welfare effects of climate policy. Later in the analysis, these are identified and discussed in more detail with regard to their implications for the analysis as well as for policymakers.¹⁴

1.4.3.1 Emission Paths

For our welfare analysis, we must first compute the emission paths of the different policy scenarios for the chosen numerical example. To calculate them, we have to specify the emission parameters of the extracted exhaustible resources. In the following, we assume that $\eta_1 = 1$ is the emission parameter of the low-cost exhaustible resource and $\eta_2 = 2$ is the one for the high-cost exhaustible resource. For our fuel market example, this reflects that conventional oil is not only cheaper, but also has lower emissions during extraction and production than unconventional oil.

During the first extraction phase, i.e. the time interval $[0, t_3)$, all energy comes from deposit 1. Since extraction from this deposit must equal energy demand, emissions from the consumption of $q_1(t)$ are $\varepsilon_1(t) = \eta_1 q_1(t)$. Over the time interval $[t_3, T)$, Phase 2, energy demand is met by extraction from deposit 1 and by renewable energy supply $\bar{q}_3 = A - \bar{p} = 5$ such that emissions at any time t in the interval $[t_3, T)$ are $\varepsilon(t) = \eta_1(Q(t) - \bar{q}_3)$. Over the time interval $[T, \bar{T})$, Phase 3, energy demand is met by extraction from deposit 2 and by renewable energy supply $\bar{q}_3 = 5$. Thus extraction from deposit 2 at any time t during the interval $[T, \bar{T})$ is $q_2(t) = D[p(t)] - \bar{q}_3$ and emissions from consumption of q_2 at any point of time in $[T, \bar{T})$ are $\varepsilon_2(t) = \eta_2(Q(t) - \bar{q}_3)$.

Figure 1.2 shows how the different policy measures illustrated in dashed lines affect CO₂ emission streams compared to the base case illustrated in solid line.¹⁵ The graphs are named analogous to those of Figure 1.1. We can see immediately how the policy measures extend the overall emitting period. In the subsidy scenario, emissions tend to be higher than in the base case (since the resource price is lower), except that z is larger and t_3 occurs sooner. This compensates for higher emissions in the beginning, such that the total extraction period of the cheaper resource increases (the exhaustion duration of the expensive resource being constant, the emission path shifts to the right). In the capacity expansion scenario, a slightly lower price path leads to slightly higher emissions during the extraction period of the low-cost deposit. Moreover, z is shorter compared to the base case, but emissions are lower due to the increased capacity. Nevertheless, the increased capacity cannot stretch the first extraction period until T ; however, emissions from the dirtier resource can be slowed down, at least until the emission paths cross. In the first tax

¹⁴ In this paper, we analyze a partial equilibrium resource model. We focus on social damages from accumulated anthropogenic carbon pollution in the atmosphere. We do not take into account further effects on production or consumption. Therefore, a welfare effect of a policy measure is positive in the present analysis if it decreases pollution damages compared to the baseline scenario without policy intervention.

¹⁵ The marginal analysis conducted in the previous section has determined the direction of a policy effect. Here, the calibration of the model determines the quantitative effect of a policy measure. For example, the chosen emission intensities influence the extent of the changes in the emission levels associated with changes in the fuel mix but not their direction. The discussion of the qualitative and quantitative effects is continued in the following sections.

scenario, due to the higher initial price, emissions can be reduced initially and their emission path can be flattened with only slight changes in t_3 and a slight increase in z . Since there are no changes in the emission flows from the dirty energy good (the emission path shifts to the right), the overall effect on \bar{T} is positive. Finally, taxing the dirty energy good has effects similar to those found when taxing the cheap exhaustible energy good and therefore lowers the periodical emissions during and at the same time increases the phases of low-cost exhaustible resource extraction (phases 1 and 2). In the third phase, which consequently starts later, emissions start lower but since the path is flatter, end up higher. Also in this policy scenario, the overall effect on \bar{T} is positive.

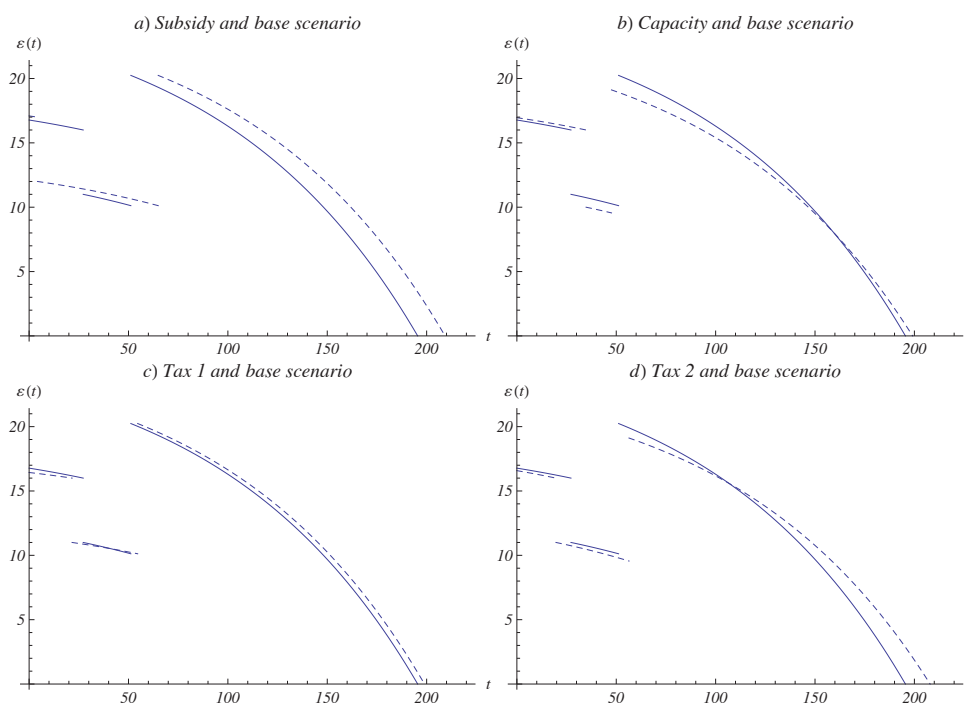


Figure 1.2: Emission paths of the policy scenarios compared with the base scenario
Note: The price paths of the different policy scenarios are shown in dashed lines, the price path of the base scenario in solid lines.

1.4.3.2 Pollution and Damages with a Zero Decay Rate

In this section, a decay rate of zero is assumed, which means that once anthropogenic CO_2 has been emitted into the atmosphere, it remains there forever. $\delta = 0$ can more broadly be interpreted as an approximation of a δ close to 0 meaning that the potentially existing decay of atmospheric carbon is just not relevant in the considered period of time and as a first approximation can be ignored (see, e.g., Sinclair 1994; van der Ploeg and Withagen 2011a). When there is no decay, the volume of pollution, here, $V(t)$, is identical to accumulated emissions, here, $E(t)$. In the following, the welfare analysis is conducted for the baseline scenario and can be performed analogously for the other policy scenarios.

Over the time interval $[0, t_3]$ in Phase 1, accumulated stock pollution (which is the accumulated stock of anthropogenic carbon in the atmosphere) is

$$V^{\text{phase 1}}(t') = \eta_1 [A - c_1] t' - \eta_1 (c_2 - c_1 + (\bar{p} - c_2)e^{-ry}) e^{-rT} \left(\frac{e^{rt'} - 1}{r} \right) \quad (1.37)$$

at time t' (for $0 \leq t' \leq t_3$).¹⁶

Analogously, over the time interval $[t_3, T)$ in Phase 2, the stock of pollution at any time $t' \in [t_3, T)$ is

$$V^{\text{phase 2}}(t') = \eta_1 (A - c_1 - \bar{q}_3) t' + \eta_1 \bar{q}_3 t_3 - \eta_1 (c_2 - c_1 + (\bar{p} - c_2)e^{-ry}) e^{-rT} \left(\frac{e^{rt'} - 1}{r} \right) \quad (1.38)$$

and from the results presented in Table 1.1, we can calculate $V(T) = 700$, which is, as expected, the size of S_1 multiplied by $\eta_1 = 1$.

Over the time interval $[T, \bar{T})$ in Phase 3, the accumulated stock pollution at time t' for $T \leq t' \leq \bar{T}$ is

$$V^{\text{phase 3}}(t') = V(T) + \eta_2 (A - c_2 - \bar{q}_3) (t' - T) - \eta_2 (\bar{p} - c_2) e^{-r(T+y)} \left(\frac{e^{rt'} - e^{rT}}{r} \right) \quad (1.39)$$

with the decay rate of pollution stock still being zero. Again, from Table 1.1, we can calculate $V(\bar{T}) = 2.500$, which is obviously once S_1 plus twice the size of S_2 since $\eta_2 = 2$.

Finally, in Phase 4, which lasts from $t = \bar{T}$ until infinity, the accumulated pollution stays in the atmosphere forever as

$$V^{\text{phase 4}}(t) = V^{\text{phase 4}}(\bar{T}) = \eta_1 S_1 + \eta_2 S_2 = 2.500. \quad (1.40)$$

In the following, the damages from the accumulated atmospheric pollution are analyzed. If the damage function $C[V(t)]$ is linear, say $C[V(t)] = \theta V(t)$ (and is also equal to $\theta E(t)$ in this section with $\delta = 0$, see above), then damage at time $0 \leq t' \leq t_3$ is $C[V(t)] = \theta \eta_1 q_1(t)$ and analogously for the other extraction phases. Together with (1.37) - (1.40), the resulting total discounted stream of damage costs from $t = 0$ to ∞ is

$$C(t_0) = \int_0^{t_3} e^{-rt} \theta V^{\text{phase 1}}(t) dt + \int_{t_3}^T e^{-rt} \theta V^{\text{phase 2}}(t) dt + \int_T^{\bar{T}} e^{-rt} \theta V^{\text{phase 3}}(t) dt + \theta V^{\text{phase 4}}(\bar{T}) \left(\frac{e^{-r\bar{T}} - 1}{r} \right). \quad (1.41)$$

¹⁶ The accumulated stock of carbon in the atmosphere can be derived from

$$V^{\text{phase 1}}(t') = \int_0^{t'} \eta_1 [A - c_1 - (c_2 - c_1 + (\bar{p} - c_2)e^{-ry}) e^{r(t-T)}] dt.$$

Rearranging this term leads to (1.37). Inserting the numerical results derived in Table 1.1 gives

$$V^{\text{phase 1}}(t') = \int_0^{t'} 1.75 (17.25 + e^{0.01(t-40.37)} + 14.25 e^{0.01(t-187.60)}) dt \text{ for } t \leq t_3.$$

With this simple linear damage function, we can calculate the discounted damages for the different policy scenarios without a further specification of θ . Inserting the values of the numerical analysis into (1.41) allows us to directly compare the welfare effects of the different policy scenarios with the business as usual case. Comparing the discounted damages for the period between 0 and infinity for the different policy scenarios based on the numerical example chosen here gives

$$C^{\text{tax } 2}(t_0) \leq C^{\text{subsidy}}(t_0) \leq C^{\text{tax } 1}(t_0) \leq C^{\text{base case}}(t_0) \leq C^{\text{capacity}}(t_0) \quad (1.42)$$

where $C^{\text{tax } 2}(t_0)$ stands for damages in the policy scenario where the high-cost exhaustible resource is taxed, $C^{\text{subsidy}}(t_0)$ for the scenario with subsidization of the renewable substitute, $C^{\text{tax } 1}(t_0)$ for the scenario where the low-cost exhaustible resource is taxed, $C^{\text{base case}}(t_0)$ for the baseline scenario, and $C^{\text{capacity}}(t_0)$ for the scenario where there is a capacity increase of the renewable substitute.

What happens now when the damage function is convex? For example, if the damage function is quadratic, say

$$C[V(t)] = a \frac{V(t)^2}{b}, \quad (1.43)$$

as in van der Ploeg and Withagen (2011a), with $a = 0.00012$ and $b = 2$, we can also compute a similar integral of discounted damages. If we continue to assume zero decay ($\delta = 0$), the volume of pollution $V(t)$ continues to be equal to accumulated emissions $E(t)$. Calculating and comparing the present value of damages, we receive qualitatively the same results, the same order, as in (1.42).

The welfare order derived under the assumption that the decay rate is zero (see inequality (1.42)) applies to both the linear and the quadratic damage functions, indicating that all policy measures, except the capacity increase, reduce the damages of carbon emissions compared to the base case situation. The damages in the scenario with a capacity expansion are higher than in all other scenarios because the capacity expansion, which comes into affect in the future, at time t_3 , lowers the initial price of energy, $p(0)$, leading to increased demand for energy for the period from extraction start until t_3 , and hence greater pollution damages earlier on. Since $r > 0$, near-term emissions are more important for the welfare and this first green paradox effect cannot be compensated by the resource-saving effect of a capacity increase on S_2 (relatively high y).

Regarding the tax on the high-cost exhaustible resource, we find that it induces a general reduction of the extraction speed (leading to higher \bar{T}), and both T and y become larger. This results in lower damages compared to the baseline scenario. Subsidizing green energy also has positive welfare effects: For t_3 , T , and \bar{T} , subsidization performs even better than the tax on the high-cost exhaustible resource. The main reason why the overall positive effect is smaller is that emissions in the beginning are higher for the subsidy case (since $p(0)$ is smaller) and y is smaller. A tax on the low-cost exhaustible resource also reduces damages, but since z is relatively short and t_3 relatively high, the positive effects are not very strong for this specific damage function.

To this point, for both types of damage function, the welfare analysis implies that green energy policy measures can be either welfare increasing or detrimental, depending on how they affect the extraction behavior of the resource owners. Of course, the results depend on the model's underlying assumptions and parameter specifications. One strong assumption is the decay rate of zero. Therefore, in the next section, a welfare analysis employing a positive decay rate of atmospheric emissions is conducted.

1.4.3.3 Pollution and Damages with a Positive Decay Rate

In this section, we assume a positive depreciation of the carbon stock in the atmosphere. This is arguably a more plausible scenario. Indeed, Archer (2005), or also Houghton et al. (1990; 1992), explain (though in a highly simplified way) that a fraction of the anthropogenic carbon emissions that are in the atmosphere re-enter the carbon cycle again and are absorbed by different carbon sinks, mostly the oceans.¹⁷ This means that although a fraction of the anthropogenic atmospheric carbon stock (let's call it α) will stay in the atmosphere forever, the other part $(1 - \alpha)$ will depreciate slowly over time at a positive rate δ . Modeling anthropogenic carbon is a widely discussed issue in resource economics literature (see, e.g., Hoel 2011; Hoel and Kverndokk 1996; Farzin and Tahvonen 1996). For the sake of simplicity, the rate of decay δ is assumed to be constant over time. Based on these considerations, for each emitted ton of CO₂ at time t , the resulting amount of CO₂ in the atmosphere at time $\tau > t$ is approximated by $\alpha + (1 - \alpha)e^{-\delta(\tau-t)}$ (Hoel 2011).¹⁸

Since there is positive decay, accumulated emissions $E(t)$ always exceed the volume $V(t)$ of atmospheric pollution for all $t > 0$. We can calculate now total pollution in the atmosphere in the first phase as

$$V^{\text{phase } 1}(t) = \alpha\eta_1 \int_0^t q_1(\tau) d\tau + (1 - \alpha)\eta_1 e^{-\delta t} \left(\int_0^t q_1(\tau) e^{\delta\tau} d\tau \right) \quad (1.44)$$

with $t \in [0, t_3)$. For $t \geq t_3$, the term $\alpha\eta_1[\dots]$, from now on $a_1(t)$, with $t = t_3$ ($a_1(t_3)$) stays constant and only the term $(1 - \alpha)\eta_1 e^{-\delta t}[\dots]$, henceforth, $b_1(t_3)$, with $t = t_3$ further depreciates, resulting in $b_1(t_3)e^{-\delta(t-t_3)}$.

Total pollution in the second phase is

$$\begin{aligned} V^{\text{phase } 2}(t) = & a_1(t_3) + b_1(t_3)e^{-\delta(t-t_3)} + \alpha\eta_1 \int_{t_3}^t (q_1(\tau) - \bar{q}_3) d\tau \\ & + (1 - \alpha)\eta_1 e^{-\delta(t-t_3)} \left(\int_{t_3}^t (q_1(\tau) - \bar{q}_3) e^{\delta(\tau-t_3)} d\tau \right) \end{aligned} \quad (1.45)$$

¹⁷ For simplicity, we abstract from any lags between emission production, pollution accumulation, and damages as described, for example, in Houghton et al. (1990; 1992).

¹⁸ As the findings of, e.g., Houghton et al. (1990; 1992) imply, the decay rate might not be constant over time. They report that the decay rate of atmospheric carbon declines over time depending on the saturation of the oceans. Though, at least as an approximation, this effect is also captured in our model since we assume that a share of anthropogenic carbon stays in the atmosphere forever.

with $t \in [t_3, T)$. Analogous to the first extraction phase, for $t \geq T$, the term $\alpha\eta_1[\dots]$ for $t = T$, from then on $a_2(T)$, stays constant and only the term $(1 - \alpha)\eta_1 e^{-\delta(t-t_3)}[\dots]$ with $t = T$ (henceforth, $b_2(T)$) further depreciates, resulting in $b_2(T)e^{-\delta(t-T)}$ for $t > T$.

Total pollution during the third phase is

$$\begin{aligned} V^{\text{phase 3}}(t) = & a_1(t_3) + a_2(T) + b_1(t_3)e^{-\delta(t-t_3)} + b_2(T)e^{-\delta(t-T)} + \alpha\eta_2 \int_T^t (q_2(\tau) - \bar{q}_3) d\tau \\ & + (1 - \alpha)\eta_2 e^{-\delta(t-T)} \left(\int_T^t (q_2(\tau) - \bar{q}_3) e^{\delta(\tau-T)} d\tau \right) \end{aligned} \quad (1.46)$$

with $t \in [T, \bar{T})$. As before, for $t \geq \bar{T}$, the term $\alpha\eta_2[\dots]$ with $t = \bar{T}$, which we will call $a_3(\bar{T})$ in the following, stays constant and only the term $(1 - \alpha)\eta_2 e^{-\delta(t-T)}[\dots]$ with $t = \bar{T}$ (henceforth, $b_3(\bar{T})$) further depreciates, resulting in $b_3(\bar{T})e^{-\delta(t-\bar{T})}$ for $t > \bar{T}$.

Moreover, from $t = \bar{T}$ on (Phase 4), there is no further anthropogenic CO₂ emitted in the atmosphere. Therefore, total pollution remains constant at

$$V^{\text{phase 4}}(t) = a_1(t_3) + a_2(T) + a_3(\bar{T}) + b_1(t_3)e^{-\delta(t-t_3)} + b_2(T)e^{-\delta(t-T)} + b_3(\bar{T})e^{-\delta(t-\bar{T})} \quad (1.47)$$

for all t with $t \in [\bar{T}, \infty)$.

Figure 1.3 shows atmospheric pollution over time that results from the different extraction scenarios, under the assumption that $\alpha = 0.25$. The different policy scenarios in comparison with the base case are presented analogous to Figures 1.1 and 1.2. As t approaches infinity, the atmospheric polluting stock of anthropogenic carbon converges to $V(t \rightarrow \infty) = 625$. This is because a fraction $(1 - \alpha)$ of the anthropogenic carbon stock depreciates from the atmosphere over time. Moreover, in case of a capacity expansion (an increase in \bar{q}_3) and taxing the high-cost exhaustible resource (sections *b*) and *d*) of Figure 1.3), the peak of accumulated pollution is clearly lower than in the base case, while for subsidization of the green energy and for a tax on the low-cost exhaustible resource, it is quite similar to the base case (sections *a*) and *c*) of Figure 1.3). Regarding the tax on the high-cost exhaustible resource, this is because emissions are postponed (\bar{T} is very large) and therefore the time path of the pollution stock is flatter. Regarding the capacity expansion scenario, pollution is slightly higher in the beginning such that due to the constant decay rate, more carbon has already depreciated from the atmosphere when the peak of the atmospheric pollution stock is reached.

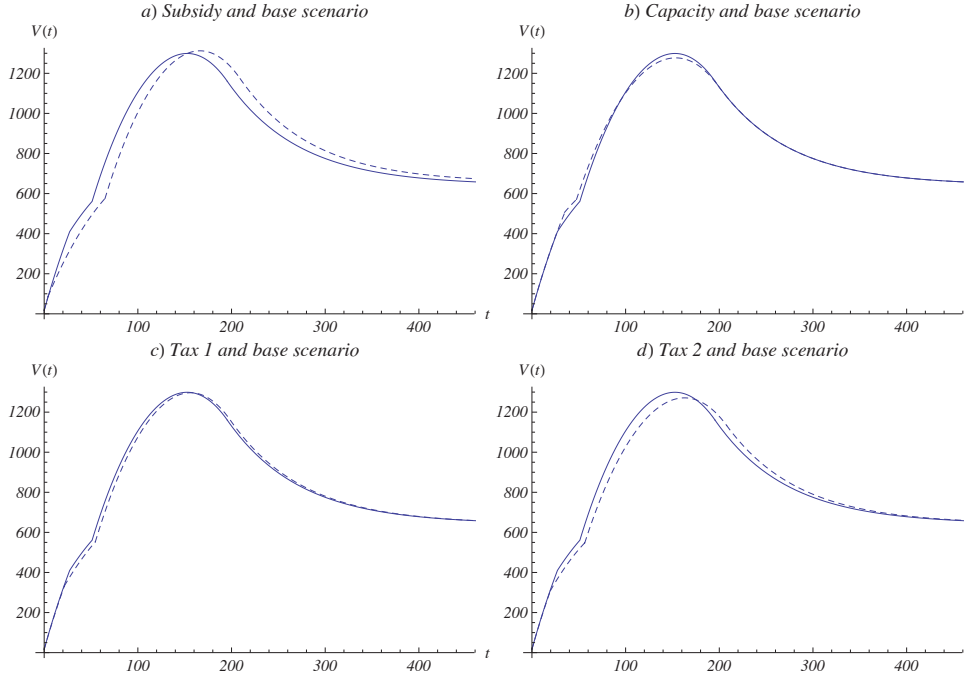


Figure 1.3: Accumulated pollution of the policy scenarios compared with the base scenario and positive decay

Note: The price paths of the different policy scenarios are shown in dashed lines, the price path of the base scenario in solid lines.

Based on the pollution paths, the welfare effects of the different policy measures are calculated and compared. Analogous to the previous section, if damage function $C[V(t)]$ is linear, say $C[V(t)] = \theta V(t)$, and using the above notation together with (1.44) - (1.47), the integral of the stream of discounted damages over all phases is

$$\begin{aligned}
 C(t_0) = & \int_0^{t_3} e^{-rt} \theta [a_1(t) + b_1(t)] dt + \int_{t_3}^{\infty} e^{-rt} \theta [a_1(t_3) + e^{-\delta(t-t_3)} b_1(t_3)] dt \\
 & + \int_{t_3}^T e^{-rt} \theta [a_2(t) + b_2(t)] dt + \int_T^{\infty} e^{-rt} \theta [a_2(T) + e^{-\delta(t-T)} b_2(T)] dt \\
 & + \int_T^{\bar{T}} e^{-rt} \theta [a_3(t) + b_3(t)] dt + \int_{\bar{T}}^{\infty} e^{-rt} \theta [a_3(\bar{T}) + e^{-\delta(t-\bar{T})} b_3(\bar{T})] dt \quad (1.48)
 \end{aligned}$$

where the first line describes the streams of discounted damages for first period emissions, the second line those for second period emissions and the third line those for third period emissions.

Inserting the values of the numerical analysis into (1.48) allows us to directly compare the welfare effects of the different policy scenarios with the business as usual case. Under the linear damage function, comparing the discounted damages of the period between 0 and infinity for the different policy scenarios gives

$$C^{\text{tax } 2}(t_0) \leq C^{\text{subsidy}}(t_0) \leq C^{\text{tax } 1}(t_0) \leq C^{\text{base case}}(t_0) \leq C^{\text{capacity}}(t_0) \quad (1.49)$$

which is the same welfare order as in the previous section with a zero decay rate (see (1.42)).

In contrast, with the convex damage function (1.43), we obtain a somewhat different ranking of the discounted stream of damages for the different policy scenarios:

$$C^{\text{tax } 2}(t_0) \leq C^{\text{tax } 1}(t_0) \leq C^{\text{subsidy}}(t_0) \leq C^{\text{base case}}(t_0) \leq C^{\text{capacity}}(t_0). \quad (1.50)$$

Comparing (1.42) with (1.49) and (1.50), we see that three of the four policy measures are welfare increasing compared to the laissez-faire situation. Again, only a capacity increase of the renewable backstop leads to higher damages compared to the base case. However, in the latter situation of positive decay and a convex damage function, the welfare order changes slightly compared to the scenario with a positive decay rate and a linear damage function, as well as compared to the zero decay situation previously analyzed. Here, a tax on the high-cost exhaustible resource still reduces damages the most compared to the base case, but now a tax on the low-cost exhaustible resource is the second and a subsidy on the renewable substitute is the third effective instrument. This is because in the subsidy scenario, emissions are higher in the beginning, and therefore damages, due to the underlying convex damage function, are relatively higher than with the linear damage function.¹⁹

The generally poor performance of the capacity increase scenario that has been found can be seen in the light of Gerlagh's (2011) definition of a strong green paradox. A relaxation of the capacity constraint of the green substitute leads not only to an increase in the near-term emissions but also to an overall welfare loss for society and, therefore, a strong green paradox occurs. This green paradox result is summarized in Proposition 8.

Proposition 8: Numerical simulations show that a capacity expansion of the green energy substitute leads to a strong green paradox since it reduces social welfare compared to the laissez-faire case.

A capacity increase might result from technological progress (e.g. second-generation bio-fuels), but can also be induced by the respective policy measures (e.g. when the government allows import of a biofuel previously banned from the market or introduces biofuel quotas). The following section sheds some further light on the policy relevance of the presented model.

1.5 Policy Relevance

The model presented in this paper exhibits a considerable degree of flexibility and is able to capture various current problems. To illustrate this broad applicability, this section provides (stylized) evidence that supports this paper's approach, showing that it is highly relevant. In

¹⁹ While the direction of an effect of a policy measure (its marginal effect) is a general result and (qualitatively) independent of the underlying parameter choice, this doesn't necessarily apply to the quantitative effect in terms of the resulting welfare order. This is especially the case if the analyzed policy measures are not marginal. In practice, policy measures are not marginal. To illustrate the effect of considering this in a policy instrument evaluation, this numerical analysis is also not. A further discussion on this can be found in the last section of this paper.

addition to the oil market application presented in Section 1.4, this section illustrates how the model can also be used to analyze the transformation of the electricity sector.

As already explained in Section 1.4, a natural application of our model is an oil market with conventional and unconventional oil as well as biofuels as a clean substitute. The cost structure and environmental impacts can be described as it is captured in the parameter choice in Section 1.4. The consideration of two rather than one ‘dirty’ resource is supported by the recent emergence of unconventional carbon resources such as extra heavy oil, oil sands, and oil shale (Gordon 2012).²⁰ Extracting oil from unconventional sites is more costly as well as more energy intensive and, thus, unconventional oil has a higher CO₂ emission intensity and extraction cost level than conventional oil. The modeling framework applied here is well suitable for capturing this issue. Specifically, beside different technological problems, biofuel production raises concerns with respect to land use since there might not be enough (suitable) land available for biofuel production and, even if there were, using it for that purpose might seriously compromise food production as well as raise sustainability concerns (see, e.g., Sinn 2012). Thus, it seems to be the case that there is a constraint imposed on the share of biofuels production. The share of biomass from global primary energy supply is currently about 15%. This is to a very large extent attributable to so-called ‘traditional biomass’ - the use of firewood, charcoal as well as agricultural residues (IEA 2012). The share of biofuels in global road transport, however, is merely 3% and several problems indicate that it is more than reasonable to assume that biomass is not a backstop technology that can be used without constraints (IEA 2011).²¹ A core result of the theoretical as well as numerical analysis is the negative welfare effect of the capacity expansion scenario. Therefore, in the context of the present analysis, the global biomass potential that actually exists can pose a considerable threat to the exhaustible resources owners and therefore can be seen as potentially problematic. In light of our findings, transport sector policies such as blending mandates must be analyzed carefully regarding possible green paradox effects.

The already mentioned electricity sector is another possible application for our model. There is a similar situation present as in the oil market example: Electricity is generated from both different ‘dirty’ and exhaustible conventional resources as well as green ones simultaneously - despite the fact that renewable energy is considerably more expensive than electricity conventionally produced. Widely discussed topics like climate change, energy security or resource scarcity increase the attractiveness of using renewable energies such as, for example, wind or solar power rather than (or at least in addition to) coal or gas. In consequence, policy instruments such as feed-in tariffs or green energy quotas are in place in many countries. For example, Germany today generates about 20% of total electricity from renewable sources such as wind and

²⁰ This might also be seen as an approximation of an increasing (instead of flat) marginal cost curve.

²¹ Even though projections certainly indicate that there is a vast potential for biomass (for example, unused and surplus land has the potential of about 550-1,500 EJ biomass production in 2050 (IEA 2011)), the way to exploit this potential is nevertheless long and stony. To mention just a few of the challenges, crop yields need to increase considerably, and substantial parts of land need to be converted. In addition to that, IEA (2011) points to regulatory requirements and stresses the importance of ensuring that food security is not compromised (see also Sinn 2012).

solar and the European Union aims at reaching this share at the European level for 2020. Clearly, there are limits, both political and technical, to increasing this share.²² In other words, assuming that a backstop resource for electricity generation is unrestrictedly available is problematic. The results of our model indicate that policy instruments intending to increase the capacity constraint of a renewable substitute are not without problems but bringing their market entry forward may have positive (long-term) effects. However, a detailed analysis of possible green paradox effects in the electricity market requires an appropriate calibration of the numerical model.

There are even more ways of interpreting our model. An example is nuclear energy - a 'conventional,' but carbon-free energy source, which is capacity-constrained by regulatory, political, and maybe even (safety-related) technological restrictions. More generally, in contrast to the case where the renewable energy is clean, the case where the backstop technology is dirty is also of interest (see, e.g., van der Ploeg and Withagen 2012a). Regarding a dirty backstop, one might think, for example, of liquid fuels produced with coal-to-liquids technologies. Of course, also for these cases, a detailed analysis of possible green paradox effects requires a corresponding calibration of the numerical model.

These reflections bear witness to the broad applicability of this paper's model. In a nutshell, the model applied in this paper can capture different situations that are currently present in the discussion about energy markets. At the same time, the results obtained in this paper clearly indicate that neglecting the important feature of capacity-constrained backstop technologies can lead to wrong policy decisions.

1.6 Summary and Conclusions

This paper addresses the considerable difficulty of decarbonizing an economy and analyzes the behavior of agents, especially regarding the supply side of energy production, to obtain a clearer understanding of how various policies may affect energy markets. The model applied in this paper has two important features. First, it encompasses three different resources with different extraction costs. One of these resources is assumed to be 'green' and capacity-constrained as demonstrated in the previous section. Second, the model allows resources with different extraction costs to be used simultaneously. These two features distinguish this paper from the majority of recent work on climate policies.

Based on a partial equilibrium model of Holland (2003) and with particular reference to the concrete oil market example, we analyze the effects of climate policy on an energy market

²² For example, substantial adjustments of the electricity transmission and distribution network are required. What is more, finding solutions for the related problems of intermittent renewable energies and the considerable lack of storage facilities is anything but easy. In addition to these technological challenges, there are also important regulatory ones. The requirement of backup power plants to guarantee network stability sparked the debate on an entire redesign of electricity markets - see the discussion on so-called capacity markets (IEA 2012). Moreover, the development of renewable energies in electricity production must be seen in the context of the energy political triangle which poses a restriction on the increase of green electricity production, see the preface and the last chapter of this thesis. Since the present chapter only focuses on the supply side production decisions of energy goods, a further consideration of those topics would go beyond the scope of this approach.

characterized by two cheap but dirty fuels and a green but expensive and capacity-constrained substitute. After an implicit determination of the endogenous variables, we evaluate the effects of four different policy scenarios on supply-side extraction and production behavior, as well as the resulting energy price path, using a comparative static approach.

The analysis is complemented by a numerical section in which the model and its results are illustrated based on the context of a concrete oil market example. Additionally, an extensive welfare analysis is conducted using various specifications for the amount and development of anthropogenic carbon in the atmosphere as well as alternative specifications of the environmental damage function.

We test our comparative static results for three different types of green paradox; the weak green paradox of Gerlagh (2011), which involves a short-term increase of carbon emissions, the overall green paradox, which occurs when the overall extraction duration of all available fossil fuels is shortened, and the strong green paradox (Gerlagh 2011), which arises when overall welfare decreases as a consequence of a policy measure. We find a weak green paradox for subsidization of the green energy, and both a weak and a strong green paradox for capacity enhancement.

A green paradox arises when a policy measure intended to slow down resource extraction or intended to reduce welfare damages from burning fossil fuels achieves the exact opposite effect – which is here increased (short-term) extraction or increasing overall climate damages. This basic green paradox is an intertemporal arbitrage effect: A policy measure which decreases future resource rents increases near term extraction of fossil fuels (see, e.g., Sinn (2008); Long and Sinn (1985); for an overview, see van der Werf and Di Maria (2011)). For our analysis, the intertemporal arbitrage effect as defined for the three specifications above can be found both for subsidization and capacity enhancement of green energy goods. In addition, reinterpreting our model in terms of a dirty instead of a clean capacity-constrained backstop, Conditions 1 and 2 of the model used here (see also Holland 2003) define the conditions for a green paradox based on an extraction-order effect to occur.

Our green backstop is pared down to its most simple form and does not include, for example, the possibility of a gradual relaxation of the capacity constraint or any uncertainty about the constraint. Nevertheless, we find that a renewable energy sector subject to a capacity constraint, a characteristic of green energy we actually observe, produces highly differentiated welfare effects for policy measures that intend to reduce near term carbon emissions by, directly or indirectly, promoting green energies. This feature differentiates our results from the general conclusions of the existing green paradox literature and is of significant consequence for policy advice. Thereby, the model allows further differentiation between different green paradox effects compared to other models in the literature as described above. Moreover, we show that the capacity constraint itself may at least to some extent reduce dependency on exhaustible resources and thereby helps policymakers to implement effective climate policies. We find in our extensive welfare analysis that while a policy measure might induce adverse short-term ef-

fects (weak green paradox), the welfare effects can nevertheless be those intended. This feature further differentiates our results from the general conclusions of the existing green paradox literature.

More concretely, for a policymaker who wants to support green energy to reduce anthropogenic carbon emissions, the welfare analysis implies that a tax on the high-cost exhaustible resource has the best welfare effects. A subsidy for the green energy or a tax on the low-cost exhaustible resource seem also to be useful instruments. All the three measures support renewable energy production without crowding out the exhaustible resources. This is due to the existence of a capacity constraint on the backstop technology, which breaks the neutrality of a constant unit tax and, due to the provision of an upper price floor, induces effectiveness of the respective policy instrument.²³ Even if a policy measure leads to a weak green paradox in the short run as it is the case for the subsidy, the overall welfare effect is positive. In contrast, increasing production capacity of the green substitute produces welfare decreasing effects since anticipation of a decreasing upper price floor speeds up exhaustible resource extraction to an extent that cannot be compensated by the fossil resource saving effect of increased renewables capacity (see, e.g., Strand 2007; Hoel 2008).²⁴

In any case, when conducting a welfare analysis and making recommendations to policymakers, the underlying welfare effects must be considered carefully in the context of the respective energy market situation. The sign of the marginal effects are generally valid and therefore also the direction of effects for the analyzed policy measures. However, since we do not analyze marginal effects in the numerical analysis, the result of the welfare analysis depends, at least to some extent, on the underlying parameter choice (at least when we have counteracting effects as it is the case for the subsidy scenario). While the direction of an effect is a general result and independent of the underlying parameter choice, the size of the effect is not. In this sense, the conducted welfare analysis illustrates the importance of a precise evaluation of the concrete market situation for policy advice.

A potential limitation of our approach is that we model the cost structures as well as the capacity constraint in a very simple way. However, both simplifications are widely used in literature and accepted as approximations for more elaborated cost and capacity structures actually observed in energy markets. The two exhaustible resources with different cost structures can be understood as a single energy good which becomes more difficult to produce (both more costly as well as more energy intensive) with increasing scarcity. Also we need two exhaustible energy goods to illustrate our oil market example as well as to point out the climate consequences of the extraction-order effect. Moreover, we abstain from introducing a more realistic, maybe variable or endogenous, capacity constraint of the renewable energy good. A reason for this is that our simply modeled capacity constraint is sufficient to evaluate and demonstrate the mechanisms

²³ This is also the reason why no overall green paradox effect can be found.

²⁴ The more the capacity constraint is weakened, the more the green substitute turns into a 'classical' backstop technology.

and implications we are interested in. Despite of being more complicated, results would not necessarily differ substantially in a more complex model.

Our approach should thus be viewed as a first step toward analyzing the complexity of energy markets comprised of a variety of energy goods with a special focus on the integration of capacity-constrained (green) backstop technologies. To our knowledge, this very important aspect of energy markets is mostly ignored in the literature. Since the present analysis is of partial nature, a consequent next research step would be to discover first-best energy policies as well as effects and trade-offs of different policy measures in a general equilibrium model with capacity-constrained alternative energy sources. Another approach may be the derivation of socially optimal investments in green capacity technology with an endogenous capacity constraint. This is an especially important issue in the context of the politically determined development plans of green energy we observe in many countries. Moreover, a closer look at the green substitute itself is needed to understand its effects on the extraction and production decisions of the energy suppliers and to find the resulting implications for climate and climate policy. A first step in this direction is done in the next chapter of this thesis. There, an analysis of the effects of increasing substitutability between an exhaustible and a renewable resource on resource extraction, climate, and the respective climate policy implications is conducted.

CHAPTER 2

The Implications of Energy Input Flexibility for a Resource Dependent Economy

2.1 Introduction

In principle, all measures that are discussed to reduce anthropogenic CO₂ emissions boil down to two basic channels. The first is decreasing the amount of energy within goods produced and consumed. This reduction can stem from a variety of different sources: It may result from innovations that allow to produce existing goods with less energy; it can be induced by the innovation of new goods that substitute old, more energy-intensive varieties or it might – in the simplest case – result from a decrease in the level of production (or negative growth). The second basic option to decrease CO₂ emissions is by substituting fossil energy by renewable energy. It is this second option that our paper focuses on.

Accomplishing the climate goals efficiently is likely to require both, falling energy intensities as well as substitution by renewable energy. Yet, despite the growing political focus on renewable energy sources, much of the literature on resource scarcity, climate change, and growth still focuses on the challenge posed by the exhaustibility of fossil resources. Usually, technological progress is considered to lower energy intensity of production and thus to alleviate resource scarcity and reduce climate emissions per unit produced. Moreover, those papers that take renewable resources into account mostly assume that energy from fossil and renewable sources are perfect substitutes (see, e.g., Heal 1976; Hoel and Kverndokk 1996; van der Ploeg and Withagen 2011b). Realistically, renewables will, however, remain only imperfect substitutes for oil, coal, and gas, at least in the foreseeable future. While fossils and renewables are nearly perfect substitutes for some activities – take electricity generated from wind and coal, or cars powered by biofuels, electricity or gasoline, for example – substitution is less likely with respect to other activities. The usage of oil in the chemical industry is just one of these examples. So, it seems appropriate to assume that fossils and renewables are only imperfect substitutes and will remain imperfect substitutes at least in the foreseeable future.

Technological development has, however, already overcome some limits to substitution and thus increased the potential for and the degree of substitutability. Today, countries like Germany generate more than 20% of their electricity from renewable sources.¹ The largest share

¹ In Germany, the share of renewable energies in final electricity consumption increased from 6.2% in 2000 to 23.5% in 2012 (BMU 2013).

of this generation stems from highly intermittent sources like wind and solar. The more or less seamless integration of this volatile electricity production into the market has become possible due to the increased flexibility of the system. Another illustrative example of increasing flexibility, or substitutability, between exhaustible and renewable resources is the use of biofuels in Brazil. Starting in the 70s, the mandatory share of ethanol in transport fuels has constantly been increased over the years. In response to this, industry developed flexible-fuel motors for both gasoline and ethanol use. In 2013, those ‘flex vehicles’ reach a share of 95% “of all new cars and light vehicle sales” in Brazil (Singh 2013, p. 347; see also, e.g., Eisenthal 2013; UNEP 2013).

It can be expected that the substitutability between renewable and fossil energy will further increase in the future. Take the example of producing gas from wind or solar power (‘power-to-gas’). While these technologies already exist today, their low degree of efficiency and thus high costs prevent production on a large scale. Yet, it is well conceivable that technological progress improves conversion efficiencies further while fossil energy prices rise such that ‘power-to-gas’ might become a viable alternative in the future. Other examples of increasing flexibility might encompass the installation of smart grids, the expansion of storage capacities or the intensified trade on electricity markets – or other technologies that are not even in their infancy today.

It is the increase in substitutability that the paper at hand focuses on. We assume that fossil and renewable energies are imperfect substitutes and also remain imperfect substitutes in the future although substitutability improves over time. Energy remains an essential input to production thus taking account of Daly and Farleys apt observation that “it is impossible to create something from nothing” (Daly and Farley 2004, p. 122). Moreover, we consider that burning fossil fuels, and thereby the emission of greenhouse gases, generates a market failure in the form of a negative environmental externality commonly referred to as climate change. Our specific interest is in the implications that a higher substitutability exerts on the level and speed of fossil fuel extraction. As to be expected, optimal extraction reacts on changes in substitutability. But, beyond this, we also consider the effect of higher flexibility on the effectiveness of climate policies. We specifically compare the results of a no policy scenario and a non-optimal policy scenario to the socially optimal case of a Pigou-like carbon tax. The non-optimal policies we consider are designed with an eye on the real world, i.e. with political rather than optimality considerations in mind. These policies are likely to be not even second-best. In this context, we analyze possible ‘green paradox’ outcomes, that is policy measures might speed up resource extraction and thus climate change rather than slowing it down.

We show that how resource owners react to climate policies also depends on whether or not the substitutability between energy inputs changes over time. Due to increasing flexibility, owners adjust their intertemporal extraction decision. We show that how resource extraction is affected by increasing substitutability depends crucially on the forces driving the increase in flexibility. We consider two alternative model specifications: First, substitutability rises exogenously over time - comparable to exogenous technological progress which is unaffected by the

decisions made by consumers and resource owners. Second, we allow substitutability to develop endogenously, depending on the input mix chosen by output producers. We specifically assume the elasticity of substitution between fossil and renewable energy to rise when fossil energy becomes more scarce. This adjustment reflects learning on the side of the producers. The scarcer fossil energy becomes, the more technologies are adapted to accommodate a steadily rising share of renewables in the energy mix.

As a consequence of increasing flexibility, we find two types of flexibility effects that influence the extraction decisions of the resource owners. The first effect speeds extraction up due to the expectation of higher flexibility in the future. This effect arises independently of whether the increase in substitutability is due to exogenous technological change or is endogenously driven. The second effect slows extraction down and arises when substitutability increases endogenously in accord with a changing input mix. Our results have several important implications for the design of policy measures. Specifically, a policy measure that induces flexibility-increasing technological progress must take into consideration the supply-side effects that result from the anticipation of increasing flexibility. The model also shows that for a policy to be effective, not only must flexibility effects be taken into account but the specific type of flexibility effect is also important.

Considering that the elasticity of substitution is not constant but variable has a long tradition in economic theory. Sato and Hoffman (1968) already argue that it is more realistic to assume a variable instead of a constant elasticity of substitution. They develop different variable elasticity of substitution production functions in an attempt to generalize the standard constant elasticity of substitution production technology (CES). Around the same time, Lu and Fletcher (1968) also introduce a generalized function where the elasticity of substitution is a function of relative factor inputs and for which the CES function is a special case. Another generalization approach can be found in Revankar (1971). Then, Kadiyala (1972) finally incorporates all the above mentioned functions as special cases in an even more generalized set-up. None of these papers, however, consider the potentially important implications that changes in the degree of substitutability could have in the context of exhaustible resources.

More recently, the new growth literature started to deal extensively with overcoming constraints to economic development that result from exhaustible resources. In this context, the role elasticity of substitution could play is, for example, acknowledged by Bretschger (2005, p. 150). He stresses that “[all] possibilities of substitution and, specifically, the effects technology exerts on promoting substitution, have to be studied.” Moreover, authors started to relate the elasticity of substitution to the degree of economic development of an economy (e.g. Mansanjala and Papageorgiou 2004, Karagiannis et al. 2004). Karagiannis et al. (2004), for example, argue that, as the elasticity of substitution depends on economic development, unrestricted endogenous growth is possible even in the absence of exogenous technological progress and despite the existence of constrained production factors. In this context, De la Grandville points out

that the elasticity of substitution is a “potent explanatory variable of economic growth” (De la Grandville 1989, p. 479).²

Growiec and Schumacher (2008) were, to our knowledge, the first to directly combine the issues of exhaustible resources and increasing elasticities of substitution. They show that (exogenous) technological progress which succeeds in increasing elasticity of substitution can be sufficient to overcome resource exhaustibility. They do, however, not take into account implications of externalities arising from exhaustible resource use and the possibility that changes in flexibility might not be exogenous but rather be determined by the decisions made by firms. By including disutility from climate change and endogenous changes in the elasticity of substitution into our analysis, we are able to derive more precise climate political implications. In contrast to Growiec and Schumacher, we limit our analysis to the case of renewable and fossil energy being complements – i.e. to an elasticity of substitution between the two inputs that is smaller than unity. With an elasticity that exceeds unity, exhaustible resources would not be essential inputs to production anymore and a positive level of production could, even in the absence of technological progress, be maintained forever – in other words, the exhaustibility of fossil resources would cease to be a problem.³ However, as argued before, at least in the short- and medium-term the assumption that fossil energy will remain an essential factor of production seems sensible.

In our paper, we assume in a first step and based on the model of Growiec and Schumacher that the elasticity of substitution increases exogenously (*IES case*). In a second step, we apply the production function of Lu and Fletcher (1968) in which the elasticity of substitution endogenously depends on the energy input mix (*VES case*). We consider the constant elasticity of substitution (*CES case*) as a benchmark scenario. The CES, IES, and VES cases are compared with respect to optimal resource extraction and evaluated regarding the effects of (optimal, laissez-faire, and non-optimal) climate policies.

The structure of the paper is as follows: In the next section, we introduce the concept of an increasing elasticity of substitution and discuss technological progress in this context. Then, we provide the general model approach (normative and positive) in Section 2.3. The exogenous and endogenous elasticities of substitution are introduced in Sections 2.4 and 2.5. Based on that, in Section 2.6, we analyze and compare the extraction behavior of supply side for different policy scenarios and the underlying production technologies. In Section 2.7 follows a numerical illustration of the results. Finally, Section 2.8 concludes.

² As the focus of our paper is on the implications of flexibility between inputs and not on growth, the latter interpretation is, however, less important in our context.

³ An analysis with energy goods becoming perfect substitutes is closely related to a backstop analysis. An example for this is Hoel (2008) who analyzes policy measures that promote a clean backstop technology, resulting in the fossil fuel stock being exhausted sooner and hence producing a green paradox outcome.

2.2 The Elasticity of Substitution, Flexibility and Technological Change

As the elasticity of substitution is a crucial component of our analysis, we (re-)introduce the underlying concept in the following and link changes in the elasticity of substitution to technological development. In this context, we discuss and refer to the different types of technological change that could overcome the potential scarcity of production factors.

Formally, the elasticity of substitution, σ , measures the change in the relative factor input ratio for a change in the relative marginal rate of substitution,

$$\sigma = - \frac{\frac{d \frac{x_1}{x_2}}{\frac{x_1}{x_2}}}{\frac{d \frac{dx_1}{dx_2}}{\frac{dx_1}{dx_2}}}, \quad (2.1)$$

where $\frac{dx_1}{dx_2}$ is the marginal rate of substitution which equals in a competitive optimum the relative factor prices ($\frac{dx_1}{dx_2} = -\frac{p_2}{p_1}$) (Allen 1938). More intuitively, regarding production functions, the elasticity of substitution measures the ease with which input goods can be substituted along an isoquant (see Hicks 1932). Regarding utility functions, it measures substitution possibilities within a bundle of goods for a given utility level. The elasticity of substitution can be understood as a measure of flexibility or efficiency (see, for example, Arrow et al. 1961, De la Grandville 1989, or Growiec and Schumacher 2008) or “as a ‘menu of choice’ available to entrepreneurs” (Yuhn 1991, p. 344). It is also Yuhn who sums these different interpretations up by stating “the higher the value of the elasticity of substitution, the greater are the possibilities for producing a given level of output with different factor combinations. When entrepreneurs have a variety of choices, they would choose the most efficient one” (Yuhn 1991, p. 344).

The value of the elasticity of substitution can range from 0 to ∞ . For $0 < \sigma < 1$, production factors are complements and for $1 < \sigma < \infty$, they are substitutes. If, in the case of complements, the input of one of the production factors goes to zero for a given technology, output inevitably converges toward zero. As we consider exhaustible fossil energy as one of the production factors, this is the situation we are facing in our paper. To overcome the dismal result of output going to zero, technological progress is required.

In general, three different types of technological progress can be distinguished that can succeed in overcoming the constraints set by the absolute scarcity of fossil energy. The first is factor-augmenting (directed) technological change. Models in which endogenous directed technological change drives growth have been discussed at length in the recent literature (see, e.g., Acemoglu 2002; Di Maria and Valente 2008; Pittel and Bretschger 2010; Acemoglu et al. 2012). The second type is factor-neutral technological change. In this case, technological progress enhances total factor productivity, i.e. it raises the productivity of all factors without changing their relative importance. Factor-neutral technological progress is usually considered when the mechanisms driving growth are of little importance for the research question posed. Finally, the third type is flexibility-enhancing technological change. Overcoming the exhaustibility of

an input requires in this case that elasticity of substitution increases until the production factors become substitutes, i.e., until $\sigma > 1$.

Yet, as discussed in the previous section, while we consider realistically that elasticity of substitution increases over time, we do not believe that renewable and fossil energy will become complements in the foreseeable future. Consequently, without any additional technological progress, economic activity would cease in our model despite the increase in flexibility. For this reason, we additionally assume total factor productivity to grow at an exogenously given rate. This allows us to focus specifically on the impact of the rising elasticity of substitution on the input mix without blurring effects from, for example, factor-augmenting technological change.

Regarding elasticity of substitution and its development over time, it is plausible to assume that the elasticity of substitution is constant in the short-run. But when an essential input becomes more and more scarce, as it is the case for exhaustible resources, it is also plausible to assume that some kind of learning process will be initiated that increases flexibility. This process can, for example, result decentrally from market processes, or it could be induced by policy measures. The two alternative set-ups we consider in this paper can be related to these two forces. On the one hand, we assume increasing flexibility to be exogenously driven. This exogenous development could, for example, result from state-funded fundamental research. The resulting technological change would in this case be independent of the decisions of private agents. On the other hand, for any given elasticity of substitution, the rising scarcity of fossil energy could induce substitution processes that change the energy mix. The stronger the adjustment, the more firms learn how to substitute the scarcer factor by the more abundant one. The elasticity of substitution thus becomes endogenous and a function of the energy mix.

2.3 The Model Framework

In our stylized model, final output is produced from a composite energy good for whose production exhaustible and renewable energy is used. The burning of fossil fuels results in emissions which cause pollution and therefore damages. In this section, we consider a general type of production function. Based on this framework, we derive the social costs of carbon in a social planner setting together with the socially optimal extraction decision and compare the solution with the market equilibrium. From this, we can derive the time path of the optimal carbon tax. Specific technologies will be introduced in the following sections in which we then explicitly consider exogenously and endogenously changing elasticities of substitution.

The production function of final output is given by

$$Y(t) = F(A(t), L(t), R(t)) = A(t)R(n(t), m). \quad (2.2)$$

$A(t)$ denotes total factor productivity which is assumed to grow at a constant rate g , $g > 0$, and the initial level of total factor productivity is set to unity, $A(0) = 1$, such that $A(t) = e^{gt}$. $R(t) =$

$R(n(t), m)$ represents the composite energy good that is produced from fossil fuels, $n(t)$, and renewable energy, m , which is supplied in constant amount at each point in time. In the following sections, we will provide different specific formulations of this energy production function. At this point, it is only assumed that R fulfills the standard property of positive decreasing marginal products.⁴

Fossil fuels n are extracted from an exhaustible resource stock denoted by $S(t)$. As we assume that storage of the extracted resource is not possible, the dynamics of the resource stock are given by

$$\dot{S}(t) = -n(t). \quad (2.3)$$

$S(0) = S_0 > 0$ is the initial stock of the resource in situ and constitutes an upper bound to resource extraction ($S_0 \geq \int_0^\infty n(t)dt$).⁵ For simplicity, we assume that there are no extraction costs for fossil fuels or production costs of renewable energy. As a consequence, the entire supply of m is always employed in production.

Households derive utility, $U[\cdot]$, from consumption, C , while pollution causes disutility in the form of damages, D . The representative household maximizes discounted lifetime utility

$$\int_0^\infty U[C(t), D(t)]e^{-\rho t} dt \quad (2.4)$$

with respect to its intertemporal budget constraint. $\rho > 0$ is the discount rate with which households discount future utility. Since we abstract from capital accumulation as well as costs of input usage, $Y(t) = C(t)$ holds.

The instantaneous utility function is of the isoelastic type

$$U(C(t), D(t)) = U(C(t)) + U(D(t)) = \frac{C(t)^{1-\eta}}{1-\eta} - \frac{D(t)^{1-\omega}}{1-\omega} \quad (2.5)$$

as in Aghion and Howitt (1998) or Grimaud and Rougé (2005). Utility of consumption and disutility of pollution are additively separable and the parameters $\eta > 0$, respectively $\omega > 0$, determine the constant relative risk aversion (CRRA) with $\frac{1}{\eta}$, respectively $\frac{1}{\omega}$ being the elasticities of intertemporal substitution. As for this utility function $U'(C) > 0$, $U''(C) < 0$ hold for all positive levels of consumption and $\lim_{C \rightarrow 0} = \infty$, the function satisfies the Inada conditions and implies a (strictly) positive level of consumption over time. $U(D)$ has essentially the same properties with $U'(D) < 0$, $U''(D) > 0$. Since damages create disutility, D enters the utility function with a negative sign.

⁴ Please note that we could alternatively assume a more general production function as Growiec and Schumacher (2008). They also include the input of a constant and inelastic supply of labor in a Cobb-Douglas type production function. This would, however, not affect the qualitative nature of our results.

⁵ Throughout this paper we will use \dot{x} to denote the time derivative of a variable $x(t)$, $\dot{x} = \frac{\partial x(t)}{\partial t}$.

Damages result from pollution, i.e. $D(t) = D(P(t))$, where $P(t)$ is the stock of pollution. We assume damages to be convex in pollution ($D'(P(t)) > 0$ and $D''(P(t)) > 0$) for all positive pollution levels. Pollution accumulates as a consequence of the burning of fossil fuels:

$$\dot{P}(t) = h(n(t)), \quad h_n > 0. \quad (2.6)$$

As a point of reference for the market solution and to understand the dynamics resulting from this model framework, we derive the optimal time paths of production and extraction as well as the social costs of carbon in the social planner solution in the following section.

2.3.1 Social Planner

The social planner maximizes the present value of the representative household's utility, (2.4) and (2.5), subject to the production technology, (2.2), and the resource and pollution dynamics, (2.3) and (2.6). The current value Hamiltonian of this optimization problem is given by

$$H = \frac{1}{1-\eta} F(A, n, m)^{1-\eta} - \frac{1}{1-\omega} D(P)^{1-\omega} - \mu_S n + \mu_P h(n) \quad (2.7)$$

where μ_S and μ_P denote the shadow values of resource extraction and emissions.⁶ μ_P is the shadow cost associated with the damages from accumulated pollution. μ_S is the scarcity rent of the resource stock.

From this we get the following first-order conditions:

$$H_n = 0 \quad \Leftrightarrow \quad F^{-\eta} F_n = \mu_S - \mu_P h_n, \quad (2.8)$$

$$-H_{S_n} = \dot{\mu}_S - \rho \mu_S \quad \Leftrightarrow \quad \dot{\mu}_S - \rho \mu_S = 0 \rightarrow \mu_S = \mu_{S_0} e^{\rho t}, \quad (2.9)$$

$$-H_P = \dot{\mu}_P - \rho \mu_P \quad \Leftrightarrow \quad \dot{\mu}_P - \rho \mu_P = D^{-\omega} D_P. \quad (2.10)$$

(2.8) gives the condition for an optimal extraction of the fossil resource by equating the marginal utility of extracting and consuming the resource to the social marginal costs of extraction.⁷ (2.9) and (2.10) implicitly describe the optimal time paths of the state variables S and P . (2.9) equalizes the growth rate of the social value of extracting a marginal unit of the resource to the discount rate and (2.10) describes the optimal dynamics of the social costs of carbon. Moreover, the transversality condition reads:

$$\lim_{t \rightarrow \infty} (\mu_S S - \mu_P P) e^{-\rho t} = 0. \quad (2.11)$$

Taking the time derivative of (2.8) and dividing the resulting expression by (2.8), we get the Ramsey-Hotelling condition that characterizes the interior solution of the present optimality problem:⁸

⁶ In the following, we will omit time coefficients if unambiguous.

⁷ Throughout this paper, x_y denotes the partial derivative of a variable x with respect to a variable y , i.e. $x_y = \frac{\partial x}{\partial y}$.

⁸ Throughout this paper, we will use \hat{x} to denote the growth rate of a variable $x(t)$, i.e. $\hat{x} = \frac{\dot{x}}{x}$.

$$\hat{F}_n - \eta \hat{F} = \frac{\dot{\mu}_S - \dot{\mu}_P h_n - \mu_P \dot{h}_n}{\mu_S - \mu_P h_n}. \quad (2.12)$$

The LHS of (2.12) determines the growth rate of utility from consumption which must equal the RHS, the growth rate of the marginal social cost of an additional unit of the resource extracted plus the growth rate of the scarcity rent. Without pollution, the RHS of (2.12) would reduce to $\frac{\dot{\mu}_S}{\mu_S}$ which, in the case of no pollution, equals the rate of discount ρ (see (2.9)). Thus we would be back to the standard Hotelling rule that equates the growth rate of the marginal benefits from extracting the resource to the discount rate.⁹

By solving the differential equation (2.10) we can derive the social costs of carbon denoted by SC :

$$SC = -\mu_P = \int_t^\infty e^{-\rho(\tau-t)} (D^{-\omega} D_P) d\tau. \quad (2.13)$$

Following van der Ploeg and Withagen (2011a, p. 7), we define the social costs of carbon to be equal to “the shadow cost of atmospheric CO₂ [which] is positive, because it measures the value in welfare terms of having a smaller CO₂ stock.” Taking the time derivatives of (2.13) gives

$$\dot{SC} = -\dot{\mu}_P = \int_t^\infty e^{-\rho(\tau-t)} (-\omega D^{-(\omega+1)} \dot{D} D_P + D^{-\omega} \dot{D}_P) d\tau. \quad (2.14)$$

Dividing (2.14) by (2.13) finally gives the growth rate of the social costs of carbon

$$\hat{SC} = \hat{\mu}_P = \frac{\int_t^\infty e^{-\rho(\tau-t)} D^{-\omega} D_P (\hat{D}_P - \omega \hat{D}) d\tau}{\int_t^\infty e^{-\rho(\tau-t)} D^{-\omega} D_P d\tau} \quad (2.15)$$

which is positive for $-\omega \hat{D} < \hat{D}_P$. As we will see in the next section, in which the regulated market equilibrium is derived, (2.15) is an important element in the dynamics of the optimal, Pigou-type carbon tax.

2.3.2 Regulated Market Equilibrium

In the present paper, we assume pollution damages to be an externality to households, that is, households take the damages from pollution as exogenous to their optimization problem. In an unregulated market economy, the negative externality will thus not be internalized. Accordingly, a regulator can improve welfare by introducing a carbon tax.¹⁰

The optimization problem of a representative household is in general the same as the optimization problem of the social planner except for the externality from burning fossil fuels and the tax on resource extraction (τ). The household maximizes the present value of utility, (2.4) and (2.5), net of taxes. Thus, the intertemporal optimization problem of the household is given by

⁹ The Hotelling rule is also referred to as the Solow-Stiglitz efficiency condition in the case of a social optimum.

¹⁰ Alternatively, the regulator could also introduce, for example, a tax on pollution. Although the resulting optimal tax rates would differ, the qualitative results would remain unchanged.

$$\max \int_0^{\infty} e^{-\rho t} [U(C, D) - \tau n] dt \quad (2.16)$$

subject to (2.2) and (2.3). The current value Hamiltonian now reads

$$H = \frac{1}{1-\eta} F(A, n, m)^{1-\eta} - \frac{1}{1-\omega} D(P)^{1-\omega} - \tau n - \lambda n \quad (2.17)$$

where – as already stated above – damages, D , are taken to be exogenous by the individual household. The modified first-order conditions for n and S are now given by

$$H_n = 0 \quad \Leftrightarrow \quad F^{-\eta} F_n = \tau + \lambda, \quad (2.18)$$

$$-H_S = \dot{\lambda} - \rho \lambda \quad \Leftrightarrow \quad \dot{\lambda} - \rho \lambda = 0 \rightarrow \lambda = \lambda_0 e^{\rho t} \quad (2.19)$$

and the transversality condition reads $\lim_{t \rightarrow \infty} \lambda S e^{-\rho t} = 0$. By proceeding as in the derivation of (2.12), we get the equivalent condition for the regulated market economy:

$$\hat{F}_n - \eta \hat{F} = \frac{\dot{\tau} + \dot{\lambda}}{\tau + \lambda}. \quad (2.20)$$

Without externality and carbon taxes, the RHS would reduce to $\hat{\lambda}$. Together with $\hat{\lambda} = \rho$ from (2.19), this determines the socially optimal extraction path. Otherwise, with the externality but in a still unregulated market economy ($\tau = 0$), the production level cannot be socially optimal. This situation will be evaluated later in the policy analysis.

To derive the optimal tax that internalizes the pollution externality, we compare the market solution presented in (2.20) with the socially optimal solution presented in (2.12). From (2.8) and (2.18) and considering that in the social optimum $\lambda = \mu_S$, the optimal tax rate, τ_O , is given by

$$\tau_O = -\mu_P h_n. \quad (2.21)$$

(2.21) shows that the social optimum can be reached by taxing resource use n since resource use and pollution are linked by $h(n)$. The tax equals the marginal damage from the extraction of an additional marginal unit of the resource. This damage is determined by the effect that another marginal unit of emissions has on pollution, h_n , and the present value of the damages that result from this additional pollution today and in the future, μ_P .¹¹

So far, we have solely considered a general type of energy production function without taking a closer look at, for example, the elasticity of substitution between fossil and renewable energy – and its potential development over time. To do this, we will choose specific functional forms for the production function integrating different assumptions about the development of the elasticity of substitution. Based on this, we can analyze the resulting consequences for socially optimal extraction as well as for extraction in a market economy. A special focus will be

¹¹ In case of a tax on pollution, the optimal tax rate would be $\tau_O^{pollution} = -\mu_P$.

on the implications of non-optimal carbon taxes in the presence of rising flexibility. Section 2.4 introduces a production function with an exogenously developing elasticity of substitution while Section 2.5 analyzes production for an endogenously adjusting substitution elasticity. Based on this, extraction paths resulting from the normative analysis of the social optimum as well as in the market solution for different policy scenarios are derived in Section 2.6.

2.4 The Exogenous Model

For the remainder of this paper, we assume the production technology of the composite energy good to have the same basic structure as a constant elasticity of substitution (CES) production function. The differences between a CES function and the production functions of this and the following section mainly stem from the differences in modeling the elasticity of substitution and its development over time.

In our first approach, the production function is given by:

$$R^X = \left(\psi n^{-\theta^X} + (1 - \psi) m^{-\theta^X} \right)^{-\frac{1}{\theta^X}} \quad (2.22)$$

with $\theta^X(t) = \frac{1 - \sigma^X(t)}{\sigma^X(t)}$ where θ^X is the elasticity parameter and σ^X denotes the elasticity of substitution as introduced in (2.1). This production function fulfills the standard properties of a CES function, i.e. positive and decreasing marginal products, linear-homogeneity of degree one, and constant returns to scale.

In contrast to the CES production function, we assume in this section that the elasticity of substitution increases exogenously over time according to

$$\sigma^X = \frac{\sigma_0^X + st}{1 + st} \quad (2.23)$$

where $s > 0$ and $0 < \sigma_0^X < 1$ are exogenously given.

In the following, we will refer to σ_0^X as the elasticity of substitution parameter and to s as the flexibility parameter. The production function resulting from (2.22) and (2.23) will be called, as already pointed out, the increasing elasticity of substitution (IES) production function.¹²

The parameter s determines the level of substitution elasticity at each point in time as well as the speed with which elasticity of substitution converges to unity. For $s = 0$, (2.23) reduces to $\sigma = \sigma_0$ and (2.22) becomes a standard CES function. The higher s , the higher the elasticity of substitution ($\frac{\partial \sigma}{\partial s} = \frac{t(1 - \sigma_0)}{(1 + st)^2} > 0$). The relation between the growth rate of the elasticity ($\hat{\sigma} = \frac{s(1 - \sigma_0)}{(1 + st)(\sigma_0 + st)}$) and s is ambiguous but turns positive if s and t are sufficiently high ($\frac{\partial \hat{\sigma}}{\partial s} = \frac{(s^2 t^2 - \sigma_0)(\sigma_0 - 1)}{(1 + st)^2 (\sigma_0 + st)^2}$). Regarding the elasticity of substitution parameter, a higher σ_0 raises σ ($\frac{\partial \sigma}{\partial \sigma_0} = \frac{1}{1 + st} > 0$) but reduces the speed with which the elasticity grows ($\frac{\partial \hat{\sigma}}{\partial \sigma_0} = -\frac{s}{(st + \sigma_0)^2}$).

¹² As long as there is no confusion, we will write R instead of R^X , σ instead of σ^X , and σ_0 instead of σ_0^X .

In the long-run, the elasticity of substitution converges to unity ($\lim_{t \rightarrow \infty} \sigma = 1$). For $0 < \sigma_0 < 1$ and $s > 0$, σ is smaller than unity at all times and approaches its long-run value from below. So, in contrast to Growiec and Schumacher (2008) and in line with our previous reasoning, n and m remain complements although flexibility increases and it becomes easier to substitute renewable energy for fossil fuels.¹³ The convergence of σ to unity and the accompanying continuous decrease of its growth rate reflects common economic intuition: The higher the degree of flexibility that has already been reached, the more difficult it becomes to increase σ further. Please note that the complementarity of m and n implies that the elasticity parameter, θ , can take values between zero and infinity.

Due to the complementarity implication, the produced amount of the composite energy good declines continuously with the decreasing input of exhaustible energy. To keep output from falling, total factor productivity, A , has to increase over time. If g is sufficiently high, a positive growth rate of consumption can be maintained even if energy production converges toward zero.

In the IES specification, the elasticity of substitution and its dynamics are independent from the actual level of extraction. Flexibility increases exogenously and irrespective of the actual energy market conditions. However, one can also argue that whether the level of flexibility changes over time should, realistically, be linked to market conditions. Therefore, the next section introduces an energy production function where the elasticity of substitution is endogenized and a function of resource scarcity.

2.5 The Endogenous Model

In this second approach, we introduce an energy production technology where the elasticity of substitution, σ^N , depends endogenously on relative factor inputs. More concretely, we use a variable elasticity of substitution (VES) production function in the Lu and Fletcher (1968) tradition, a generalization of the CES production function. In our VES function, the elasticity of substitution increases with falling fossil resource inputs. To interpret this, one might think of technological progress as it has already been addressed in the introduction and Section 2.2. The new energy production function that replaces (2.22) reads:

$$R^N = \left(\psi n^{-\theta^N} \gamma \left(\frac{m}{n} \right)^{-z(1+\theta^N)} + (1 - \psi) m^{-\theta^N} \right)^{-\frac{1}{\theta^N}} \quad (2.24)$$

with $\theta^N = \frac{1-\sigma_0^N}{\sigma_0^N} > 0$ (i.e. $0 < \sigma_0^N < 1$), $\gamma = \frac{1-\sigma_0^N}{1-\sigma_0^N-z}$ and $z > 0$.¹⁴ This VES production function equals a standard CES production function except that $\psi n^{-\theta^N}$ is multiplied by the term $\gamma \left(\frac{m}{n} \right)^{-z(1+\theta^N)}$.

¹³ For $\sigma_0 > 1$, elasticity of substitution would converge to unity from above and fossil and renewable resources would always remain substitutes.

¹⁴ For a derivation of the VES production function, see Lu (1967) or Lu and Fletcher (1968).

In analogy to the previous section, we now label z the flexibility parameter as it captures the sensibility of the production technology with respect to resource scarcity. For $z = 0$, the term $\gamma \left(\frac{m}{n}\right)^{-z(1+\theta^N)}$ collapses to unity and (2.24) to the standard CES function with $\sigma = \sigma_0^N$. For the contribution of the exhaustible resource to energy production to be positive, $\sigma_0^N + z < 1$ is assumed. As $\sigma_0^N > 0$ and $z > 0$ this implies $0 < z < 1$. Under these conditions, the VES production function shares some important properties with the CES production function, namely positive and decreasing marginal products as well as homogeneity of degree one.

The substitution elasticity of (2.24) can be derived as shown in (2.1) as the VES production function is homogenous of degree one.¹⁵ The elasticity of substitution now equals

$$\sigma = \frac{\sigma_0}{1 - z \left(1 - \frac{dm}{dn} \frac{n}{m}\right)} \quad (2.25)$$

where $\frac{dm}{dn} = -\frac{R_n}{R_m}$. Deriving R_n and R_m from (2.24) and inserting them into (2.25) gives after some manipulation

$$\sigma = \frac{\sigma_0}{1 - z \left(1 + \frac{\gamma(\theta - z(1+\theta))}{\theta^{\frac{1-\psi}{\psi}} \left(\frac{m}{n}\right)^{z(1+\theta)-\theta} + \gamma z(1+\theta)}\right)}. \quad (2.26)$$

Again, we concentrate on the case of complements where, as exhaustible resources become scarcer, production flexibility and therefore σ increase but, analogously to the exogenous model, do not exceed unity. For $z = 0$, complementarity between m and n is given for $0 < \sigma_0 < 1$. As σ depends positively on the input ratio $\frac{m}{n}$ (i.e. $\frac{\partial \sigma}{\partial m/n} > 0$), the elasticity of substitution rises over time when the fossil input falls while the renewable input remains constant. For $n \rightarrow 0$, the elasticity converges to unity from below.

The (heuristic) intuition for the dynamics of the substitution elasticity is straightforward: An increase in the scarcity pressure of exhaustible resources as n converges toward zero induces learning efforts to improve production conditions and, as a consequence, flexibility increases.

With (2.24) and (2.26) and our additional assumptions regarding the parameter values, the general dynamics of σ and R under the VES specification resemble the dynamics of the IES case: Flexibility increases over time but exhaustible resources remain an essential production factor. As the energy inputs remain complements, energy output will again go to zero if the growth of total factor productivity is too low.

2.6 The Effects of Increasing Flexibility and Climate Policy on the Extraction Path

As already stated in the introduction, the main interest of our paper is on how an increasing elasticity of substitution between exhaustible and renewable energy affects the extraction decision of fossil resource owners and thereby climate as well as climate policies. So, in this section, we

¹⁵ In this section and as long as there is no confusion, we will write R instead of R^N , σ instead of σ^N , θ instead of θ^N , and σ_0 instead of σ_0^N .

take a closer look at the implications on extraction and optimal climate policy. But beyond that, we also consider policies that are not first-best. As policies in the real world hardly fulfill the criteria of first-best and can, as pointed out by Sinn (2008) and others (e.g. Hoel and Jensen 2012), even lead to an increase in the speed of extraction, we are especially interested in the question how these non-optimal policies work under increasing flexibility. In addition to the standard intertemporal arbitrage effect, further effects from rising flexibility that influence the extraction decision of resource owners can be expected. More concretely, beside the standard intertemporal arbitrage effect, we find two flexibility effects in our IES and VES approaches. Before we start with the analytical derivation of the effects, their intuition will be provided in the following section.

2.6.1 The General Intuition

Extraction of fossil energy sources follows a Hotelling-like path that results from the intertemporal profit (resp. welfare) maximization of the resource owner (resp. social planner). This maximization implies that the present value of the resource is independent of when it is extracted. While it has been shown in a broad range of literature how a policy maker can introduce instruments that influence resource prices and thereby the extraction decision of a resource owner, in the present paper, we show that increasing substitutability between resource inputs also influences resource extraction. This section describes how increasing flexibility affects the intertemporal extraction decision. Afterward, we shortly recapitulate the effects that climate policy – in this case in the form of a carbon tax – has on extraction over time.

From the two production technologies analyzed in the present paper (IES and VES), two types of flexibility effects arise. In the IES case, the resource owner's extraction decision is mainly influenced by an additional effect that shifts extraction toward the present. We label this effect the *exogenous flexibility effect* as it arises in case flexibility cannot be influenced by the market participants (the exogenous flexibility effect is independent of the market participants' behavior). In the VES case, in which flexibility is endogenously induced, a second effect arises that we label the *endogenous flexibility effect*. This effect counteracts the first effect at least partially as it tends to slow down extraction. Both flexibility effects as well as the tax effect introduced below result from intertemporal arbitrage. Resource owners anticipate future changes in the market conditions and adjust the timing of their extraction accordingly.

The intuition behind the two flexibility effects is as follows. The exogenous flexibility effect arises as the resource owner anticipates that while over time scarcity of resources increases, the elasticity of substitution also increases. In the IES case, this is because elasticity of substitution is an increasing function of time (see Section 2.4), and in the VES case, it follows from the increasing scarcity of exhaustible resources that induces a flexibility-enhancing effect (see Section 2.5). In both cases, rising flexibility implies that production becomes less dependent on the input of fossil fuels such that the future value of the resource falls. This effect is exogenous to resource owners. Without an adjustment of the extraction path, this would mean that the

present value of resources extracted in the future is lower than the present value of the resources extracted today. Resource owners react to this by extracting more resources today and less in the future until present values are equalized again.

In addition to the exogenous flexibility effect, the endogenous flexibility effect arises when resource owners can influence the speed with which elasticity of substitution changes. In the VES case, resource owners understand that the faster the resource is extracted, the higher is elasticity of substitution (due to rising scarcity) which leads to a faster decrease of the value of the resource. Anticipating this, resource owners have an incentive to flatten the extraction path in order to slow down the increase of the elasticity of substitution. Therefore, the endogenous flexibility effect counteracts, at least to some extent, the exogenous flexibility effect.

Similar to the flexibility effects, a tax alters the extraction path if it changes the present value of extraction differently at different points in time. This is the standard *tax effect*. If the tax rate is chosen optimally and reflects the social costs of carbon, the RHS of (2.12) and (2.20) are the same and resource owners reallocate their extraction over time such that the extraction path in the market economy equals the extraction path in the social optimum. But what happens if the tax is not chosen optimally?

In general, the extraction decision of a resource owner is determined by (2.20)

$$-\eta \hat{F} + \hat{F}_n = \frac{\dot{\tau} + \dot{\lambda}}{\tau + \lambda}$$

where the effect of the tax on extraction depends on the concrete realization of $\dot{\tau}$ and τ . In order to determine the effects of a specific tax on resource extraction and welfare, we have to compare the market outcome under taxation to the laissez-faire situation (i.e. without climate policy, $\tau = 0$).

In general whether or not taxation leads to an increase or a decrease in welfare depends on whether the tax succeeds in moving the extraction rate closer to the social optimum. As damages from emissions are exogenous to the individual agents in a market economy, they do not take account of the fact that earlier extraction leads to a faster accumulation of the pollution stock and thus a higher present value of damages. In comparison to the social optimum, resources are therefore extracted too fast in an unregulated market economy. Policies that improve welfare should therefore induce resource owners to postpone resource extraction.

In order to elucidate the pure effect of taxation on resource extraction in the absence of increasing flexibility, let us consider the case of a production function of the CES type as given in (2.22) with a constant elasticity of substitution $\sigma = \sigma_0$ and $\theta = \frac{1-\sigma_0}{\sigma_0}$. In this case the LHS of (2.12) can be shown to equal

$$-\eta \hat{F}^C + \hat{F}_n^C = (1 - \eta)g - \vartheta \hat{n}^C \quad (2.27)$$

with $\vartheta > 0$ and where C refers to the constant elasticity of substitution case.¹⁶ The expression on the RHS is positive if the intertemporal elasticity of consumption, $1/\eta$, is not too low. As \hat{n}^C is negative, the value of $-\eta\hat{F}^C + \hat{F}_n^C$ decreases if the speed of resource exhaustion slows down. From (2.12), we see that this implies that taxation leads to slower extraction if $\frac{\hat{\tau} + \hat{\lambda}}{\tau + \lambda} < \frac{\hat{\lambda}}{\lambda}$. As $\hat{\lambda} = \rho$ holds, this implies that the speed of extraction falls if the growth rate of the tax is lower than the discount rate.¹⁷ This result is well-known from resource economics (see, for example, Sinn 2008).

To summarize, in comparison to the unregulated market solution, a carbon tax unambiguously a) lowers welfare if the growth rate of the tax exceeds the discount rate, and b) increases welfare if the growth rate of the tax is lower than the discount rate (but higher than or equal to the socially optimal growth rate of τ).¹⁸

2.6.2 Extraction Paths

To obtain analytical expressions of the extraction paths for the model versions with the variable substitution elasticity, we employ the conditions derived for the general functional forms in the social optimum as well as in the market equilibrium (Section 2.3) and combine them with the specific functional forms described in Section 2.4 and 2.5. For the constant elasticity of substitution case, we employ (2.22) with $\sigma = \sigma_0$ as in the previous section.¹⁹

Proceeding as described, we get for the socially optimal extraction path

$$\hat{n}_O^i = - \left[\frac{\dot{\mu}_S^i - \dot{\mu}_P^i h_n - \mu_P^i \dot{h}_n}{\mu_S^i - \mu_P h_n^i} - (1 - \eta)g - \Delta^i \right] \frac{1}{\Omega^i} \quad (2.28)$$

with $i = C, X, N$ and for the equilibrium condition of the regulated market economy

$$\hat{n}_M^i = - \left[\frac{\hat{\tau} + \hat{\lambda}^i}{\tau + \lambda^i} - (1 - \eta)g - \Delta^i \right] \frac{1}{\Omega^i}. \quad (2.29)$$

In case no policy is conducted in a market economy (laissez-faire case), we get

$$\hat{n}_{LF}^i = - \left[\rho - (1 - \eta)g - \Delta^i \right] \frac{1}{\Omega^i}. \quad (2.30)$$

where $\hat{\lambda} = \rho$ holds. Of course, the laissez-faire scenario is more a theoretical illustration than an actual phenomenon. Even if many countries have no explicit carbon taxes, they have energy

¹⁶ To be precise: $\vartheta = \left[1 - (1 - \eta)\psi \left(\frac{R}{n}\right)^{\theta^C} \right] + \theta^C \left[1 - \psi \left(\frac{R}{n}\right)^{\theta^C} \right]$ with $\psi \left(\frac{R}{n}\right)^{\theta^C} = \frac{1}{1 + \frac{1-\psi}{\psi} \left(\frac{m}{n}\right)^{-\theta^C}} < 1$.

¹⁷ This follows from $\frac{\hat{\lambda} + \hat{\tau}}{\lambda + \tau} = \rho + \frac{\tau}{\lambda + \tau}(g_\tau - \rho)$. From this expression, we also see that a carbon tax does not change the extraction speed if $\hat{\tau} = \hat{\lambda}$. If, however, $\hat{\tau} > \hat{\lambda}$, extraction speeds up due to taxation.

¹⁸ If the growth rate of the tax is even lower than the socially optimal growth rate, welfare decreases again compared to the social optimum. In this case, given the level of impatience of the households, too much of resource use is shifted to the future. Given that $\hat{\tau}$ is low enough, welfare could even decrease compared to the unregulated market economy.

¹⁹ For more details on the derivation of (2.28) to (2.30), see Appendix A.

taxes, command-and-control measures, or emission trading systems in place which could also be translated into carbon taxes.

While the functional forms of the optimal and market extraction paths are the same for all three model versions, Δ^i and Ω^i differ which then, consequently, also changes the shadow prices λ , μ_S , and μ_P . For the three models we get:

$$\Delta^C = 0 \quad (2.31)$$

$$\Delta^X = (1 - \eta) \frac{s\theta^X}{1 - \sigma_0} \ln(R) + \left[((1 - \eta) + \theta^X) \chi \dot{\theta}^X - \theta^X \ln(n) \right] \hat{\theta}^X \quad (2.32)$$

$$\Delta^N = 0 \quad (2.33)$$

$$\Omega^C = 1 - (\epsilon^C ((1 - \eta) + \theta^C) - \theta^C) > 0 \quad (2.34)$$

$$\Omega^X = 1 - (\epsilon^X ((1 - \eta) + \theta^X) - \theta^X) > 0 \quad (2.35)$$

$$\Omega^N = 1 - (\epsilon^N ((1 - \eta) + \theta^N) - \theta^N) \gamma^{-1} > 0 \quad (2.36)$$

with $\epsilon^C = \psi \left(\frac{R}{n} \right)^{\theta^C}$, $\epsilon^X = \psi \left(\frac{R}{n} \right)^{\theta^X}$, $\epsilon^N = \psi \gamma \left(\frac{R}{n} \right)^{\theta^N} \left(\frac{n}{m} \right)^{z(1+\theta^N)}$, and $\chi = \psi \left(\frac{R}{n} \right)^{\theta^X} \ln(n) + (1 - \psi) \left(\frac{R}{m} \right)^{\theta^X} \ln(m)$.

It can easily be seen that for $s = 0$, resp. $z = 0$, the extraction rates for the IES and VES case coincide with the extraction paths of the standard CES case, i.e. $\Delta^C = \Delta^X = \Delta^N$ and $\Omega^C = \Omega^X = \Omega^N$.

With an optimal carbon tax, the extraction rates that result from (2.28) and (2.29) are obviously the same. In this case, the representative household chooses the socially optimal extraction path and the market outcome is therefore socially optimal. If the tax design is, however, not optimal, extraction in the market economy and the social optimum will differ. With respect to the current state of climate policies, it is fair to assume that none of these policies are designed optimally. Therefore, it is most relevant to consider how a non-optimal carbon tax influences extraction.

As can clearly be seen from (2.28) to (2.30), the extraction rates cannot be solved analytically. We will solely draw some general conclusions about the effects of flexibility in the next section and then calibrate and simulate the time paths of resource extraction numerically in Section 2.7.

2.6.3 Effects of Increasing Flexibility

As can easily be seen from (2.28) to (2.30), the effects that a production technology has on extraction are qualitatively the same across all policy scenarios. Whether the growth rate of extraction is higher or lower in the IES or VES cases compared to the CES technology depends on the signs and magnitude of the terms in (2.32), (2.33), (2.35), and (2.36) that are due to the increasing flexibility.

Due to the complexity of the analyzed differential equations and their dependency on endogenous variables (the shadow prices as well as the extraction rate itself), inferences from the analytical expressions still have to be tested numerically. Only then the endogeneity can fully be taken into account. Analyzing the analytical terms merely gives ‘ceteris paribus’ results, ignoring the reactions of the endogenous variables.

Let us first compare the CES and the IES case. Compared to the CES extraction rate, the additional term Δ^X appears in the IES case in the square brackets of (2.28), (2.29), and (2.30) while $\Delta^C = 0$. The functional forms of Ω^C and Ω^X are the same. The effect of the rising elasticity of substitution on extraction thus depends on the sign of Δ^X . Whether Δ^X is positive or negative depends, however, crucially on the scarcity of the fossil fuel input. Let us assume first that the exhaustible resource is relatively abundant. In this case, Δ^X is negative if σ converges to unity (see Appendix C). If fossil resources, however, become sufficiently scarce, Δ^X turns positive. So, the exogenous flexibility effect increases the speed of resource extraction the more, the scarcer the resource becomes.

Comparing the CES and VES extraction rates shows that while for both cases Δ^i is equal to zero, Ω^N differs from Ω^C by the term $\gamma^{-1} = (1 - z(1 + \theta^{N-1}))$. We know that $\gamma > 0$ because per definition, $1 - \sigma_0 - z > 0$. Therefore, we have $0 < \gamma^{-1} < 1$. Then, Ω^N exceeds Ω^C and the speed of resource extraction is faster. This reflects the combination of the exogenous and endogenous flexibility effect which in sum still raises the speed of extraction.

2.7 Numerical Analysis

As stated before, the endogeneity and high complexity of the resource dynamics only allow to draw first tentative conclusions about the effect of increasing flexibility from the analytical expressions. Therefore, we derive the time paths of the endogenous variables numerically in this section. Based on the extraction paths, we can compare the development of the economy under the standard CES technology with the development in the IES and VES scenarios. This allows us to gain a better understanding of the direction and magnitude of the effects of interest. Moreover, we take a look on the resulting implications for climate policy and climate change. In a preliminary step to the numerical analysis, we specify functional forms for emissions, h , pollution, P , and damages, D .

Regarding the pollution dynamics and the flow of emissions, we assume the pollution stock to be non-degenerating over time and emissions to be a linear function of the fossil fuels burnt, i.e. $\dot{P} = h(n) = \varepsilon n$, with $\varepsilon > 0$ being a constant emission parameter. This specification can be interpreted as a very simplified representation of the climate system. The burning of fossil fuels leads (at least in the absence of carbon capture and storage) to a specific amount of emissions, determined by the carbon content of the fuel.²⁰ Emissions accumulate in the atmosphere and

²⁰ For simplicity, we abstract from the heterogeneity of fossil fuels in this paper.

cause climate change. Climate physics estimates the effect of accumulated carbon on temperatures to be largely irreversible for about a thousand years – in contrast to the CO₂-stock which degenerates much faster (see Solomon et al. 2009). As with respect to the damages from climate change, it is the temperature that matters and not the carbon stock, it seems a good approximation of reality to assume pollution – interpreted in temperature terms – to be non-degenerating. Given this assumption, the stock of pollution is given by

$$P = \int_0^t \varepsilon n(\tau) d\tau. \quad (2.37)$$

Damages from pollution are a function of this pollution stock

$$D(P) = aP^2 \quad (2.38)$$

with $a > 0$ and where the social damages of carbon emissions are convex, i.e. $D_P, D_{PP} > 0$ (see, for example, van der Ploeg and Withagen 2011b).

The numerical analysis will be conducted in the following subsections for a parametrization that was chosen for the different scenarios and flexibility cases to have the highest possible degree of comparability. Throughout the analysis, parameters have the same values across policy scenarios as well as across production technologies (for example, $m^C = m^X = m^N$ or $\psi^C = \psi^X = \psi^N$).²¹ As we are interested in the implications of rising flexibility under the different policy regimes, we consider the different policy scenarios – optimal policy, non-optimal policy and laissez-faire – successively in the following subsections. Since the level and dynamics of resource extraction are the decisive factors for emissions and climate change, n is always simulated first. The time paths of the other variables – energy production, total production, the elasticity of substitution, accumulated pollution, and climate damages – are then presented subsequently.

2.7.1 Optimal Policy Scenario

The optimal resource extraction path under the three technologies is described by (2.28), respectively (2.29), for the case of a regulated market equilibrium with a first-best carbon tax. The optimal resource extraction paths for the CES, IES, and VES production functions are depicted in Figure 2.1. The blue line shows the standard constant elasticity (CES), the red line the exogenously increasing (IES), and the green line the endogenously increasing (VES) elasticity of substitution case.

From Figure 2.1, we can immediately see that IES has the highest near term extraction with $n_0^X > n_0^N > n_0^C$. This is due to the exogenous flexibility effect. Moreover, from $n_0^N > n_0^C$ but $n_0^N < n_0^X$ we can see how the endogenous flexibility effect reduces the extraction-increasing ef-

²¹ The specific parametrization chosen for the following analysis is $\eta = 1.8, \omega = 2, \sigma_0^X = \sigma_0^N = 0.2, s = z = 0.1, \varepsilon = 0.6, \rho = 0.05, m = 0.8, a = 0.6, \psi = 0.6,$ and $g = 0.03$.

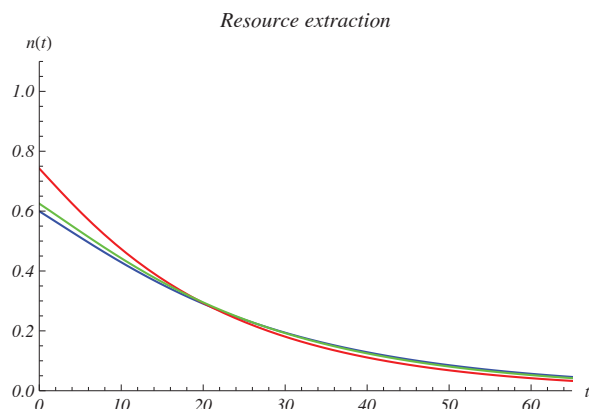


Figure 2.1: Time paths of resource extraction in the optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

fect of the exogenous flexibility effect. Intuition for these results is provided in detail in Section 2.6.1.

The driving force behind the different paths of resource extraction is the increasing flexibility in the IES and VES case. This increasing flexibility depends crucially on the parameters s and z . s is the flexibility parameter that determines how fast σ^X converges toward unity as t approaches infinity and z is the flexibility parameter that determines how sensitive σ^N reacts on the relative scarcity of n . The concrete realizations of s and z thus influence the speed with which σ^X and σ^N converge to unity and thereby also the speed of extraction and the initial resource extraction n_0^X and n_0^N .

Numerical simulations show very intuitive results: In the IES case, an increasing s increases the exogenous flexibility effect which tends to speed up extraction and thereby implies a higher n_0^X . The higher s , the faster σ^X converges toward unity and n_0^X converges toward an upper bound. An equivalent result can be found for the VES case as the elasticity of substitution is most sensitive to changes in the input mix when $z \rightarrow 1$.

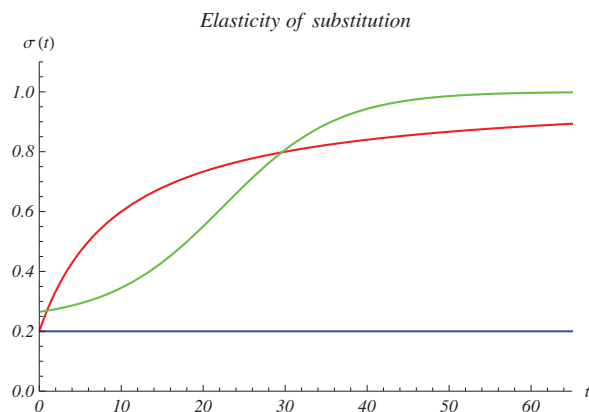


Figure 2.2: Time paths of elasticity of substitution in the optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

In Figure 2.2, we see the time paths of the elasticity of substitution that result from an exemplary value of $s = z = 0.1$. As a benchmark, the constant elasticity of substitution of the CES production function is depicted ($\sigma_0^{C,X,N} = 0.2$). We see that σ^X is a concave function of time and converges to unity. As in the IES case, in the VES case, σ^N converges toward unity, first with convex, than with concave shape. Comparing σ^X and σ^N , σ^N starts from a much higher level despite our assumption $\sigma_0^X = \sigma_0^N$. This is due to the fact that, in the VES case, the initial elasticity of substitution is given by (2.26) and not by σ_0^N . From (2.26), it follows directly that the underlying flexibility mechanism affects the level of σ^N even at $t = 0$ and due to the dependency of σ^N on relative factor scarcity, σ^N starts at a higher level than σ^X .

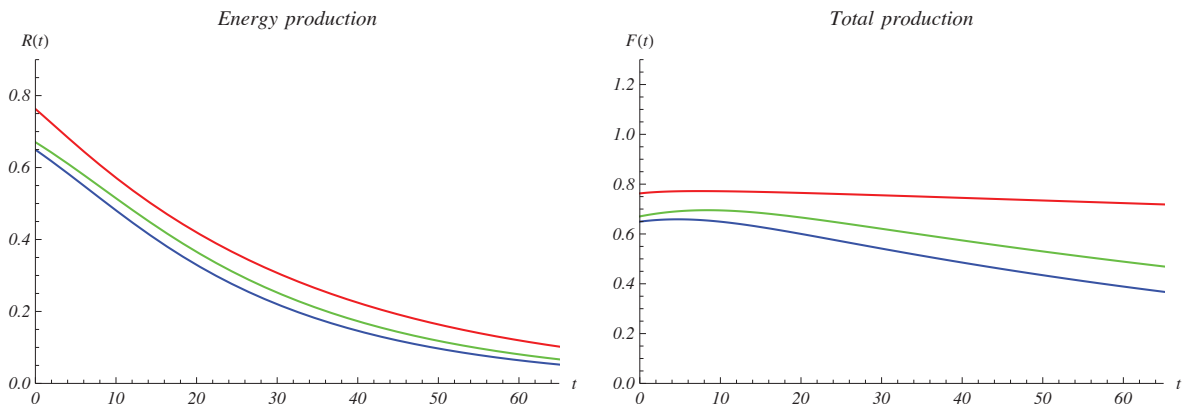


Figure 2.3: Time paths of energy and total production in the optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

The LHS of Figure 2.3 shows the production of the composite energy good. As we assume renewable and fossil energy to remain imperfect substitutes, the increasing flexibility of IES and VES cannot compensate for exhaustibility. So, energy production always converges toward zero. The initial level and concrete time path of energy production, however, depend on the extraction path of n as well as on the production technology. In the CES case, production starts the lowest and also remains the lowest at all points in time. R^N starts higher than R^C , but lower than R^X . R^X starts the highest and also remains the highest over time. The total amount of energy produced in the IES and VES scenarios is higher than in the CES case although the amount of resources available for production is always the same. This result is of course attributable to the increasing elasticity of substitution. A higher elasticity of substitution can least partly relieve the scarcity pressure of the exhaustible resource.

The second graph of Figure 2.3 shows final output production. Its long-term development depends crucially on the parameter choice for the exogenous rate of technological progress. The presented numerical example is deliberately chosen such that only in the IES case, the decrease of energy production is (almost) compensated by the exogenous technological progress. Of course, for sufficiently fast growth of factor productivity, the level of output in all three scenarios could grow over time - the ordering of growth rates would, however, be unaffected. We see that the decrease of production is slower for VES and IES than under CES. This result shows

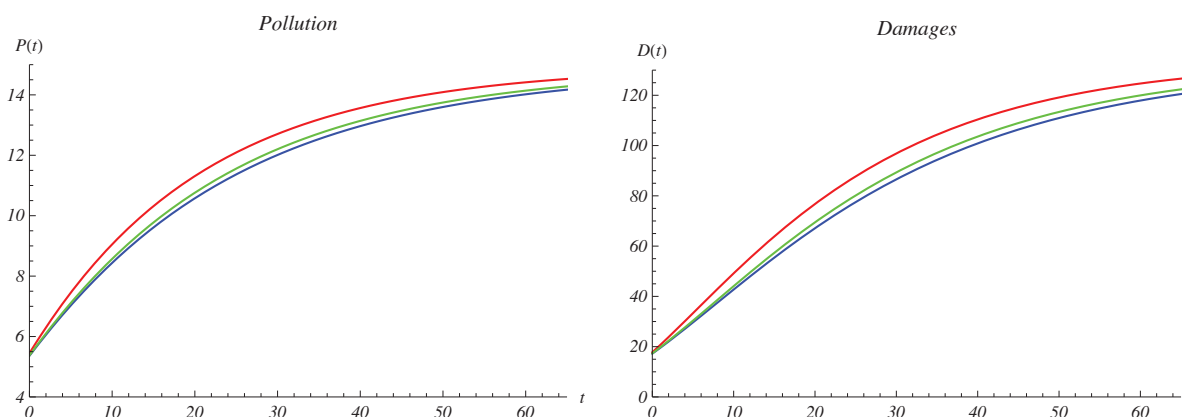


Figure 2.4: Time paths of pollution and damages in the optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

nically that economies whose flexibility improves over time are less dependent on other types of technological progress.

Pollution and damages from fossil energy use are shown in Figure 2.4. We see that for any underlying production technology, pollution and damages converge toward an upper limit. This maximum level of pollution and damages is determined by the available stock of fossil energy resources, as in our economy the entire resource stock is exhausted ($\lim_{t \rightarrow \infty} P = \varepsilon S_0$, $\lim_{t \rightarrow \infty} D = a(\varepsilon S_0)^2$). The speed at which damages converge toward this level depends on the speed of resource extraction. The steeper the extraction path, the faster pollution and damages converge toward their maximal level of damages.

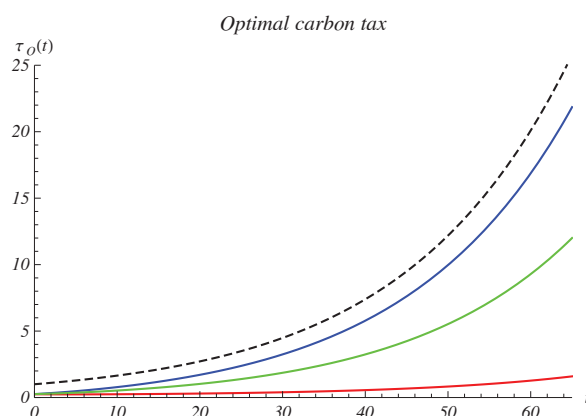


Figure 2.5: Time paths of the optimal carbon tax and shadow price of the fossil resource

Note: Blue line: CES; Red line: IES; Green line: VES; Black and dashed line: shadow price of fossil resource

Let us finally take a look at the optimal tax rates for the different technology scenarios in Figure 2.5. The optimal tax rate is determined by the social costs of carbon and the increase in pollution due to a marginal increase in extraction (see (2.21)). The tax rates are convex functions of the damages. Their time path results from the respective time path of pollution accumulation. Moreover, we see that the growth rates of the respective optimal tax are lower than the discount rate (see the black, dashed line). Therefore, the optimal carbon tax reduces, as expected, the

speed of resource extraction (see Section 2.6.1). We can see that CES has the steepest τ_O and IES the flattest. Different reasons for this can be found. Once, in both flexibility cases, the extraction decision is more sensitive regarding future price changes. Second, in the CES case, dependency on the resource and therefore its value is higher. Consequently, the tax rate also has to be higher to reduce extraction to the optimal level.

First tentative conclusions about welfare can be drawn based on the underlying utility function, which weighs utility of consumption against the respective climate effects that produce disutility from pollution. We can observe a trade-off between higher consumption utility and higher pollution disutility in both the IES and VES case compared to the standard CES production function. In Figure 2.3, we can see the production gains of increasing flexibility. On the other hand, Figure 2.4 reveals the disutility-increasing effect of IES and VES compared to the CES technology. On a first sight, the consumption gains seem to outweigh increased damages. This is because regarding consumption we have flexibility gains that result in higher overall production, while with respect to the damages we only have an intertemporal relocation (higher short-term damages).

2.7.2 Laissez-Faire Scenario

Analogous to the previous section, we start the numerical analysis of the laissez-faire scenario with an illustration of the respective extraction paths whose functional forms are given by (2.30).

On the LHS of Figure 2.6, we see the extraction paths for the CES, IES, and VES production functions. As before, extraction starts the highest in the IES case and the lowest in the CES case. Not surprisingly, we see steeper extraction paths and higher initial extraction in all laissez-faire scenarios by comparing Figure 2.1 with Figure 2.6. This has already been explained by the missing internalization of the negative externality of resource extraction resulting in too high extraction levels.

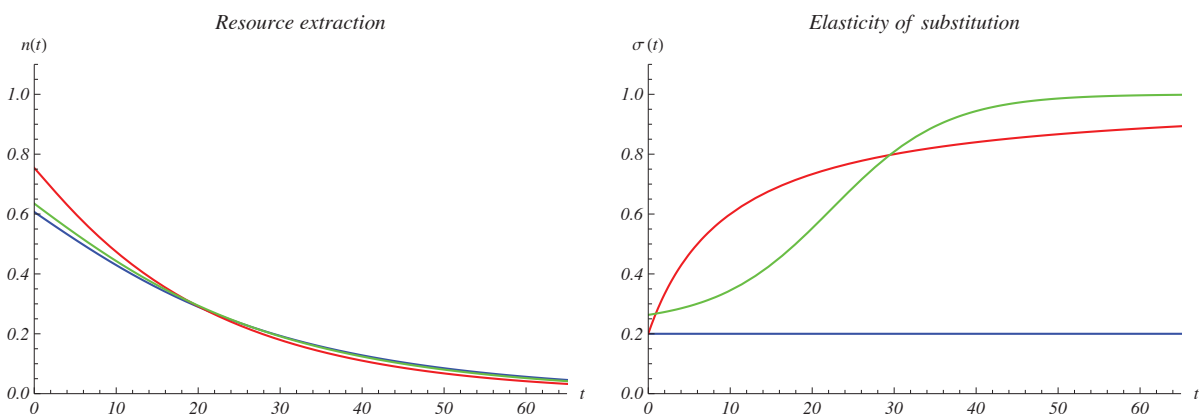


Figure 2.6: Time paths of resource extraction and elasticity of substitution in the laissez-faire scenario

Note: Blue line: CES; Red line: IES; Green line: VES

The RHS of Figure 2.6 shows the time paths of elasticity of substitution which are basically the same as in the optimal policy scenario. Since σ^C and σ^X are determined exogenously, their time paths remain unchanged. σ^N still converges towards unity but compared to the previous example, we have $\sigma_{LF}^N(t=0) < \sigma_O^N(t=0)$. The reason is that in the laissez-faire scenario, we have higher initial extraction than in the social optimum (recall that $\frac{\partial \sigma^N}{\partial n} < 0$, see (2.26)).

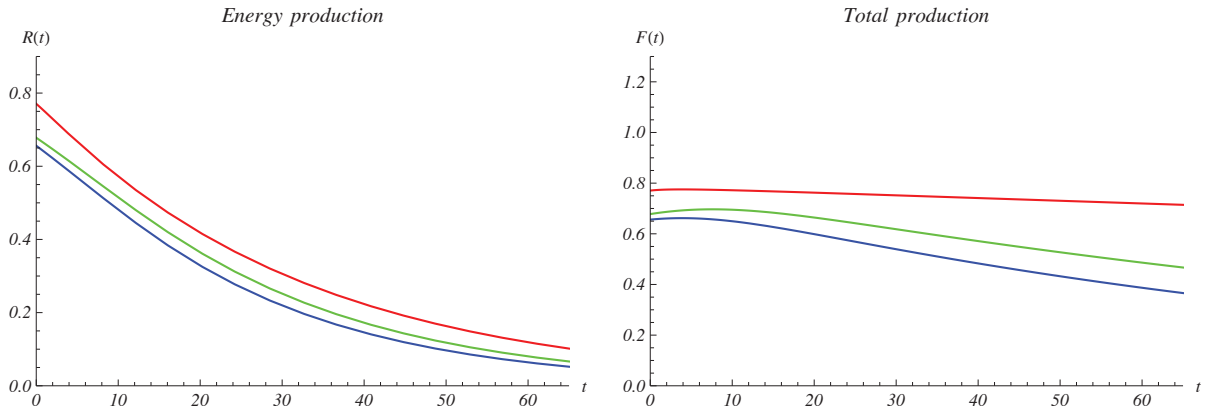


Figure 2.7: Time paths of energy and total production in the laissez-faire scenario
Note: Blue line: CES; Red line: IES; Green line: VES

In Figure 2.7, we see energy and total production. In accordance to the higher initial extraction level, energy production paths also start higher but the ordering of the production levels remains the same.

The time paths of total production on the RHS of Figure 2.7 can again directly be related to the energy production paths with exogenous growth in total factor productivity determining long-term development. Compared to the optimal paths from Figure 2.3, production starts on a higher level due to the higher initial energy production.

Figure 2.8 shows the damages resulting from the climate externality. The picture is again similar to the optimal policy scenario: Convergence is slowest in the CES case and fastest in the IES case. As all fossil resources are exhausted, the levels to which damages and pollution converge remain the same. However, compared to the optimal policy scenario, damages and pollution accumulation start at a higher level due to the higher initial extraction in the laissez-faire scenario.

2.7.3 Non-Optimal Policies

In this section, we consider policies in which the carbon tax is set non-optimally by a policy maker. We assume that the tax rate increases exogenously at constant rate. The resulting time path of the tax is thus given by $\tau = \tau_M = \tau_{M0}e^{\pi t}$ where $\pi > 0$ is the growth rate of the tax. As can be seen in Figure 2.9, the tax schedule chosen in this section lies above the socially optimal tax rates for the different scenarios (see Figure 2.5) with a growth rate higher than the discount

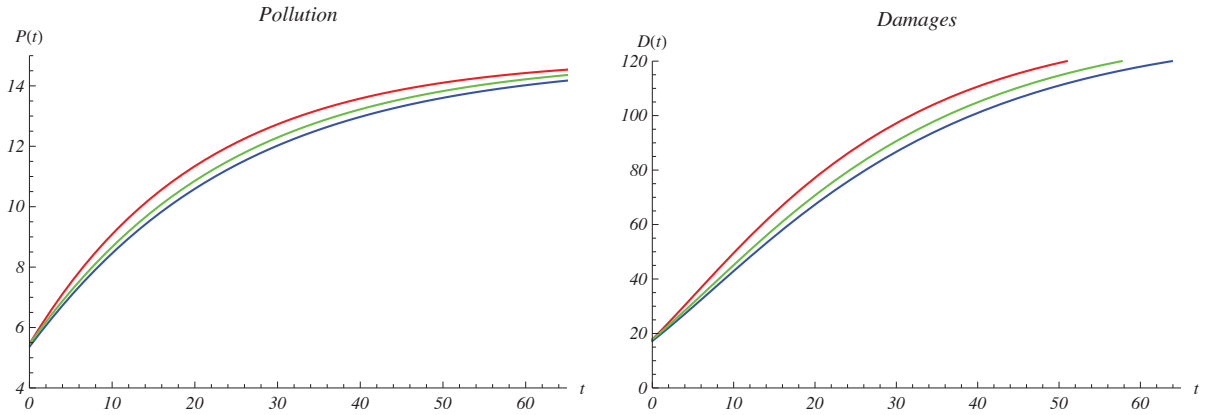


Figure 2.8: Time paths of pollution and damages in the laissez-faire scenario
Note: Blue line: CES; Red line: IES; Green line: VES

rate (for the tax to be neutral, its time path should equal the one of the shadow price of the fossil resource).

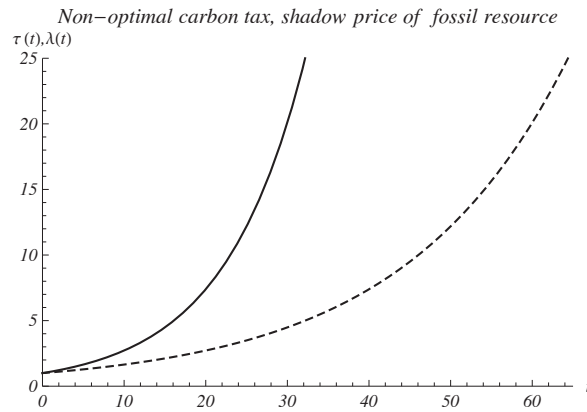


Figure 2.9: Time paths of the non-optimal carbon tax and the shadow price of the fossil resource
Note: The solid line shows the carbon tax, the dashed line the shadow price.

On the LHS of Figure 2.10, we see the extraction paths of the exhaustible resource. Again, extraction in the IES and VES case is faster than in the CES case. Compared to the social optimum (resp. the optimal policy scenario), we see that the extraction paths are relatively steeper and start on a higher level - even compared to the laissez-faire situation. This is due to the fact that the non-optimal carbon tax not only increases at a faster rate than the optimal tax but the parameter values were also chosen such that $\rho < \frac{\dot{\tau}_M + \dot{\lambda}}{\tau_M + \lambda}$ which leads to $n(0)_M > n(0)_{LF}$. Therefore, in the chosen example, climate policy even increases initial extraction and the extraction speed of resources. An explanation of the underlying intertemporal arbitrage effect has been provided in Section 2.6.1.

The RHS of Figure 2.10 shows how the elasticities of substitution evolve over time. Compared to the previous scenarios, σ^X and σ^C are unchanged while σ^N is lower than before at $t = 0$ (due to $n(0)_O^N < n(0)_{LF}^N < n(0)_M^N$).

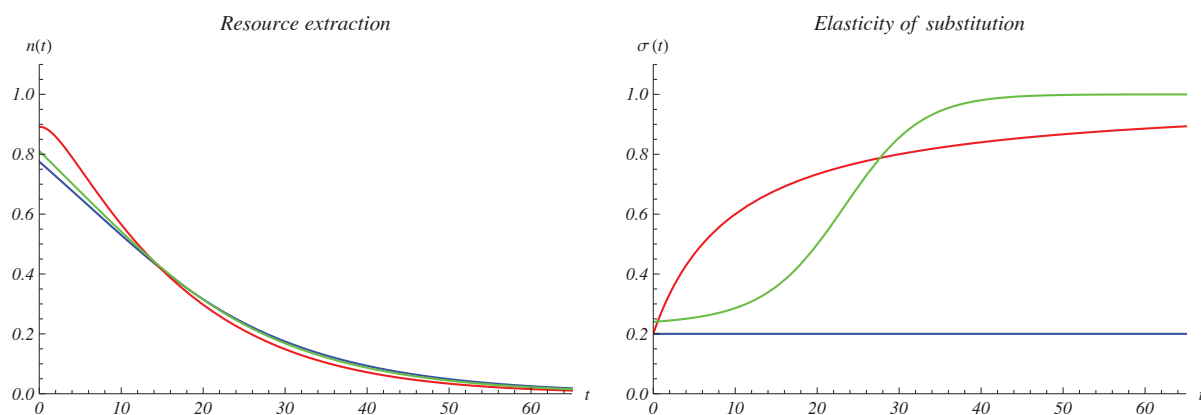


Figure 2.10: Time paths of resource extraction and elasticity of substitution in the non-optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

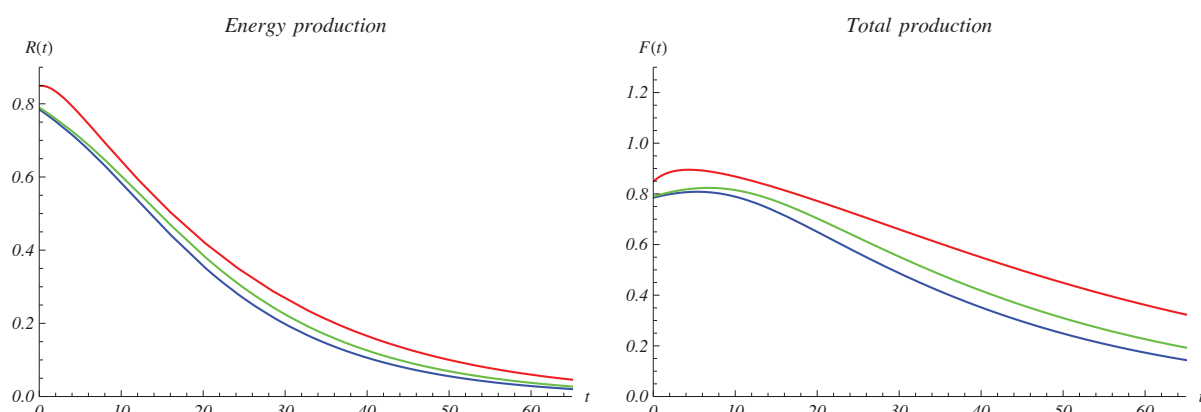


Figure 2.11: Time paths of elasticity of energy and total production in the non-optimal policy scenario

Note: Blue line: CES; Red line: IES; Green line: VES

Figure 2.11 shows the time paths of total and energy production. Again, the order of total and energy production is essentially the same as before. Due to the higher initial extraction levels in this policy scenario, initial energy production is higher than in the previous scenarios. With respect to total production, the effect of the faster decrease in energy inputs in all scenarios is reflected in the sharper decline of total production. Even in the IES case, total factor productivity growth cannot compensate for the drag of the declining energy input anymore.

The climate effects are depicted in Figure 2.12. Since initial extraction is higher than in either previous scenario, pollution and damages accumulate faster. Therefore, in the present example, choosing a non-optimal carbon tax can be more detrimental for climate change than having no carbon taxation at all.

2.8 Results and Conclusions

In the present paper, we have analyzed the effects of increasing flexibility, or substitutability, in an energy market with both exhaustible and renewable energy goods that are used for produc-

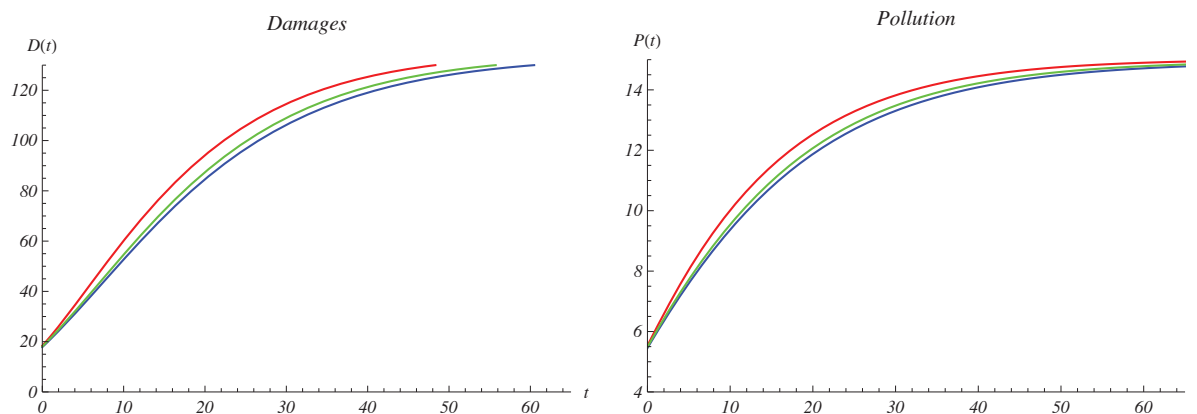


Figure 2.12: Time paths of pollution and damages in the non-optimal policy scenario
Note: Blue line: CES; Red line: IES; Green line: VES

tion of a composite energy good. Burning exhaustible resources leads to carbon emissions and thereby produces a negative climate externality. Exhaustible and renewable energies are modelled as complements with an elasticity of substitution smaller than one, but over time, the elasticity increases and converges toward unity (therefore, the energy goods remain complements but their substitutability increases). This increase is modelled both exogenously and endogenously on the basis of a standard CES production function which is extended for the respective scenario. We analyze the effects of this flexibility increase both analytically and numerically and compare the results to the standard CES case. Moreover, we analyze the impact of three policy scenarios, optimal, laissez-faire, and non-optimal policy, in the context of increasing flexibility.

We find two flexibility effects that change the extraction decision of resource owners in case of increasing flexibility. One is the exogenous flexibility effect that arises under both specifications of increasing substitutability. This effect tends to increase short-term extraction and thereby steepens the extraction path indicating that resource owners anticipate future price decreases and thereby a smaller value of their resources due to higher flexibility. The endogenous flexibility effect arises only for an endogenously increasing elasticity of substitution. This effect tends to decrease initial extraction and flattens the extraction path as the resource owner anticipates the positive relation between resource scarcity and increasing flexibility.

Under the production specifications in our paper, extraction increases unambiguously under both, the exogenous and endogenous scenario. In the endogenous case, resource owners react to the knowledge that rising resource scarcity increases the elasticity of substitution and try to attenuate this effect by slowing down resource extraction (endogenous flexibility effect). However, as the exhaustible resource becomes inevitably scarcer, they cannot forestall the increase of flexibility completely. Thus the exogenous flexibility effect dominates and initial resource extraction rises.

The shift of resource extraction to the present due to increasing flexibility is comparable to the policy-induced green paradox that Sinn (2008) describes. Only, in our case we have a technology-induced rather than policy-induced Green Paradox.

With respect to policies that aim at increasing flexibility (recall the example of biofuels in the Brazilian transport sector), our results show clearly that these policy measures must be considered in the light of the intertemporal reallocation effect that results from the anticipation of rising flexibility. Moreover, feedback effects of policy on the development of the elasticity have to be taken into account if the elasticity evolves endogenously. In the case of our production function, policies affect resources extraction which in turns changes the elasticity of substitution.

From our results we can also draw first conclusions about welfare. Compared to the CES technology, we find welfare gains due to increased energy production in the increasing flexibility scenarios as well as welfare losses due to faster climate change. While consumption profits from level effects of higher flexibility that result in higher overall production, we only have an intertemporal relocation with respect to the damages (higher short-term damages). So, if the damages from climate change are not too strong, the consumption gains might outweigh increased damages.

The negative climate externality from exhaustible resource consumption demands for policy intervention which is analyzed here in form of a carbon tax imposed on resource consumption. This tax influences the resource owner's extraction decision due to the so-called tax effect. Resource owners anticipate the effects of taxation on the future value of the resources in situ and adjusts their extraction path accordingly. If the carbon tax is set optimally, the climate externality is internalized and resource extraction is at the socially optimal level. With respect to non-optimal climate policies, we confirm the result known from the literature that policies which aim to slow down resource extraction but whose design is determined from political rather than optimality considerations are likely to result in even faster resource extraction, i.e. a tax-induced green paradox still arises under increasing flexibility.

The paper reveals further research questions. For example, a complete endogenization of the flexibility increasing process seems to be an issue of high importance. Here, one might think of a separate R&D sector that can produce and sell patents for better integration of renewable energy into the energy market. The demand for those patents increases as resources become scarcer and energy prices increase. In this context, it is interesting to find and analyze the effects on resource extraction, but also on climate as well as climate policies. Moreover, even though the issue of increasing substitutability between different energy sources is of high importance in the present discussions about climate change and scarce resources, there is only little empirical research. Not only in the context of climate policy, but also in the context of determinants for long-term growth, this topic is of high importance.

CHAPTER 3

The Development of Renewable Energies and Supply Security: A Trade-Off Analysis

3.1 Introduction

The impossibility of any longer ignoring the problem of greenhouse gas emissions has caused a shift in energy policy worldwide. Many governments for all in the Western countries have begun to emphasize the environmental aspects of their energy policy. However, designing an optimal energy policy should not be based on a one-dimensional view. Indeed, there are three benchmarks against which each energy-political initiative should be measured: its environmental soundness, its effects on security of supply, and its impact on energy prices. These three aspects comprise what may be called the energy-political triangle or, better yet, “trilemma,” a term that already implies potential conflicts.

However, energy-political initiatives are usually studied one-dimensionally in terms of their explicit goal (see, e.g., Telson 1975), and the current situation of energy market transition in Germany is no exception. The importance of such approaches is not without value, of course, but in regard to the energy-political triangle, they are not sufficient. Therefore, using the German electricity market as an example, this paper analyzes environmentally motivated instruments with respect to their further consequences for the energy-political triangle.

Designing an electricity market always involves some tension between (normative or positive) economic considerations and technical requirements and possibilities. This is especially true in the matter of supply security. From an economic perspective, a fundamental problem is estimating the value of supply security since it is not reflected in any price (de Nooij et al. 2007; Bliem 2005). The fact that security of supply is a public good complicates the situation; without a regulative intervention, it would be underprovisioned. As a consequence of these problems, security requirements for the net operators are mainly technically in nature (Woo and Pupp 1992).¹

The economic literature, however, contains a wide range of papers that estimate the social value of supply security, which is often approximated by the (social) damages of outages (see, e.g., de Nooij et al. 2007; Ghajar and Billinton 2006; Willis and Garrod 1996) and is the ap-

¹ Net operators provide and maintain the necessary infrastructure such that electricity can be fed into the grid by different entities and distributed.

proach taken here. The different estimation methods are described later in a separate section. The obtained results imply both technical and economic considerations. For example, de Nooij et al. (2010) and Munasinghe and Gellerson (1979) show how security standards based on estimating the value of supply security could replace those based on engineering practice. Thus, evaluating the value of supply security can be seen as the first step in identifying socially optimal interruption levels (Baarsma and Hop 2009). Furthermore, it can be used in case of shortages to optimally allocate electricity (de Nooij et al. 2007; Serra and Fierro 1997; Forte et al. 1995). The present analysis combines technical and economic considerations such that the social welfare effects of the technically determined transition on the electricity market can be evaluated.

The analysis is based on the German electricity market, which in recent years has experienced a considerable prioritization of environmental policy.² The development of renewable energies is considered an appropriate way of reducing the country's CO₂-emissions. Therefore, renewable energy, as well as several energy efficiency goals for 2020, were defined in a national energy concept initiating a transition process on the electricity market. Unless electricity imports shall increase, the planned nuclear phase-out has put even more pressure on this project. After the transformation, the structure of the electricity market will be decentralized instead of centralized as it is currently. The renewable energies instrument designed to accomplish this transition is analyzed in this paper considering the energy-political benchmarks: First and foremost, the social welfare effects of the supply security targets are analyzed in a cost-benefit framework based on the contributions of de Nooij et al. (2010) and Tishler et al. (2006). Then, the paper goes one step further than, to the author's knowledge, the majority of supply security analyzes by comparing the value of supply security with its costs of provision in the context of the expansion of the low- and medium-voltage distribution grid.³ Based on that comparison, conclusions are drawn in regard to the climate targets and their effects on electricity prices.

The paper is organized as follows. Section 3.2 analyzes targets and measures of the transformation process in the German electricity market and also in a European context with respect to the year 2020 from the perspective of the energy-political triangle. The cost-benefit analysis follows in Section 3.3. After presenting the methodological approach in Section 3.3.1, the necessary cost and benefit parameters are calculated in Sections 3.3.2 and 3.3.3. Then, in Section 3.3.4, the resulting net present value is derived. A discussion of other aspects of the analysis as well as the energy-political triangle follows in Section 3.4. Section 3.5 summarizes the results, draws conclusions, and discusses future research areas.

² An overview of the development of renewable energies in Germany and selected regions can be found in Figure 1 in the preface of this thesis.

³ The distribution grid comprises different grid types (mostly low- to medium-voltage grids) and arranges the transport of electricity between generation and consumption. In contrast, transmission networks consist of high voltage power lines, distributing electricity over wide areas. For a discussion of the planned expansion of the high- and maximum-voltage transmission network, see Section 3.4.

3.2 Targets and Measures

The structure of the analyzed problem is illustrated in Figure 3.1, where three policy levels can be distinguished: goals, indicators, and instruments. The energy-political triangle is the base of the analysis since it determines the goals, or targets, against which each policy instrument must be measured.⁴ But since these goals are stated in an abstract, sometimes even conflicting terminology, they are hardly testable. Thus, they are specified in the middle level by three indicators, one for each goal. The indicators are precise and measurable parameters with which the effect of the instrument with regard to the specific goal can be tested. This interrelation between goals and indicators is illustrated by the dotted arrows. Finally, the upper level represents the policy instruments of interest in the present analysis; these is the development of renewable energies complemented by the second instrument, grid development. The red, solid arrows between the two upper levels point out the conceptual structure underlying the present paper, as will be explained in Section 3.3. The dashed arrows indicate further interrelations between the instruments and goals, respectively their indicators, that will be addressed in Section 3.4. The goals and indicators are next defined and explained in detail with respect to the concrete situation of the German electricity market.

A primary target of energy policy is *environmental sustainability* of the electricity market. Environmentally unsound electricity production can have high social costs in form of external environmental damages. Focusing on the climate related aspects of electricity production, problems of internalization arise from the public good character, especially in an international context, or because damages may occur with delay (and therefore may appear less likely). Most prominent is the climate change induced by anthropogenic greenhouse gas (GHG) emissions. Growing awareness of future climate problems has put the reduction of anthropogenic CO₂-emissions at the center of attention.

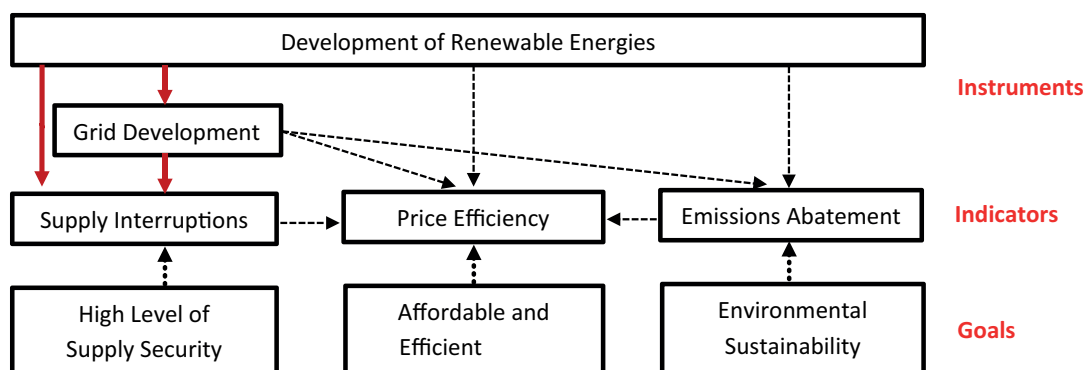


Figure 3.1: Structure of the problem - instruments, indicators, and goals

⁴ For a more general discussion of the energy-political triangle, see the preface of this thesis.

There is a vast range of legislation and regulation related to emissions reduction. For example, the European 20-20-20 targets to be reached by 2020 have been enacted (EC 2009).⁵ There are also national-level targets; for example, in Germany, a 40 percent reduction in greenhouse gases by 2020 and a reduction of at least 80 percent by 2050 with respect to the base year 1990 (BMW and BMU 2010). Several measures have been designed to achieve these targets at both the national and international level, for instance, the European emissions trading system (ETS) (EC 2009) and the heavy promotion of renewable energies in Germany.⁶

Development of renewable energies is the German government's central instrument for reaching the environmental goals and thus is analyzed in this paper (see Figure 3.2). Accordingly, the success in CO₂-emissions abatement is used as an indicator of the instrument's utility with respect to the climate goals (compare target indicators in Figure 3.1).

The second energy-political goal is a *high level of security of electricity supply*. In this paper, the term security of electricity supply is used in a purely technical sense: A low level of supply security is associated with a high number of supply interruptions and is therefore costly for society. A reliable grid-bounded electricity supply can be seen as an important economic good, meaning that provision of the grid, a natural monopoly, is of particular importance. Moreover, Reichl and Schmidthaler (2012) point out that households view provision of an interruption-free electricity supply as a duty of electricity companies, respectively, the government. Various indices measure the technical supply security level (for an overview, see CEER 2012; VDE 2006). In general, the most important dimensions of this technical supply security are frequency, duration, and extent of supply interruptions.⁷

Even though there are some substitution possibilities that may alleviate the consequences of supply interruptions, the damages incurred by a low level of technical supply security are substantial for an economy. In case of firms, for example, damages arise from interruption of work and production processes; in case of households, damage manifests in the form of lost leisure time and also in the form of lost goods (de Nooij et al. 2007). From the government's perspective, lost tax revenues are one form of damage, but so is competitive disadvantage that arises in an international context due to a low level of supply security. For a more detailed overview of

⁵ The targets to be met by 2020 include a reduction of GHG emission by 20 percent compared to 1990 levels, 20 percent of energy consumption to be contributed from renewable resources as well as a decrease of primary energy use by 20 percent compared to 1990 levels (EC 2009).

⁶ The EU-ETS is an EU-wide emissions trading scheme which regulates the emissions of greenhouse gases in the European Union via a certificate system. The EU-ETS follows a 'cap-and-trade' approach, i.e. there is a fixed amount of GHGs, which can be emitted (cap), and a respective amount of certificates is issued, which can be traded (trade). Regarding the development of renewable energies in Germany, the most important legislation is the German Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG) which came into law in 2000 and determines feed-in tariffs (§§16-22 EEG) for renewable energy electricity as well as feed-in priority (§5 EEG).

⁷ More generally, the term security of electricity supply encompasses various aspects of supply security. For example, in contrast to the here analyzed technical security, political security focuses on the supply security and therefore availability of primary energy sources such as oil, gas, and coal. These political supply security aspects are not covered in this paper. For an overview of the different concepts of supply security, see Winzer (2011).

damages caused by supply interruptions, see frontier economics (2008), Bliem (2005), de Nooij et al. (2003), Wacker and Billinton (1989), or Munasinghe and Sanghvi (1988).⁸

This paper focuses on supply security problems that arise from the integration of decentralized renewable energies into the electricity system with a special focus on their grid integration (see Figure 3.2). The development of renewable energies leads to decentralized power production. To ensure a constant quality of technical supply security (as described above) and to decrease the risk of network overload (i.e. the probability of a power outage), the grid must be appropriately designed. Consequently, grid development is a second energy-political instrument analyzed in the present paper (see Figure 3.1).⁹ The suitable target indicator in this situation is the level of (technical) supply security as it will be explained in Section 3.3.2.1 and which is experienced to be very high in Germany.¹⁰ Therefore, maintaining the status quo of supply security is often, and also in this paper, stated to be an energy-political minimum target.

The comprehensive cost aspects of electricity provision are covered in the third dimension of the energy-political triangle summarized by the target of *affordable and efficient electricity prices*. In industrialized countries, physical access to electricity is nearly universal. However, affordability is still an issue reflecting distributional effects of electricity prices. In regard to the second aspect of the price goal, efficiency, it is important to consider the total social costs of electricity, including, for example, external costs like those resulting from carbon emissions which are in practice hardly measurable. Obtaining efficient electricity prices is especially difficult since the electricity market faces different challenges, chiefly regarding market power situations (for example, the provision of an electricity grid is a natural monopoly) and the resulting market regulatory costs. Further politically defined targets, for instance, in the context of industry policy, may be in opposition to the efficiency goal.

Based on these considerations, the price goals may be in conflict. For example, in the past few years, awareness of the non-internalized damage resulting from carbon emissions in power generation has increased. Internalizing this externality would improve efficiency (since prices should reflect the marginal social costs of electricity) but would increase electricity prices. Additionally, internalization should take place in an international context to avoid problems in the context of international competition (an example for this is carbon leakage). In the following, the focus is on the question of whether instruments increase the efficiency of electricity prices as shown in the price target indicator in Figure 3.1.

⁸ In all industrialized countries there is a great deal of legislation and regulation aimed at assuring a secure grid-bounded supply of electricity to the general public. In this context, the European net operators have joined in a European compound system (ENTSO-E). An international operation handbook (UCTE 2004) ensures the proper handling of cross-border supply and has enabled the EU to develop a single-grid European network (EC 2011a). A German conversion of the operation handbook is the transmission code of the German net operators (VDN 2007).

⁹ For example, §9 Abs. 1 EEG describes the grid development obligation of system operators in the event of renewable energy capacity increase. On an international level, developing a European network can be seen as a precondition for the Europe-wide development of renewable energies under the security constraint. For an overview of the different measures, see CEER (2012) or VDE (2006).

¹⁰ An overview of the development of the supply security situation in Germany can be found in Table D.1 of Appendix D.

3.3 The Trade-Off between Green Policy and Supply Security

By means of a cost-benefit approach, the paper now analyzes the interrelation between renewable energies development and supply security targets regarding the distribution grid on the German electricity market. The analysis is based on the transformation process between 2010 and 2020; estimations beyond 2020 entail too much uncertainty to be useful. The comparative static approach (indicated with the red and solid arrows in Figure 3.1) is explained in Section 3.3.1, followed by the quantitative evaluation of the discounted cash flows of the benefits (Section 3.3.2) and costs (Section 3.3.3) that will be compared in a net present value framework (Section 3.3.4).

3.3.1 Methodological Approach

Figure 3.2 shows and evaluates the interrelations between renewable energy and supply security goals on a social monetary cost basis: The upper quadrants illustrate the technical relations, which are valued on a social cost and benefit level in the lower quadrants.

The top left-hand quadrant of the figure shows the relation between grid structure and supply security on the electricity market and thereby evaluates the level of technical supply security as explained previously. The abscissa illustrates development of the grid structure; the ordinate covers supply security effects. The figure shows that improving the distribution grid structure via grid investments increases the level of supply security (denoted by an upward-sloping curve). Important for the present analysis, the relation between grid and producer structure is implicitly covered since changes in the production structure of electricity work as a location parameter of the curve. In the top right-hand quadrant, the level of supply security from the ordinate is transferred to the abscissa.

In the two lower quadrants of the figure, the technical information from above is translated into social costs and benefits. The lower left-hand quadrant shows the associated accumulated investments for any given distribution grid development status in an upward-sloping curve.¹¹ The social damages of supply interruptions that result from any given level of supply security are illustrated as a downward-sloping curve in the lower right-hand quadrant; the higher the level of supply security, the lower are the social damages resulting from power outages.

As illustrated in Figure 3.2, the comparative statics of the cost-benefit analysis will be made in three steps. First, it is assumed that there is a centralized electricity production and a well-adapted grid structure, resulting in a high supply security level. *Ceteris paribus*, development of renewable energies in the second step will result in decentralized electricity production and thereby reduce the level of supply security when there are no sufficient adaptations in the grid structure. In step three, grid investments are made in an effort to avoid increasing social interruption damages resulting from a lower supply security level. In the cost-benefit analysis,

¹¹ By assumption, current expenses, such as maintenance costs, are not considered in this static framework.

investment costs are compared to avoided interruption damages, or social benefits, that arise from holding the level of supply security constant. All three steps are explained in more detail as follows.

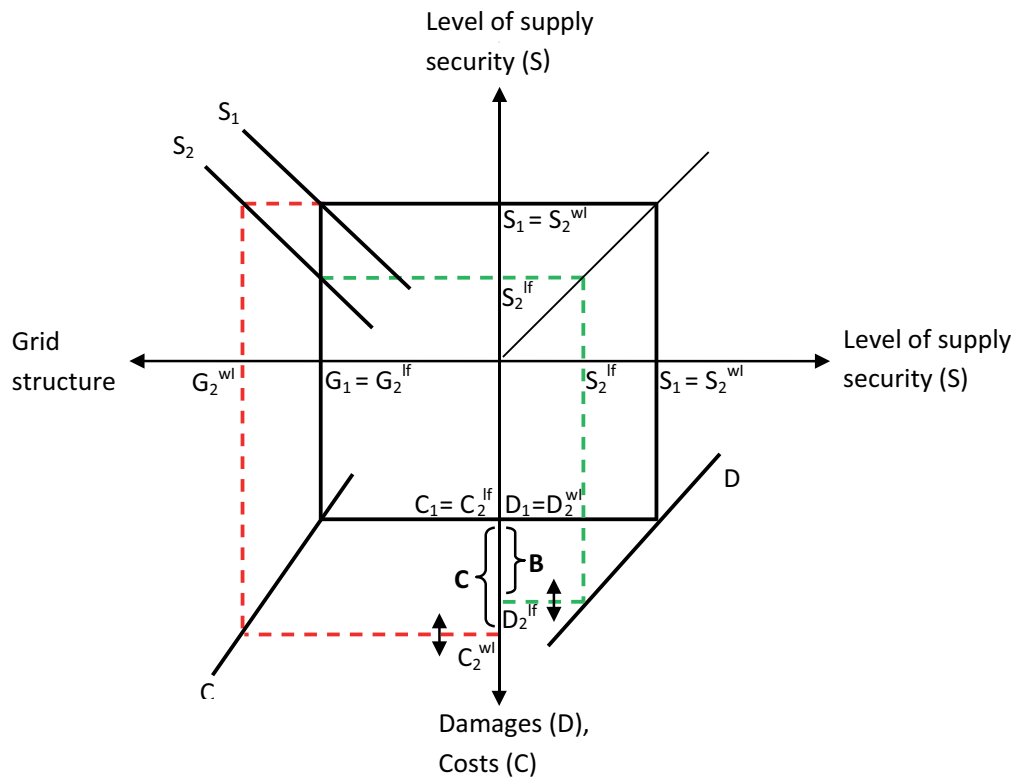


Figure 3.2: Model setup: A three-step approach

The first step where the basic situation on the electricity market is evaluated is illustrated in Figure 3.2 by black, solid lines. The top left-hand quadrant shows the initial grid development situation represented by the upper graph S_1 . For a given producer structure, the initial grid status G_1 results in supply security level S_1 . G_1 is associated with the respective accumulated investment costs C_1 , as shown in the lower left-hand quadrant. Finally, the lower right-hand quadrant shows the social damages D_1 that result from the initial supply security level S_1 .¹²

Growing awareness of climate problems has induced the government to encourage the development of renewable energies. The resulting consequences are examined in the second step, where new, deviating outcomes are shown with red, dashed lines. The renewables development can be understood as an external shock to the energy market that induces more decentralized power production.¹³ Holding all else constant ('laissez-faire' situation, no investments in the

¹² In the basic situation, it is assumed that C_1 and D_1 coincide, indicating that costs and benefits in the initial electricity market situation are equal. This assumption is solely made for illustrative purposes and redundant in the context of the following calculations.

¹³ This can lead, for any given distribution situation, to a reduction of technical supply security. The development of renewable energies tends to result in electricity being treated more like a common, tradable commodity, for

grid structure), the producer structure works as a location parameter in the upper left-hand quadrant shifting S_1 downward to S_2 ; that is, no further investment is induced by the development of renewable energies ($G_1=G_2^{lf}$ and $C_1=C_2^{lf}$). Consequently, the level of supply security decreases to S_2^{lf} and therefore the social damages increase up to D_2^{lf} .

The third step, shown by green, dashed lines, illustrates the effects of grid investment in maintaining the basic level of supply security. As can be seen in the upper left-hand quadrant, maintaining the former security level is achieved by moving along S_2 until grid structure G_2^{wI} is reached. In parallel, the aggregated investment costs increase to C_2^{wI} . Due to grid investments, the level of supply security ($S_1=S_2^{wI}$) ('with investment' situation) as well as the social damages ($D_1=D_2^{wI}$) remain constant at the initial level.

The difference between C_2^{wI} and $C_1=C_2^{lf}$ in the lower left-hand quadrant represents the costs (C) of maintaining the basic level of supply security. The benefits (B), in terms of avoided interruption damages, are represented by the difference between $D_1=D_2^{wI}$ and D_2^{lf} in the lower right-hand quadrant. The relative magnitude of benefits and costs (which depends on the relative slopes of the curves) determines whether the benefits of maintaining the basic level of supply security outweigh the costs. A quantitative assessment of the costs and benefits is performed next.

3.3.2 The Benefits

Representing avoided (social) interruption damages ('B' in the lower right-hand quadrant of Figure 3.2), the benefits can be measured as the value of supply security (VoSS) approximated by

$$VoSS[EUR] = SAIDI[min] * VoLL[\frac{EUR}{kWh}] * Load[\frac{kWh}{min}]. \quad (3.1)$$

The VoSS is the product of the SAIDI (System Average Interruption Duration Index), a reliability index that measures the level of supply security as the cumulated duration of supply interruptions in minutes per consumer over a specified time horizon (mostly a year, see Consentec 2010), the VoLL (Value of Lost Load), which measures the damages of an electricity shortfall per unit of electricity lost, and the average (lost) load (consumption of electricity per minute) in each minute of interruption (see de Nooij et al. 2007; Bliem 2005). In the following sections, the different parameters are evaluated: First, the different SAIDI levels and then the valuation parameters VoLL and the average (lost) load in kWh.¹⁴

instance, transport is no longer unidirectional and supply and demand may be geographically separated (Reichl and Schmidthaler 2012). This creates challenges to technical supply security if it has been missed to develop the necessary grid capacities (Reichl and Schmidthaler 2012) and, consequently, may increase the number of outages.

¹⁴ A unit of electricity is measured in kWh which means kilo (=1000) Watt per hour and is a measure for consumed energy of a system.

3.3.2.1 The Level of Supply Security

In this paper, the level of supply security is approximated with the SAIDI, an internationally employed reliability index that is also part of the German Electricity Network Access Ordinance (ARegV), see §20 ARegV (Bundesnetzagentur 2010). The SAIDI describes the quality of supply security by measuring “the average amount of time per year that the power supply for a customer is interrupted” (CEER 2008, p. 20).¹⁵ CEER (2008) calculates the SAIDI as

$$SAIDI = \sum_i \frac{N_i r_i}{N_T} \quad (3.2)$$

“where the summation is taken over all incidents, either at all voltage levels or only at selected voltage levels; r_i gives the restoration time for each incident; N_i gives the number of customers interrupted by each incident; N_T gives the total number of customers in the system for which the index is calculated” (CEER 2008, p. 20).

The SAIDI can be interpreted as a proxy for the level of the technical supply security and, as shown in the upper quadrants of Figure 3.2, approximated by $1/SAIDI$. In the following, the estimations are conducted for the year 2020. To estimate the avoided damages, the difference ($\Delta SAIDI$) between the SAIDI of the investment situation ($SAIDI_{2020}^{wI}$, see step 3 in Section 3.3.1) and the SAIDI that would occur in the laissez-faire situation ($SAIDI_{2020}^{lf}$, see step 2 in Section 3.3.1) needs to be calculated. $\Delta SAIDI$ measures the avoided decrease in supply security and, evaluated with the parameters described in (3.1), which will be done in the next sections, can be interpreted as the social benefits that accrue from maintaining the existing quality of supply security.

Since, by assumption, the SAIDI of the investment situation ($SAIDI_{2020}^{wI}$) shall equal the initial SAIDI level ($SAIDI_{2010}$), it can be inferred for the low- and medium-voltage level from the German Federal Network Agency (Bundesnetzagentur 2013) as

$$SAIDI_{2020}^{wI} = SAIDI_{2010} = 14.90min \quad (3.3)$$

being the average for all private and commercial users in Germany. In the following, $SAIDI_{2020}^{lf}$ will be estimated on the basis of the relation between the SAIDI and the structural parameter load density.¹⁶ This relation is well-established, for example, in the German revenue cap regulation, and follows a strong nonlinear, negative (hyperbolic) functional form of

$$SAIDI(LD) = \frac{a}{LD^c} + b \quad (3.4)$$

¹⁵ SAIDI is an internationally employed DISQUAL index (UNPEDE 1997). Weighted with the number of customers, it can also be found in the IEEE Standard 1366 (IEEE 2012).

¹⁶ Load density is measured by the quotient of the annual peak load of a geographical area and its size. For a definition of geographical area, see the German Electricity Network Fee Regulation Ordinance, StromNEV §24 Abs.2.

with the SAIDI in min, the load or supply density indicated as LD in (kW/sqkm), and a, b, and c as constants (see Consentec 2010).¹⁷ In the present paper, the parameter load density is used - with certain restrictions - as a proxy parameter to measure the suitability of the grid structure with respect to the producer structure. This can be explained as follows.

Figure 3.3 illustrates the underlying considerations in forecasting $SAIDI_{2020}^{lf}$. The curves illustrate the negative relation between load density and SAIDI, which is indicated by (3.4). Note that this figure can be understood as an extension and elaboration of the top left-hand quadrant of Figure 3.2, only the slopes of the graphs in both figures are reversed since S can be associated with $1/SAIDI$. Feeding-in renewable energy and increasing energy efficiency lead to a sinking load density in 2020 compared to 2010.¹⁸

The upper curve illustrates the negative relation between load density and SAIDI, which is indicated by (3.3) and shows that in the laissez-faire case without compensating grid investments, the supply security in 2020 decreases from $SAIDI_{2010}$ to $SAIDI_{2020}^{lf}$. When there is sufficient grid investment to maintain the former level of supply security, the curve shifts parallelly downward such that the level of supply security increases (the SAIDI decreases) for any given level of load density. The curve $SAIDI'$ illustrates the new relation between load density and SAIDI based on the new grid investments that have taken place. Compensating grid investments take place until $SAIDI_{2020}^{wI}$ equals $SAIDI_{2010}$. The difference between $SAIDI_{2010}$ and $SAIDI_{2020}^{lf}$ is $\Delta SAIDI$ and indicates the avoided changes in the level of supply security due to a grid expansion parallel to the development of renewable power production. Consequently, $\Delta SAIDI$ refers to the difference between $S_1=S_2^I$ and S_2^{lf} in the top left-hand quadrant of Figure 3.2.

The following calculations are based on a regression analysis of Consentec (2010).¹⁹ Consentec (2010) estimates the parameters of (3.4) for the medium-voltage level as

$$SAIDI(LD) = \frac{1397}{LD^{0,8}} + 0,35. \quad (3.5)$$

¹⁷ Several papers, such as Consentec (2010), which will later be referred to, show in regression analyzes that load density, which is a proxy for the size or development status of the grid system (VDE 2006), is the best parameter for explaining the quality of supply security. Load density can be seen as a proxy for redundancy in the electricity grid (Reichl and Schmidthaler 2012). A lower load density approximately reflects a lower redundancy of the electricity grid and therefore a higher probability of grid failures. The hyperbolic relation can be found independently of the used grid concept or of adding additional explanatory parameters (Consentec 2010). For further details about the relation between load density and structural supply reliability, see Filges et al. (2011), vom Felde (2010), BEE (2009), Vennegeerts and Obergünner (2005), and VDE (1995).

¹⁸ One reason for sinking load density is that because of the feeding-in of renewable energy, the grid will no longer be used for unidirectional electricity transport only, which could even lead to a load reversal (Reichl and Schmidthaler 2012). For the year 2020, it can be assumed that other factors influencing the load density, such as a decreasing population, will not be much different from today.

¹⁹ Consentec uses the anonymized supply interruptions data of the FNN interruptions statistics (see www.vde.com) which are collected based on §52 of the German Law on Energy Management (EnWG). Though this rough estimation doesn't necessarily meet the requirements of a precise prognosis, it clearly gives an idea of the magnitude of the change in the SAIDI level. Moreover, considering the specific difficulties of evaluating future supply interruptions (see, e.g., Consentec 2010), the simplicity and easy applicability of this method can be seen as a clear advantage.

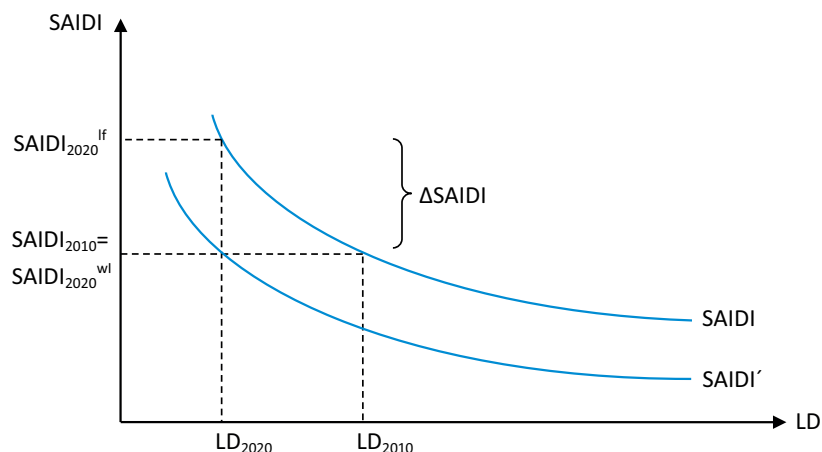


Figure 3.3: Illustration for the estimation of the SAIDI

(3.5) is especially appropriate for estimating SAIDI_{2020}^{lf} since the grid situation of today reflects the laissez-faire scenario of 2020: There is a change in load density, but the grid structure, captured in the concrete realization of the parameter values in (3.5), stays the same. Using (3.5), SAIDI_{2020}^{lf} can be forecasted. For this purpose, forecasts for load density in 2020 are needed. In the following, estimations of the annual peak load for the year 2020 based on different demand scenarios defined by the German energy agency (Dena 2010) are used to calculate load density; these estimates are the best available to date as they show the largest range of estimates covering the forecasts of most other studies (see, e.g., BEE 2009).

The estimation results are presented in Table 3.1.²⁰ Depending on the underlying expectations about development of electricity demand, from 2010 to 2020, supply security will decrease from 14.90 minutes to about 20 minutes per customer and year. The difference of the SAIDIs, illustrated by ΔSAIDI in Figure 3.3, amounts to about 5 minutes per customer and year.

Year	Scenario	SAIDI
2010	SAIDI_{2010}	14.90
2020	SAIDI_{2020}^{lf} in decreasing electricity demand scenario	20.18
2020	SAIDI_{2020}^{lf} in constant electricity demand scenario	19.39

Table 3.1: Estimation of the SAIDI for the laissez-faire case in 2020 (SAIDI_{2020}^{lf})
Note: Calculations are based on data from Consentec (2010) and Dena (2010).

To translate the technical results into social monetary units and to calculate the VoSS (Section 3.3.2.3), the SAIDIs will be multiplied by the value of a lost kWh, the VoLL, which is derived in the next section, and the average amount of electricity lost per minute of outage.

²⁰ Consentec (2010) emphasizes that for the considered range of load densities, the regression analysis is most exact for the medium-voltage level; however, less significant for the low-voltage level. Therefore, in the low-voltage level, the SAIDI over the analyzed period is assumed to be constant. This is of minor importance for the present analysis since most interruptions take place in the medium-voltage level (Consentec 2010; Bundesnetzagentur 2013).

3.3.2.2 Value of Lost Load

Estimating the value a society places on frictionless electricity supply is not straightforward. For one thing, being much lower than the economic value of a not delivered unit of electricity, the user price of electricity does not include the (marginal) avoided damages of supply interruptions.²¹ Moreover, an insurance system for power interruptions reflecting a market price for supply security only exists partially and for large end users (de Nooij et al. 2007; Bliem 2005).

The value of frictionless electricity supply in social welfare terms can be estimated in various ways. One important measure is the value of lost load (VoLL), which evaluates the value of a unit of electricity lost for the electricity consumer. Calculating the VoLL is useful for assessing investment decisions in the area of network reliability, for example, in the context of a cost-benefit analysis as done here. Moreover, in the event of supply shortages, applying it may also help to optimally allocate electricity. In the normative optimum, the VoLL of one kWh, interpreted as its marginal utility, should be equal to the marginal costs to improve its frictionless delivery. A detailed overview of the different methods for calculating the VoLL can be found in de Nooij et al. (2007), Ajodhia et al. (2002), Wacker and Billinton (1989), Billinton et al. (1993), Woo and Pupp (1992), and Caves et al. (1990). In the following, four estimation methods are presented.

One way to measure VoLL is to analyze stated preferences obtained from interviews or surveys. In this approach, the interviewees are asked questions regarding their marginal willingness to pay for reducing the number or duration of interruptions per period or what would be the least sum of money acceptable in compensation for decreasing supply security (see de Nooij et al. 2007). Although this method has several advantages, such as a high flexibility in the design of the questionnaire, doubts may arise as to the robustness of the answers since interviewees might be overstrained by the topic (frontier economics 2008).

A second estimation method involves the use of case studies to analyze and evaluate the effects of power outages (Corwin and Miles 1978). For instance, surveys can be conducted to discover the social damages of past power interruptions (Serra and Fierro 1997). Despite the loss of generality and the high complexity of every specific outage, case studies evaluate true interruption situations and therefore avoid certain problems inherent in stated preference methods. For instance, consumers do not have to be confronted - and maybe overburdened - with fictional scenarios.

Another important method is the evaluation of revealed preferences. The behavior of households and firms concerning investments in supply security, for example, buying backup generators or signing interruptible contracts, can be analyzed and used to evaluate willingness to pay for supply security (de Nooij et al. 2007; Caves et al. 1992). However, one problem with

²¹ One reason is that the end user electricity price partly consists of average costs, such as the grid user fees, which are lower than the marginal costs. Moreover, it can be assumed that electricity prices do not siphon off the consumers' surplus, which would include the value of lost load.

this method is that many measures taken to ensure supply security may not be voluntary, but required by law as it is the case for hospitals.

The valuation method used in this paper is a macroeconomic production function approach.²² Under this approach, the VoLL answers the question of how much value added is produced with one kWh and thus approximately determines the foregone value added due to the electricity outage (opportunity costs concept; Willis and Garrod 1996). Then, the VoLL estimates the social “damage per unit of electricity [that is] not delivered” (de Nooij et al. 2003). The VoLL is estimated using statistical data on electricity consumption and the value added of firms or, respectively, the value of private-life time of households since they produce no value added (e.g., de Nooij et al. 2007; Tishler 1993; Munasinghe and Gellerson 1979). There are several aggregation methods for evaluating outage damages. Here, lost production is calculated in each sector directly and then aggregated with the value of lost leisure time of households to arrive at a total in a top-down fashion. This will be explained in the following. Moreover, Chen and Vella (1994) show how linkages between sectors can be included using input-output-tables. An advantage of this macroeconomic production function approach is the availability of empirical data. A problem is that because of the aggregation, some direct and indirect damages will not be taken into account and certain substitution and catch-up effects may be missed (Bliem 2005).

To calculate the VoLL with a production function approach, data on final electricity consumption and its value added are needed. Then, the relation between electricity consumption and economic performance can be calculated. The results are given in Table 3.3.

Since households do not create economic value that can be related to electricity consumption, an alternative estimation method is needed. In case of supply interruptions, the loss of private-life time (household activities and leisure time) is the most relevant damage to households (see Section 3.2). Therefore, in this paper, as in de Nooij et al. (2007) and Bliem (2005), on the basis of Becker (1965), the value of time is calculated to evaluate the costs of lost private-life time. The basic assumption is that private-life time is a normal good with a decreasing value in hours spent and increasing value in hours worked (see de Serpa 1971).²³ Under the assumption of a well-functioning labor market, the optimal amount of working time is reached when the income generated by the last hour worked equals the value of an hour of private-life time (de Nooij et al. 2007). Then, the marginal hour work has approximately the same value (utility) as the marginal hour of leisure time.²⁴ Based on Munasinghe’s model (1980), it is assumed that an interruption of electricity supply leads to postponement of household activities at the expense of leisure time. Then, as Munasinghe argues, a marginal hour of leisure time has the same value as a marginal hour of household activities. Therefore, the net marginal income is approximated by the average net income per hour.

²² See also Consentec (2010) who performed a similar calculation of the German VoLL for the year 2008.

²³ For a discussion and some drawbacks of this model, see de Nooij et al. (2007) or Sanghvi (1982).

²⁴ Other approaches exist that estimate the value of leisure time. Examples are estimations based on observations of speeding behavior and speed limits can be found in Wolff (2011) or Ashenfelter and Greenstone (2004).

Scenario	Value of time (million EUR)	Electricity Consumption (TWh ¹)	VoLL (EUR per kWh)
Base scenario	2,106,028.64	139.9	15.05
Scenario less leisure time	2,039,245.55	139.9	14.58
Scenario lower tax burden	1,982,243.81	139.9	14.17

Table 3.2: Average value of time, electricity consumption, and VoLL of households 2008-2010
Note: Calculations are based on data from the Federal Statistical Office (Statistisches Bundesamt 2011a; 2011b; 2012a), Kern (2010), and BDEW (2011).

¹ 1 TWh = 1 Tera Watt hour = 10^{12} Wh

The relevant data for calculating the value of time were collected from the German Federal Statistical Office (in German: Statistisches Bundesamt). The interrelation between electricity dependency and duration of different activities is decisive in assessing substitution possibilities for households in case of outages. Most non-working time, except that spent sleeping, is used for leisure and household activities (see Table E.1 in Appendix E) and most of these activities are at least partially electricity dependent and only partly substitutable. An overview of the electricity dependency of households can be found in Table E.2 of Appendix E. Following Bliem (2005), a substitution possibility of 50 percent for private-life time is assumed, which means that in case of an outage, half of the activities can be substituted without producing utility losses.

From standard statistical parameters under the described assumptions, the value of time for households as an average for the years 2008 to 2010, the average electricity consumption as well as the resulting VoLL is shown in Table 3.2 for different scenarios. The value of time is the product of the number of employees times their average net wage rate (gross wage rate minus an approximated 50 percent income tax), leisure time, as well as household work in hours per year and adjusted by the substitution parameter by another 50 percent. The calculation also includes the unemployed population, but since unemployed people have by nature more leisure time, their value of one hour leisure time has been reduced by a further 50 percent. To obtain the VoLL, the value of time is divided by household electricity demand in the year 2010.

According to Table 3.2, the VoLL of households is estimated to be around 15 euros per kWh. A sensitivity analysis in the form of two additional estimation scenarios confirms the robustness of the results: Assuming 10 percent less leisure time for non-working people (scenario 'less leisure time') in comparison to the base scenario or assuming a lower accumulated income tax rate (scenario 'lower tax burden') of 45 instead of 50 percent does not change the results substantially (see Table 3.2).²⁵

²⁵ There are several reasons why these results could be over- or underestimations. For instance, better substitution possibilities or a higher variety of leisure activities could indicate an overestimation. Also, the VoLL could be both over- or underestimated since in reality, a random hour of leisure is lost - an hour that could exceed (or fall below) the value of an average hour (see de Nooij et al. 2007; Becker 1965). Day and Reese (1992) give as an example an electricity interruption during a championship football game. Another aspect is that most of the value added is produced during weekdays when the opportunity costs might be higher than implied by the average VoLL calculated above. However, even though the results lie in the middle range of the different VoLL

The VoLL estimates for the different sectors and households are presented in Table 3.3. The sectoral VoLLs are calculated from the average sectoral value added and electricity consumption for the years 2008 to 2010. The table reveals that the VoLL differs significantly across sectors. The higher electricity consumption compared to the value added, that is, the higher the electricity intensity of a sector, the lower is the VoLL.²⁶

Sector	Value added (billion EUR)	Electricity consumption (TWh)	VoLL (EUR per kWh)
Agriculture	19.26	8.67	2.22
Industry	621.50	221.43	2.81
Public Administration	298.64	45.93	6.50
Trade and Services	1,146.44	74.6	15.37
Transport	124.03	16.3	7.61
Households ¹	2,106.03	139.9	15.05
Economy-wide VoLL			12.51

Table 3.3: Economy-wide VoLL as average of the years 2008-2010

Note: Calculations are based on data from the Federal Statistical Office (Statistisches Bundesamt 2012b) and BDEW (2011).

¹ Value of leisure time, see Table 3.2, base scenario

Weighting the different sectoral VoLLs with the respective share of sectoral value added and the share of the value of time with respect to the aggregated value leads to an overall (weighted average) VoLL of about 12.51 euros per kWh.²⁷ Table 3.3 clearly shows that not only for the producing sectors, but also for households, the damages of a supply interruption far exceed the cost of electricity. A reason for this could be that in this non-marginal analysis, the difference between the end user electricity price and the VoLL reflects the consumers' surplus.²⁸

3.3.2.3 Value of Supply Security

From the respective levels of SAIDI, the value of a lost unit of electricity (VoLL), and the amount of electricity (load) lost, the value of supply security (VoSS) can be calculated for the different scenarios as shown in (3.1). The VoSS, which here is interpreted as the benefits, or avoided social damages, due to grid investments made so as to hold constant the quality of supply security (the

estimates, as can be seen in Table F.1 of Appendix F, they need to be viewed as conservative estimations because, for example, the VoLL of households increases with the duration of the outage (see Reichl and Schmidthaler 2012).

²⁶ This implies that, in line with Ramsey pricing, in case of supply shortages, consumers with the lowest price elasticity should be treated as the least important when it comes to an allocation of supply (de Nooij et al. 2007). The concept of Ramsey-pricing (Ramsey 1927) was introduced in the context of taxation as a form of achieving a second-best pricing solution in the case of a natural monopoly via regulation.

²⁷ Two studies analyzing the German electricity sector, Consentec (2010) and frontier economics (2008), estimate a VoLL of 8 EUR/kWh. The estimated VoLL of the present paper would be the same, too, if the unweighted sectoral average were used.

²⁸ Since electricity demand is viewed as inelastic, the demand curve is relatively steep and the average consumers' surplus high, as illustrated by the high VoLL.

VoLL calculated in Table 3.3 is assumed to maintain constant until 2020) arise from Δ SAIDI according to Figure 3.2. The technical results of the upper quadrants, which can be associated with Δ SAIDI, are weighted with economic values (see (3.1)) as shown in the lower quadrants. The benefits occur in the difference between $D_1=D_2^{wI}$ and D_2^{lf} , indicated with “B” in the lower right-hand quadrant.

	Constant electricity demand scenario	Decreasing electricity demand scenario
Damages of one minute electricity outage (in million EUR)	12.139	12.139
Outage damages for the respective level of SAIDI (in million EUR)		
SAIDI ₂₀₁₀	180.876	180.876
SAIDI ₂₀₂₀ ^{wI}	180.876	172.045
SAIDI ₂₀₂₀ ^{lf}	235.347	233.064
Benefits of grid expansion in 2020 (in million EUR)	54.471	61.020

Table 3.4: Benefits in 2020 in current values

Note: Calculations are based on data from Tables 3.1 to 3.3.

Differentiated for alternative demand scenarios, Table 3.4 shows the calculation of the benefits, Δ VoSS, for the year 2020 in current values. The table shows that a Germany-wide power outage of one minute leads on average to damages of about 12.139 million EUR. Multiplied by the respective SAIDIs, the social damages arising from power outages in the different years can be calculated. From that it follows that in 2010, the economic damages in Germany resulting from supply interruptions in the distribution grid amounted to 180.876 million EUR. The next row of Table 3.4 shows the outage damages for the year 2020 in the investment scenario. In this scenario, it is assumed that $SAIDI_{2010} = SAIDI_{2020}^{wI}$. Therefore, in the constant electricity demand scenario, the outage damages compared to 2010 remain constant (180.876 million EUR). In the decreasing demand scenario, due to the lower amount of electricity used per minute, total outage damages decrease (172.045 million EUR). In the laissez-faire situation of the year 2020, the increasing SAIDI leads to higher economic damages from outages as can be seen in the next row of Table 3.4. In the constant electricity demand scenario, damages amount up to 235.347 million EUR and in the decreasing electricity demand scenario, damages are 233.064 million EUR.²⁹ The difference between the estimated damages with and without investments in supply security is the benefit in the year 2020, shown in the last row of Table 3.4, and amounts to 54.472, respectively 61.020 million EUR. These are the avoided damages since, due to grid development, the SAIDI level does not increase by another 5 minutes. To calculate the annual benefits between 2010 and 2020, it will be assumed that the load density for the different esti-

²⁹ The demand scenarios refer to those assumed on the basis of Dena (2010), see Table 3.1.

mations of the ceteris paribus case develops linearly, resulting in the annual Δ SAIDI levels that will be used in Section 3.3.4.

3.3.3 The Costs

After calculating the benefits of maintaining the quality of supply security, the investment in the associated grid expansion is considered. Costs resulting from investments in the low and medium voltage distribution grid arise mainly from the installation of open wires in the form of alignments and circuits, cables with the respective trenches as well as current transformers, transformer stations, and local network stations (compact stations including transformers) (BET et al. 2011). The investment measures and costs for the electricity grid are sketched in Figure 3.2. The upper left-hand quadrant shows that the grid has to be developed by the amount of the difference between G_2^{wI} , the new development level of grid structure, and $G_1=G_2^{lf}$, its previous level. To evaluate the grid development in terms of costs, the accumulated grid investments from $C_1=C_2^{lf}$, the previous amount of aggregated investments into the grid structure, have to be compared with C_2^{wI} , the respective new level. The total investment costs are indicated by 'C' in the lower left-hand quadrant.

The considered investment costs refer to calculations of BET et al. (2011), which estimate, based on current technical standards, the amount of investment necessary due to the development of renewable electricity production in the low- and medium-voltage distribution grid (without maintenance and plant connection costs). On the basis of model net regions, BET et al. (2011) estimate the Germany-wide investment needed to appropriately expand the grid at the low- and medium-voltage level for two scenarios: The energy scenario (Prognos et al. 2010) developed for the government's energy concept (BMW and BMU 2010) and the BMU lead scenario developed by Nitsch et al. (2010). The individual components of the model net regions "are parametrized and estimated using conventional, standardized technique and planning principles" (BET et al. 2011, p. 2).³⁰ The costs are summarized in Table 3.5.

	Energy concept	BMU Lead scenario
min (in million EUR)	10,000	21,000
max (in million EUR)	13,000	27,000

Table 3.5: Costs of distribution grid development from 2010 up to 2020

Source: BET et al. (2011)

In this paper, by assumption, the costs estimated for distribution grid development are used as estimations of the costs incurred in holding the level of supply security at least constant under the new, decentralized producer structure (see BET et al. 2011). Table 3.5 shows the cost ranges. Depending on the respective scenario, the costs lie between 10 and 27 billion euros.³¹ In the

³⁰ For a detailed description of the calculations, see BET et al. (2011).

³¹ The range of estimates is so large because the projections of installed capacity under the energy concept (BMW and BMU 2010) and the lead scenario (Nitsch et al. 2010) vary widely. This results especially from different

following, it is assumed that the costs are distributed equally among the time span from 2010 to 2020. Therefore, the yearly costs are approximated as between 0.91 and 2.4 billion euros in current values.

3.3.4 Calculation of the Net Present Value

The effects of the planned transformation process in the energy sector on supply security can be described in the following net present value framework. The sign of the net present value indicates the direction of the trade-off between the development of renewable energies and the supply security goals. The costs, C , and the benefits, B , can be compared graphically in the lower quadrants of Figure 3.2.

A simplifying assumption is that during the analyzed period of the transformation process, investments in development of the grid structure and renewable energy production go hand in hand. While the benefits from a constant quality of electricity supply increase during the period, the yearly costs are assumed to be constant. Additionally, as explained in Section 3.3.3, it is assumed that all the investment costs have to be paid by 2020. The discount rate is assumed to be 5 percent.

Benefit scenarios Cost scenarios	Constant demand	Decreasing demand
	Energy concept (min)	-8,575.661
Energy concept (max)	-11,192.182	-11,169.310
Lead scenario (min)	-18,269.570	-18,146.698
Lead scenario (max)	-23,402.611	-23,379.739

Table 3.6: Net present value in million euros

Note: Calculations are based on data from Tables 3.4 and 3.5.

Table 3.6 shows the results of the cost-benefit analysis. The rows distinguish between two cost scenarios, as done in Table 3.5. In the columns, the benefits are shown differentiated for the two development scenarios of electricity demand, as indicated in Table 3.4. The resulting net present values differ strongly between the analyzed scenarios. The net present value is much lower in the analyzed lead scenario since they assume a higher development of renewables which is associated with a higher grid investment as shown in the previous section ('min' and 'max' refer to the respective costs ranges as shown in Table 3.5). The larger the development of renewable energies and the less electricity demand can be reduced, the more negative is the net present value. This indicates that the transformation process will be costly in terms of maintaining the present supply security level, although the magnitude of these costs depends on the underlying scenario.

assumptions made about the development of photovoltaic capacity in Germany (BET et al. 2011). In a sensitivity analysis, BET et al. (2011) show that the results are stable and that dimensioning the transformation levels does not influence the cost volume much.

3.4 Discussion

The paper in hand analyzes the trade-off between the development of renewable energies and maintaining a high level of supply security. Since the analysis is of partial nature, other aspects must be taken into account to obtain a complete picture. This section extends the analysis to the context of further considerations about costs and benefits as well as price and climate goals as defined in the energy-political triangle.

First, the above analysis considers only the distribution grid. Extending the analysis to the transmission grid would increase both costs and benefits. Grid development costs arising from renewable energies development would increase the price of electricity for households by about 1 ct. per kWh by 2020 (less for privileged electricity consumers), according to Dena (2011). Furthermore, the probability of system blackouts changes with the transmission grid development (and to some extent also with the distribution grid development): With higher network stability, the probability of such ‘low probability high impact’ events can be reduced and supply security benefits increased.³² Moreover, when looking at the investments in the distribution grid, BET et al. (2011) emphasize that their calculations need to be viewed as conservative. This is, on the one hand, because strict, technical regulation is usually in force instead of an economic optimization of the grid development and, on the other hand, because grid operators can to some extent abstain from repairs or replacements needed for the current grid due to the grid investments necessary for the green energy development. Considering these effects would reduce the investment costs reflected in the present analysis.

Second, issues of the considered time horizon must be discussed. It can be expected that the positive effects of grid investment will persist longer than the analyzed time horizon. Therefore, the benefits may be underestimated. Additionally, considering a longer time horizon would decrease the annual investment cost of grid development and thereby increase the net present value. Nevertheless, the present analysis refrains from examining the transformation process beyond 2020 since uncertainty about future developments is too high in the energy market and therefore not easily assessable.

Third, several other aspects of the development of renewable energy must be taken into account. It is often argued in this context that a diversified electricity production structure potentially reduces the need to acquire energy sources from abroad and therefore technological and political risks (EC 2011b). Additional positive effects might come in the form of technological progress: Supporting renewable energy at an early stage can lead to first-mover advantages for society in the form of growth potentials or competition advantages on an international level.

³² One example of a system blackout is the 2003 blackout in the northeastern United States and Canada. The overloading of the power grid that failed because of poor maintenance and insufficient investment led to a domino effect of failing power lines. More than 50 million people were affected. The power supply was restored for a majority of those affected after two days. The costs of the system failure are estimated at 4.5 to 8.2 billion USD (ELCON 2004).

Fourth, the development of renewable energy avoids costs of ETS emission certificates since the share of CO₂-emitting electricity production decreases with an increasing share of green electricity production.³³ The effect indicating an overestimation of the costs can be roughly quantified at about 0.17 ct. per kWh in 2011.³⁴ Nevertheless, the EEG-induced marginal abatement costs (see Section 3.2), distributed among the (non-privileged) end users as a renewable energies apportionment ('EEG-Umlage'), by far exceed the ETS-induced marginal abatement costs and therefore overcompensate for avoided certificate costs.³⁵ Also not included are potential cost effects of the development and installation of storage and back-up technologies or those of phasing out nuclear energy. Considering those effects, further electricity price increases can be expected (see Erdmann 2011). Moreover, Sinn (2012) points out that the German renewable energies development creates welfare losses since it leads to a cost-inefficient abatement of CO₂. On the one hand, different feed-in tariffs for different technologies induce varying marginal abatement costs of CO₂-emissions. On the other hand, the German abatement is inefficiently high compared to other ETS countries' CO₂ abatement costs based for example on ETS certificate prices.

Fifth, several other effects on the electricity price are worth mentioning. The integration of renewable energies into the electricity system can reduce the electricity wholesale market prices due to the merit-order effect.³⁶ Sensfuß and Ragwitz (2008) estimate an average wholesale price reduction of 0.78 ct. per kWh for the year 2006 in Germany and expect this effect to increase with an increasing amount of renewable energy in the market. An additional price-decreasing effect arises from the savings from avoided fuel costs for electricity generation (EC 2011b). Nevertheless, wholesale prices should remain high enough to cover the electricity prime costs to ensure sufficient power plant investment (Nitsch et al. 2010).

³³ EUA, or EU-allowance, is an allowance unit of one ton of carbon dioxide and thereby the trading unit in the EU ETS.

³⁴ In 2011, due to the feeding-in of electricity from renewable energies, about 87.3 million tons of carbon were avoided (BMU 2012). Because EUA prices amounted on average to 12.10 EUR per ton of carbon for the year 2011 (Bluenext 2012), the avoided costs were about 1,056.33 million EUR. With an electricity production of about 612.1 billion kWh (BDEW 2012), this leads to avoided certificate costs of approximately 0.17 ct. per kWh. Of course, this is only a rough calculation that ignores second-order effects and contains various simplifying assumptions. For instance, in this static calculation, it is neglected that a higher demand for certificates in Germany would have a price-increasing effect on EUAs. On the other hand, EUA prices decreased significantly during the last months. However, the exercise is useful in providing an idea of the order of magnitude of the effect.

³⁵ In the year 2011, the apportionment costs were about 3.53 ct. per kWh. The EEG apportionment is added to all non-privileged electricity consumers' prices and contains, among others, the difference in cost between the wholesale market prices and the feed-in tariffs of electricity (§37 EEG). The EEG apportionment is expected to exist beyond the year 2020, even increasing until at least the middle of the decade (Nitsch et al. 2010). For the year 2013, the apportionment amounted to 5.28 ct. per kWh and for 2014, it increases to 6.24 ct. per kWh (see Amprion et al. 2012, 2013).

³⁶ Merit order defines the sequence in which electricity of different energy sources is fed into the system and thereby determines the electricity wholesale price. Depending on the demand for electricity at a given point in time, different sources for generation will be used, beginning with the one with lowest marginal costs. The last, and most expensive, unit of electricity fed into the system sets the price. In this context, merit order effect means the replacement of power plants with higher marginal costs by cheaper ones, e.g. the crowding-out of fossil fuel plants by photovoltaic or wind energy on days with high sun-intensity or a lot of wind. Thereby, the effect implies falling prices for electricity.

Sixth, beside the absolute price effects, which are clearly in conflict with the goal of affordability as defined in the energy-political triangle, the distributive consequences of the renewable energies subsidy scheme need to be considered. Just to mention in this context is the most prominent distributive consequence regarding the renewable energies development in Germany: Many analyzes, such as Techert et al. (2012), show that the costs (i.e. mainly the EEG apportionment) are more than proportional borne by the low-income population, whereas the higher-income population can profit from the high (relatively to the risk) green energy investment revenues (Gavel and Korte 2012).

Finally, the renewable energies instrument as defined and analyzed in the present paper should be assessed in terms of its effectiveness in mitigating CO₂ since this is its primary aim. For example Sinn (2012) finds that the net effect of the EEG-implied emissions reduction is zero due to the interrelation of the EEG with the European emissions trading system (ETS). Since the latter covers almost 100 percent of European electricity production, a decreasing demand for emission certificates in Germany induced by renewable energies development reduces the European certificate prices and thereby increases the demand for certificates in other ETS countries by about the same amount. Based on this effect, Sinn (2012) emphasizes that other countries' CO₂-emissions are subsidized by Germany's abatement efforts.³⁷

3.5 Results and Conclusions

The present paper analyzes the welfare effects of maintaining the current level of supply security given the large-scale integration of green power into the energy system and quantifies the effects of the resulting trade-off. In a cost-benefit analysis, the discounted cash flows of the benefits of maintaining the high level of supply security and of the costs of the respectively associated grid investments are compared. The benefits are calculated as the avoided damages of a decreasing quality of supply security that would occur in case of a *ceteris paribus* development of renewable energies. They result from an increase in the average (per year) outage duration for each consumer served (SAIDI). The resulting value of lost load is evaluated with a production function approach. The investment costs of the associated grid expansion of the distribution grid are calculated by BET et al. (2011).

The net present value shows that the costs of maintaining a constant supply security level by far exceed the induced welfare gains. When looking at climate goals, the efficiency of the instrument is controversial since it induces different marginal abatement costs not only for different green energies but also with regard to the abatement costs resulting from the European emissions trading system. Moreover, the mitigation effect on CO₂-emissions is doubtful because of the interrelation between the European emissions trading system (ETS) and the German renewable energies subsidy scheme (EEG). Finally, considering the price target, society suffers, not only

³⁷ In case the certificate price drops to zero indicating ineffectiveness of the instrument, the situation might be different. Then, implementing an additional instrument such as feed-in tariffs might be welfare increasing, see, for example, Lecuyer and Quirion (2013).

in the matter of efficiency, but also regarding the distributive goals as a consequence of higher grid fees and the EEG apportionment. Thus, the analysis implies that the strong focus on the development of renewable energies in Germany, accompanied by a strict grid regulation, results in a triple trade-off for environmental, price, and supply security considerations.

Nevertheless, the results cannot simply be dismissed as the ‘natural’ outcome of a trilemma between different energy-political goals but as a specific consequence of a deliberately chosen energy-political strategy – even though the trade-offs captured in the energy-political triangle are also inherent to the analyzed setting. By way of illustration, aiming to reduce CO₂-emissions at the national level, the choice of a more diversified set of instruments can, to some extent, result in welfare gains. This can be illustrated by the example of energy efficiency. If it cannot be improved, the increasing use of renewable energy becomes much more expensive and the social costs of the transformation process increase. This result from the previous analysis is complemented by further effects such as additional back-up power that has to be provided without sufficiently increasing energy efficiency. Of course, also in this context, cost-benefit considerations are necessary to optimize the measures. Consider, for instance, the possible consequences of a more economically (and less technically) oriented grid regulation. Regarding the negative net present value of the analysis, the question arises as to whether regulation may be too strict for socially optimal investments by network operators. For example, given the renewable energy development plans, more flexibility in the supply security goals (which are implied in the technical guidelines for the grid operators and can be interpreted as at least maintaining the current quality of supply security) could be welfare increasing.

The energy-political triangle is exactly what its name implies – political. Conflicts among the targets arise from the mixture or maybe even confusion of different positive and normative demands within the triangle. An alternative target set could partially circumvent the problem. For instance, it is well worth considering an instrument choice solely based on the claim of socially efficient electricity prices since that would combine aspects of both price and climate targets. Since efficient prices should include the total social costs of electricity production and distribution, aspects of technical supply security would also be covered. Such a consideration could, for example, take place as a component of grid fees, which could contain the costs of providing this public good. Even if such a requirement does not satisfy all political demands, for example, those having to do with equitable distribution, it seems that some conflicts could be avoided and it might serve as a better orientation guide. Clear benchmarks in this context are of particular importance due to the absence of market signals. This is most problematic for the determination of the optimal level of supply security, which is almost completely dependent on the national regulatory situation since the electricity grid, which provides supply security, is a natural monopoly and strictly regulated in Germany.

The present analysis implies that the conflict between the development of renewable energies and supply security is based on an imprecise differentiation between the climate instruments and goals. Therefore, a clearer specification of the goals themselves in the sense of the target indi-

cators and an examination of the instruments regarding them is essential to avoid inefficiencies up until complete ineffectiveness. The strong focus on renewable energies development, which overlooks the consequences for the energy-political triangle, for all in the context of the climate goals themselves but also for the negative net present value and price effects, indicates that a proper examination in terms of targets, target indicators, and instruments has not taken place in Germany. The consequent, inefficient instrument choice and transition process is reflected in the follow-up costs analyzed in this paper. Even though the complexity of different energy-political demands makes finding a first-best solution difficult, if not impossible, the chosen instruments do not appear to be even a second-best solution.

Therefore, what is needed, is an open and broad social discussion about the future electricity market in Germany. Such a discussion must cover a wide range of issues, including not only the development of renewable energies as a potential means on efficiently meeting climate targets, but also the impact of nuclear phase out as well as the consequences of creating energy markets on a European level. Especially important is a more precise definition of energy-political goals, indicators, and instruments. This paper is intended as a contribution to this essential discussion.

There are several possible extensions of the approach taken in this paper that deal with the compatibility of the different energy-political targets. Since the present results indicate that incentive regulation and technical standards have to be sufficiently flexible to ensure a more efficient electricity market transformation, the role of regulation should be further evaluated in this context. In addition, the introduction of demand-side flexibility measures such as interruptible contracts as described previously has to be analyzed as an option to increase the compatibility of supply security and price targets in the context of the integration of renewable energies into the electricity system. Finally, further research is needed with regard to the economic effects of phasing out nuclear energy and the resulting effects on supply security and emission reduction goals.

APPENDIX A

A Razor's Edge Case

In this Appendix, we identify conditions for the parameter values such that T is exactly equal to t_3 , Phase 2 collapsing to a single point at it is done in Holland (2003). If $T = t_3$, then from time t_3 , energy supply comes both from deposit 2 and from the clean energy sector (deposit 1 having been exhausted, we have identical starting-times of clean energy production and extraction from the high-cost deposit with $T = t_3$). As defined before, the time at which deposit 2 is exhausted is called \bar{T} . At \bar{T} and from then on, the price of energy must equal $\bar{p} = U'(\bar{q}_3) \equiv \phi(\bar{q}_3)$. During the time interval $t \in [t_3, \bar{T})$, the Hotelling rule must hold for deposit 2:

$$(p(t) - c_2) e^{-rt} = (p(t_3) - c_2) e^{-rt_3} = (p(\bar{T}) - c_2) e^{-r\bar{T}} = (\bar{p} - c_2) e^{-r\bar{T}}.$$

From this equation, the explicit price path between t_3 and \bar{T} as well as the extraction duration can be determined. With $p(t_3) = c_3$, it follows that the length of time it takes for the price to rise from c_3 to \bar{p} is

$$x \equiv \frac{1}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right]$$

where x is defined as $x \equiv \bar{T} - t_3$. Moreover, for all $t \in [t_3, \bar{T})$, the price path is

$$p(t) = c_2 + \frac{(p(t_3) - c_2) e^{-rt_3}}{e^{-rt}} = c_2 + (c_3 - c_2) e^{r(t-t_3)}.$$

From this, total demand for energy over the time interval $[t_3, \bar{T})$ can be determined as

$$\int_{t_3}^{\bar{T}} D[p(t)] dt = \int_{t_3}^{\bar{T}} D[c_2 + (c_3 - c_2) e^{r(t-t_3)}] dt = \int_0^x D[c_2 + (c_3 - c_2) e^{r\tau}] d\tau$$

with $x \equiv \bar{T} - t_3$ and the substitution $\tau \equiv t - t_3$. Total demand must be met by total supply, which is the output of the clean energy sector and extractions from deposit 2:

$$\int_0^x D[c_2 + (c_3 - c_2) e^{r\tau}] d\tau = x\bar{q}_3 + \int_0^x q_2(\tau) d\tau.$$

It follows that if S_2 is just equal to a threshold value S_2^{\max} defined by

$$S_2^{\max} \equiv \int_0^x D [c_2 + (c_3 - c_2) e^{r\tau}] d\tau - \frac{\bar{q}_3}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right],$$

then t_3 is indeed the time at which deposit 2 begins to be extracted (and sold at price $p(t_3) = c_3$ at that moment), and the time at which deposit 1 has just been exhausted.

Can we determine t_3 in this case? Analogous to the above, since over the time interval $[0, t_3]$ deposit 1 is being exploited, the Hotelling rule applied to deposit 1 must hold with equality for all $t \leq t_3$:

$$(p(t) - c_1)e^{-rt} = p(0) - c_1 = (c_3 - c_1)e^{-rt_3}.$$

Rearranging gives us the price path between $t = 0$ and $t = t_3$ and, under the consideration that total demand must be met by total supply, we obtain

$$\int_0^{t_3} D [c_1 + (c_3 - c_1) e^{-r(t_3-t)}] dt = S_1.$$

This equation determines t_3 and hence $p(0)$ as functions of S_1 (given the assumption that $S_2 = S_2^{\max}$). We summarize the results for this razor's edge case in the following proposition.

Proposition: A Razor's edge case If the size of deposit 2 is equal to the threshold value S_2^{\max} defined by

$$S_2^{\max} \equiv \int_0^x D [c_2 + (c_3 - c_2) e^{r\tau}] d\tau - \frac{\bar{q}_3}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right],$$

with

$$x \equiv \frac{1}{r} \ln \left[\frac{\bar{p} - c_2}{c_3 - c_2} \right],$$

then the equilibrium time path of extraction is continuous and consists of three phases:

Phase 1 (the time interval $[0, t_3]$): The whole market is supplied from deposit 1 only: $Q = q_1$. This deposit will be exhausted at time t_3 , where t_3 is the solution of

$$\int_0^{t_3} D [c_1 + (c_3 - c_1) e^{-r(t_3-t)}] dt = S_1.$$

At time t_3 , the price of energy is $p(t_3) = c_3$.

Phase 2 (the time interval $[t_3, \bar{T}]$): The whole market is supplied from both the high-cost deposit (deposit 2) and the clean energy sector: $Q = q_2 + \bar{q}_3$ where $q_2(t) > 0$ for all t in $[t_3, \bar{T}]$. The length of this phase is equal to x . At time \bar{T} , the price of energy is \bar{p} , and deposit 2 is exhausted.

Phase 3: From time \bar{T} on until infinity, the whole energy market is satisfied by the clean energy sector: $Q = \bar{q}_3$.

APPENDIX B

Analytical Derivation of the Extraction Rates

Solving the CES and the IES Model:

In the following, we derive the growth rates of resource extraction for the social optimum as well as the market economy. The analogous results for the CES model follow straightforwardly.

The socially optimal growth rate of resource extraction, \hat{n}_O^X , can be determined from (2.12). To solve for \hat{n} , we derive \hat{F} and \hat{F}_n from (2.2), (2.22) and (2.23) which gives

$$\hat{F} = g + \frac{s}{\sigma_0 - 1} \ln(R^{-\theta^X}) + \frac{1}{\theta^X} (\chi \dot{\theta}^X + \theta^X \epsilon^X \hat{n}), \quad (\text{B.1})$$

$$\begin{aligned} \hat{F}_n = g + \frac{s}{\sigma_0 - 1} \ln(R^{-\theta^X}) - (\theta^X + 1) \hat{n} - \ln(n) \dot{\theta}^X \\ + \left(\frac{1}{\theta^X} + 1 \right) (\chi \dot{\theta}^X + \theta^X \epsilon^X \hat{n}) \end{aligned} \quad (\text{B.2})$$

with $\epsilon^X = \psi \left(\frac{R}{n} \right)^{\theta^X}$, and $\chi = \psi \left(\frac{R}{n} \right)^{\theta^X} \ln(n) + (1 - \psi) \left(\frac{R}{m} \right)^{\theta^X} \ln(m)$.¹

Inserting these expressions into (2.12) gives the socially optimal time path of resource extraction:

$$\begin{aligned} \hat{n}_O^X = \frac{(\dot{\mu}_S - \dot{\mu}_P h_n - \mu_P \dot{h}_n)}{(\mu_S - \mu_P h_n) [\epsilon^X ((1 - \eta) + \theta^X) - \theta^X - 1]} \\ + \frac{(\mu_S - \mu_P h_n) \left[(1 - \eta) \left(g + \frac{s}{\sigma_0 - 1} \ln(R^{-\theta^X}) \right) + \left(\frac{1}{\theta^X} (1 - \eta) + 1 \right) \chi \dot{\theta}^X - \ln(n) \dot{\theta}^X \right]}{(\mu_S - \mu_P h_n) [\epsilon^X ((1 - \eta) + \theta^X) - \theta^X - 1]}. \end{aligned} \quad (\text{B.3})$$

(2.20) together with equations (B.1) and (B.2) gives the growth rate of resource extraction in the market economy, \hat{n}_M^X :

$$\hat{n}_M^X = \frac{(\dot{\tau} + \dot{\lambda}) - (\tau + \lambda) \left[(1 - \eta) \left(g + \frac{s}{\sigma_0 - 1} \ln(R^{-\theta^X}) \right) + \left(\frac{1}{\theta^X} (1 - \eta) + 1 \right) \chi \dot{\theta}^X - \ln(n) \dot{\theta}^X \right]}{(\tau + \lambda) [\epsilon^X ((1 - \eta) + \theta^X) - \theta^X - 1]}. \quad (\text{B.4})$$

¹ Growiec and Schumacher (2008) interpret ϵ^X as the share of n on R based on the assumption of constant returns to scale in the underlying production function.

The equilibrium for the laissez-faire case can simply be obtained from (B.4) by setting $\tau = 0$.

The solution for the standard CES case with a constant elasticity of substitution results from (B.3) and (B.4) by setting $s = 0$. In this case, σ is given by σ_0 and $\dot{\theta}$ is equal to zero.

Solving the VES Model:

The growth rate of n for the VES case can again be derived from (2.12). Using (2.2), (2.24) and (2.26) we get for \hat{F} and \hat{F}_n

$$\hat{F} = g + \epsilon^N \left(1 - \frac{z(1 + \theta^N)}{\theta^N} \right) \hat{n}, \quad (\text{B.5})$$

$$\hat{F}_n = g + \hat{n} \left[(\theta^N - z(1 + \theta^N)) \left(\epsilon^N \left(\frac{1}{\theta^N} + 1 \right) - 1 \right) - 1 \right] \quad (\text{B.6})$$

with $\epsilon^N = \frac{\gamma \psi n^{-\theta^N} \left(\frac{m}{n} \right)^{-z(1+\theta^N)}}{R^{-\theta^N}}$. Inserting these equations into (2.12) gives the socially optimal growth rate of extraction

$$\hat{n}_O^N = \frac{(\dot{\mu}_S - \dot{\mu}_P h_n - \mu_P \dot{h}_n) - (\mu_S - \mu_P h_n)g(1 - \eta)}{(\mu_S - \mu_P h_n) \left[(\theta^N - z(1 + \theta^N)) \left(\epsilon^N \left(\frac{1}{\theta^N} (1 - \eta) + 1 \right) - 1 \right) - 1 \right]} \quad (\text{B.7})$$

where μ_P and μ_S as well as the respective time derivatives have been determined previously in Section 2.3.1.

Analogously, the growth rate of resource extraction in the market economy can be derived from (2.20):

$$\hat{n}_M^N = \frac{(\dot{\tau} + \dot{\lambda}) - (\tau + \lambda)g(1 - \eta)}{(\tau + \lambda) \left[(\theta^N - z(1 + \theta^N)) \left(\epsilon^N \left(\frac{1}{\theta^N} (1 - \eta) + 1 \right) - 1 \right) - 1 \right]}. \quad (\text{B.8})$$

To obtain the laissez faire solution again set $\tau = 0$.

APPENDIX C

The Effect of Flexibility: The Case of Δ^X

From Section 2.6.2, Δ^X is given by

$$\Delta^X = (1 - \eta) \frac{s\theta^X}{1 - \sigma_0} \ln(R) + \left[((1 - \eta) + \theta^X) \chi - \theta^X \ln(n) \right] \hat{\theta}^X$$

with $R = R^X = \left(\psi n^{-\theta^X} + (1 - \psi) m^{-\theta^X} \right)^{-\frac{1}{\theta^X}}$ and $\chi = \psi \left(\frac{R}{n} \right)^{\theta^X} \ln(n) + (1 - \psi) \left(\frac{R}{m} \right)^{\theta^X} \ln(m)$ gives

$$\begin{aligned} \Delta^X &= (1 - \eta) \frac{s}{1 - \sigma_0} \ln \left(\psi n^{-\theta^X} + (1 - \psi) m^{-\theta^X} \right) \\ &+ \left[((1 - \eta) + \theta^X) \left(\psi \left(\frac{R}{n} \right)^{\theta^X} \ln(n) + (1 - \psi) \left(\frac{R}{m} \right)^{\theta^X} \ln(m) \right) - \theta^X \ln(n) \right] \hat{\theta}^X \end{aligned}$$

Using the equation for R gives

$$\psi \left(\frac{R}{n} \right)^{\theta^X} = \psi \left(\frac{\left(\psi n^{-\theta^X} + (1 - \psi) m^{-\theta^X} \right)^{-\frac{1}{\theta^X}}}{n} \right)^{\theta^X} = \frac{1}{1 + \frac{1 - \psi}{\psi} \left(\frac{m}{n} \right)^{-\theta^X}}$$

and analogously

$$(1 - \psi) \left(\frac{R}{m} \right)^{\theta^X} = \frac{1}{1 + \frac{\psi}{1 - \psi} \left(\frac{n}{m} \right)^{-\theta^X}}.$$

Inserting these expressions into Δ^X we get

$$\begin{aligned} \Delta^X &= (1 - \eta) \frac{s}{1 - \sigma_0} \ln \left(\psi n^{-\theta^X} + (1 - \psi) m^{-\theta^X} \right) \\ &+ \left[((1 - \eta) + \theta^X) \left(\frac{1}{1 + \frac{1 - \psi}{\psi} \left(\frac{m}{n} \right)^{-\theta^X}} \ln(n) + \frac{1}{1 + \frac{\psi}{1 - \psi} \left(\frac{n}{m} \right)^{-\theta^X}} \ln(m) \right) - \theta^X \ln(n) \right] \hat{\theta}^X \end{aligned}$$

where $\hat{\theta}^X = -\frac{s}{st+\sigma_0^X}$.

To see the effect that an increasing elasticity of substitution has on Δ^X , consider its limit when σ^X converges toward unity. In this case, the first term goes to zero while the term in square brackets, [...], is positive if fossil resources are not too scarce:

$$\lim_{\sigma \rightarrow 1} [\dots] = [((1 - \eta)) (\psi \ln(n) + (1 - \psi) \ln(m))].$$

If, however, resource extraction converges also to zero, this term becomes negative. Given that the growth rate of θ^X is also negative, this implies the results on the extraction path laid out in Section 2.6.3.

APPENDIX D

The German SAIDI

Table D.1 shows the supply security situation in Germany for the previous years regarding the low- and medium-voltage level as well as aggregated over both voltage levels.¹ Duration and number of interruptions apply to the about 48 million electricity consumers, both private and commercial, and are collected by the more than 800 German network operators in the low- and medium-voltage level (Bundesnetzagentur 2013). The quality of supply security in Germany is very high; for example, in 2009, electricity in Germany was available for 99.9965 percent of the time (BDEW 2010).²

year	Low Voltage Level		Medium Voltage Level		Aggregated SAIDI
	number of interruptions	SAIDI (min)	number of interruptions	SAIDI (min)	sum of SAIDIs (min)
2012	159.0	2.57	32.0	13.35	15.91
2011	172.0	2.63	34.7	12.68	15.31
2010	169.2	2.80	37.1	12.10	14.90
2009	163.9	2.63	35.1	12.00	14.63
2008	171.5	2.57	36.6	14.32	16.89
2007	196.3	2.75	39.5	16.50	19.25
2006	193.6	2.86	34.4	18.67	21.53

Table D.1: Average unavailability (SAIDI) of electricity per customer and year
Source: Bundesnetzagentur (2013)

¹ Longer time series of the German SAIDI were to the author's knowledge unavailable because publication of this information in Germany has not been mandatory before 2006 (§52 EnWG).

² The level of supply security in Germany is also very high when compared to an international level, see, e.g., CEER (2012).

APPENDIX E

Value of Leisure Time

Table E.1 shows the time spent on different daily activities for about 5,400 households and more than 12,000 persons between 2001 and 2002. It evaluates the average time organization for the period of 2001 and 2002 with selected activities in hours and minutes per day of the week (Monday-Sunday). It is differentiated between employed people, here, full-time workers, and unemployed people, here, retirees. The table makes clear that most non-working time, except the time spent sleeping, is used for leisure and household activities.

Activity	Employed ¹	Not employed ²
Sleeping, meals, body care	10:31	11:53
Employment, (continuing) education	5:40	0:11
Volunteer work	2:36	4:46
Social contacts, entertainment, events	1:56	2:14
Sports, hobbies, games, mass media	3:17	4:57

Table E.1: Average time organization for selected activities in hours and minutes (h:min) per day in 2001/02

Source: Statistisches Bundesamt and BMFSFJ (2003)

¹ Full-time employed people; ² Retirees

Table E.2 shows the extent to which household activities rely on electricity. We can see that the most important household and leisure activities are at least partially electricity dependent and only partly substitutable.

Activity	Electricity dependent?	Substitution possible?
Sleeping, others personal area	limited	mainly
Employment, honorary, and volunteer work	mainly	limited
Mass media	mainly	limited
Shopping, housekeeping, and childcare	partly	partly
Social life, entertainment, and culture	partly	limited
Eating, drinking	partly	mainly
Cooking	mainly	limited
Qualification, education	partly	partly
Sports, activities in nature	partly	partly
Hobbies and games	partly	partly

Table E.2: Electricity dependency of selected activities

Note: Results are based on Bliem (2005) and de Nooij et al. (2007).

Some leisure activities, but also general household activities, shown in Table E.1, for instance, ‘mass media,’ are even mostly electricity dependent with only limited substitution possibilities. With regard to damages of supply interruptions, this means that the higher electricity dependency and the lower substitution possibilities, the higher are social damages.

APPENDIX F

Comparison of VoLL Analyses

Table F.1 presents and compares the results from different VoLL estimates. It shows inflation-adjusted VoLLs in EUR values with the base year 2011 that were estimated for various countries with different methods (macroeconomic analysis, contingent valuation methods, costs of back-up capacity, meta-analysis, choice experiment, shadow price of planned capacity). It must be kept in mind that a precise evaluation of the damages resulting from power outages is situation dependent and includes factors in addition to outage duration, sectors, regions, years, or time of day. Consequently, the VoLL cannot be seen as constant over time and identical between different electricity consumers. To control for this, for example, many authors differentiate the estimations with regard to interruption durations (see, e.g., Curtin and Doherty 2007). However, an estimation of generic values is not possible due to the complexity of supply interruption situations (see also frontier economics 2008). The estimations in Table F.1 therefore must be viewed as approximations or, at best, averages.

The table shows that the VoLLs of the analyzed sectors differ significantly in their level, but not so much in the relation to each other. Nevertheless, it is clear that the value of an uninterrupted power supply by far exceeds electricity consumer prices. This applies not only to the economic sectors, but also to private households.

Method	Author(s)	Year	Region	Sector	VoLL [EUR/ kWh]
Macroeconomic Analysis	present paper ¹	2008 2010	Germany	Agriculture	2.22
				Industry	2.81
				Public Administration	6.50
				Trade, Services	15.37
				Transport	7.61
				Households	13.61
Macroeconomic Analysis	Leahy at al. (2012)	2008	Republic of Ireland	Commerce	13.2
				Industry	3.8
				Households	23.22
Macroeconomic Analysis	Tol (2007)	2005	Republic of Ireland	Average	7.7
				Agriculture	5.8
				Services	11.6
				Transport	65.8
Residential	63.9				
Macroeconomic Analysis	de Nooij et al. (2007)	2001	Netherlands lands	Agriculture	4.61
				Production	2.21
				Services	9.39
				Households	19.37
Macroeconomic Analysis	Bliem (2005)	2004	Austria	Agriculture	3.7
				Construction	48.1
				Production	2.4
				Services	10.5
				Households	18.1
Survey: Willingness to pay	CRA (2008) ^{2,3}	2007	Australia	Agriculture	0.08
				Commercial	0.03
				Industrial	0.02
				Residential	0.01

Survey: Willingness to pay	Samdal et al. (2006) ^{4,5}	2001 2003	Norway	Agriculture Commercial Industry Residential	2.84 18.77 12.52 1.52
Survey: Willingness to pay	Reichl et al. (2013) ⁸	2008	Austria	Agriculture Construction Production Households	4.0 45.2 3.7 1.4
Survey: Mail-out and direct measurement	Electricity Authority New Zealand (2012) ^{2,6}	2010	New Zealand	Average	12.51- 26.65
Survey: Costs of backup capacity	Gilmore and Lave (2007) ⁷	2004- 2006	USA	Average	22.80- 25.48
Shadow price of planned capacity	Curtin and Doherty (2007) ²	2007	Ireland	Weighted average	8.98
Meta Analysis	frontier eco- nomics (2008)	2007	Germany	Average	8.3- 16.5

Table F.1: Comparison of VoLL estimates of different analyses

Note: Values are shown in EUR, inflation adjusted for 2011.

¹ In nominal prices; ² Interruption duration is 8 hours; ³ Exchange rate 2007: 1 AUD = 0.61159 EUR; ⁴ Annual average interruption duration is 1.3 hours; ⁵ Exchange rate 2003: 1 NOK = 0.12507 EUR; ⁶ In 2011 prices; ⁷ Exchange rate 2006: 1 USD = 0.79678 EUR; ⁸ Interruption duration is 12 hours in summer

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