Market vs. policy failures:

How governments affect electricity markets and what they should do.

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Darko Jus

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Referent: Prof. Dr. Dr. h.c. mult. Hans-Werner Sinn

Korreferentin: Prof. Dr. Karen Pittel

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Introduction

Motivations and contributions

Modern societies are highly dependent on the availability and use of energy, which is required as an input factor in industrial production, by domestic households and for transportation purposes. While energy is essential for most (economic) activities in our society, its transformation and use is a prime example of economic activities involving substantial market failures. Probably the most severe market failure is associated with the combustion of fossil energy, which is the main driver of the anthropogenic climate change. It has been termed a ‘market failure on the greatest scale the world has seen’ by the Stern Review, inducing intense debate among economists and politicians (Stern, 2007, p. 27).

One potential means of moderating the problem of climate change is the increased use of renewable energy, which could be achieved by either imposing a price on carbon dioxide emissions, thereby indirectly increasing the competitiveness of renewable energy, or by directly influencing its private favorability with subsidies. Many countries have opted for both, but the subsidizing of renewable energy in particular has led to an expansion, which is certainly remarkable: for example, around 23,000 wind turbines and more than 1,200,000 photovoltaic modules have been installed in Germany as of 2012, and have contributed to more than 10 percent to Germany’s electricity supply already in 2011. However, citing Milton Friedman’s famous words that ‘there is no such a thing as a free lunch’, support for renewable energy has been accompanied with high additional costs channeled towards electricity consumers in the form of a levy. The costs are rising from year to year, having reached a sum of in excess of 15 billion euros in Germany for 2011 alone, thereby illustrating the special relevance of this topic for society.

This dissertation analyzes four key aspects related to the development of renewable energy. Firstly, in the presence of a climate change externality, a first-best allocation on the electricity market generally cannot be achieved with a renewable energy subsidy, thus highlighting its imperfectness in replacing a correct pricing of carbon dioxide emissions (Chapter 2). Secondly, supposing the existence of an emission trading system, this dissertation investigates the effects of additionally supporting renewable energy. Surprisingly, when considering a one-country model, the market participant who loses rents due to the introduction of a levy-financing subsidy scheme, such as the case of Germany, proves to be the fossil electricity producers rather than the electricity consumers (Chapter 3). Thirdly, considering a more realistic two-country framework, it becomes more likely that domestic electricity consumers have to accept a higher electricity price, while rents are shifted to foreign electricity consumers as a consequence of unilateral renewable energy support (Chapter 4). Fourthly, this dissertation studies reasons for employing technology-specific feed-in tariffs, and in contrast to usual intuition, finds them to be (static) efficiency improving when policy has committed to achieving a strong renewable energy target (Chapter 5).

The second inspiration for considering energy policy was the unforeseeable catastrophe that hit Japan in March 2011. Whereas the fierce earthquake and resulting tsunami caused great immediate suffering among the population, the consequences of the nuclear catastrophe will have a much longer lasting effect. The truly shocking images of the Fukushima Dai-ichi nuclear power plant that spread across the world not only triggered a wave of sympathy, but have also influenced attitudes towards the use of nuclear power elsewhere in the world. The policy reaction in Germany was particularly strong, where nuclear power was swiftly declared unwanted, moreover with alarmingly little economic dispute. There has not been intense debate about possible market failures, which certainly exist, and whether nuclear power would still be undesired even after they are resolved. This dissertation focuses on the externality arising due to the limited liability enjoyed by nuclear power companies, particularly in the case of catastrophic accidents. It reveals the existence of an incentive for excessive risk-taking in the nuclear industry, reviews current regulation and proposes better solutions towards the aim of providing an unbiased ground for further thoughts on the favorability of nuclear power (Chapter 6).

Market power and other forms of strategic behavior of market participants will not be analyzed in this dissertation, despite certainly being of importance in reality. This is a carefully considered simplification that allows for a stronger focus on other market failures, while offering the potential for the future extension of the presented models.

FUNCTIONS OF THE PUBLIC SECTOR ACCORDING TO MUSGRAVE

Richard Abel Musgrave defined the basic functions of the public sector as the "allocation function", "distribution function" and "stabilization function". The allocation function is concerned with market failures, aiming to establish efficient economic outcomes. The distribution function is a necessary element of the public sector, since market outcomes – independent of their efficiency – may not be in line with social preferences for the distribution of goods and wealth, and therefore ex-ante or ex-post redistributive policies may be desirable. Finally, the stabilization function is supposed to reduce fluctuations in employment and prices through the application of monetary or fiscal policy. It is important to emphasize that, according to Musgrave, the scope of public policy is determined by the need for intervention arising from these three functions. Therefore, if none of them applies, governments should not take action. This reasoning is also valid for sub-disciplines of public economics, such as energy, environmental and climate policy.

One of the most important results in the field of economics is the *first fundamental theorem of welfare economics*, which states that a competitive equilibrium reached within a market free of market failure is Pareto-efficient. However, such markets seldom exist, with Musgrave thus concluding that "public policy is needed to guide, correct, and supplement" the market mechanism in certain respects (Musgrave and Musgrave, 1989, p. 5). This perspective on the role of the public sector forms the basis for all further thoughts presented in this dissertation.

INEFFICIENT RESOURCE ALLOCATION AS A JUSTIFICATION OF PUBLIC POLICY

From the public policy perspective of seeking allocative efficiency, analyzing market outcomes consists of a two-step procedure, whereby the insights summarized in the *first fundamental theorem of welfare economics* serve as a guiding element. The first step is the normative view, which aims to define how the energy transformation industry *should* look in order to satisfy allocative efficiency. From the *first fundamental theorem of welfare economics*, an allocatively efficient allocation would result in the absence of public goods, externalities, information asymmetries and market power, if all market players rationally maximize their net benefit.

In the second step, this desired outcome is compared with the market outcome, which has possibly already been influenced by public policy interventions. Any difference between the efficient allocation and pure market allocation could be understood as a justification for a public policy intervention, assuming its ability to improve the allocation of resources. Similarly, any difference between the efficient allocation and market outcome after public policy has intervened would disclose a potential need for fewer, more or other public policies for correcting the market failure, or would reflect public policy's inability to induce the efficient allocation.

THE CLIMATE CHANGE EXTERNALITY AND CURRENT PUBLIC POLICY

From the end of pre-industrial times, the consequences on the global climate of emitting carbon dioxide into the atmosphere were not well established for more than two centuries. Despite the existence and reasons for climate change being already known among experts in the 1980s, this topic only has received considerably more attention by public policy since the publication of the IPCC First Assessment Report in 1990 (see, IPCC 1990). From an economic perspective, the climate change externality arises given that the benefits of emitting carbon dioxide generally only accrue to the party causing the emissions, whereas the costs, in the form of climate change, spread among large parts of the world. Without public policy intervention, there would be no market for carbon emissions and the associated costs would be insufficiently accounted for by carbon emitting individuals and firms.

The Kyoto Protocol was adopted in 1997, predominantly for this reason. It is considered as the major international climate policy achievement to date, although its actual effectiveness in substantially reducing world greenhouse gas emissions has been strongly questioned. Despite a number of major polluting economies having refused to burden themselves with reduction targets, it has not discouraged other (groups of) countries at the frontline the EU from implementing policies, with the aim of reducing their own consumption of fossil resources and increasing the market penetration of alternative, often renewable, energy sources, thereby aiming to achieve their Kyoto goals or self-imposed targets.

For example, the EU implemented an emission trading system (EU ETS) in 2005, according to which large industrial carbon dioxide emitters and electric power plants must obtain emission permits, designed to increase the costs of emitting carbon dioxide (see, Directive 2003/87/EC). This also represents the stated reason for the introduction of carbon related taxes and other similar policies. It is disputable whether the pricing of carbon dioxide emissions achieved following such measures is sufficient, and whether it follows a necessary time path to achieve a slowing down of the climate change process (see, Sinn 2008a, 2008b, 2012). Independent of the answer to this question, it is evident that these measures alone would not have triggered such a substantial development of renewable energy as observed during the past decade, without generous additional support.

In Europe, Germany was a forerunner with its *Electricity Feed-in Act*[1] of 1991, which was extended and renamed as the *Renewable Energy Act*[2] in 2000 (see, EEG, 2000). The latter is often regarded as the most effective scheme for supporting renewable energy, also documented by the figures in Chapter 1 of this dissertation. In certain ways, this dissertation will address whether the support of renewable energy of this kind is a public policy intervention that can be justified by the Musgravian definition of its functions.

CLIMATE CHANGE AS A REASON FOR SUBSIDIZING RENEWABLE ENERGY (CH. 2)

The support of renewable energy is often justified by arguments related to climate change (see, for example, EEG, 2012). The validity of this reasoning is studied in Chapter 2 of this dissertation, whereby no other externalities are taken into account at this point. Owing to the climate change externality that results in an insufficient pricing of carbon emissions, fossil energy might be employed too excessively in electricity generation, consequently the development of renewable energy, which is a substitute for fossil energy, might be hindered.

Public policy could simultaneously solve both problems by implementing a correct pricing of carbon emissions. The use of fossil energy would decrease under such circumstances, and thereby the electricity price would tend to rise, which would consequently induce an efficient use of renewable energy. On the other hand, if public policy chooses to tackle this market failure by subsidizing renewable energy due to a

[1] Stromeinspeisungsgesetz (StrEG), came into force on 1st January 1991.
[2] Gesetz für den Vorrang Erneuerbarer Energien (EEG), came into force on 1st April 2000.

correct carbon pricing being infeasible or undesirable, it generally fails to achieve an efficient market outcome. The reason is that by subsidizing renewable energy, the actual problem of an insufficient pricing of carbon emissions cannot be solved and thus an overprovision of fossil electricity remains.

In the absence of a correct pricing of carbon emissions, the maximal subsidy to renewable energy that can be justified is equal to the climate change externality resulting from the use of fossil energy. The latter is estimated at only a few euro cents by Krewitt and Schlomann (2006), and if applied, it would replicate an internalization of the climate change externality by lifting the remuneration of renewable electricity to the social marginal costs of fossil electricity. In contrast to this second-best policy, an intervention that aims to reduce fossil electricity generation to its efficient level by supporting renewable energy requires an inefficiently high subsidy, and would induce a socially over-excessive development of renewable energy.

INTERACTION BETWEEN RENEWABLE ENERGY SUPPORT AND AN ETS (CH. 3)

The model developed in Chapter 2 is extended in Chapter 3 to account for the existence of an emission trading system (ETS), such as the EU ETS. Within this framework, Chapter 3 offers a positive analysis of how subsidizing renewable energy influences the market outcome, and particularly how it interacts with the ETS.

The considered government finances a subsidy for renewable electricity by imposing a levy on electricity consumption. The analysis reveals that despite electricity consumers being formally obliged to pay for the renewable energy support, in effect the scheme does not impose a burden on them. The levy on electricity consumption reduces ceteris paribus the demand for fossil electricity, the amount of which, however, is given by the number of emission permits provided by the regulator. Hence, as the levy is imposed and given that the marginal cost of fossil electricity is price setting, the price of emission permits decreases on a one-to-one basis for the same quantity to be consumed. Simultaneously, the subsidy-driven expansion of renewable also reduces demand for fossil electricity, which leads to a further decrease in the price of emission permits. Overall, the permit price reduction is larger than the levy imposed on electricity consumers for the financing of the subsidy. This is simply another way of saying that the total electricity supply has increased owing to additional renewable electricity generation, while the provision of fossil electricity remains constant. Thus, for a given demand for electricity, the new equilibrium is to be found at a lower consumer price, therefore implying a higher consumer rent.

Effectively, the renewable energy subsidy is financed by extracting rents from the ETS via the decrease in value of the emission permits. The analysis reveals that electricity consumers do not need to sacrifice their rent, rather only the owners of emission permits. Moreover, possible limitations of the results are discussed.

UNILATERAL SUPPORT OF RENEWABLE ENERGY WITHIN A COMMON ETS (CH. 4)

The model developed in Chapter 3 is extended to a more realistic two-country framework in Chapter 4, supposing a common electricity market and both countries comprising ETS. The data shows that the assumption of a group of countries unilaterally supporting renewable energy is a reasonable description of the situation in the EU. Analyzing such a policy and once again presuming that the subsidy is financed by a levy on domestic electricity consumption, this generates quite different results to those in Chapter 3.

By the same mechanism as in the one-country model, the permit price decreases when a country subsidizes renewable electricity and imposes a levy on electricity consumption for its financing. However, since only consumers in the subsidizing country contribute to the financing, the scheme particularly benefits electricity consumers in the other country. Their electricity consumption increases, implying a shifting of rents towards them. Moreover, since more electricity is consumed abroad, an increasing consumer price in the renewable energy supporting country becomes a possible outcome, and occurs when renewable energy necessitates a high subsidy for becoming privately profitable and/or when foreign electricity consumers react strongly to changes in the electricity price. Therefore, despite the intuition provided in Chapter 3, this model explains why German electricity consumers might be suffering a burden owing to the extensive renewable energy support, while simultaneously describing that countries can appropriate rents by free-riding on the renewable energy policies of other countries with which they share a common electricity market. Finally, the model predicts increasing net electricity exports for the subsidy implementing country, whereas those of passive countries are expected to decrease. This is briefly compared with stylized data, from which it can be seen that the quantity of electricity net exported by Germany and Spain, two countries in which renewable energy capacity has risen sharply in the past decade, has indeed increased, whereas it has decreased in the case of France.

A NEW VIEW ON TECHNOLOGY-SPECIFIC FEED-IN TARIFFS (CH. 5)

Feed-in tariffs are currently the preferred instrument for supporting renewable energy in many countries. They are differentiated between renewable energy technologies in most countries, generally favoring less advanced ones with a higher tariff. For example, photovoltaic electricity in Germany has received a six times higher tariff than wind electricity at a certain point in time.

Assuming that policy has committed to achieving a renewable energy target, the efficiency of a feed-in tariff scheme can be judged under static efficiency and dynamic efficiency aspects. Abstracting from externalities and assuming a lump-sum financing, static efficiency would be achieved by a uniform feed-in tariff for all renewable energy technologies. This guarantees that the best way for producing renewable electricity is sought, thus minimizing costs of electricity production. On the other hand, whilst providing a possible argument for technology-specific feed-in tariffs, the concept of dynamic efficiency is also much more complex and carries a high degree of uncertainty, given that it necessitates predictions about future developments. Therefore, it is often argued that no evident justification for the strong differentiation of feed-in tariffs can be immediately inferred from either of the two concepts.

However, considering a situation in which policy has committed to an excessively strong renewable energy target, implying a burden on electricity consumers who again finance the subsidies through a levy, Chapter 5 provides a new motivation for differentiating feed-in tariffs based on static efficiency. Given the constraint of the renewable energy target, total rents maximizing public policy differentiates the feed-in tariffs whenever the price elasticities of supply are not uniform among renewable energy technologies. This is due to alternative technologies generating unequal marginal excess burdens for consumers when the marginal expenditures are not the same. Therefore, (constrained) static efficiency requires feed-in tariffs to be differentiated when a lump-sum financing of the renewable energy support is not chosen.

Moreover, an even stronger differentiation of the feed-in tariffs is needed if public policy aims to maximize the consumer surplus rather than total rents. To minimize the costs for consumers, public policy effectively acts as a monopsonistic buyer of renewable energy, equalizing marginal expenditures between the technologies rather than the marginal costs. Thus, the redistributional motive of shifting rents from producers of renewable electricity to electricity consumers represents another argument for employing technology-specific feed-in tariffs.

AN APPROACH FOR CONSIDERING NUCLEAR POWER FROM AN ECONOMIC PERSPECTIVE

The state of a country’s economic development is a driver for its population’s attitudes towards environmental protection. Protecting the environment often implies not choosing production methods that are less costly in the short-run, therefore implying a trade-off between short-run consumption possibilities and a higher degree of environmental preservation. This holds for decisions regarding the use of renewable energy, but can also be similarly applied when considering the use of nuclear power. The latter may be seen as a trade-off between increasing consumption possibilities by generating electricity on the one hand, and the level of safety threatened by the small yet existing probability of nuclear accidents on the other. Based on this reasoning, there could indeed be a rationale for Germany’s choice to phase-out nuclear power after being reminded of its risk by the 2011 Fukushima catastrophe, whereas countries such as China or India, where consumption needs are not yet equally satisfied, still pursue their nuclear power expansion. However, it is puzzling that no other highly developed country has taken measures comparable with Germany’s decision.

According to these arguments, the decision regarding the use of nuclear power depends on the characteristics of the country, including the preferences of its population, which should be respected by its government. However, all costs and benefits need to be weighed against each other to guarantee an optimal choice, which requires nuclear power generation being free of market failures for an unbiased decision to be reached. However, in reality nuclear power generation does suffer from market failures, one of which stems from the limited liability of nuclear power companies. They cannot lose more than the legally defined liability capital or their equity capital, even if the damage is much larger in the case of a severe accident. This reduces the incentive to invest in costly nuclear safety, leading to an inefficient safety level in nuclear reactors. Therefore, public policy in line with Musgrave's perspective is necessary to establish an efficient risk-taking.

Eventually, after the optimal level of risk-taking is implemented, society may still decide not to use nuclear power. However, this decision must not be taken on the basis of nuclear power plants that are too risky, but rather given that the level of care satisfies allocative efficiency. Moreover, once nuclear power companies take the risk of catastrophes into account, it may be the case that the use of nuclear power becomes too expensive and subsequently disappears by its own accord. Therefore, solving the problem of limited liability and excessive risk-taking is both an important element of the future use of nuclear power and a necessary basis for decisions regarding nuclear phase-outs.

EXCESSIVE NUCLEAR RISK-TAKING AND THE NEED OF PUBLIC POLICY (CH. 6)

Chapter 6 explains the economic problem concerning the safety of nuclear reactors. Considering the maximization problem of a nuclear power company, a negative externality leading to inefficiently unsafe nuclear power reactors is derived. This is a re-interpretation of Sinn (1980, 1983, 2003), who identifies that limited liability of a company leads to an excessive risk preference if losses beyond the equity capital are possible. Limited liability may arise in two forms, through the amount of equity capital or by legislation. Only three countries (Germany, Japan and Switzerland) have chosen to impose a legally unlimited liability of nuclear power companies, whereas all other countries offer strong de jure liability limitations.

For example, Tokyo Electric Power Company (TEPCO), the company operating the Fukushima Da-ichi power plant, reported equity capital to the amount of JPY 2.47 trillion prior to the accident, which only constitutes a small proportion of the actual costs of the catastrophe. Similarly, the liability of other nuclear power companies around the world is limited de jure or de facto in the case of catastrophic accidents. Therefore, Chapter 8 discusses several potential regulatory instruments in terms of their ability to improve the efficiency of risk-taking, including direct safety regulation, minimum equity capital requirements, mandatory insurance, mutual risk-sharing pools and catastrophe bonds. Whereas the (stronger) use of some of these potential instruments cannot induce an efficient risk choice, other instruments carry serious implementation problems and would, if imperfectly implemented, also fail to establish allocative efficiency.

Hence, a new proposal for a regulatory regime is presented in the final part, the core of which consists of a two-stage approach. In the first stage, capital markets evaluate the risk stemming from each reactor via catastrophe bonds, which are risk-linked securities in the sense that the (a share of the) value of the bond must be sacrificed by their owners if a pre-specified event occurs, such as a nuclear catastrophe. In the second step, the regulator uses this private risk assessment and intervenes by charging an actuarially fair premium, thereby (under ideal conditions) inducing the optimal level of risk-taking. Society then acts as an explicit insurer for nuclear risk, but is, on average, fairly compensated. Thus, the proposal consists of combining the ability of capital markets to evaluate risk-taking and society's reserve capacity to absorb high risks. Furthermore, issues related to the design and implementation of this regulation are discussed.

1. Key developments in the German electricity industry since 1945

1.1 Plan of the chapter

This chapter provides an introduction to the main developments within the German electricity industry since 1945, with the aim of briefly explaining the stages through which the electricity industry has passed and emphasizing how strongly this path was steadily influenced by public policy interventions. There is practically no period in which the government has not attempted to affect the electricity market and steer it in a specific way. Despite the electricity sector becoming increasingly privately owned and liberalized over the past two decades, government involvement remains high.

After World War II, the focus of energy policy in Germany was on supporting the coal industry, before the nuclear power industry later attracted significant funding from the government. By contrast, a major current aim of energy policy is to increase the use of renewable energy, with the motivation of reducing the consumption of fossil energy, which discovered to contribute to the climate change process. Furthermore, it is supposed to replace nuclear power, which will be phased-out in Germany according to a decision made in 2011. This peculiar policy path of supporting certain developments before eventually trying to redeem them itself represents a motivation to analyze and question today's energy policy. As argued in the introduction, this dissertation follows the view that government intervention is only justified in line with the functions of the public sector as defined by Musgrave.

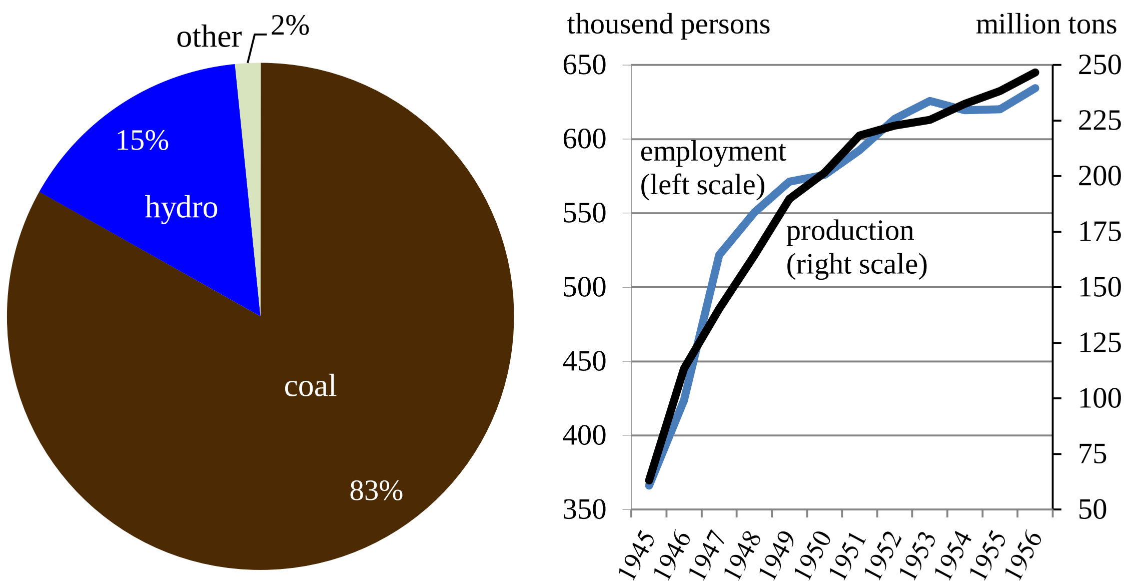
In addition to documenting the historic development of the government involvement in the electricity sector, this chapter explains some details of current public energy policies that will be taken into account by the models in later chapters.

1.2 Coal-intensive economic recovery (1945-1956)

Germany's economic recovery after World War II led to a rapidly increasing energy demand. Given that crude oil was only significantly available in North America at this time, Germany's energy need was met by coal – largely extracted from domestic deposits.

The price of coal remained low through regulation until 1956, whereas the industry simultaneously received varies kinds of support measures that aimed to boost its output in the period from 1945 to 1956 (see Figure 1.1, right diagram), the year in which Germany's coal production reached its all-time peak. At this time, over 630,000 persons were employed in the coal mining sector, with around 490,000 working in the coal-rich Ruhr region. Consequently, over 80 percent of electricity generation relied on coal in 1956, with the remaining power generation based on hydro energy, waste and other biomasses (see Figure 1.1, left diagram).

Figure 1.1: Electricity generation in 1956 (left) and coal statistics (right), West Germany



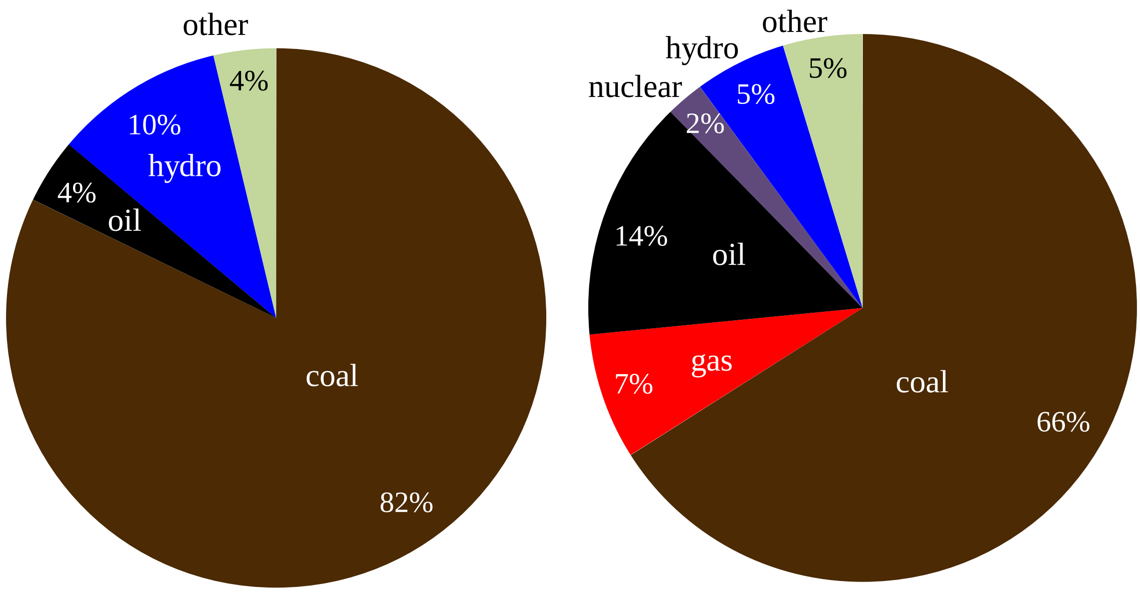
Source: AG Energiebilanzen for the left diagram, Statistik der Kohlenwirtschaft for the right diagram.

1.3 Rise of cheap crude oil and first signs of environmental care (1957-1971)

The coal price control was ended in 1956 by the decision of the Authority of the European Coal and Steel Community, which led to a price increase and domestic coal becoming more expensive (see BIS, 1956, p. 82-84). In the following years, coal from abroad and mineral oil from the Middle East entered the market at very competitive prices (see Storchmann, 2005). Despite coal production in Germany remaining subsidized throughout the 1960s, its share in electricity generation decreased. However, it was still the most important source in 1971, with a share of 66 percent (see Figure 1.2, right diagram).

After several smaller test plants, the first commercial nuclear power plant went online in East Germany in 1966 (Rheinsberg Nuclear Power Plant), with a gross capacity of 70 MW, and in West Germany in 1967 (Gundremmingen A Nuclear Power Plant), with a gross capacity of 250 MW. Although a few more nuclear power plants were constructed before the end of the 1960s, nuclear power only occupied a tiny 2 percent share of total electricity generation in 1971. However, the strong governmental support at this time already indicated the imminent rise of nuclear power use. The share of hydro power in total electricity generation declined as the total electricity generation increased faster than the use of hydro power. The shares in 1961 and 1971 are illustrated in Figure 1.2.

Figure 1.2: Electricity generation in 1961 (left) and 1971 (right), West Germany



Source: AG Energiebilanzen.

In addition to changes on the supply side of electricity, the 1960s marked the decade in which high-level policy makers began emphasizing environmental problems. Willy Brandt – Chancellor of West Germany 1969-1974 – already expressed his worries about the (local) air pollution in the Ruhr region stemming from the industrial plants and the coal-fired power plants in 1961. Despite mandating that “the sky over the Ruhr region must be blue again” (see, UBA, 2011), Brandt’s concerns were not pushed forward given that he did not become Chancellor in 1961. Ideas for protecting the environment – or more precisely, protecting humans from environmental degradation, as it was termed at that time – re-gained weight when the social-liberal coalition eventually came in office in 1969.

During this course, the 1970 Action Program for Environmental Protection[3] and the 1971 Environmental Program[4] represented the first major governmental initiatives aiming to better protect humans from environmental problems.

1.4 Renewable energy research funding and the rise of nuclear power (1972-1985)

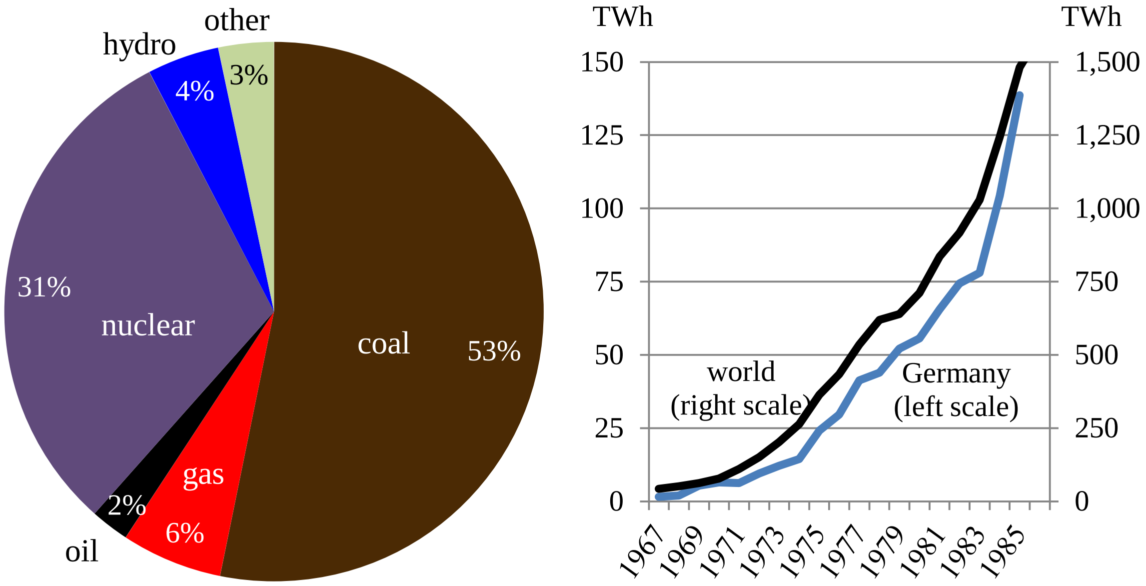
In 1972, the so-called *Meadows Report* was published by the Club of Rome and attracted a lot of interest. Its main conclusion was that industrial growth could not continue forever, owing to finite energy resources and the world's limited pollution-carrying capacity (see, Meadows et al., 1972). The first oil crisis shook the oil importing countries one year later, with the shortage of supply and strongly rising price of oil powerfully envisaging the dependency and need for alternatives. Therefore, inspired by the turbulences on world oil markets, a German government began to substantially support research and development in the field of renewable energy for the first time in 1974.[5] In nominal terms, more than 200 million euros were devoted to wind and solar energy research until 1985, with most used for promoting research towards large-scale wind power plants. Moreover, funding was also directed to solar energy research, which rose sharply in 1982 and remained substantial thereafter (see, BMU, 2012b).

Despite public protests against nuclear power increasing until the end of the 1970s, and an Enquete Commission of the German Bundestag constituting that future energy supply could also be secured without the use of nuclear power, overwhelmingly more support was (still) flowing to the development and use of nuclear energy. Technology support and research funding for nuclear fission and nuclear fusion amounted to over 1 billion euros annually after 1974 until 1985, peaking at around 2 billion in 1982 (see, BMU, 2012b). Including other implicit and explicit government support to nuclear energy, such as the liability limitation (as discussed in Chapter 8), the amount by which nuclear energy was subsidized would significantly multiply. The extensive government support program that had begun as early as the 1950s had led to a boom in terms of newly commissioned nuclear power plants in the late-1970s and the 1980s. Electricity generation from nuclear power similarly increased strongly in Germany as in the rest of the world (see

[3] Sofortprogramm zum Umweltschutz.
[4] Umweltprogramm.
[5] See Lauber and Mez (2004) and Jacobsson and Lauber (2006) for more details on Germany's energy policies from 1974 to 2005.

Figure 1.3, right diagram). Consequently, the share of nuclear power in total electricity generation rose to 31 percent in West Germany in 1985, thereby reducing the share of fossil energy despite coal remaining subsidized throughout this period (see Figure 1.3, left diagram).

Figure 1.3: Electricity generation in 1985, West Germany (left), and nuclear electricity generation (right)



Source: AG Energiebilanzen for the left diagram, BP Statistical Review of World Energy June 2012 for the right diagram.

1.5 The Chernobyl disaster and the increase of renewable energy support (1986-1999)

The Chernobyl catastrophe is considered the most severe accident in civil nuclear power use to date. On Saturday, 26th April 1986, reactor No. 4 exploded, leading to radioactive fallout in large parts of Europe. Public opinion in Germany was neither truly in favor of nuclear power, nor was there a majority against its use prior to the accident in Chernobyl, however the opposition amplified thereafter (see, Jahn, 1992). The Green party demanded an immediate phase-out, whereas the social democrats advocated a gradual shutdown of nuclear power plants. Five more nuclear power plants went on line until 1989, having already been in construction in 1986, but no additional plants were built thereafter. As an immediate reaction to the Chernobyl catastrophe, the German government consisting of the

CDU/CSU and the FDP established the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in June 1986.

Shortly after the nuclear catastrophe in Chernobyl, several reports outlined the imminent problem of global warming and its connection with carbon dioxide emissions from burning fossil fuels. One such report was by the German Meteorological Society (Deutsche Meteorologische Gesellschaft, DMG) and German Physical Society (Deutsche Physikalische Gesellschaft, DPG), which forecasted global warming of 3 degrees Celsius over the next 100 years. Therefore, the DPG advocated a stronger expansion of the use of nuclear power (see, Bruns et al., 2011). Consequently, the German Bundestag installed an Enquete Commission entitled ‘Protecting the Earth's Atmosphere’ in 1987. Its final report was published in 1990, recommending the reduction of carbon dioxide emissions with targets of minus 30 percent by 2005 (relative to 1987), minus 50 percent by 2020 and minus 80 percent by 2050 (see, Schmidbauer et al., 1990). From an international perspective, the 1988 establishment of the Intergovernmental Panel on Climate Change (IPCC) was an important step in the process of increasing scientific knowledge about climate change. In their First Assessment Report published in 1990, the group of scientists emphasized the existing certainty about the greenhouse effect and performed calculations about possible temperature increases and sea level rises (see, IPCC, 1990).

Following the results and advice provided by the Enquete Commission during 1987-1990, the German Bundestag adopted the so-called *Electricity Feed-In Act* (Stromeinspeisungsgesetz, StrEG) in December 1990. The StrEG came into force on 1st January 1991, and is considered the predecessor of today’s *Renewable Energy Act* (*EEG*). Under its terms, utility firms were obliged to accept renewable electricity in their supply area (StrEG, §2) and pay a tariff for each kWh, as defined in §3 of the act. Abstracting from some specific details, the feed-in tariff was defined as 75 percent of the average per kWh revenue received by the utility firm from final consumers, in the case of electricity from hydro energy, dump gas, sewage gas, and biomass energy. In the case of solar and wind energy, the feed-in tariff was even 90 percent of the previously stated per unit revenue. This resulted in a nominal compensation per kWh generated from wind energy and photovoltaic of 8-9 euro cent between 1991 and 2000 (see Table 1.1).

There were several additional programs aiming to support renewable energy, and together with the feed-in tariff they succeeded in inducing a noticeable increase in wind energy use. A first substantial increase in wind energy capacity was achieved owing to the *100/250 MW wind program* launched in 1989. The initial aim was to boost the capacity by 100 MW, but was later extended to 250 MW owing to high demand. The program guaranteed a premium of 4.09 euro cent per kWh generated from wind energy for an initial fixed period of 10 years. The premium was reduced to 3.07 euro cent per kWh in 1991, which was then granted in addition to the feed-in tariff defined by the *Electricity Feed-In Act*. Moreover, German states offered their own support programs contributing to the development of wind energy during the 1990s (see, Bruns et al., 2011).

Table 1.1: Feed-in tariffs according to the *Electricity Feed-In Act* in euro cent/kWh (nominal) and newly installed capacity in MW

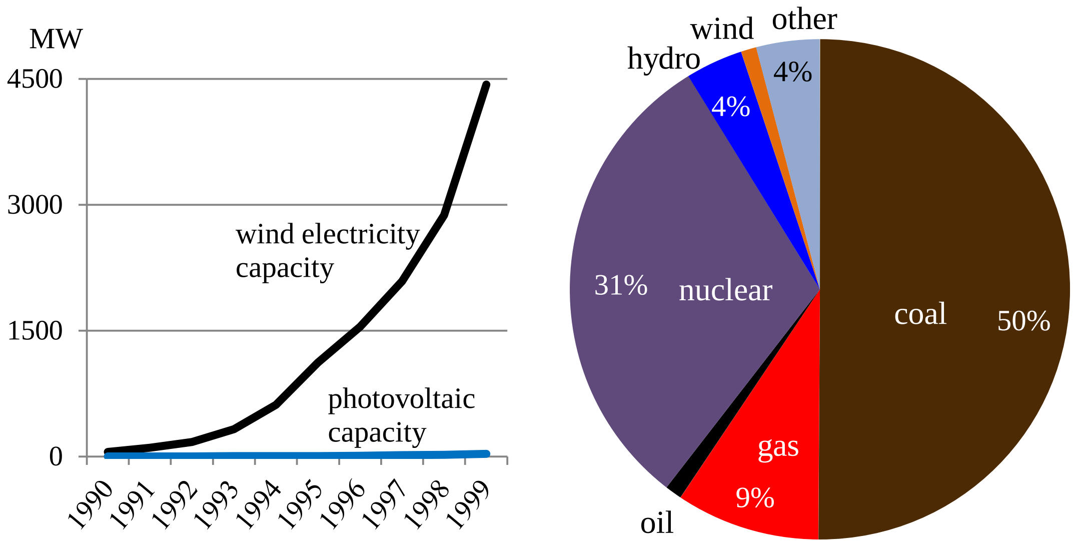
	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000[1]
wind/solar electricity feed-in tariff	8.49	8.45	8.47	8.66	8.84	8.80	8.77	8.58	8.45	8.25
newly installed capacity, wind	51	68	152	293	504	428	534	793	1,568	1,665
newly installed capacity, solar	1	1	2	1	2	3	7	5	9	44

[1] replaced on 1st April 2000 by the *Renewable Energy Act*.

Source: BMU (2012a) for the newly installed capacities, Staiss (2001) for the feed-in tariffs.

A similar attempt to increase the capacity installations of photovoltaic and demonstrate the technological viability was the *1,000 roofs program* that became effective in 1991 and ended in 1994. As part of the program, investment costs of photovoltaic installations were subsidized by up to 70 percent. The program was eventually extended to 2,250 installations, again owing to high demand (see, Bruns et al., 2011). Parallel to the *1,000 roofs program* German states additionally allocated funds towards photovoltaic. Whereas no follow-up federal program was launched after the *1,000 roofs program* had ended, individual states and municipalities continued or even extended their support measures. These were powerful enough to induce some new capacity installations, although the unit costs of photovoltaic electricity were above 1 euro/kWh at this time. Compared with a total capacity of 4,500 MW from wind energy power plants, photovoltaic capacity only reached 32 MW by 1999 (see Figure 1.4, left diagram). Following the change in government in 1998, a new support program for photovoltaic was launched, called *100,000 roofs*. It offered investment grants and subsidies in terms of low-interest loans, and its combination with other support programs was possible (see, Bruns et al., 2011).

Figure 1.4: Wind and photovoltaic electricity capacity (left), electricity generation in 1999 (right), Germany



Source: BMU (2012a) for the left diagram, AG Energiebilanzen for the right diagram.

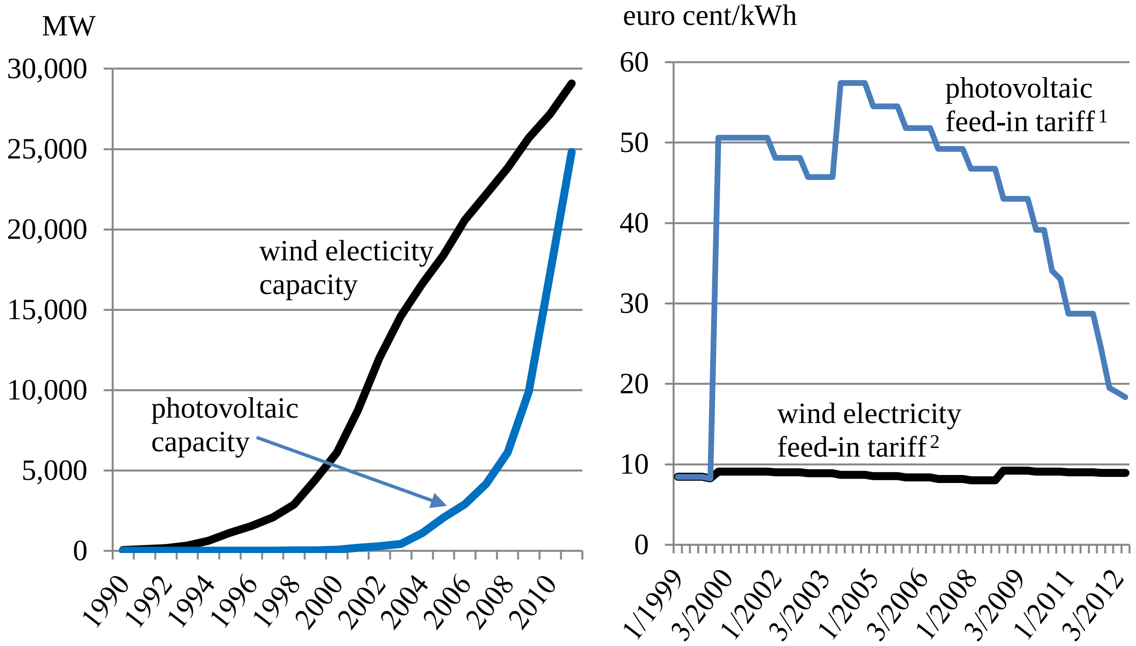
However, consideration of Germany's electricity generation in 1999 shows that despite the capacity for using wind energy having significantly expanded, it contributed only 1 percent to the total generation (see, Figure 1.4, right diagram). With coal still the major source and nuclear energy accounting for almost one third, this situation was very similar to the shares in 1985.

1.5 Renewable energy boom and the Fukushima accident (2000-today)

The government elected in 1998 directly began to prepare a new law intended to replace the *Electricity Feed-In Act* and enable Germany to faster increase its use of renewable energy. This new law, the *Renewable Energy Act (EEG)*, was enacted in April 2000 and has been amended several times since.

In its 2012 version, the *EEG* defines its goals as follows: 'a sustainable development of energy supply, particularly for the sake of protecting our climate and the environment, to reduce the costs of energy supply to the national economy, also by incorporating external long-term effects, to conserve fossil fuels and to promote the further development of technologies for the generation of electricity from renewable energy sources' (EEG, 2012). In terms of concrete goals, the act aims to increase the share of renewable energy in total electricity generation to 35 percent by 2020, 50 percent by 2030, 65 percent by 2040, and 80 percent by 2050.

Figure 1.5: Wind and photovoltaic electricity capacity (left) and feed-in tariffs (right), Germany



[1] rooftop up to 10 kW, [2] onshore; the duration for which the tariff applies has changed over time: according to EEG (2012) the current tariff applies for the first five years and is extended based on the yield of the specific power plant.

Source: BMU (2012a) for the left diagram, EEG (2000), EEG (2004), EEG (2009) and EEG (2012) for the right diagram.

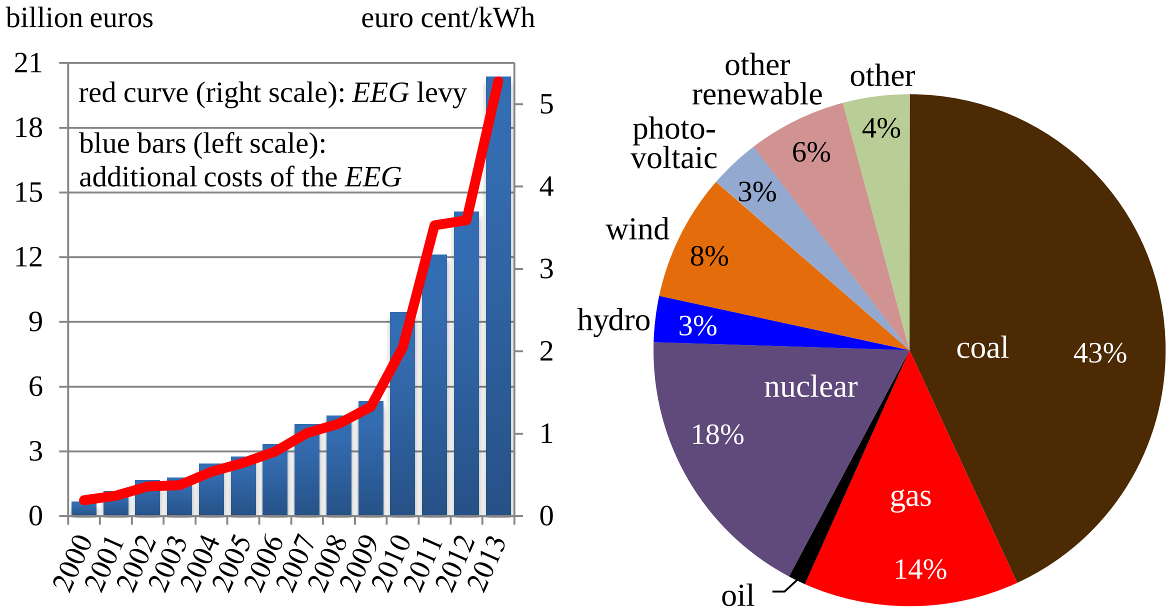
The *EEG* defines two main benefits for producers of renewable electricity. First, it obliges the transmission system operator to connect the renewable energy power plant to the grid and feed its electricity into it with priority. Second, it defines a feed-in tariff paid per kWh of electricity over a pre-defined period (see, Figure 1.5, right diagram). A feed-in tariff is a price fixed by the regulator above the market price of electricity. Thus, the difference between the feed-in tariff and regular market price represents a subsidy to the producer of renewable electricity.

Owing to the feed-in tariffs that are differentiated between renewable energy technologies in Germany, otherwise unprofitable installations subsequently become profitable, and therefore the capacity of wind and photovoltaic electricity has increased strongly since 2000 (see, Figure 1.5). The expenses for paying the feed-in tariffs are rolled over to the electricity consumers: after paying the feed-in tariff to the renewable electricity provider, the transmission system operator is allowed to calculate the additional costs and charge the respective amount per kWh from the utility firm, which eventually rolls these costs over to the electricity consumers. Figure 1.6 (left diagram) summarizes the development of the additional costs of the *EEG* and the time path of the levy that electricity consumers are obliged to pay in order to finance the subsidy. The additional costs are calculated against a reference market price of electricity, and thus do not account for renewable electricity typically having a lower value owing to its intermittency. Thus, the additional costs shown here are to be understood as a lower bound of the actual costs.

On the other hand, despite the estimated additional costs rising from year to year and probably exceeding 20 billion euros in 2013, the actual share of renewable electricity of total electricity generation remains quite low (see, Figure 1.5, right diagram). For example, photovoltaic, contributed less than 3 percent of the German electricity supply in 2011, despite alone leading to 6.8 billion euros of additional costs. These exploding expenses for the support of photovoltaic have particularly induced the German government to amend the *EEG* in 2012, thereby stepwise reducing the feed-in tariff for photovoltaic and implementing further changes designed to slow down the cost increase (see, Figure 1.5, right diagram).

Another topic currently shaping Germany's energy policy is nuclear energy. After the Tōhoku earthquake and tsunami that led to the Fukushima nuclear catastrophe on 11th March 2011, the German government decided to impose a three-months moratorium on the operations of the oldest nuclear power reactors on 14th March 2011. This meant that in addition to Krümmel and Brunsbüttel – the two nuclear power reactors that had been (temporary) disconnected since 2007 – and Biblis B which had been undergoing a planned revision since 25th February 2011, another five nuclear power reactors were shut down on March 17th and 18th. Moreover, the German government initiated an 'Ethics Commission for a Safe Energy Supply', which published its report at the end of May 2011 (see, Töpfer et al., 2011). Following its recommendation, on 30th June 2011 the German Bundestag decided to completely phase-out nuclear power by 2022. In terms of the nuclear reactors that were shut down in March, this implied that they would no longer be reconnected.

Figure 1.6: Additional costs of the *EEG*[1] and the *EEG* levy (left), electricity generation in 2011, Germany

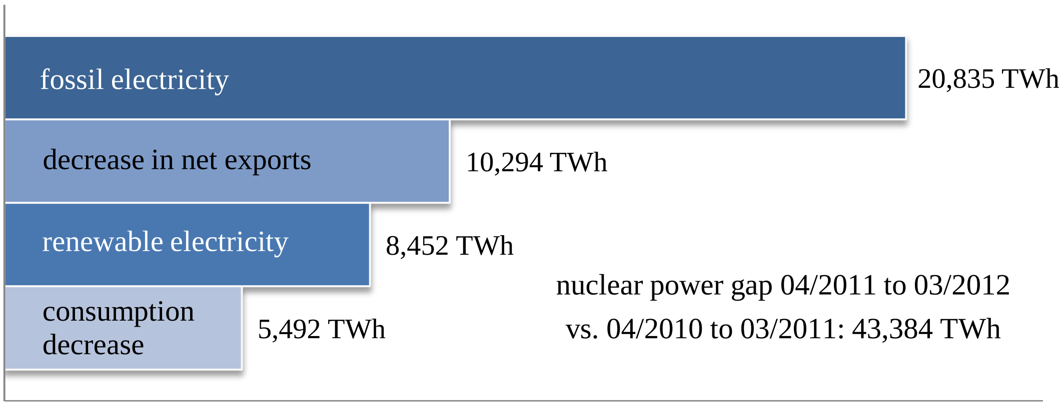


[1] Year 2013: forecast.

Source: BMU, Zeitreihen zur Entwicklung der Kosten des EEG, October 2012, for the left diagram (available at:www.erneuerbare-energien.de%2Ffiles%2Fpdfs%2Fallgemein%2Fapplication%2Fmsexcel%2Fee_ zeitreihe_eeg-kosten.xls&ei=ddbEUI7pNIXltQa3uYDACA&usg=AFQjCNGXcwtjGHn_NCn68nsgPPGbq1pilg), AG Energiebilanzen for the right diagram.

Naturally, this had an impact on the electricity generation mix in 2011, with the share of nuclear energy declining to less than 18 percent (see, Figure 1.6, right diagram). Figure 1.7 summarizes the adjustment in the German electricity sector following the shutdown of the oldest nuclear power reactors in March 2011 in a stylized manner. Nuclear power generation was lower during the period from April 2011 until March 2012 by 43,384 TWh compared with the same period one year previously. However, this was compensated mainly by an increase in fossil electricity generation (plus 20,835 TWh) and a decrease in net electricity exports (10,294 TWh). Renewable electricity generation increased by 8,452 TWh, although this largely occurred by coincidence, owing to more favorable wind conditions than in previous years.

Figure 1.7: Adjustment in the German electricity sector after the partial shutdown of nuclear power in March 2011



Source: ENTSO-E, own calculations.

This clearly highlights that most of the missing nuclear electricity was replaced with fossil electricity. Fossil energy power plants are typically those ones employed to balance the variable supply of renewable energy sources, namely to be switched off when electricity supply from renewable energy is high (and which by law has to be fed in with priority). Thus, the utilization rates particularly of lignite power plants decreased during the period in which renewable energy capacity increased in Germany. These free capacities have been used to some degree since March 2011 in replacing the nuclear power that is not available due to the partial phase-out. Consequently, one might argue that the nuclear phase-out appears to offset a part of the achieved reduction of fossil energy use.

2. Climate change as a reason for subsidizing renewable energy

2.1 PLAN OF THE CHAPTER

The previous chapter has illustrated the strong support for renewable electricity in Germany, which also holds for many other countries, particularly in the EU. The first questions to consider are: Why do countries support renewable energy and do they achieve their stated objectives? For example, a main purpose of the *Renewable Energy Act* in Germany is ‘to facilitate a sustainable development of energy supply, particularly for the sake of protecting our climate and the environment’ (EEG, 2012). This chapter studies the validity and the scope of this argument.

The chapter begins with a brief discussion of the economic problem underlying the process of climate change. After having defined the climate change externality, it will be evaluated whether a subsidy for renewable energy can achieve a similar result as a direct pricing of carbon dioxide emissions, for instance through an emission trading system (ETS) or a carbon tax. For example, in addition to various national policies the EU has introduced the EU Emission Trading System (EU ETS), which obliges large carbon dioxide emitters to purchase emission permits that are limited in quantity and therefore have a positive price (see, section 3.2 for a description of the EU ETS). Abstracting from other potential market failures in the development of renewable energy, one might wonder whether supporting renewable energy is necessary and sensible. The answer partly depends on whether the EU ETS and other national policies establish a correct pricing of carbon dioxide emissions. If they do, there is no need for additionally supporting renewable energy for reasons related to climate change. However, since renewable energy support exists in each country within the EU, it is certainly interesting to analyze how such support can affect the market outcome, and particularly whether it can be a good substitute for a non-existing or complement of an imperfect carbon pricing.

Section 2.4 will illustrate that a country choosing to support renewable energy rather than implementing a direct pricing of carbon emissions generally fails to achieve the first best allocation on the electricity market. This results for a subsidy financed from the government budget, and when financed by a levy on the consumption of electricity, as in the case of Germany and several other countries. Prior to proceeding with the discussion of renewable energy support, the following subsection briefly outlines the economic problem concerning carbon dioxide emissions.

2.2 Carbon dioxide emissions as a negative externality and the Green Paradox

According to the *first theorem of welfare economics*, a competitive market with ideal properties, e.g. being free of market failures, achieves an efficient allocation of resources. Therefore, there is no normative basis for public policy interventions from an efficiency perspective in such a case. However, markets typically fail to achieve an efficient allocation of resources when the benefits or costs of activities are not fully taken into account by the individual market participants.

Considering the problem of consuming a fossil resource, the following example illustrates why the pure market would fail. When a firm or individual consumes fossil energy and consequently emits carbon dioxide, the benefit of this activity is generally private (in the form of additional profits or higher utility). However, the costs consist of two components: the costs of obtaining the fossil resource and those associated with adding carbon dioxide to the atmosphere. Given that the stock of carbon dioxide in the atmosphere affects the global climate, these additional costs spread among a large number of countries, thereby affecting many people, and not only the carbon dioxide emitter.

In a laissez-faire world, people negatively affected by climate change could attempt to negotiate with the polluters, as suggested by Coase (1960). Accordingly, the injured party could compensate a polluter for reducing the emissions to an efficient level, with both gaining from this arrangement. However, in reality both the number of people affected by climate change and the number of polluters is too large, and therefore, such a negotiation would suffer from a free-riding or public good problem in addition to high transaction costs. Consequently, negatively affected individuals cannot obtain a contractual relationship with carbon dioxide emitting firms or individuals, and therefore the costs of adding carbon dioxide to the atmosphere are not sufficiently accounted for. This example describes a negative externality as defined in any public economics textbook.

Having identified a negative externality, there could be a justification for a public policy intervention that would ideally establish a correct pricing of the marginal costs of emitting carbon dioxide. However, this problem is more complex than other pollution problems, since fossil resources are non-renewable and thus public policy must take an intertemporal consideration by their owners into account. This has been emphasized by Sinn (2008a, 2008b, 2012) and further discussed by a large body of literature, for instance Jus and Meier (2012a, 2012b). It was shown that the time path of resource extraction crucially depends on the development of climate policies over time, for instance, the growth rate of carbon taxes. Resource extraction will accelerate when the strictness of climate policy increases at a rate exceeding the discount rate of the resource owner, and decelerate in the opposite case (Dasgupta and Heal, 1979, ch. 12; Sinn, 2008a; Edenhofer and Kalkuhl, 2011). Therefore, if the aim of public policy is to reduce the speed of extraction and consumption of fossil resources, a global carbon tax with a growth rate smaller than the discount rate of resource owners would represent an alternative.

However, undesired outcomes following policy interventions may arise if such a global carbon tax is not available or increases too quickly over time, in which case resource owners might find it more profitable to increase their extraction speed in anticipation of higher future taxes. The latter phenomenon is known as *Green Paradox* (Sinn, 2008a, 2008b, 2012), which might arise owing to carbon taxes becoming sufficiently stricter over time or support of renewable energy that also threatens to reduce the demand for fossil resources in the future.

This short excursion on climate policy in the light of dynamically optimizing resource owners has highlighted certain difficulties in internalizing the climate change externality; however, those will not be further considered in this dissertation. Instead, one may read the following analysis in the light of a government that is aware of the dynamic problem, yet needs to choose how to internalize the climate change externality. As previously argued, many countries have explicitly chosen to support renewable energy for this reason, and after having introduced the modeling of the electricity market, the consequences and the feasibility of such a policy will be considered.

2.3 PRICE-SETTING ON THE ELECTRICITY MARKET: AN ALLOCATION THEORY VIEW

Before entering the discussion of public policies, it is beneficial to briefly explain how the electricity market will be modeled throughout this and the following two chapters, and particularly how the setting of the market price is assumed.

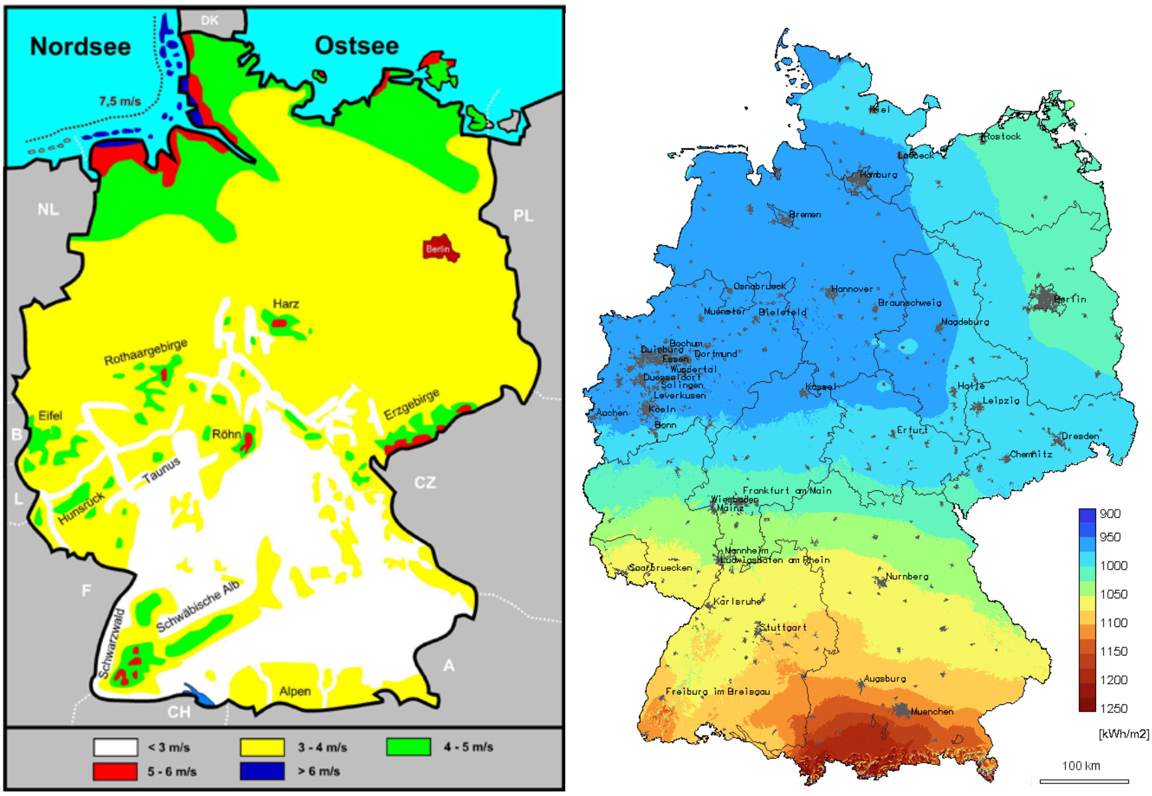
The electricity market consists of a downward sloping demand curve and two groups of suppliers, fossil electricity and renewable electricity producers. The two groups are modeled by representative agents, who are assumed to behave competitively. Hence, the demand for electricity can be met with fossil electricity and renewable electricity, and these are assumed to be perfect substitutes from the consumers' perspective. This is a reasonable assumption since the modeled electricity market ignores many technical details that are particularly relevant in the short-run but not as much in the medium- and long-run, for example, concerning the balancing of the network. The setting of such a focus is unavoidable for obtaining a clearer picture of allocative results delivered by the market over a longer period of time, and for analyzing public policy interventions aiming to change the market outcome. Moreover, it appears appropriate given that the German *Renewable Energy Act* defines targets that extend until 2050 (see, EEG, 2012).

THE COST FUNCTIONS AND THE DEMAND

In order to explain the electricity market as modeled here, it is important to discuss the underlying cost functions for the generation of fossil and renewable electricity. Concerning the generation of fossil electricity, it is reasonable to assume that a fossil energy power plant can be equally built and operated as many times as desired at the same cost, which is mainly driven by the cost of capital and the fossil fuel. Thus, constant returns to scale is a reasonable description of the production of fossil electricity, which implies a horizontal marginal cost curve. Moreover, when employing fossil resources to generate electricity, the fossil electricity producers consider only their private cost of this activity, whereas the cost stemming from climate change is not taken into account. This negative externality as discussed in the previous section will be introduced later in this chapter when public policies will be studied.

In the case of renewable electricity, the properties of the cost function are slightly different. In contrast to fossil electricity, where an additional unit can be generated at the same cost as the previous one, increasing marginal costs, i.e. decreasing returns to scale, will be assumed for renewable electricity. This follows from the fact that the locations available for renewable electricity generation differ in quality, which can be observed for both wind and solar energy. For example, owing to unequal prevailing average wind speeds, there is a large variation in the favorability of available locations in the case of wind energy, as illustrated in Figure 2.1 (left diagram) for Germany. It can be noted that the average wind speed is particularly high at the coastline, as in some mountainous regions further south. Consequently, the yield from an otherwise equal wind energy power plant will differ across locations.

Figure 2.1: Favorability of wind energy (average wind speed, left diagram) and photovoltaic (yearly sum of solar irradiation, right diagram) in Germany



Source: Odenwaldwind Gesellschaft für regenerative Energie mbH, available at: www.odenwaldwind.de, for the left diagram; Photovoltaic Geographical Information System (PVGIS), available at: http://re.jrc.ec.europa .eu/pvgis/, for the right diagram.

Moreover, the cost may also differ from location to location. For instance, the different grounds on which the wind turbines are installed could lead to different costs for the foundation. The most evident case is offshore wind energy, for which the foundation is generally manifold more costly than for onshore wind turbines, yet the yield can also be substantially higher than onshore.

A similar argument applies for photovoltaic, the favorability of which is highly dependent on the solar irradiation. The latter also differs fairly strongly between regions within Germany, being highest in the very south (see Figure 2.1, right diagram). However, not only regional differences in the solar irradiation generate differences in the quality of locations. Two otherwise identical gable rooftops are of an unequal quality in terms of their yield if one faces (with one side) the south whereas the other has no surface directed towards the south.

Given that renewable electricity producers must choose where to begin with the use of renewable energy, it is assumed that they would select the best locations first and only afterwards gradually move on to the more and more unfavorable ones. Consequently, since the quality of the available locations for the use of renewable energy decreases as more of it is being generated, it can be concluded that also the marginal cost of renewable electricity increases in the generated quantity.

Finally, considering the demand for electricity, it will be assumed that consumers are willing to buy more electricity if the price is lower, that is, the demand for electricity is a downward sloping function of its price. In the following, p will denote the market price of electricity and $E(p)$ is the demand for electricity, with $E'(p) < 0$. Consequently, the inverse demand function will be denoted by $p(E)$, with $p'(E) < 0$ and where E denotes the quantity of electricity.

The market price is determined by the intersection of the downward sloping inverse demand curve and the electricity supply curve. The electricity supply curve represents the total quantity of electricity which renewable and fossil electricity producers together wish to produce at any given price. The properties of this supply curve will be characterized in more detail in the next section by explaining the maximization problems of the suppliers of fossil and renewable electricity. Market power on the supply side will not be considered, meaning that the supply of electricity is assumed to be perfectly competitive. This implies that no single producer of electricity can influence the market price of electricity.

THE MAXIMIZATION PROBLEMS ON THE SUPPLY SIDE

The supply of electricity consists of the supply of fossil and renewable electricity. After introducing the problem of the representative fossil electricity producer, the representative renewable electricity producer will be considered.

The representative producer of fossil electricity solves

$$\max_{E_F} \Pi_F = p \cdot E_F - C_{F,priv}(E_F) \tag{2.1}$$

where Π_F denotes his profit, being determined by the revenue $p \cdot E_F$ and the private cost of producing fossil electricity, $C_{F,priv}(E_F)$. The market price of electricity is denoted by p, and the quantity of fossil electricity generated is E_F. The cost $C_{F,priv}(E_F)$ is increasing in E_F, but since constant returns to scale are assumed, the marginal cost is constant. Thus, the cost function can be written as $C_{F,priv}(E_F) = a \cdot E_F$, implying $C'_{F,priv} = a$ with $a > 0$. As previously discussed, this assumption is based on the argument that a fossil energy power plant can be equally built and operated as many times as needed at the same cost. The first order condition of this problem is:

$$\frac{\partial \Pi_F}{\partial E_F} = p - C'_{F,priv} = 0 \quad \leftrightarrow \quad p = a \tag{2.2}$$

Since the marginal cost does not change when E_F changes, the following conclusions can be made: if the market price of electricity is below the marginal cost of fossil electricity, the supply of fossil electricity is zero; if it is equal or above the marginal costs of fossil electricity, the representative fossil electricity producer is willing to supply any quantity.

Similarly, the representative renewable electricity producer solves:

$$\max_{E_R} \Pi_R = p \cdot E_R - C_R(E_R) \tag{2.3}$$

where Π_R denotes his profit, being determined by the revenue $p \cdot E_R$ and the cost $C_R(E_R)$. At this stage no government support scheme for renewable electricity is in place, and therefore the renewable electricity producer receives only the market price of electricity p for any unit he produces. He also takes the market price of electricity as given while choosing which quantity of renewable electricity, denoted by E_R, to produce. The cost $C_R(E_R)$ is increasing in E_R and also the marginal costs increase in the generated quantity. In the following it will be assumed that the marginal cost is given by $C'_R(E_R) = b + s_R \cdot$

E_R, with $b, s_R > 0$. Thus, s_R is the slope of the marginal cost curve. The reason for the increasing marginal cost is, as explained above, that ever worse locations for the generation of renewable electricity need to be employed in order to expand the quantity. Consequently, the first order condition of the renewable electricity producer's problem is:

$$\frac{\partial \Pi_R}{\partial E_R} = p - C_R'(E_R) = 0 \qquad \leftrightarrow \qquad p = b + s_R \cdot E_R \tag{2.4}$$

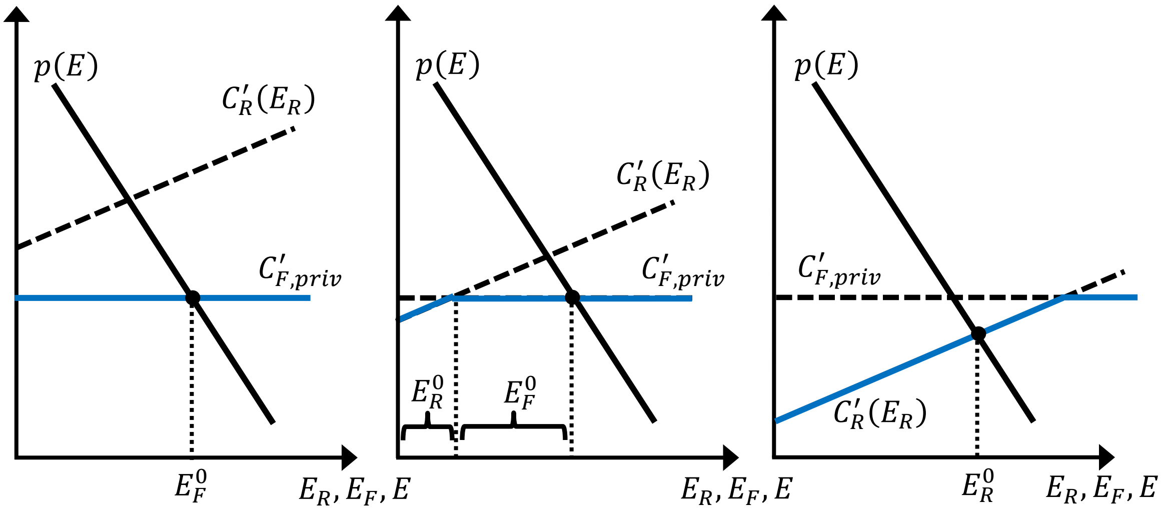
THE POSSIBLE MARKET OUTCOMES

Having characterized the behavior of the suppliers of electricity, both from renewable and fossil energy, the market outcome itself can be analyzed. Three different outcomes can arise on the electricity market as modelled here. These depend – for a given downward sloping inverse demand function – on the relationship between the marginal costs of fossil and renewable electricity.

Firstly, the cost of generating the first unit of renewable electricity can be higher than the constant marginal cost of fossil electricity, i.e. $b > a$. This scenario is depicted in the left diagram in Figure 2.2. Since the producers of fossil electricity are willing to supply any quantity at a price which equals their marginal cost, in this case only fossil electricity will be consumed. The electricity supply curve (illustrated by the blue solid line) corresponds to the marginal cost curve of fossil electricity.

Secondly, the first units of renewable electricity can be less costly than the marginal cost of fossil electricity, but as more and more unfavourable locations for the generation of renewable electricity need to be employed and the marginal cost of renewable electricity increases, fossil electricity eventually becomes less costly. In this scenario b is smaller than a, but $b + s_R \cdot E_R$ becomes larger than a before the marginal cost curve of renewable electricity intersects with the inverse demand function. This scenario is depicted in the middle diagram in Figure 2.2. In this case both renewable and fossil electricity will be generated and consumed. The electricity supply curve is again illustrated by the blue solid line, which at first follows the marginal cost curve of renewable electricity and switches to the one of fossil electricity once it becomes less costly. Since the intersection of the inverse demand and the supply curve is again where the marginal cost of fossil electricity is of relevance, also here the market price of electricity is determined by the marginal cost of fossil electricity. This is always the case when a positive quantity of fossil electricity is sold on the electricity market.

Figure 2.2: Three possible electricity market outcomes



Source: own illustration.

The third possible market outcome is based on marginal cost functions, which appear unrealistic at this time and therefore this case is only mentioned for the sake of completeness. If generating renewable electricity had very low marginal costs relative to fossil electricity, an outcome in which all demand is satisfied with renewable electricity could arise. This would occur if the downward sloping inverse demand function $p(E)$ intersected with the upward sloping marginal cost function of renewable electricity even before the generation of fossil electricity becomes less costly than renewable electricity. This scenario is depicted in the right diagram in Figure 2.2. The market price of electricity would be given by the marginal cost of renewable electricity at the point where it intersects with the inverse demand function. However, this scenario will not be further considered in the following analysis.

Concerning the other two scenarios, it is debatable whether the left or the middle diagram in Figure 2.2 is the better description of today's situation on the electricity market. Both have in common that the marginal cost of fossil electricity is determining the market price of electricity and therefore these two scenarios deliver similar results in the later analysis. Thus it is reasonable to focus in the following on one of them, which will be the situation as described in the left diagram in Figure 2.2.

In the next section it will be introduced that the private cost of generating fossil electricity differs from the social cost, because of climate change. The modelling of the supply behavior of the fossil and renewable electricity producers will remain unchanged. However, knowing that the fossil electricity producers do not take the cost of climate change into account when maximizing their profits, the regulator will interfere. One possibility to affect the market outcome would be to introduce a direct pricing of the climate change externality by, for example, levying a tax on fossil electricity. This would induce the optimal allocation as will be explained. In practice, however, the subsidizing of renewable electricity as a means for internalizing the climate change externality receives a lot of sympathy. Thus, the next section will also examine how valid the argument of subsidizing renewable electricity for climate change reasons actually is.

2.4 CLIMATE CHANGE: A VALID REASON FOR SUBSIDIZING RENEWABLE ENERGY?

THE EFFECT OF SUBSIDIZING RENEWABLE ELECTRICITY ON THE ELECTRICITY MARKET

Suppose public policy chooses to implement a renewable energy support scheme. More specifically it implements a unit subsidy σ for renewable electricity, which is paid to the producers of renewable electricity in addition to the market price of electricity. The subsidy is in the first step financed from the general government budget, which is external to this problem. However, in a second step this assumption will be relaxed and a levy on electricity consumption for the financing of the subsidy expenditure will be introduced.

With the unit subsidy being in place, the representative renewable electricity producer solves:

$$\max_{E_R} \Pi_R = (p + \sigma) \cdot E_R - C_R(E_R) \tag{2.5}$$

by choosing his optimal quantity E_R, which is now also influenced by the unit subsidy σ. The costs $C_R(E_R)$ are defined as in the previous section, that is, the marginal cost function is $C_R'(E_R) = b + s_R \cdot E_R$, with $b, s_R > 0$. The first order condition of this problem is:

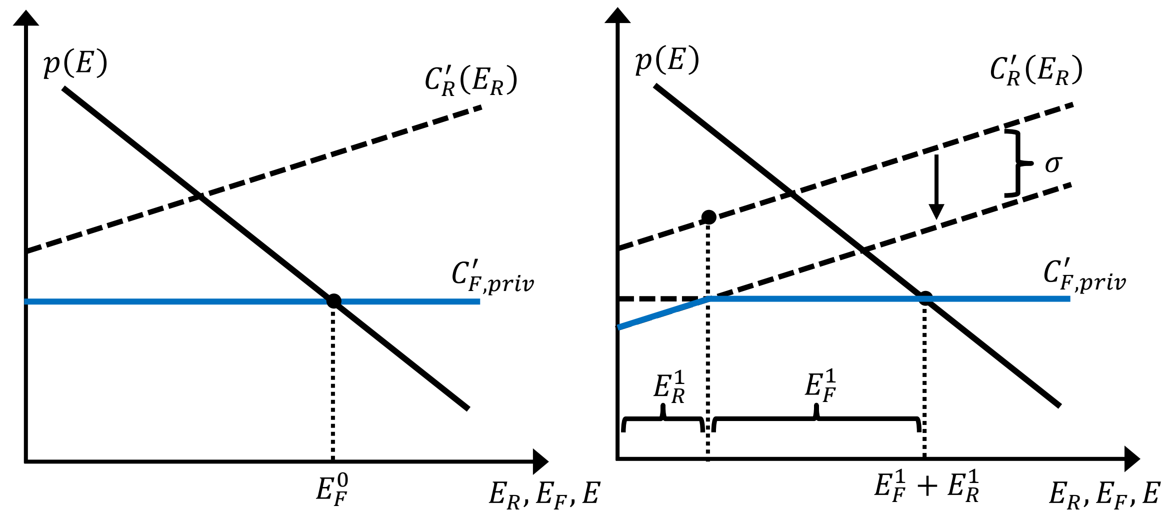
$$\frac{\partial \Pi_R}{\partial E_R} = p + \sigma - C_R'(\mathrm{E_R}) = 0 \qquad \leftrightarrow \qquad p = \mathrm{b} + \mathrm{s_R} \cdot \mathrm{E_R} - \sigma \tag{2.6}$$

As only the renewable electricity producers receive the subsidy, the representative producer of fossil electricity solves the same problem as described in section 2.3, leading to the same first order condition as given by (2.2).

As explained in the previous section, the constant marginal cost of fossil electricity determines the market price of electricity, because the producers of fossil electricity are willing to supply any quantity at this price. It is assumed that a positive quantity of fossil electricity will be generated even after the unit subsidy to renewable electricity is introduced, and thus the market price of electricity remains equal to the marginal cost of fossil electricity.

The effect of introducing the unit subsidy is shown in Figure 2.3, where $p(E)$ as before denotes the downward sloping inverse demand function. The left diagram illustrates the situation before the introduction of the subsidy, which corresponds to the left diagram in Figure 2.2. Without the subsidy no renewable electricity would be profitable since the marginal cost of renewable electricity is always higher than the marginal cost of fossil electricity.

Figure 2.3: Electricity market outcome before (left diagram) and after (right diagram) the introduction of the unit subsidy to renewable electricity



Source: own illustration.

In the right diagram in Figure 2.3, the unit subsidy to renewable electricity is interpreted as a reduction of the marginal cost of renewable electricity. On the one hand, since a positive quantity of fossil electricity is still being generated, the market price of electricity is given by the marginal cost of fossil electricity. On the other hand, even though the marginal cost of renewable electricity is always higher than the marginal cost of fossil electricity, a sufficiently large unit subsidy induces renewable electricity producers to generate a positive quantity (as shown in the right diagram in Figure 2.3). The new electricity supply curve is again illustrated by the blue solid line.

The analysis shows that a unit subsidy to renewable electricity can increase the generation of renewable electricity, while decreasing the generation of fossil electricity on a one-to-one basis. This results since the total quantity of electricity generated remains unchanged even after the introduction of the subsidy, which is a consequence of the consumer price remaining at $C'_{F,priv}$ while also the inverse demand function does not change.

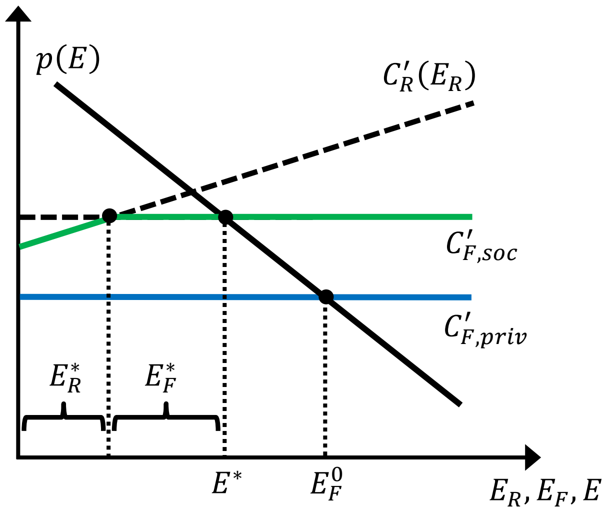
INTRODUCING THE CLIMATE CHANGE EXTERNALITY

As this section aims to discuss the validity of the climate change externality to serve as an argument in favor of subsidizing renewable electricity, in the following it will be assumed that a climate change externality exists in the sense that the social marginal cost of fossil electricity $C'_{F,soc}$ is higher than the private marginal cost $C'_{F,priv}$. In such a case, the use of fossil resources is less costly privately than socially, and fossil electricity generation would be inefficiently high. This is illustrated in Figure 2.4. It is similar to Figure 2.3 except that there is now a curve labelled $C'_{F,soc}$, which shows the social marginal cost of fossil electricity including the climate change cost. Fossil electricity generation decided upon by private agents is inefficiently high since they only consider the private cost of this activity. Therefore the market outcome is described by the intersection between the inverse demand curve and the private marginal cost of fossil electricity, implying that units of fossil electricity are generated at social costs that are higher than the price which consumer are willing to pay (as given by the inverse demand curve $p(E)$).

THE SOCIAL PLANNER'S CHOICE AND THE FIRST BEST POLICY

In order to explain how well the subsidizing of renewable electricity is able to move the market outcome towards the social optimum, the latter needs to be defined first. If a social planner wanted to maximize the sum of the consumer and producer rent by choosing how much electricity from which source to generate, he would follow a simple rule. On the one hand, he would advise society to produce all units of electricity with lower marginal cost than the marginal willingness to pay of the consumers $p(E)$. On the other hand, society should generate units of renewable electricity when they are less costly than fossil electricity, and vice-versa.

Figure 2.4: Private and social marginal cost of fossil electricity



Source: own illustration.

Thus, given the illustration in Figure 2.4, E_R^* units of renewable electricity and E_F^* units of fossil electricity should be generated. Of course, the social planner considers the social marginal cost of fossil electricity rather than the private marginal cost, thereby following first the marginal cost curve of renewable electricity and then the social marginal cost of fossil electricity (see, green curve in Figure 2.4) until this intersects with the consumers' marginal willingness to pay.

As has been discussed above, in contrast to the social planner, the private market follows the blue supply curve, which results in an inefficiently high consumption of electricity as a result of the market price being too low. In particular, the consumption of fossil electricity is inefficiently high, whereas renewable electricity generation is lower than optimal in this example.

The social planner solution can be implemented by the government through a tax on fossil electricity, thereby internalizing the externality. This tax would need to be of the size of the difference between the private and the social marginal cost of fossil electricity, thereby increasing the market price to the social marginal cost of fossil electricity. Owing to this measure, both the generation of fossil and renewable electricity would become efficient and no further policy would be needed.

COMPARING THE SOCIAL PLANER'S CHOICE WITH THE MARKET OUTCOME WITH SUBSIDY

Abstracting from the above explained first best policy this section will study the following question: How does the social planner solution compare with the market outcome when public policy chooses to support renewable electricity by paying a unit subsidy in addition to the market price of electricity (see Figure 2.3)? The problem of such a policy intervention is that it does not change the market price of electricity since the private marginal cost of fossil electricity remains price-setting, even though it is well possible that – as shown in Figure 2.3 – renewable electricity replaces part of the fossil electricity generation, as a consequence of the implementation of the unit subsidy. However, this does not resolve the problem of the inefficiently high total consumption of electricity, which stems from the inability of the subsidy to increase the consumer price of electricity.

Consequently, since the total consumption of electricity remains too high, by implementing a unit subsidy to renewable electricity, instead of a tax on fossil electricity, public policy only can choose between three outcomes, none of which equals the social planner solution: Firstly, public policy can choose to implement a unit subsidy of $\sigma = C'_{F,soc} - C'_{F,priv}$ for each unit of renewable electricity. This policy leads to an efficient provision of renewable electricity as in this case all units of renewable electricity that have lower marginal costs than the social cost of fossil electricity are indeed generated (this case is further discussed in the next section). However, since the electricity price remains at the private marginal cost of fossil electricity due to climate change still not being taken into account, fossil electricity generation is inefficiently high.

Secondly, public policy can implement a unit subsidy which leads to an expansion of renewable electricity to an amount that implies a reduction of fossil electricity generation to E_F^* (the quantity which the social planner would select, see Figure 2.4). In fact this best represents the idea of "solving the climate change problem by increasing the use of renewable energy" that is sometimes stated by policymakers. However, this analysis illustrates that to reduce the generation of fossil electricity to E_F^*, the generation of renewable electricity needs to become inefficiently high in the sense that units of renewable electricity are generated at costs that are even beyond the social marginal cost of fossil electricity. This can be seen in Figure 2.4. A unit subsidy to renewable electricity reduces fossil electricity generation to E_F^* only if more than E_R^* of renewable electricity is generated. More precisely, since the total electricity consumption remains unchanged as long as the consumer price does not increase, an additional quantity of renewable electricity, given by $E_F^0 - E^*$ in Figure 2.4, would needs to be produced for fossil electricity to shrink to E_F^*. Hence, renewable electricity generation is $E_R^* + E_F^0 - E^*$ which is greater than E_R^* (see Figure 2.4). Considering the marginal cost curve of renewable electricity, and moving further to the right of the quantity E_R^*, it can be seen that a further increase implies the marginal cost of renewable electricity to rise above the social marginal cost of fossil electricity. Thus, if the aim is to reduce fossil electricity generation to the level resulting when the externality is internalized the inefficiently high provision of renewable electricity must be accepted.

Thirdly, public policy could induce a situation in which both renewable electricity and fossil electricity are inefficiently high, thereby choosing a combination in between the first and the second alternative as described above.

Recall, however, that the social planner solution can be implemented by taxing fossil electricity and thereby internalizing the externality. Concerning the policy of subsidizing renewable electricity, the underlying reason for its infeasibility to induce the efficient generation of both renewable and fossil electricity is that it cannot affect the equilibrium market price of electricity. Fossil electricity is price-setting and, providing the externality is not included in the market price, overall electricity consumption is inefficiently high. This constitutes the actual problem, whereas the under-development of renewable electricity is only a consequence.

2.5 How much should renewable electricity be subsidized for climate reasons?

Having understood the main mechanism, it can be questioned what a government should do in such a situation, namely if it cannot directly internalize the climate change externality by a tax on fossil electricity? If, as assumed here, less fossil electricity is generated for each unit of renewable electricity entering the market, public policy could implement a renewable energy subsidy as high as the difference between the social and private marginal cost of fossil electricity and the outcome would represent an improvement in terms of the rents compared with the laissez-faire market outcome. As can be seen from Figure 2.4, such a unit subsidy would imply that those units of renewable electricity, which can be generated at costs below the social marginal cost of fossil electricity, would be generated. Thus, given that the total quantity of electricity generated remains unchanged, at least the total social cost of producing this quantity could be reduced by implementing a subsidy of this size. Any higher subsidy would imply that renewable electricity is generated at higher costs than the social cost of fossil electricity, and thus cannot be justified.

Given this result, it is valuable to consider estimates of the external cost of fossil electricity, as it should constitute the upper bound of a subsidy to renewable electricity. Most interesting is a study of the German Aerospace Center (DLR) and Fraunhofer Institute for Systems and Innovation Research (ISI) for the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), which finds external climate costs of coal electricity of 5.5-7.4 euro cents/kWh and gas electricity of 2.7 euro cents/kWh (see, Krewitt and Schlomann, 2006). This estimation is based on costs of carbon dioxide emissions of 70 euros/ton. With a lower valuation of 15 euros/ton, for example, the external climate costs are estimated to be well below 2 euro cents/kWh, even in the case of coal. Given that a subsidy to renewable energy should not exceed the per unit external climate cost if based on arguments related to climate change, these estimates contrast the manifold higher subsidies paid to photovoltaic, for example in Germany, as shown in Chapter 1.

Thus far the financing of the subsidy expenditure through the (exogenous) government budget was assumed. This assumption will be changed in the following section, supposing the financing by a levy on electricity consumption.

2.6 FINANCING OF THE SUBSIDY THROUGH A LEVY ON ELECTRICITY CONSUMPTION

Thus far, this chapter has not considered that a levy on electricity consumption is imposed for the financing of the subsidy expenditure in most countries with support schemes for renewable energy. One possible interpretation of such a levy is that it actually represents a corrective tax, despite not being intended in this way, and this idea will be developed within this section.

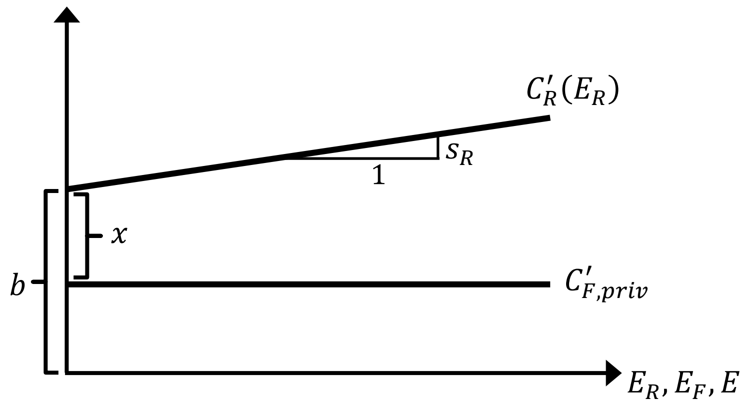
The main intuition of the levy is as follows: In addition to paying the price for electricity to the producers, consumers need to pay the unit levy τ, which is used to finance the subsidy expenditure. As the producers of fossil electricity do not wish to sell electricity at a price below their marginal cost, the producer price remains at $C'_{F,priv}$ (still assuming that a positive quantity of fossil electricity is generated even after the introduction of the levy-financed subsidy). Thus, the consumer price increases to $C'_{F,priv} + \tau$.

Before studying the overall implications, it first needs to be determined more specifically how the supply of renewable electricity reacts to the subsidy and how the demand is affected by the levy.

RENEWABLE ELECTRICITY EXPANSION DUE TO THE SUBSIDY

Suppose again that the initial situation is as illustrated in the left diagram in Figure 2.3. The regulator implements a unit subsidy for renewable electricity σ with the aim of increasing its generation. With the subsidy being in place the renewable electricity producer solves the maximization problem stated in (2.5) with the first order condition being given by (2.6). To determine explicitly by how much the unit subsidy increases renewable electricity generation, it is convenient to define a further variable: Let x be the gap between the private marginal cost of fossil electricity $C'_{F,priv}$ and the cost of the least costly renewable electricity unit $C'_R(E_R = 0) = b$, since $C'_R(E_R) = b + s_R \cdot E_R$. Thus, it follows that $x = b - C'_{F,priv}$ (see Figure 2.6), which is assumed to be positive in line with the left diagram in Figure 2.3. Consequently, a unit subsidy to renewable electricity becomes only effective in inducing the renewable electricity producers to generate a positive quantity after closing the gap denoted by x.

Figure 2.6: Marginal cost curve of renewable electricity



Source: own illustration.

The marginal cost of renewable electricity can be rewritten by substituting $x + C_{F,priv}'$ for b:

$$C_R'(E_R) = C_{F,priv}' + x + s_R \cdot E_R \tag{2.7}$$

which then can be used for $C_R'(E_R)$ in the first order condition of the representative renewable electricity producer, that was derived to be $p = C_R'(E_R) - \sigma$ in (2.6):

$$p = C_{F,priv}' + x + s_R \cdot E_R - \sigma \tag{2.8}$$

where p denotes the producer price, while interpreting the unit subsidy as a reduction of the marginal cost of renewable electricity. Since on the electricity market as modeled here the fossil electricity producers are willing to supply any quantity at a producer price that is equal to their marginal cost (see, maximization problem of the representative fossil electricity producer), also the producer price for renewable electricity will be equal to $p = C_{F,priv}'$. Substituting this expression in (2.8) gives:

$$C_{F,priv}' = C_{F,priv}' + x + s_R \cdot E_R - \sigma \tag{2.9}$$

which can be rearranged to:

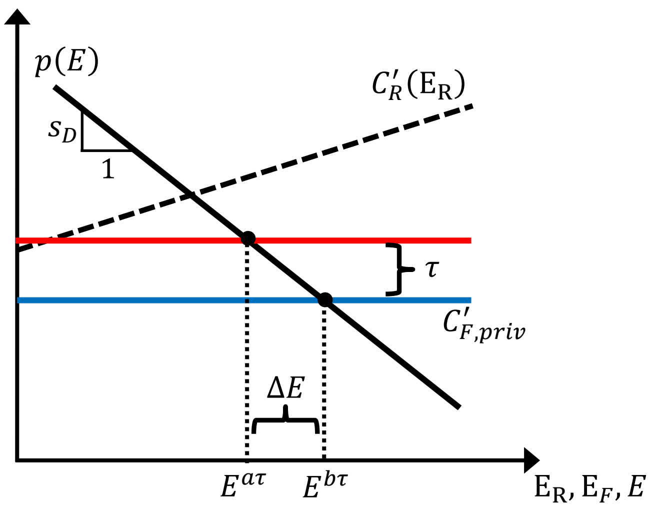
$$E_R(\sigma) = \begin{cases} \dfrac{\sigma - x}{s_R} & \text{for } \sigma > x \\ 0 & \text{otherwise} \end{cases} \tag{2.10}$$

Equation (2.10) determines the quantity of renewable electricity as a function of the unit subsidy σ, and the parameters x and s_{R}. It can be seen that renewable electricity generation only becomes positive if the size of the unit subsidy exceeds x, the gap between the marginal cost of fossil electricity and the least costly unit of renewable electricity.

THE UNIT LEVY ON ELECTRICITY CONSUMPTION

The new element in this section is the financing of the subsidy expenditure by a unit levy on electricity consumption, denoted by τ. The necessary size of this unit levy in order to completely finance the subsidy expenditure will be determined later. As explained above, consumers must pay the unit levy τ in addition to the producer price of electricity. Since the producer price for fossil electricity is $C'_{F,priv}$ before and after the introduction of the policy, the consumer price will increase to $C'_{F,priv} + \tau$ due to the levy.

Figure 2.7: The unit levy on electricity consumption



Source: own illustration.

Figure 2.7 illustrates the implications of the introduction of the unit levy on the electricity consumption. Electricity consumers want to consume less electricity after the introduction of the unit levy since the consumer price increases and their inverse demand curve is downward sloping. More precisely, in Figure 2.7 the consumed quantity before the introduction of the levy (superscript "$b\tau$") is $E^{b\tau}$, whereas after its introduction (superscript "$a\tau$") it shrinks to $E^{a\tau}$. Thus, the reduction of the electricity consumption is given by ΔE. This reduction can be determined after making an assumption on the functional form of the inverse demand curve. Suppose that the inverse demand function $p(E)$ is linear, that is, $p(E) = d - s_D \cdot E$, where d is a positive parameter and $-s_D$ the slope of the inverse demand function with $s_D > 0$.

As long as no levy is implemented the consumed quantity of electricity is determined by $p(E) = C'_{F,priv}$, i.e. the intersection of the inverse demand curve and the marginal cost of fossil electricity. Substituting $d - s_D \cdot E$ for $p(E)$, it can be derived that:

$$d - s_D \cdot E^{b\tau} = C'_{F,priv} \quad \leftrightarrow \quad E^{b\tau} = \frac{d - C'_{F,priv}}{s_D} \tag{2.11}$$

In the other case, when the unit levy τ is in place and the consumer price of electricity is $C'_{F,priv} + \tau$ electricity consumers choose the quantity according to $p(E) = C'_{F,priv} + \tau$. Consequently, after substituting $d - s^D \cdot E$ for $p(E)$ the consumed quantity after the introduction of the levy can be derived:

$$d - s_D \cdot E^{a\tau} = C'_{F,priv} + \tau \quad \leftrightarrow \quad E^{a\tau} = \frac{d - C'_{F,priv} - \tau}{s_D} \tag{2.12}$$

Hence, ΔE is the difference between $E^{b\tau}$ and $E^{a\tau}$, which is equal to:

$$\Delta E = E^{b\tau} - E^{a\tau} = \frac{d - C'_{F,priv}}{s_D} - \frac{d - C'_{F,priv} - \tau}{s_D} = \frac{\tau}{s_D} \tag{2.13}$$

In other words, owing to the introduction of the unit levy, the electricity consumption shrinks by $\frac{\tau}{s_D}$. This is interesting in so far as it was argued in section 2.4 and 2.5 that the subsidy to renewable electricity alone cannot resolve the problem of inefficiently high total electricity consumption. Thus, the unit levy on electricity consumption can possibly be interpreted as a corrective tax, and the following paragraphs will discuss under which condition it may even induce overall efficiency on the electricity market.

THE SELF-FINANCING CONDITION

In the next step, the necessary size of the unit levy τ for the financing of the subsidy expenditure needs to be determined. This unit levy is in practice not meant to be a corrective tax and is also not a choice variable for policy, rather it is determined implicitly by the choice of the unit subsidy to renewable electricity and the subsequent market mechanism. The "self-financing condition" which needs to hold in order to equate the revenue from imposing the levy on electricity consumption and the subsidy expenditure can be formulated as:

$$\tau \cdot E^{a\tau} = \sigma \cdot E^{R} \tag{2.14}$$

where the left-hand side constitutes the levy revenue, the unit levy τ times the consumed electricity quantity after introducing the levy $E^{a\tau}$, and the right-hand side the subsidy expenditure, which can be written as the unit subsidy σ multiplied with the quantity of renewable electricity E^{R}.

As discussed in section 2.4, according to the first best policy, a tax on fossil electricity of the size of the difference between the private and the social marginal cost would internalize the externality. The question is now, whether a scheme consisting of the unit subsidy to renewable electricity and the unit levy on electricity consumption can mimic this first best outcome. In fact, given the assumptions made in this chapter, a unit levy on electricity consumption of the size of the difference between the private and the social marginal cost indeed reduces the electricity consumption to the optimal quantity. This is the case since it raises the consumer price to $C'_{F,soc}$. However, as such a levy on electricity consumption fails to increase the producer price of renewable electricity to $C'_{F,soc}$, fossil electricity generation remains inefficiently high, while renewable electricity generation is lower than efficient. Therefore, a unit subsidy to renewable electricity of the size of $\sigma = C'_{F,soc} - C'_{F,priv}$ would be needed in addition to mimic the social planner allocation. Recall that the renewable electricity subsidy should not be larger than $\sigma = C'_{F,soc} - C'_{F,priv}$ as it would otherwise imply that units of renewable electricity are produced at costs beyond the social marginal cost of fossil electricity.

However, as mentioned previously, the levy on electricity consumption is in fact not a choice variable for policy, rather it is determined by the self-financing condition as stated in (2.14). Thus, only if the financing condition itself implies the relationship $\sigma = C'_{F,soc} - C'_{F,priv} = \tau$, both the provision of renewable electricity and also the electricity consumption would indeed be efficient. But how would the electricity market outcome look like in such a case? If $\sigma = \tau$, the self-financing condition (2.14) would simplify to:

$$E^{a\tau} = E^{R} \tag{2.15}$$

Hence, electricity consumption and renewable electricity provision would only become efficient at the same time if the unit subsidy $\sigma = C'_{F,soc} - C'_{F,priv}$ implied an expansion of renewable electricity corresponding to the quantity determined by $p(E) = C'_{F,soc}$. Accordingly, fossil electricity generation would need to shrink to zero. Therefore, a levy-financed subsidy can only be considered as a substitute of a correct pricing of the climate change externality in this (very) special case.

On the contrary, whenever a subsidy $\sigma = C'_{F,soc} - C'_{F,priv}$ requires a levy that is smaller than the unit subsidy ($\tau < \sigma$) for its financing, electricity consumption remains inefficiently high, yet bringing society somewhat closer to the efficient allocation. In such a case, the price of consuming fossil electricity would not rise to $C'_{F,soc}$, rather only to $C'_{F,priv} + \tau < C'_{F,soc}$.

2.7 Conclusions

There are two main takeaway points from this chapter: firstly, a first-best allocation on the electricity market generally cannot be achieved with a renewable energy subsidy, thus highlighting its imperfectness in replacing a correct pricing of carbon dioxide emissions. Secondly, there is no justification for subsidies that go beyond the climate change externality for reasons related to climate change. Krewitt and Schlomann (2006) have estimated these to be sizably smaller than current subsidies paid to photovoltaic in Germany, for example. Moreover, the maximal subsidy justifiable on the basis of the climate change externality is even smaller when some imperfect pricing of carbon dioxide emissions is already in place, for example in the form of a carbon tax, given that it reduces the size of the externality. Similarly, an emission trading system (ETS) inducing a correct pricing of carbon dioxide emissions reduces the maximal justifiable renewable energy subsidy based on climate change reasons to zero. However, in contrast to an imperfect carbon tax, where, as explained in this chapter, a subsidy to renewable can be welfare improving, if chosen properly, the renewable energy subsidy cannot have a similar effect when an ETS exists yet fails to achieve a sufficient pricing of carbon dioxide emissions. This is the case since an ETS caps the quantity of carbon dioxide emissions, and thus there is no replacement of fossil electricity when renewable electricity is generated. The next chapter will explain this in more detail.

The modeling approach introduced in this chapter will be extended in the next two chapters to a set-up that takes the existence of an ETS into account. Whereas only one country will be considered in Chapter 3, the analysis will then be extended to a two-country set-up in Chapter 4.

3. Interaction between renewable energy support and an ETS

3.1 Plan of the chapter

In the following chapter, the previously developed model will be extended and thereby prompt a different question. In comparison with Chapter 2, this chapter will offer the major difference of explicitly modelling an emission trading system (ETS), which can be interpreted as public policy already having implemented a measure for fighting the climate change externality. Moreover, after the internalization of the climate change externality formed the focus of the previous chapter, a positive analysis will be conducted regarding the support of renewable energy and its interaction with an ETS. However, a few normative aspects will be mentioned in the concluding section of this chapter.

On 15th October 2012, the German transmission system operators in charge of estimating the levy for the subsidizing of renewable energy published their calculation for 2013, with the levy rolled over to the German electricity consumers increasing from 3.592 euro cents/kWh in 2012 to 5.277 euro cents/kWh in 2013.[6] For a household with an annual consumption of 4,000 kWh, this involves paying a total of around 211 euros, or around 67 euros more than in 2012, for the support of renewable electricity.

However, the purpose of the following analysis is to show that a country with an ETS in place can in fact subsidize renewable energy, financed with such a levy on electricity consumption, without reducing the surplus of electricity consumers. This is a surprising result given the back-of-the-envelope calculations in the previous paragraph, and also an important aspect concerning the distribution of rents when a support scheme for renewable energy is implemented. The analysis reveals a new ‘source’ for the financing of renewable energy support, in contrast to the general view that electricity consumers must bear the burden. However, the limitations of the result will also be discussed. Prior to developing the theoretical model, the main features of the European Union Emission Trading System (EU ETS) will briefly be summarized in the next section, as they are supposed to be captured by the model.

[6] See, “Prognose der EEG-Umlage 2013 nach AusglMechV – Prognosekonzept und Berechnung der ÜNB”, available at: http://www.eeg-kwk.net/de/file/Konzept_zur_Berechnung_und_Prognose_der_EEG-Umlage_2013.pdf, 15th October 2012.

3.2 The European Union Emission Trading System

The European Union Emission Trading System (EU ETS) was introduced in 2005, and according to the European Commission constitutes “the cornerstone of its strategy for cutting its own greenhouse gas emissions cost-effectively” (EC, 2008, p. 5). It follows the ‘cap and trade’ principle, according to which total emissions are capped by the number of issued permits, whereas afterwards polluters are allowed to trade the permits in order to minimize the cost of the emissions reduction. It covers almost all power generation units and energy intensive manufacturing. Moreover, aviation emissions have been included since January 2012. The participating countries are the EU countries, plus Iceland, Norway and Liechtenstein.

The ETS implies that any polluter who wants to emit carbon dioxide needs to have the respective number of emission permits, or otherwise pay a manifold higher fee. To date, most of the permits have been provided to the polluters for free (grandfathered). However, there are plans to increase the share of permits auctioned in the future. A positive price of emission permits results if the amount of emissions defined by the number of permits is smaller than what polluters would have liked to emit if emitting was free of charge. The permit price reflects their scarcity, and – if the number is chosen properly – acts in the same way as a Pigouvian tax, hence internalizing the climate change externality.

3.3 Modeling of the ETS

The existence of an ETS implies that any fossil electricity producer needs to obtain the respective number of emission permits which corresponds to his carbon dioxide emissions. On the market for emission permits, which will be explained in the following, this constitutes the demand side. The supply of emission permits is assumed to be fixed by the regulator and given by the quantity $\overline{M}$. By definition, this quantity of emission permits allows the fossil electricity producers to generate a (maximum) of $\overline{E_F}$ units of fossil electricity.

It is assumed that the emission permits are grandfathered to the fossil electricity producers. Since transaction costs are not modeled, the initial allocation is not of relevance. However, it will be discussed at the end of this chapter how the results would change if the permits were auctioned instead of grandfathered.

Once the emission permits have been grandfathered to the fossil electricity producers, they can be traded and a positive price of emission permits will emerge if they are scarce, that is, if $\overline{E_F}$ is lower than the quantity of fossil electricity, which would have been produced if the ETS was not in place. To understand how this price of emission permits is formed the demand for emission permits will be discussed in more detail further below.

The basic framework in the following will be the same as in Chapter 2: electricity can again be generated from renewable and fossil energy and these two groups of suppliers are modeled by representative agents. The cost functions have the same properties as before, that is, concerning the generation of fossil electricity constant returns to scale are supposed, since a fossil energy power plant can be equally built many times at the same cost. Concerning the generation of renewable electricity, it is again assumed that the marginal cost increases when more renewable electricity is generated. The reason is that locations with a lower quality, for example less favorable wind conditions, need to be used in order to expand renewable electricity generation. This increases the cost of an additional unit relative to the previous. Finally, the electricity demand is represented by a downward sloping function of the price, meaning that consumers are willing to buy more electricity if the price is lower.

As in Chapter 2, the market price, which is taken as given by both the representative fossil and renewable electricity producer, is determined by the intersection of the downward sloping inverse demand curve and the electricity supply curve. The latter describes the quantity of electricity which renewable and fossil electricity producers together wish to produce at any given price. It will also be further explained below.

THE MARKET FOR EMISSION PERMITS

Similarly to the maximization problem discussed in Chapter 2, the representative producer of fossil electricity now solves:

$$\max_{E_F} \Pi_F = p \cdot E_F - C_{F,priv}(E_F) - p_M \cdot E_F \tag{3.1}$$

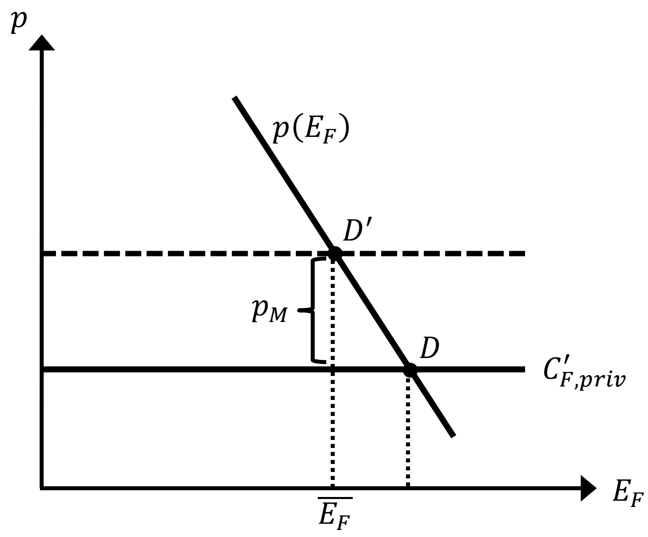
where Π_F denotes his profit, p the market price of electricity which a single producer takes as given, E_F the quantity of fossil electricity he generates, and $C_{F,priv}(E_F) = a \cdot E_F$ is the private cost of fossil electricity, which implies $C'_{F,priv} = a$. In contrast to Chapter 2, however, a new term appears in the profit function, which is the expenditure for buying the necessary emission permits on the market, $p_M \cdot E_F$, where p_M is the price of an emission permit required for generating one unit of fossil electricity. If the fossil electricity producer has been granted emission permits for free, this term can alternatively be interpreted as the opportunity cost of using the respective number of permits himself instead of selling them on the permit market. Also the price of emission permits is taken as given by a single fossil electricity producer and will be determined below. The first order condition of this problem is:

$$\frac{\partial \Pi_F}{\partial E_F} = p - C'_{F,priv} - p_M = 0 \quad \leftrightarrow \quad p = C'_{F,priv} + p_M \tag{3.2}$$

To understand the functioning of the permit market better, it is useful to abstract from renewable electricity for the moment. In this case, the electricity market outcome is as shown in Figure 3.1, where $p(E_F)$, with $p'(E_F) < 0$, denotes the inverse demand for fossil electricity. In line with the discussion in Chapter 2, if no ETS was in place, the market allocation would be given by point D, where it holds that $p(E_F) = C'_{F,priv}$. This outcome corresponds to the first order condition of the fossil electricity producer as derived in Chapter 2.

With the ETS, the quantity of fossil electricity following from $p(E_F) = C'_{F,priv}$ cannot be produced anymore as the supplied quantity of emission permits restricts the quantity of fossil electricity to $\overline{E_F}$. Since only this quantity can be generated (and still abstracting from renewable electricity), the consumers' marginal willingness to pay for electricity at the quantity $\overline{E_F}$ is higher than $C'_{F,priv}$(see point D'). This difference between the marginal cost of fossil electricity and the consumers' marginal willingness to pay at $\overline{E_F}$ is the value of having an additional emission permit, as consumers are willing to pay this higher price whereas the actual cost of generating another unit is only $C'_{F,priv}$. Hence, $p(\overline{E_F}) - C'_{F,priv}$ is the price at which the emission permits are traded among fossil electricity producers in the absence of renewable electricity. Consequently, the market price of electricity will be $p(\overline{E_F}) = C'_{F,priv} + p_M$, implying that fossil electricity producers require the cost of emission permits to be paid by consumers, which results as their marginal cost curve is assumed to be horizontal (see Figure 3.1).

Figure 3.1: Effect of an ETS on fossil electricity generation



Source: own illustration.

Adding renewable electricity generation to this framework does not change the intuition concerning the functioning of the permit market significantly. Renewable electricity producers do not need emission permits and therefore they do not participate in this market. Thus, the representative renewable electricity producer solves:

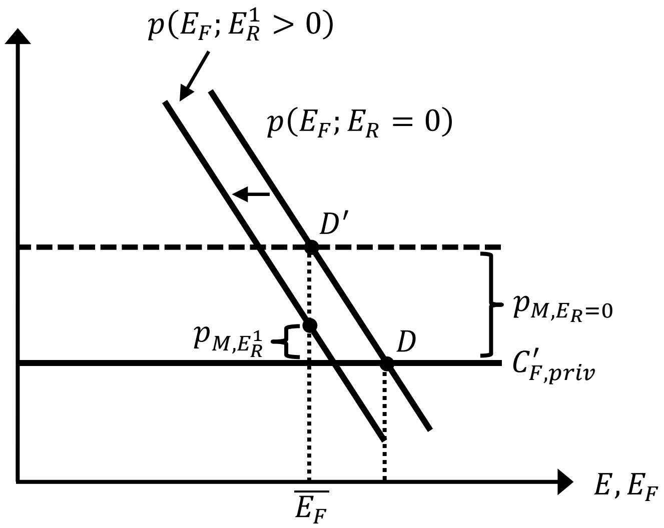
$$\max_{E_R} \Pi_R = p \cdot E_R - C_R(E_R) \tag{3.3}$$

where Π_R denotes his profit, determined by the revenue $p \cdot E_R$ and the cost $C_R(E_R)$. The subsidy to renewable electricity is not considered at this stage, but will be reintroduced later. Therefore, the renewable electricity producer is rewarded by the market price of electricity p for any unit produced, taking this price as given while choosing which quantity of renewable electricity, E_R, to produce. The cost $C_R(E_R)$ is increasing in E_R and also the marginal costs increase as more renewable electricity is generated. Again, the specific formulation for the marginal cost $C'_R(E_R) = b + s_R \cdot E_R$, with $b, s_R > 0$, will be used in the following. As in Chapter 2, the first order condition of the representative renewable electricity producer is:

$$\frac{\partial \Pi_R}{\partial E_R} = p - C_R'(E_R) = 0 \qquad \leftrightarrow \qquad p = b + s_R \cdot E_R \tag{3.4}$$

However, although renewable electricity producers do not need to buy emission permits, they nevertheless have an impact on the permit market. Consumers have a demand function for electricity and for them it is irrelevant whether they consume fossil or renewable electricity. Hence, if at a given price of electricity more renewable electricity is generated and subsequently consumed, the consumers' remaining demand for fossil electricity is lower. This is illustrated in Figure 3.2, where $p(E_F; E_R = 0)$ describes the inverse demand curve for fossil electricity in the (hypothetical) case that no renewable electricity is generated. Thus, $p(E_F; E_R = 0)$ in Figure 3.2 is the same as $p(E_F)$ in Figure 3.1. Consequently, since everything remains as in Figure 3.1, also the resulting permit price, here denoted $p_{M,E_R=0}$ is equal to the permit price shown in Figure 3.1.

Figure 3.2: Effect of renewable electricity generation on the permit price



Source: own illustration.

Suppose now that ceteris paribus the generated quantity of renewable electricity is E_R^1, whereby $E_R^1 > 0$. Since a positive quantity of renewable electricity is generated and hence also consumed, at any price of electricity consumers want to buy less fossil electricity given that they have a given demand for electricity and are indifferent between fossil and renewable electricity. In terms of Figure 3.2 this means that the inverse demand for fossil electricity shifts to the left, which is illustrated by the new inverse demand curve for fossil electricity $p(E_F; E_R^1)$.

Of course the choice of the renewable electricity quantity is not exogenous, but results from the maximization problem of the renewable electricity producer; however, the example given here is meant to illustrate how different amounts of renewable electricity influence the emission permit price. As can be seen in Figure 3.2, when the renewable electricity generation is higher, the scarcity of emission permits is lower, that is, the gap between the consumers' marginal willingness to pay for fossil electricity at the quantity $\overline{E_F}$ and the marginal cost of fossil electricity becomes smaller. Thus, also the new permit price, given by p_{M,E_R^1}, is lower than $p_{M,E_R=0}$ which results since the quantity of renewable electricity E_R^1 is larger than $E_R = 0$.

Consequently, the permit price can be written as a function of the renewable electricity generation in the following way:

$$p_M(E_R) = p(\overline{E_F}; E_R) - C'_{F,priv} \tag{3.5}$$

that is, as the difference between the consumers' marginal willingness to pay for fossil electricity at the quantity $\overline{E_F}$ (which is influenced by the quantity of renewable electricity), and the marginal cost of fossil electricity. Ceteris paribus, the permit price decreases when E_R increases, i.e. $p_M{}'(E_R) < 0$.

THE EQUILIBRIUM PERMIT PRICE

The previous section has explained how the permit price is influenced by changes in the generation of renewable electricity. The latter is the result of a maximization problem of renewable electricity producers and the aim of this section is to illustrate how it is affected by the existence of the ETS and more specifically how the equilibrium on the electricity and the permit market emerges.

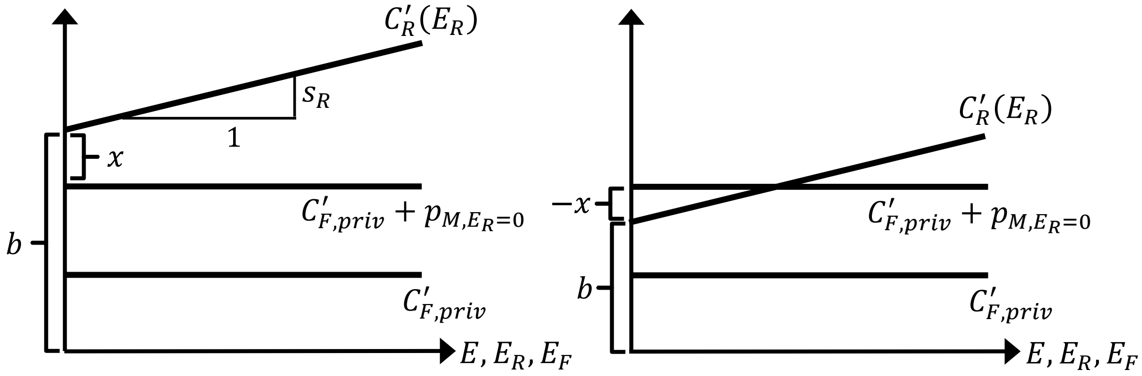
Suppose, the price of an emission permit in the case that no renewable electricity is generated is denoted $p_{M,E_R=0}$. This situation was illustrated in Figure 3.2, and the question is: Under which condition is the renewable electricity quantity actually zero? Since the subsidy to renewable electricity is not yet considered at this stage, the producer of renewable electricity follows the first order condition as derived in (3.4). The market price of electricity is $p = C'_{F,priv} + p_{M,E_R=0}$ if renewable electricity generation is indeed zero. For this to be true, this price must be insufficient to cover the cost of the first unit of renewable electricity, i.e. $C'_{F,priv} + p_{M,E_R=0}$ must be smaller than b. If this is the case, $p_{M,E_R=0}$ is the equilibrium permit price, and due to the assumptions made this is the highest possible permit price.

However, if the electricity price $C'_{F,priv} + p_{M,E_R=0}$ is sufficiently high to cover the cost of the first unit of renewable electricity, its quantity will be positive and $p_{M,E_R=0}$ cannot be the equilibrium permit price. The permit price decreases when renewable electricity generation increases, and the steps towards the equilibrium price can be explained as follows (being aware that the model is static): If it is profitable to generate renewable electricity at the price of $C'_{F,priv} + p_{M,E_R=0}$, the first unit of renewable electricity will be generated. As this occurs, the inverse demand for fossil electricity shifts to the left (see Figure 3.2) and the permit price decreases. As this happens, also the market price of electricity decreases since being equal to the sum of the marginal cost of fossil electricity and the permit price. Thus, the profitability of additional units of renewable electricity becomes lower. If it is still profitable to generate more renewable electricity, this will be done, with the same consequences for the permit price as described previously. One may imagine this process to continue until the permit price has reached a level, which leads to market clearing on both markets: On the one hand, starting from $p_{M,E_R=0}$ the permit price has fallen to a level $p_M(E_R)$ at which the renewable electricity producer does not wish to produce more since his first order condition, $C'_{F,priv} + p_M(E_R) = C'_R(E_R)$, is fulfilled (see (3.4) and substitute $p = C'_{F,priv} + p_M(E_R)$). On the other hand, the permit price has declined in accordance with condition (3.5), which is the equilibrium condition for the permit market given that the supply of permits is fixed at $\overline{E_F}$. Hence, also the permit price does not change anymore.

RENEWABLE ELECTRICITY GENERATION BEFORE THE INTRODUCTION OF THE SUBSIDY

As in Chapter 2, in order to determine the actual quantity of renewable electricity, it is useful to introduce the parameter x. It now denotes the gap between the (hypothetical) price of electricity when no renewable electricity is generated, $C'_{F,priv} + p_{M,E_R=0}$, and the cost of the least costly renewable electricity unit, $C'_R(E_R = 0) = b$. Thus, $x = b - (C'_{F,priv} + p_{M,E_R=0})$, which is also illustrated in Figure 3.3.

Figure 3.3: Emission trading system and the marginal cost of renewable electricity



Source: own illustration.

The parameter x can be positive, in which case without a subsidy no renewable electricity would be generated even when the ETS is in place. This is shown in the left diagram in Figure 3.3, and $p_{M,E_R=0}$ would indeed be the equilibrium permit price. In the right diagram x is negative meaning that at the hypothetical price of $p = C'_{F,priv} + p_{M,E_R=0}$ it is be profitable to generate renewable electricity, and therefore $p_{M,E_R=0}$ is not the equilibrium permit price.

With the parameter x – whether positive or negative – the marginal cost of renewable electricity can be written as follows:

$$C'_R(E_R) = C'_{F,priv} + p_{M,E_R=0} + x + s_R \cdot E_R \tag{3.6}$$

where $C'_{F,priv} + p_{M,E_R^0=0} + x$ was substituted for b in the original formulation. Substituting (3.6) and $p = C'_{F,priv} + p_M(E_R)$ in the first order condition of the renewable electricity producer as derived in (3.4) yields:

$$C'_{F,priv} + p_M(E_R) = C'_{F,priv} + p_{M,E_R=0} + x + s_R \cdot E_R \tag{3.7}$$

Solving (3.7) for E_R gives the following expression:

$$E_R^{b\sigma} = \frac{\left(p_M(E_R^{b\sigma}) - p_{M,E_R=0}\right) - x}{s_R} \tag{3.8}$$

where E_R has now the superscript "$b\sigma$" to indicate that this is the result for E_R before the introduction of the subsidy. The term $p_M\left(E_R^{b\sigma}\right) - p_{M,E_R^0=0}$ represents the difference between the actual permit price $p_M\left(E_R^{b\sigma}\right)$ and the hypothetical permit price assuming no generation of renewable electricity $p_{M,E_R=0}$. This difference, $p_M(E_R) - p_{M,E_R=0}$, will be denoted $\Delta p_M(E_R)$ in the following. By definition, it is zero for $E_R^{b\sigma} = 0$, and becomes increasingly negative as E_R increases, since the permit price decreases when more renewable electricity is generated. Thus, since $\Delta p_M \leq 0$, $E_R^{b\sigma}$ will only be positive if $x < 0$, which is in line with the arguments made concerning Figure 3.3. Hence, $E_R^{b\sigma}$ can be written as:

$$E_R^{b\sigma} = \begin{cases} \dfrac{\Delta p_M\left(E_R^{b\sigma}\right) - x}{s_R} & \text{for } x < 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.9}$$

In the next step once again the support to renewable electricity through a unit subsidy can be analyzed. The specific questions to be answered are: How does the levy-financed subsidy scheme interact with the emission permit market? And will the electricity consumers face an additional burden due to such a subsidy that is financed by a unit levy on electricity consumption?

3.4 Introducing renewable energy support in addition to an ETS

The aim of this section is to introduce a levy-financed subsidy to renewable electricity and to analyze how this affects the market outcome, including the consumer price of electricity. As in Chapter 2, the problem of the representative renewable electricity producer needs to be modified in order to determine how the subsidy affects the generation of renewable electricity.

The change in renewable electricity as a function of the permit price

With the subsidy being in place, the representative renewable electricity producer solves:

$$\max_{E_R} \Pi_R = (p + \sigma) \cdot E_R - C_R(E_R) \tag{3.10}$$

where σ denotes the unit subsidy, and all other variable are as defined in the maximization problem (3.3). The first order condition of the problem of the representative renewable electricity producer is:

$$p + \sigma = C_R'(E_R) \quad \leftrightarrow \quad p + \sigma = C_{F,priv}' + p_{M,E_R=0} + x + s_R \cdot E_R \tag{3.11}$$

where C_R' is substituted by the expression derived in (3.6).

Since the maximization problem of the fossil electricity producer does not change compared with the previous section (first order condition: $p = C_{F,priv}' + p_M$), and the marginal cost curve of fossil electricity is assumed to be horizontal, the market price of electricity remains at $C_{F,priv}' + p_M(E^R)$ (assuming a positive quantity of fossil electricity being generated). Thus, replacing p on the left-hand side of equation (3.11), yields:

$$C_{F,priv}' + p_M(E_R) + \sigma = C_{F,priv}' + p_{M,E_R=0} + x + s_R \cdot E_R \tag{3.12}$$

and rearranging shows that the quantity of renewable electricity that will be generated after the implementation of the subsidy is given by:

$$E_R^{a\sigma} = \frac{p_M(E_R^{a\sigma}) - p_{M,E_R=0} + \sigma - x}{s_R} \tag{3.13}$$

where the quantity of renewable electricity now has the superscript "$a\sigma$", indicating that this value relates to "after the introduction of the subsidy". The term $p_M(E_R^{a\sigma}) - p_{M,E_R^0=0} \equiv \Delta p_M(E_R^{a\sigma})$ again represents the difference between the actual permit price $p_M(E_R^{a\sigma})$ and the hypothetical permit price assuming no generation of renewable electricity $p_{M,E_R=0}$. Since $\Delta p_M(E^{R,a\sigma}) \leq 0$ for the same reasons as discussed above, $E_R^{a\sigma}$ can only be positive if $\sigma - x > 0$, that is, if the subsidy is sufficiently large to close the gap to the least costly renewable electricity unit:

$$E_R^{a\sigma} = \begin{cases} \dfrac{\Delta p_M(E_R^{a\sigma}) + \sigma - x}{s_R} & \text{for } \sigma - x > 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.14}$$

Having determined the renewable electricity generation before and after the introduction of the subsidy, the next step is to determine by how much it increases due to the subsidy, that is, to calculate $E_R^{a\sigma} - E_R^{b\sigma}$. Three cases need to be distinguished, but only one will afterwards be further considered: The trivial case is when the renewable electricity generation is zero even after the introduction of the subsidy (which implies that it was also zero without the subsidy). In this case the difference between these two states is thus also zero (first row on the right-hand-side of (3.15)). The second case is that after the subsidy is introduced the renewable electricity generation becomes positive, but was zero before (second row on the right-hand-side of equation (3.15)). In this case $E_R^{a\sigma} - E_R^{b\sigma}$ equals $E_R^{a\sigma}$, which was derived above. Finally, in the third case renewable electricity was positive before the introduction of the subsidy and increases due to it. This result for $E_R^{a\sigma} - E_R^{b\sigma}$ is shown in the third row on the right-hand-side of equation (3.15) and uses the expressions for $E_R^{a\sigma}$ and $E_R^{b\sigma}$ as derived in this section and section 3.3, respectively.

$$E_R^{a\sigma} - E_R^{b\sigma} = \begin{cases} 0 & \text{for } \sigma - x \leq 0 \\ \dfrac{\Delta p_M(E_R^{a\sigma}) + \sigma - x}{s_R} & \text{for } x \geq 0 \text{ and } \sigma - x > 0 \\ \dfrac{\Delta p_M(E_R^{a\sigma}) - \Delta p_M(E_R^{b\sigma}) + \sigma}{s_R} & \text{for } x < 0 \end{cases} \quad (3.15)$$

In the following, the analysis will focus on the second case, i.e. the situation in which the renewable electricity generation is zero without the subsidy, but becomes positive once being subsidized. Hence, it will be assumed that $E_R^{a\sigma} - E_R^{b\sigma} = E_R^{a\sigma} = \frac{\Delta p_M(E_R^{a\sigma}) + \sigma - x}{s_R}$. The case in which renewable electricity generation is positive already before the introduction of the subsidy is analytically more complex, but eventually delivers similar results. Moreover, considering Europe, it appears currently a reasonable assumption that renewable electricity generation would be (close to) zero without being subsidized even though an ETS is in place.

THE CHANGE IN TOTAL ELECTRICITY CONSUMPTION

The change in the renewable electricity generation owing to the introduction of the subsidy was determined; however it depends on the change in the permit price, $\Delta p_M(E_R^{a\sigma})$, that was not yet derived. In order to derive $\Delta p_M(E_R^{a\sigma})$, it will be employed that the total generation of electricity needs to equal the total consumption of electricity. This condition holds before and after the introduction of the subsidy, and hence also the change in the consumed electricity between these two situations is equal to the change in total electricity generation.

Thus, in the following it will first be determined by how much the electricity consumption changes due to the introduction of the subsidy and the unit levy on electricity consumption which is imposed for the financing. The actual size of the levy, needed for the self-financing condition to hold, will be determined later.

Before the implementation of the subsidy scheme, the consumed quantity of electricity is determined by:

$$p(E^{b\sigma}) = C'_{F,priv} + p_{M,E_R=0} \tag{3.16}$$

where the superscript “$b\sigma$” again indicates “before the introduction of the subsidy”. The quantity is given by the point where the inverse demand intersects with the sum of the marginal cost of fossil electricity and the permit price, $C'_{F,priv} + p_{M,E_R=0}$. The permit price is $p_{M,E_R=0}$ since the assumption was made that renewable electricity generation is zero before the subsidy is implemented.

Assuming – as in Chapter 2 – linearity of the inverse demand function, $p(E^{b\sigma})$ can be replaced by $p(E^{b\sigma}) = d - s_D \cdot E^{b\sigma}$, where $d > 0$ is a parameter, and $-s_D$ the slope of the inverse demand function (see Figure 2.7 in Chapter 2). Hence, equation (3.16) changes to:

$$d - s_D \cdot E^{b\sigma} = C'_{F,priv} + p_{M,E_R=0} \tag{3.17}$$

which can be solved for the consumed quantity of electricity before the introduction of the subsidy scheme, $E^{b\sigma}$:

$$E^{b\sigma} = \frac{d - C'_{F,priv} - p_{M,E_R=0}}{s_D} \tag{3.18}$$

The procedure to determine the quantity of electricity consumed after the introduction of the subsidy scheme is similar. Due to the introduction of the subsidy, the permit price is not anymore $p_{M,E_R=0}$ but $p_M(E_R^{a\sigma})$ as the quantity of renewable electricity becomes positive. Moreover, consumers must pay a unit levy on electricity consumption denoted by τ, which reduces their willingness to pay for electricity to $p(E^{a\sigma}) - \tau$. Hence, the electricity market clearing condition in analogy to (3.16) is now:

$$p(E^{a\sigma}) - \tau = C'_{F,priv} + p_M(E_R^{a\sigma}) \tag{3.19}$$

where the superscript “$a\sigma$” indicates “after subsidy”. Using again the specific formulation for the inverse demand curve, $p(E^{a\sigma}) = d - s_D \cdot E^{a\sigma}$, (3.19) becomes:

$$d - s_D \cdot E^{a\sigma} - \tau = C'_{F,priv} + p_M(E_R^{a\sigma}) \tag{3.20}$$

Solving for $E^{a\sigma}$ yields:

$$E^{a\sigma} = \frac{d - C'_{F,priv} - p_M(E_R^{a\sigma}) - \tau}{s_D} \tag{3.21}$$

which is the quantity of electricity consumed after the subsidy was introduced (which affects $p_M(E_R^{a\sigma})$ via the change in the renewable electricity quantity) and given that a levy on the electricity consumption needs to be imposed for the financing of the subsidy expenditure.

Finally, the change in the consumed electricity quantity due to the introduction of the policy scheme can be calculated:

$$E^{a\sigma} - E^{b\sigma} = \frac{d - C'_{F,priv} - p_M(E_R^{a\sigma}) - \tau}{s_D} - \frac{d - C'_{F,priv} - p_{M,E_R=0}}{s_D}$$

$$\leftrightarrow \quad E^{a\sigma} - E^{b\sigma} = -\frac{p_M(E_R^{a\sigma}) - p_{M,E_R=0} + \tau}{s_D} = -\frac{\Delta p_M(E_R^{a\sigma}) + \tau}{s_D} \tag{3.22}$$

where $\Delta p_M(E_R^{a\sigma}) < 0$ is the change in the permit price owing to the positive renewable electricity quantity.

Equation (3.22) becomes more intuitive after considering the change in the consumer price. Before the introduction of the subsidy, consumers pay $C'_{F,priv} + p_{M,E_R=0}$ per unit of electricity. After the introduction of the subsidy and the corresponding levy, the size of which yet needs to be determined, consumers pay $C'_{F,priv} + p_{M,E_R=0} + \Delta p_M(E_R^{a\sigma}) + \tau$ with the difference being $\Delta p_M(E_R^{a\sigma}) + \tau$. Hence, equation (3.22) states that the consumed electricity quantity increases if the consumer price decreases, that is, if the reduction of the permit price $\Delta p_M(E_R^{a\sigma})$ is larger than the imposed levy. In this case $\Delta p_M(E_R^{a\sigma}) + \tau < 0$ would hold.

THE CHANGE IN THE EMISSION PERMIT PRICE

One aspect that was discussed at the beginning of this chapter when the ETS was introduced becomes important now. It is the fact that the quantity of emission permits is fixed by the regulator and allows only for a generation of fossil electricity of $\overline{E_F}$. Given that this fixed quantity represents a binding limitation, the price of emission permits is positive (see Section 3.3). It is assumed that this price remains strictly positive even after the introduction of the subsidy scheme, which has a dampening effect on it. The permit price would only become zero if the fossil electricity producers would voluntarily want to produce no more than $\overline{E_F}$. Abstracting from this outcome, which makes the quantity fixed by the ETS irrelevant, fossil electricity generation equals $\overline{E_F}$ before the subsidy scheme is introduced and remains $\overline{E_F}$ after the subsidy and the corresponding levy are in place.

Consequently, since fossil electricity generation remains unchanged, only renewable electricity generation is affected by the introduction of the subsidy. As explained above, the next step is to employ the condition that total electricity generation is equal to the electricity consumption, both before and after the introduction of the subsidy scheme. Since fossil electricity generation is $\overline{E_F}$ in both cases, the condition equalizing the change in the consumed electricity and the change in the produced electricity reduces to the relationship:

$$E^{a\sigma} - E^{b\sigma} = \overbrace{E_R^{a\sigma} - E_R^{b\sigma}}^{=E_R^{a\sigma}} \tag{3.23}$$

where the left-hand-side corresponds to the change in electricity consumption and the right-hand-side to the change in the renewable electricity generation. Using the results derived in the previous two sections for $E^{a\sigma} - E^{b\sigma}$ and $E_R^{a\sigma}$, (3.23) can be written as:

$$-\frac{\Delta p_M(E_R^{a\sigma}) + \tau}{s_D} = \frac{\Delta p_M(E_R^{a\sigma}) + \sigma - x}{s_R} \tag{3.24}$$

which allows to determine Δp_M as a function of σ and τ, given the parameters s_D, s_R and x. Solving equation (3.24) for Δp_M gives:

$$-\frac{\Delta p_M}{s_D} - \frac{\Delta p_M}{s_R} = \frac{\sigma - x}{s_R} + \frac{\tau}{s_D} \quad \leftrightarrow \quad \Delta p_M(\sigma, \tau) = \frac{\frac{\sigma - x}{s_R} + \frac{\tau}{s_D}}{-\left(\frac{1}{s_D} + \frac{1}{s_R}\right)}$$

$$\leftrightarrow \quad \Delta p_M(\sigma,\tau) = -\frac{s_D \cdot (\sigma - x) + s_R \cdot \tau}{s_R + s_D} \tag{3.25}$$

which is the change in the permit price relative to the situation in which no subsidy is implemented and hence no renewable electricity is generated. Given that $s_R, s_D > 0$, both a higher renewable electricity subsidy σ as well as a higher unit levy on electricity consumption τ, ceteris paribus, reduce the permit price. The subsidy increases the quantity of renewable electricity, thereby decreasing the remaining demand for fossil electricity and thus having a dampening effect on the permit price. The levy decreases the demand for electricity in general and for any given quantity of renewable electricity it decreases the demand for fossil electricity in particular. Hence, also this decreases the permit price.

THE CHANGE IN THE CONSUMER PRICE

The result obtained for Δp_M can now be used to analyze how the consumer price will actually change due to the introduction of the subsidy and levy. As derived above, the consumer price is given by $C'_{F,priv} + p_{M,E_R=0}$ before the introduction of the subsidy and levy, and becomes $C'_{F,priv} + p_{M,E_R=0} + \Delta p_M(\sigma,\tau) + \tau$ afterwards. Thus, the difference is:

$$\left(C'_{F,priv} + p_{M,E_R=0} + \Delta p_M(\sigma,\tau) + \tau\right) - \left(C'_{F,priv} + p_{M,E_R=0}\right) = \Delta p_M(\sigma,\tau) + \tau \tag{3.26}$$

If $\Delta p_M(\sigma,\tau) + \tau > 0$, it means that consumers pay more for electricity after the introduction of the subsidy scheme, and vice-versa. Substituting for $\Delta p_M(\sigma,\tau)$ the expression derived in the previous section yields:

$$\Delta p_M(\sigma,\tau) + \tau = -\frac{s_D \cdot (\sigma - x) + s_R \cdot \tau}{s_R + s_D} + \tau = -\frac{s_D \cdot (\sigma - x) + s_R \cdot \tau}{s_R + s_D} + \tau \cdot \frac{s_R + s_D}{s_R + s_D}$$

$$= -\frac{s_D \cdot (\sigma - x) - s_D \cdot \tau}{s_R + s^D} = -\frac{s_D}{s_R + s_D} \cdot (\sigma - x - \tau) \tag{3.27}$$

that is, the consumer price decreases if the combination of the unit subsidy σ and the unit levy τ satisfies $\sigma - x > \tau$. As the next section will show, this is at the same time also the condition for renewable electricity generation to increase. It yet needs to be proven, however, that such a combination of σ and τ is also conform with the financing condition according to which the levy revenue must be sufficient to cover the subsidy expenditure.

THE CHANGE IN RENEWABLE ELECTRICITY GENERATION AS A FUNCTION OF THE POLICY

The result obtained for Δp_M can also be used to determine $E_R^{a\sigma}$, the quantity of renewable electricity after the introduction of the policy scheme, only as a function of σ, τ and the parameters. Substituting the respective expression for Δp_M in $E_R^{a\sigma}$ as derived in (3.14) yields:

$$E_R^{a\sigma} = \frac{\Delta p_M(\sigma, \tau) + \sigma - x}{s_R} = \frac{-\frac{s_D \cdot (\sigma - x) + s_R \cdot \tau}{s_R + s_D} + \sigma - x}{s_R}$$

$$= \frac{-s_D \cdot (\sigma - x) - s_R \cdot \tau + (s_R + s_D) \cdot (\sigma - x)}{(s_R + s_D) \cdot s_R} = \frac{-s_R \cdot \tau + s_R \cdot (\sigma - x)}{(s_R + s_D) \cdot s^R}$$

$$\leftrightarrow \qquad E_R^{a\sigma} = \frac{\sigma - x - \tau}{s_R + s_D} \qquad \text{for } \sigma - x - \tau > 0 \qquad (3.28)$$

This equation states that given a unit subsidy of σ and a unit levy on electricity consumption of τ, renewable electricity generation only becomes positive if σ is larger than x plus τ.

THE SELF-FINANCING CONDITION

Finally, one element is missing to conclude the analysis. It concerns the question whether a scheme consisting of the subsidy to renewable electricity and the levy on electricity consumption can be defined such that the subsidy expenditure is financed by the levy revenue, and yet the consumer price decreases. As introduced in Chapter 2, the subsidy expenditure needs to be financed by a unit levy on electricity consumption, τ, which is to be determined according to the following self-financing condition:

$$\tau \cdot E^{a\sigma} = \sigma \cdot E_R^{a\sigma} \qquad (3.29)$$

where the left-hand-side corresponds to the levy revenue, being determined by τ multiplied with the consumed electricity quantity after the scheme is implemented $E^{a\sigma}$, and the right-hand-side the subsidy expenditure, being determined by σ times the quantity of renewable electricity. However, $E^{a\sigma}$ can be substituted by $\overline{E_F} + E_R^{a\sigma}$ as the electricity consumption equals the generation.

Moreover, recall that the same condition needs to be fulfilled for the renewable electricity generation to increase and the consumer price to decrease due to the introduction of the levy-financed subsidy scheme. The aim of this section is to verify whether a scheme satisfying this condition ($\sigma > x + \tau$) is financeable with the aforementioned levy on electricity consumption. The answer becomes clear after re-writing the self-financing condition (3.29) with $E^{a\sigma} = \overline{E_F} + E_R^{a\sigma}$ in the following way:

$$\tau \cdot \left(\frac{\overline{E_F} + E_R^{a\sigma}}{E_R^{a\sigma}} \right) = \sigma \tag{3.30}$$

and substituting this expression for σ in (3.28). If after substituting the self-financing condition into the equation determining $E_R^{a\sigma}$ a positive renewable electricity quantity (as a function of the unit levy τ) can be generated, then it also possible to achieve the implementation of such a levy-financed subsidy scheme while the consumer price of electricity decreases. Substituting (3.30) for σ in equation (3.28) yields:

$$E_R^{a\sigma} = \frac{\tau \cdot \left(\frac{\overline{E_F} + E_R^{a\sigma}}{E_R^{a\sigma}} \right) - x - \tau}{s_R + s_D} = \frac{\tau \cdot \left(\frac{\overline{E_F}}{E_R^{a\sigma}} \right) - x}{s_R + s_D} \tag{3.31}$$

which can be solved for $E_R^{a\sigma}$ or τ to obtain a clear picture of the relationship between τ and $E_R^{a\sigma}$. Solving (3.31) for τ leads to the following expression:

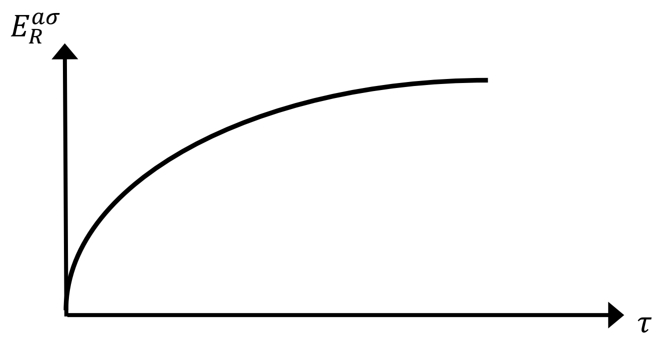
$$\tau = \frac{(E_R^{a\sigma})^2 \cdot (s_R + s_D) + E_R^{a\sigma} \cdot x}{\overline{E_F}} \tag{3.32}$$

Since $s_R, s_D, x, \overline{E_F} > 0$, the relevant branch of this equation is as illustrated in Figure 3.4. According to equation (3.32) and its graphical illustration, any $E_R^{a\sigma} > 0$ can be achieved by setting an appropriate levy τ and the corresponding subsidy for renewable energy. More specifically, Figure 3.4 shows that for achieving a higher renewable electricity quantity, an exponentially growing unit levy on electricity consumption τ is needed. By substituting any feasible combination of $E_R^{a\sigma}$ and τ according to (3.32) back into the financing condition (3.30), the respective level of the unit subsidy σ can be found. This unit subsidy to renewable electricity satisfies the self-financing condition given the desired $E_R^{a\sigma}$ and the necessary τ, implying that it actually induces an increase of the renewable electricity generation to the quantity as defined by the relationship between $E_R^{a\sigma}$ and τ according to

(3.32). Hence, it has been shown that any expansion of the renewable electricity quantity is feasible while respecting the self-financing condition. This at the same time means that also the consumer price decreases when such a policy scheme is implemented.

The results derived thus far can be summarized as follows. An increase in the generation of renewable electricity can be achieved without imposing a burden on electricity consumers, although it initially appears that they finance the expenses by paying a levy. This stems from the fact that fossil electricity generation does not shrink as long as the permit price remains positive, and therefore any increase in renewable electricity generation implies a higher equilibrium quantity on the electricity market. Therefore, it follows that the consumer price shrinks and thus consumers are better off than prior to the support scheme being implemented.

Figure 3.4: Feasible renewable electricity expansion as a function of the levy



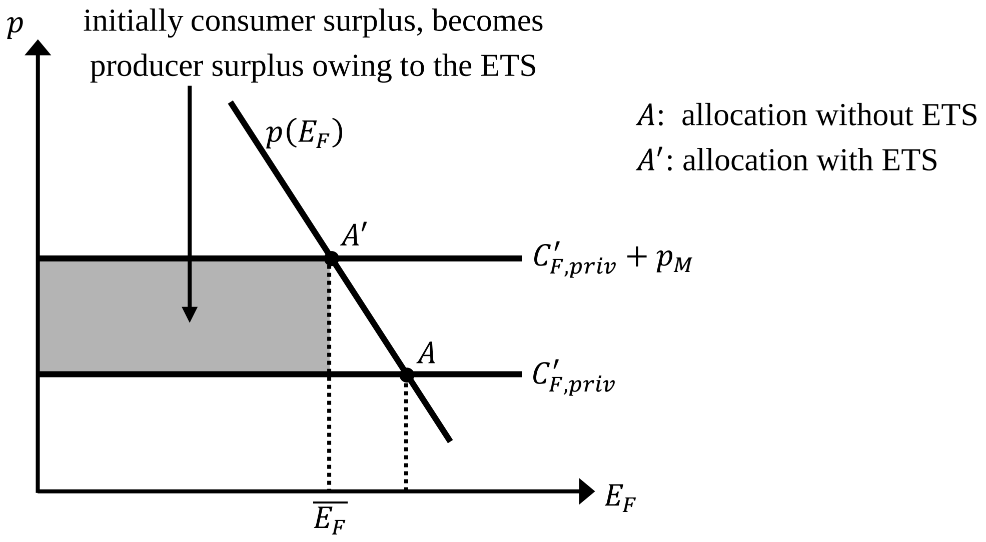
Source: own illustration.

EXPLANATION OF THE RESULT

To better explain the underlying mechanism, the effect of introducing an ETS first needs to be understood. There are two basic alternatives for how emission permits can be brought into the market: auctioning and grandfathering. If auctioning is chosen by the regulator, the polluting firms pay a price upfront for receiving the permits. By contrast, if grandfathering is the allocation method, the permits are given to the polluting firms for free and thus no revenue is collected by the regulator.

Suppose the permits are grandfathered, which is largely the case in the EU. The permits given to the firms have a value if they are sufficiently scarce, which is given in total by their number multiplied with the market price at which they are traded. As the electricity market is modeled here before the introduction of the ETS, fossil electricity producers do not have a positive producer surplus given that their supply curve is horizontal. It also remains horizontal after the introduction of the ETS; however, it shifts upwards by the permit price allowing those producers who have been grandfathered a permit to generate a profit per unit of electricity equaling the permit price. It can be obtained either by generating electricity and selling it at the higher electricity market price, or by selling the permit itself. However, abstracting from externalities, the introduction of an ETS reduces the consumer surplus since it results in a higher consumer price and a lower quantity of electricity, which is illustrated in Figure 3.5.

Figure 3.5: Effect on the surpluses of an ETS with grandfathered permits

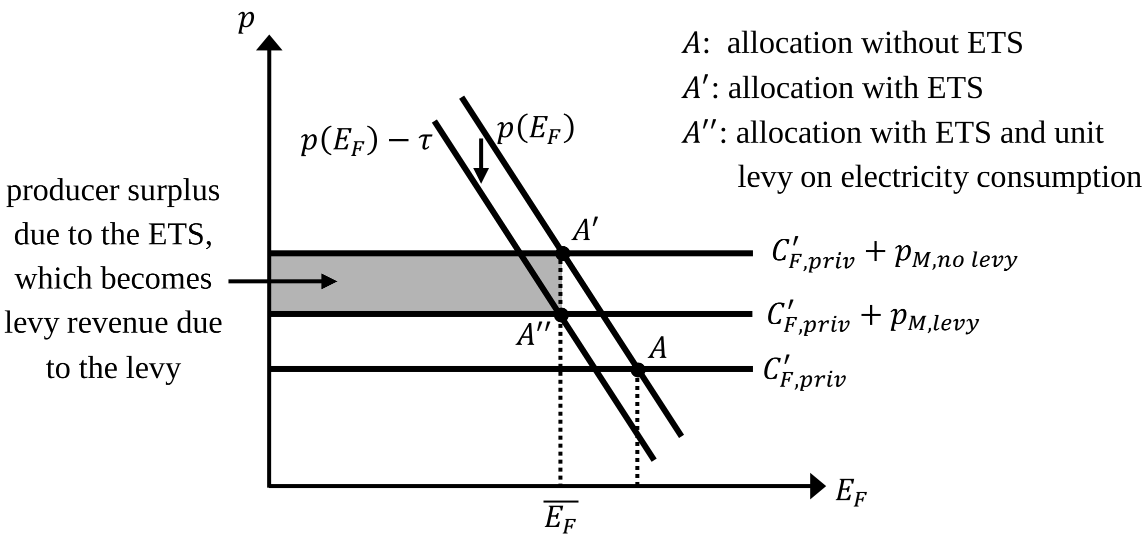


Source: own illustration.

The existence of an ETS is important for the impact of introducing a renewable energy support scheme, as both the unit subsidy and the unit levy on electricity consumption affect the demand for fossil electricity and subsequently the permit price. The levy shifts the inverse demand curve downwards and, ceteris paribus, the price of emission permits would need to fall by exactly as much as the size of the levy for the same amount of fossil electricity $\overline{E_F}$ to be cleared on the market. This can be understood from Figure 3.6, where $p(E_F)$ shifts downwards by the size of the levy when this is introduced. Consequently, also the permit price shrinks by this amount as otherwise not all permits would be used because of the insufficient demand at the higher permit price. Therefore, Figure 3.6 explains that by increasing the levy the originally generated surplus of the fossil electricity producers, through establishing the ETS with grandfathered permits, can be transformed into levy revenue on a one-to-one basis.

In contrast to a grandfathering of permits, an initial auctioning would not necessarily create rents for permit holding firms (depending on the auctioning mechanism). Nevertheless, the process of transforming producer surplus into levy revenue has similarities to the case in which the emission permits are immediately auctioned. With an auctioning, the regulator would collect revenue from selling the permits, which could be similarly used for subsidizing renewable energy without imposing an additional burden on the electricity consumers.

Figure 3.6: Effect on the surpluses of levy on electricity consumption



Source: own illustration.

However, there exists one limitation for the expansion of the renewable electricity generation via the above-described mechanism. As it was derived, the price of emission permits p_M declines when the subsidy and the levy are increased. Once a permit price of zero is reached, the quantity of fossil electricity would shrink with a further increasing levy. Therefore, whereas the levy could continue to increase, the base on which it is imposed would shrink and thus a maximal collectable levy revenue exists after which a further increase in the levy reduces the levy revenue. This maximal levy revenue would set the upper bound on the subsidy that can be financed, and therefore also on the feasible renewable electricity expansion.

3.5 A FIRST SET OF LIMITATIONS OF THE OBTAINED RESULTS

There are two aspects in which the described model could be extended, with both tending to weaken the results obtained in the previous section. The first extension concerns the demand for emission permits, as whereas until now it was assumed that they are only being demanded by the fossil electricity generating industry, in reality the ETS covers also other industries (see Section 3.2 on the EU ETS). Therefore, if these other industries were willing to buy a larger amount of emission permits when their price falls (namely if they have a downward sloping demand for permits), the number of permits is no longer fixed for the electricity sector. A reduction of the permit price resulting from a reduced demand for fossil electricity would thus induce that a higher number of permits are used in other industries. Hence, whereas the output of the other industries would tend to increase, the supply of fossil electricity would decrease. This latter effect presents the possible outcome of electricity consumers being faced with a lower electricity supply, which would lead to a higher equilibrium price and reduce their rent. Note that second-round effects stemming from the other industries are not considered.

A second limitation of the results obtained thus far can be drawn based on a model by Böhringer and Rosendahl (2010), which was also similarly formulated by Fischer and Preonas (2010). They emphasize that a change in the price of emission permits may have an impact on the composition of fossil electricity generation. Both papers consider fossil electricity generation from coal and from gas, and hence the total amount of emission permits is shared between coal and gas electricity producers. However, coal electricity is more emission intensive than gas electricity, and thus, as argued in Böhringer and Rosendahl (2010), coal electricity benefits more strongly than gas electricity if the permit price declines. Consequently, there would be a shift from gas electricity generation to coal electricity, which would reduce the total fossil electricity generation for a given amount of emission permits. Similar to the previous argument, increasing electricity prices following the implementation of a renewable energy support scheme becomes a possible outcome.

However, this discussion also highlights that combining renewable energy support with an ETS may actually imply another undesired effect, in benefitting the dirtier coal electricity relative to gas electricity.

In contrast to the analysis in the previous section, these two limitations already illustrate why electricity consumers might be giving up some of their consumer rent for the subsidizing of renewable energy. A further and possibly most important limitation of the results obtained in this chapter will be derived and discussed in Chapter 4. The analysis will be extended to a two-country set-up, explaining how the results change if the renewable energy subsidizing country shares a common electricity market and common ETS with other countries. This extension serves to bring the analysis closer to the actual institutional framework in Europe.

3.6 Conclusions

Whilst the discussion in this chapter was thus far based on a positive analysis, some normative implications warrant mention in this section. Firstly, it is important to emphasize that the introduction of the ETS can improve allocative efficiency if the negative effects of using fossil energy are otherwise not being priced-in correctly. As illustrated in Figure 3.5, the electricity consumption shrinks and reaches the efficient level if the ETS is properly designed. Secondly, as previously argued at the end of Chapter 2, no renewable energy subsidy can be justified based on reasons related to the climate change externality if the ETS induces a correct pricing of carbon dioxide emissions. In such a case, the introduction of a levy-financed subsidy reduces total rents as renewable electricity is subsequently generated at costs higher than the social cost of fossil electricity. Simultaneously, the electricity consumption again becomes inefficiently high given the declining consumer price, for the underlying reason that the permit price decreases owing to the subsidy and because of the levy. However, it should also be emphasized that the levy itself does not create an inefficiency, rather it only transforms the producer surplus of firms generating fossil electricity into levy revenue. An inefficient allocation arises owing to the subsidizing of renewable energy, when it does not require support, which is the case when the market price of electricity already equals the social unit cost of fossil electricity.

In contrast to an imperfect carbon tax, as discussed in Chapter 2, in the case of an imperfect ETS no renewable energy subsidy can be justified, given that the ETS fixes the quantity of fossil electricity through an endogenous permit price, thereby making it independent of the generation of renewable electricity. Public policy supporting renewable energy can only be reasoned by the existence of other externalities in addition to the climate change externality, or simply because subsidizing renewable energy is a political choice even in the absence of non-internalized externalities.

4. Unilateral support of renewable energy within a common ETS

4.1 Plan of the chapter

A crucial element of the model discussed in Chapter 3 is the government deciding over its subsidy scheme while being the only party of the emission trading system (ETS). An interesting alternative formulation would allow each country to determine the subsidy for domestic renewable electricity (and the corresponding levy on electricity consumers), whereas the country itself exists within a common electricity market and multi-country ETS. In fact, this represents a better description of the current setting within the EU, and will thus be considered in this chapter. A main question will assess whether the feasibility of subsidizing renewable energy without burdening domestic electricity consumers in the model still applies, if extended in this way.

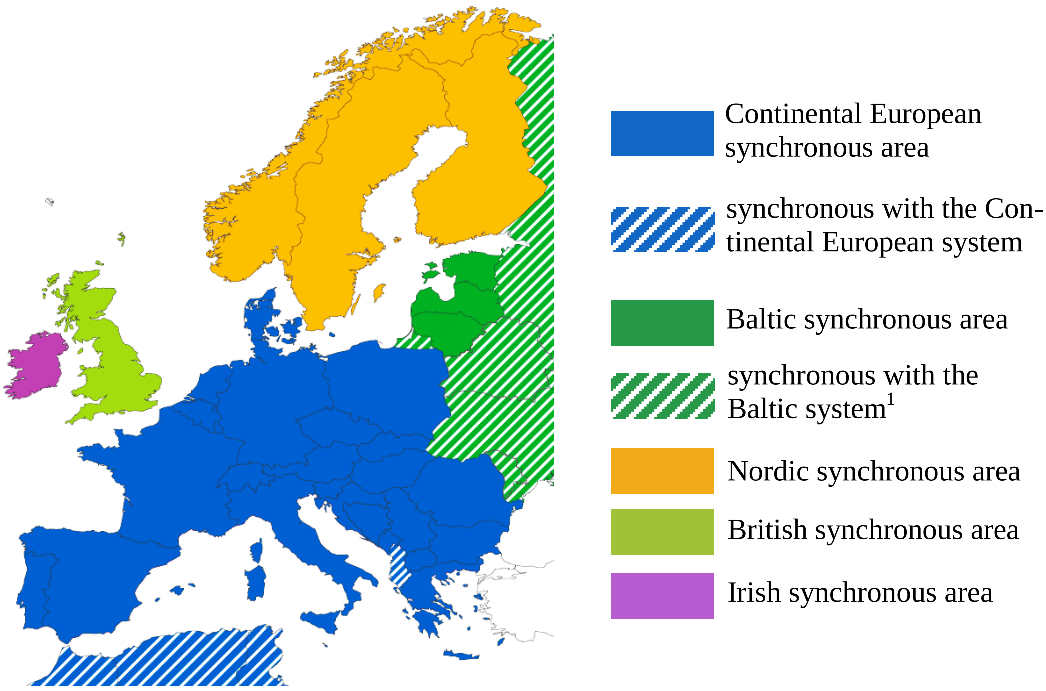
The main purpose of the previous one-country analysis was to highlight that a country can in principle subsidize renewable energy and thereby shift rents from the fossil to the renewable electricity industry and electricity consumers. Two relevant limitations of the results have already been discussed: firstly, there could be a shift towards 'dirtier' fossil electricity; and secondly, carbon emissions could be shifted to other industries. Both would have the same effect of reducing the fossil electricity generation (while total emissions as defined by the ETS would remain constant), and consequently the electricity consumers' rent would tend to shrink.

This chapter will show that unilateral renewable energy policy can lead to a substantial redistribution of rents across countries. Again, the main mechanism is a decrease in the permit price owing to one country unilaterally subsidizing renewable energy. However, since only consumers in this country finance the subsidy expenditure by paying a levy on electricity consumption, a wedge is created between the consumer prices in the two modeled countries. The consumer rent increases in the country that does not support renewable electricity given that the consumer price shrinks with certainty, with both being accompanied by increased electricity imports from the subsidy implementing country, for a given distribution of fossil energy power plants. Consequently, since rents are transferred to the other country, an increasing consumer price in the renewable energy supporting country emerges as a possible outcome. Hence, a further intuition why German electricity consumers might be suffering a burden owing to the extensive renewable energy support is provided by modeling the institutional framework within the EU more closely.

4.2 The European internal market for electricity

The integration of national electricity markets and creation of a single European market for electricity represents an explicit goal of the EU (see, 2009/72/EC). Several milestones have already been achieved, primarily through the Directive 96/92/EC of the European Parliament and of the Council of 19th December 1996 establishing rules for an internal market for electricity in the EU. These ‘common rules for the generation, transmission, distribution and supply of electricity’ were further developed by the Directive 2003/54/EC of 26th June 2003, and Directive 2009/72/EC of 13th July 2009. The current aim is to fully integrate national energy markets by 2014 (EC, 2011a; ENTSO-E, 2011).

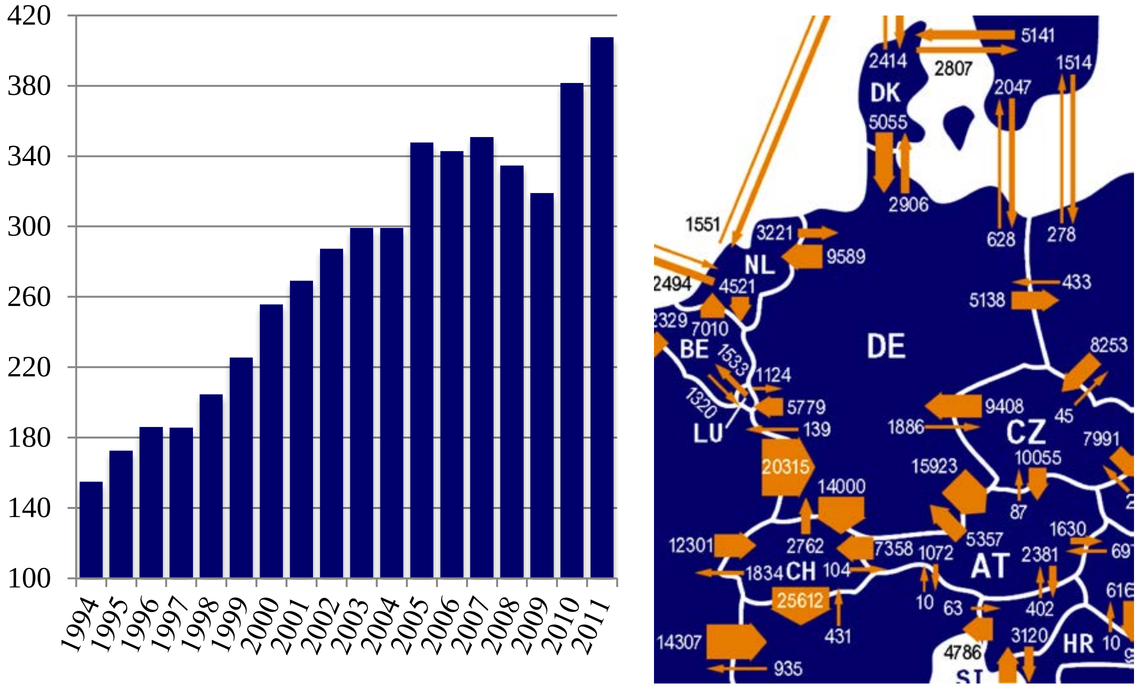
Figure 4.1: Wide area synchronous grids in Europe



[1] Western part of the Ukraine is synchronous with the Continental European system.
Source: ENTSO-E, own illustration.

An important element within this process was marked by the creation of the European Network of Transmission System Operators for Electricity (ENTSO-E) in 2008. This is an association of 41 transmission system operators from 34 countries, aiming to facilitate the market integration by sharing an interconnected transmission grid. The ENTSO-E is divided into five sub-groups, the largest of which consists of the former members of the Union for the Co-ordination of Transmission of Electricity (UCTE). The members of this regional group, which is often termed “Continental Europe” include Austria, Belgium, the Czech Republic, Denmark, France, Germany, Italy, the Netherlands, Poland, Slovakia, Spain, and Switzerland. A total of 24 countries comprise this group and all them share one synchronous grid, meaning that electricity can (theoretically) flow between these countries without boundaries (see Figure 4.1). In addition to the Continental European synchronous area, there are also the Nordic and the Baltic synchronous areas, whereas Great Britain and Ireland (as well as Iceland and Cyprus) have isolated systems.

Figure 4.2: Electricity exchange between ENTSO-E countries in TWh (left), electricity exchange in 2011 in GWh (right)



Source: ENTSO-E

Naturally, certain capacity constraints and barriers exist in practice; with the main challenges according to ENTSO-E (2011) being the network development, harmonization of market mechanisms (forward markets, day-ahead markets and intra-day markets) and issues related to the managing of the new energy mix. However, market integration has already been significantly achieved in large areas of Europe, with Figure 4.2 (left diagram) highlighting how much electricity crosses national borders within the ENTSO-E per year. The quantity has increased from around 150 TWh to more than 400 TWh since 1994. The right diagram in Figure 4.2 illustrates the electricity flows between Germany and its neighboring countries in terms of the electricity grid in 2011. Therefore, the European market for electricity is certainly a single market to some degree, which represents the key intuition to be carried over to the model later in this chapter.

4.3 Harmonized EU renewable energy policies or unilateral action?

Prior to considering a model with a country that unilaterally supports renewable energy, this section aims to establish a better understanding of how the notion of 'unilateral support' should be interpreted. One could argue that very little scope exists for unilateral policies in the EU, since the main targets are defined at the European level. For example, the Directive 2009/28/EC has specified renewable energy targets for all EU countries for 2020.[7] Indeed, Ragwitz et al. (2011) and IEA (2008) illustrate that all EU countries have already long had renewable energy support policies in place, dating back at least to the 1990s in the case of the EU15 countries and to the early 2000s with the new EU member countries. Despite differing in many ways and are thus not being easily comparable, at first glance all EU countries appear to promise attractive (monetary) benefits for the use of renewable energy.

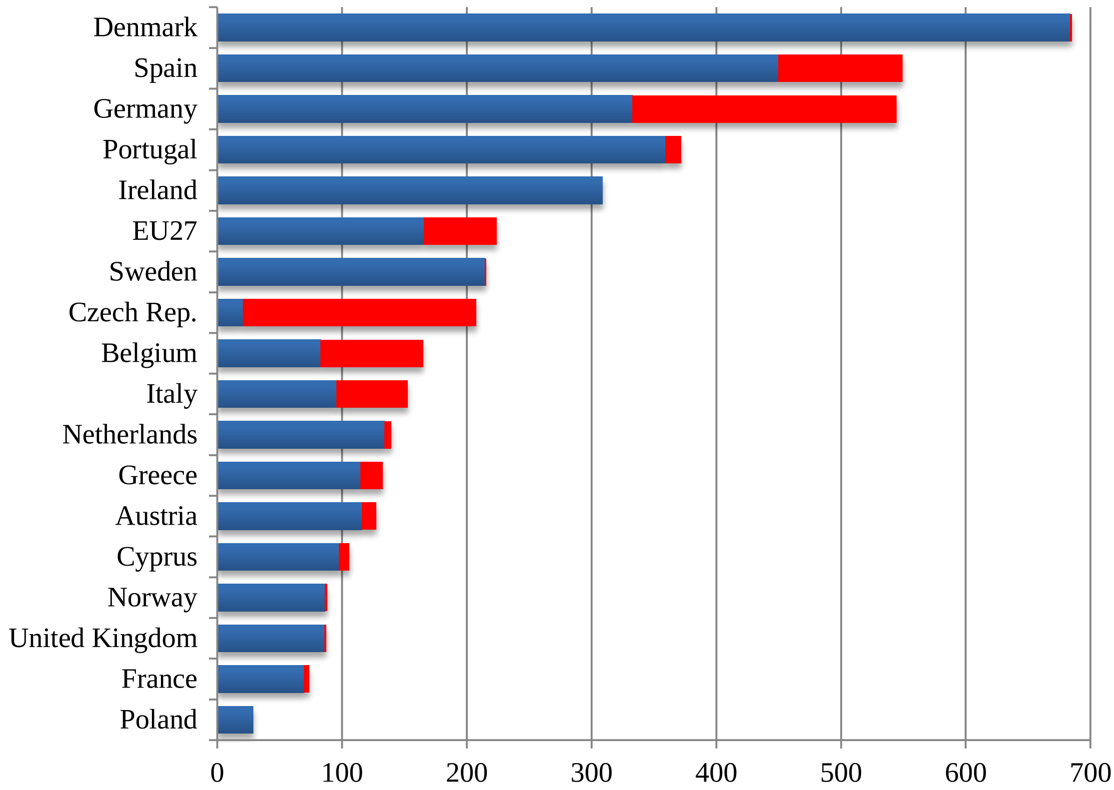
Therefore, it is somewhat surprising that the actual renewable energy development varies greatly between the EU countries, as illustrated in Figure 4.3, where countries are ranked according to the per capita sum of the installed wind and solar power capacity. Denmark, Spain and Germany lead this ranking by some distance, whereas Poland and France find themselves at the bottom. It is somewhat unsurprising that Denmark stands at the top, given its highly favourable conditions for the use of wind energy. This also holds for some regions in Spain, which moreover ranks fourth in Europe for solar irradiation after Malta, Cyprus and Portugal (see, PVGIS[8]). However, it is surprising that Germany has a manifold stronger development of wind and solar energy than its direct neighbors Poland, France and the Netherlands, but also compared with Italy, for example. This

[7] See Chapter 5, section 5.3, for further information on the European renewable energy targets.
[8] Photovoltaic Geographical Information System, available at: http://re.jrc.ec.europa.eu/pvgis/.

pattern can already be interpreted as some countries having stronger, or at least more effective, renewable energy support policies than others.

According to Ragwitz et al. (2011), a main difference in renewable energy policies across EU countries is manifest in some countries choosing to implement feed-in tariffs whereas others have opted for green certificate schemes. Among others, Butler and Neuhoff (2008), Campoccia et al. (2009) have analyzed the effectiveness of each of the two, with mixed results subsequently found. However, the risk in policy design has also been mentioned as an important determinant for the effectiveness of renewable energy support in recent literature (see, Bürer and Wüstenhagen, 2009, Gross et al., 2010 and Lüthi and Wüstenhagen, 2012). Lüthi and Wüstenhagen (2012) find that the duration of the administrative process is even more important than the level of the feed-in tariff, from an investor's perspective. They also conclude that the number of policy changes negatively affects the willingness of investors to select a country.

Figure 4.3: Installed wind (blue) and solar (red) power capacity in 2010 in W per capita



Source: Eurostat (nrg_113a, demo_gind).

Therefore, it can be concluded that despite all EU countries having renewable energy support schemes in place, this does not imply that they de facto provide an environment which similarly attracts renewable energy investments. Returning to Figure 4.3, it could be argued that the renewable energy policy of a group of countries can be considered as unilateral in terms of its effectiveness, which justifies studying unilateral renewable energy support in the model in the following section.

4.4 EFFECTS OF UNILATERALLY SUPPORTING RENEWABLE ENERGY IN A MODEL WITH ETS

The previous two sections have illustrated that a reasonable description of some EU countries' policies is the unilateral support of renewable energy within a common electricity market. Before this being taken into account, the modelling of the ETS needs to be extended in comparison with the one-country set-up in Chapter 3.

THE ELECTRICITY MARKET WITH TWO COUNTRIES

The model used in the following is similar to the one in Chapter 2 and 3, with the main difference being that two countries will be considered rather than one. The two countries share a common electricity market and also have a common ETS.

The supply of electricity stems from two groups of suppliers, fossil electricity and renewable electricity producers and these are modeled by representative agents who are assumed to behave competitively. Hence, the market price of electricity is taken as given by all market participants. The cost functions for producing fossil and renewable electricity remain as in the previous two chapters. Concerning the generation of fossil electricity, constant returns to scale are assumed, since a fossil energy power plant can be built and operated as many times as desired at the same cost. Thus, the marginal cost curve is horizontal and assumed to be the same in both countries. If this was not the case, since transmission losses and other frictions are not modeled, fossil electricity would only be generated in one of the two countries. Consequently, this set-up allows considering only one representative fossil electricity producer, who can supply fossil electricity to both countries.

For renewable electricity, it is again assumed that the marginal cost increases in the generated quantity. The main reason for this choice is that increasingly unfavorable locations for the use of renewable electricity need to be employed in order to further extend the quantity, thereby making each additional unit more costly than the previous one, which holds in both countries. However, it is supposed that without government support to renewable electricity, renewable electricity is not profitable in either of the two countries in order to make the analysis comparable with the one in Chapter 3. Since only the government of one country decides to support renewable electricity, thus renewable electricity being then generated only in this country, modeling one representative renewable electricity producer is sufficient.

Consumers are immobile between the countries, but electricity can flow freely and without any transmission losses. In both countries, electricity demand is represented by a downward sloping function of the price, implying that consumers are willing to buy more electricity if the price is lower. As before, fossil and renewable electricity are assumed to be perfect substitutes from the consumers' perspective. Since renewable electricity is assumed to be unprofitable without government support, the total demand of both countries is initially satisfied with fossil electricity only.

MODELLING OF THE ETS AND THE EQUILIBRIUM WITHOUT RENEWABLE ENERGY SUPPORT

The existence of the ETS implies that a fossil electricity producer needs to have the respective number of emission permits which corresponds to his carbon dioxide emissions. The supply of emission permits is again fixed, however this time not for a country individually, but by an international regulator who decides on the total quantity for both countries. This quantity of emission permits allows the fossil electricity producers to generate a (maximum) of $\overline{E_F}$ units of fossil electricity.

It is again assumed that the emission permits are grandfathered to the fossil electricity producers, and can subsequently be traded among them. As explained in Chapter 3, section 3.3, the price of emission permits will be positive, if $\overline{E_F}$ is lower than the quantity of fossil electricity, which fossil electricity producers would have been producing if the ETS was not in place. Also the intuition for how the price on the permit market is formed remains as described in section 3.3. As explained there, the permit price depends on the quantity of renewable electricity, which as was also illustrated in Figure 3.2. The more renewable electricity is generated, the lower is the remaining demand for fossil electricity and therefore also the permit price is lower. Hence, the permit price can be written as:

$$p_M(E_R) = p(\overline{E_F}; E_R) - C'_{F,priv} \tag{4.1}$$

which is the same formulation as (3.6) and where p_M is the price of an emission permit needed for generating one unit of fossil electricity. According to (4.1) the price of an emission permit is equal to the difference between the consumers' marginal willingness to pay for electricity, given that a quantity E_R of renewable electricity is generated and the fossil electricity quantity is fixed by the regulator at $\overline{E_F}$, and the marginal cost of fossil electricity. Moreover, as in Chapter 3, $p_{M,E_R=0}$ will denote the permit price assuming that no renewable electricity is generated, that is, $p_M(E_R = 0) \equiv p_{M,E_R=0}$.

The maximization problem of the representative producer of fossil electricity is similarly as in Chapter 3:

$$\max_{E_F} \Pi_F = p \cdot E_F - C_{F,priv}(E_F) - p_M \cdot E_F \tag{4.2}$$

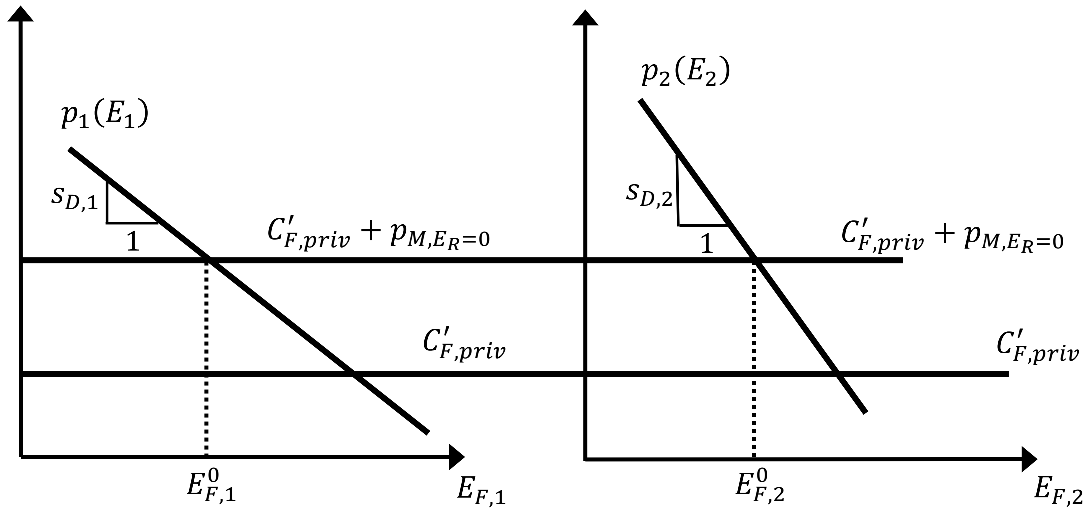
where Π_F denotes his profit, p the market price of electricity which a single producer takes as given, E_F the quantity of fossil electricity he generates, and $C_{F,priv}(E_F) = a \cdot E_F$ the private cost of fossil electricity, which implies $C'_{F,priv} = a$. The expenditure for buying the necessary emission permits on the market is $p_M \cdot E_F$, and also the price of emission permits is taken as given by the representative fossil electricity producer. Alternatively, if the fossil electricity producer has been granted emission permits for free, this term can be interpreted as the cost of using the respective number of permits himself instead of selling them on the permit market. The first order condition of this problem is:

$$\frac{\partial \Pi_F}{\partial E_F} = p - C'_{F,priv} - p_M = 0 \quad \leftrightarrow \quad p = C'_{F,priv} + p_M \tag{4.3}$$

Since the marginal cost of fossil electricity is constant and given that the price of emission permits is positive, the market price of electricity is $C'_{F,priv} + p_{M,E_R=0}$. The equilibrium permit price is initially $p_{M,E_R=0}$, since it was assumed that without government support no renewable electricity is profitable. Thus, the consumed quantity of electricity in both countries is determined by the intersection of the respective inverse demand function with the horizontal supply curve given by $C'_{F,priv} + p_{M,E_R=0}$, as illustrated in Figure 4.4.

The left diagram relates to country 1, whereas the right diagram depicts the market outcome in country 2. The inverse demand function in country 1 is assumed to be $p_1(E_1) = d_1 - s_{D,1} \cdot E_1$, with $d_1, s_{D,1} > 0$ and E_1 being the consumed quantity of electricity. Similarly, in country 2 the inverse demand function is supposed to be $p_2(E_2) = d_2 - s_{D,2} \cdot E_2$, with $d_2, s_{D,2} > 0$ and E_2 being the consumed quantity of electricity in this country. Moreover, because of the ETS, the two consumed quantities sum up to $\overline{E_F}$, i.e. $E_{F,1}^0 + E_{F,2}^0 = \overline{E_F}$.

Figure 4.4: Emission trading system and the marginal costs of renewable electricity



Source: own illustration.

Renewable electricity support in country 1

As outlined in the previous section in the initial situation no renewable electricity is generated. With the aim of changing this, country 1 implements a unit subsidy to renewable electricity, which as in Chapter 3 is financed by a unit levy on electricity consumption. Since this policy is a unilateral decision, the levy applies only to the domestic consumption.

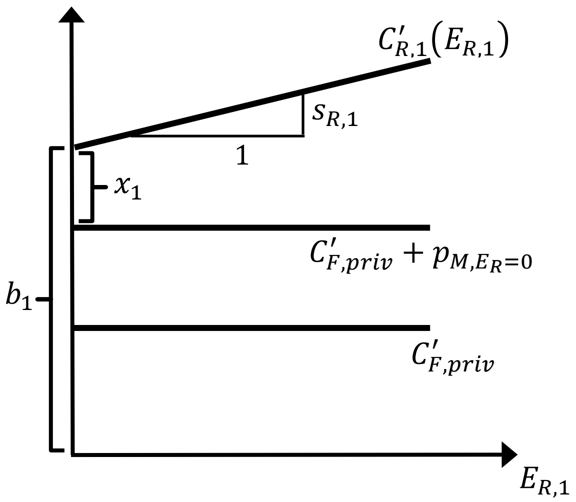
With the subsidy being in place, the representative renewable electricity producer in country 1 solves:

$$\max_{E_{R,1}} \Pi_{R,1} = (p + \sigma_1) \cdot E_{R,1} - C_{R,1}(E_{R,1}) \tag{4.4}$$

where $\Pi_{R,1}$ denotes his profit, determined by the revenue $p \cdot E_{R,1}$ and the cost $C_{R,1}(E_{R,1})$. The unit subsidy is denoted σ_1 and the quantity of renewable electricity $E_{R,1}$. The cost $C_{R,1}(E_{R,1})$ is increasing in $E_{R,1}$ and also the marginal cost increases as more renewable electricity is generated. As in Chapter 3, the specific formulation for the marginal cost function $C'_{R,1}(E_{R,1}) = b_1 + s_{R,1} \cdot E_{R,1}$ with $b_1, s_{R,1} > 0$ will be used in the following.

Moreover, in order to determine the actual quantity of renewable electricity after the introduction of the subsidy, the parameter x_1 is introduced. It denotes the gap between the (hypothetical) price of electricity when no renewable electricity is generated, $C'_{F,priv} + p_{M,E_R=0}$, and the cost of the least costly renewable electricity unit in country 1, $C'_{R,1}(E_{R,1} = 0) = b_1$. Hence, $x_1 = b_1 - (C'_{F,priv} + p_{M,E_R=0})$, which is also illustrated in Figure 4.5.

Figure 4.5: Marginal cost of renewable electricity in country 1



Source: own illustration.

The first order condition of the representative renewable electricity producer's problem is:

$$p + \sigma_1 = C'_{R,1}(E_{R,1}) \quad \leftrightarrow \quad p + \sigma_1 = C'_{F,priv} + p_{M,E_R=0} + x_1 + s_{R,1} \cdot E_{R,1} \qquad (4.5)$$

where $C'_{F,priv} + p_{M,E_R=0} + x_1$ was substituted for b_1 in the specific formulation of $C'_{R,1}(E_{R,1})$. Since the government in country 2 does not implement a subsidy to renewable electricity, the generated quantity remains zero throughout this chapter, and is therefore not further considered.

Substituting $p = C'_{F,priv} + p_M(E_{R,1})$ from the fossil electricity producer's maximization problem in (4.5) and solving for $E_{R,1}$ yields:

$$E_{R,1}^{a\sigma} = \frac{\left(p_M\left(E_{R,1}^{a\sigma}\right) - p_{M,E_R=0}\right) + \sigma_1 - x_1}{s_{R,1}} \tag{4.6}$$

where the superscript "$a\sigma$" stands for "after the introduction of the subsidy". The term $p_M\left(E_{R,1}^{a\sigma}\right) - p_{M,E_R=0} \equiv \Delta p_M\left(E_{R,1}^{a\sigma}\right)$ is the difference between the actual permit price $p_M\left(E_{R,1}^{a\sigma}\right)$, arising given that a positive quantity of renewable electricity is generated, and the hypothetical permit price assuming no generation of renewable electricity $p_{M,E_R=0}$. Recall from Chapter 3 that the permit price decreases when the renewable electricity generation increases, since ceteris paribus the demand for fossil electricity shrinks. Thus, Δp_M is zero as long as the renewable electricity generation is zero, but becomes increasingly negative as $E_{R,1}^{a\sigma}$ increases. Consequently, since $\Delta p_M < 0$, the renewable electricity generation in country 1 only becomes positive if the chosen unit subsidy is larger than x_1, i.e. if it can close the gap to the least costly renewable electricity unit. Thus, $E_{R,1}^{a\sigma}$ can be written as:

$$E_{R,1}^{a\sigma} = \begin{cases} \dfrac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \sigma - x_1}{s_{R,1}} & \text{for } \sigma_1 - x_1 > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4.7}$$

THE CHANGE IN ELECTRICITY CONSUMPTION IN BOTH COUNTRIES

Having determined the change in the renewable electricity generation in country 1 owing to the unilateral introduction of the subsidy, it can now be analyzed how the electricity consumption will change in both countries. Consequently, the electricity quantities consumed before and after the introduction of the subsidy need to be determined and can be compared subsequently.

Before the implementation of the subsidy scheme, the consumed quantity of electricity is in both countries determined by:

$$p_i\left(E_i^{b\sigma}\right) = C'_{F,priv} + p_{M,E_R=0} \tag{4.8}$$

where the superscript "$b\sigma$" indicates "before the introduction of the subsidy", and $i = 1{,}2$ represents the two modelled countries. Equation (4.8) characterizes for both countries the intersection of the respective inverse demand curve with the consumer price, which is $C'_{F,priv} + p_{M,E_R=0}$ given that no country has a policy to support renewable electricity in place (see Figure 4.4). Using the assumption that $p_i\left(E_i^{b\sigma}\right) = d_i - s_{D,i} \cdot E_i^{b\sigma}$, the two quantities are given by:

$$d_i - s_{D,i} \cdot E_i^{b\sigma} = C'_{F,priv} + p_{M,E_R=0}$$

$$\leftrightarrow \quad E_i^{b\sigma} = \frac{d_i - C'_{F,priv} - p_{M,E_R=0}}{s_{D,i}} \tag{4.9}$$

After country 1 has implemented the renewable electricity support scheme, the consumer prices in the two countries are not equal anymore, since only the consumers in country 1 are obliged to pay a levy on electricity consumption for the financing of the subsidy expenditure. Moreover, owing to the subsidy in country 1, and consequently renewable electricity generation becoming positive, the equilibrium permit price is not anymore $p_{M,E_R=0}$, rather it is $p_M\left(E_{R,1}^{a\sigma}\right) < p_{M,E_R=0}$ for the reasons discussed above and in section 3.3. Thus, the consumer price in country 1 is:

$$p_1(E_1^{a\sigma}) = C'_{F,priv} + p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1 \tag{4.10}$$

where τ_1 denotes the unit levy on electricity consumption in this country, the necessary size of which will be determined later. In contrast, consumers in country 2 pay for a unit of electricity:

$$p_2(E_2^{a\sigma}) = C'_{F,priv} + p_M\left(E_{R,1}^{a\sigma}\right) \tag{4.11}$$

Using again the specific formulation for the inverse demand curves, $p_i(E_i) = d_i - s_{D,i} \cdot E_i$, the consumed quantities after the unilateral introduction of the subsidy in country 1 (thus, with the superscript "$a\sigma$"), are:

$$d_1 - s_{D,1} \cdot E_1^{a\sigma} = C'_{F,priv} + p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1$$

$$\leftrightarrow \quad E_1^{a\sigma} = \frac{d_1 - C'_{F,priv} - p_M\left(E_{R,1}^{a\sigma}\right) - \tau_1}{s_{D,1}} \tag{4.12}$$

and,

$$d_2 - s_{D,2} \cdot E_2^{a\sigma} = C'_{F,priv} + p_M\left(E_{R,1}^{a\sigma}\right)$$

$$\leftrightarrow \quad E_2^{a\sigma} = \frac{d_2 - C'_{F,priv} - p_M\left(E_{R,1}^{a\sigma}\right)}{s_{D,2}} \tag{4.13}$$

where $E_1^{a\sigma}$ is the consumed quantity of electricity in country 1 and $E_2^{a\sigma}$ the respective quantity in country 2.

Calculating the difference between $E^{a\sigma}$ and $E^{b\sigma}$ for both countries yields:

$$E_1^{a\sigma} - E_1^{b\sigma} = \frac{d_1 - C'_{F,priv} - p_M\left(E_{R,1}^{a\sigma}\right) - \tau_1}{s_{D,1}} - \frac{d_1 - C'_{F,priv} - p_{M,E_R=0}}{s_{D,1}}$$

$$\leftrightarrow \quad E_1^{a\sigma} - E_1^{b\sigma} = -\frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1}{s_{D,1}} \tag{4.14}$$

and,

$$E_2^{a\sigma} - E_2^{b\sigma} = \frac{d_2 - C'_{F,priv} - p_M\left(E_{R,1}^{a\sigma}\right)}{s_{D,2}} - \frac{d_2 - C'_{F,priv} - p_{M,E_R=0}}{s_{D,2}}$$

$$\leftrightarrow \quad E_2^{a\sigma} - E_2^{b\sigma} = -\frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right)}{s_{D,2}} \tag{4.15}$$

where in both results $\Delta p_M\left(E_{R,1}^{a\sigma}\right) = p_M\left(E_{R,1}^{a\sigma}\right) - p_{M,E_R=0}$ was substituted. Equation (4.15) shows that due to the introduction of the subsidy in country 1, the electricity consumption in country 2 increases since $\Delta p_M\left(E_{R,1}^{a\sigma}\right) < 0$. Consumers in this country profit from the lower electricity price arising from the reduction of the permit price. On the other hand, it is ambiguous whether the electricity consumption in country 1 increases or decreases. A similar equation for the change in the electricity consumption in the subsidy implementing country was derived in Chapter 3, where it was afterwards shown that the consumer price indeed decreases following the introduction of the levy-financed subsidy to renewable electricity. Whether this still is the case when two countries are modelled, but only one introduces such a scheme will be discussed in the following.

THE CHANGE IN THE EMISSION PERMIT PRICE

The next step in the analysis is to derive $\Delta p_M\left(E_{R,1}^{a\sigma}\right)$, and thereby to obtain a clearer picture of the above derived changes in the quantities and prices. By the definition of the ETS, the quantity of fossil electricity that is generated is fixed by the regulator and given by $\overline{E_F}$. As long as the quantity $\overline{E_F}$ is strictly binding, the permit price is positive. Only if the fossil electricity producers voluntarily wish to produce not more than $\overline{E_F}$ the permit price shrinks to zero. It will be abstracted from this case in the following, as it describes as situation in which the restriction due to the ETS is irrelevant. Therefore, it is assumed that fossil electricity generation is $\overline{E_F}$ before and after the unilateral subsidy introduction by country 1.

It follows that, since fossil electricity generation remains unchanged, on the supply side only the renewable electricity generation in country 1 changes due to the introduction of the subsidy. The market clearing condition on the electricity market, equalizing total electricity generation and total electricity consumption holds before and after the introduction of the subsidy scheme in country 1. Thus, also the change in total electricity consumption over both countries needs to equal the change in electricity generation, from which it follows that:

$$\left(E_1^{a\sigma} - E_1^{b\sigma}\right) + \left(E_2^{a\sigma} - E_2^{b\sigma}\right) = E_{R,1}^{a\sigma}$$

$$\leftrightarrow -\frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1}{s_{D,1}} - \frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right)}{s_{D,2}} = \frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \sigma_1 - x_1}{s_{R,1}} \tag{4.16}$$

where the left-hand-side describes the sum of the changes in electricity consumption in country 1 and country 2 as previously derived and the right-hand-side the change in electricity generation, which is given by the renewable electricity generation in country 1. This condition can be solved for $\Delta p_M\left(E_{R,1}^{a\sigma}\right)$, the change in the permit price, as a function of σ_1 and τ_1:

$$(4.16) \quad \leftrightarrow \quad \Delta p_M\left(E_{R,1}^{a\sigma}\right) \cdot \left(-\frac{1}{s_{D,1}} - \frac{1}{s_{D,2}} - \frac{1}{s_{R,1}}\right) = \frac{\sigma_1 - x_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}$$

$$\leftrightarrow \quad \Delta p_M\left(E_{R,1}^{a\sigma}\right) \cdot \left(\frac{1}{s_{D,1}} + \frac{1}{s_{D,2}} + \frac{1}{s_{R,1}}\right) = -\frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} \cdot s_{D,1}}$$

$$\leftrightarrow \quad \Delta p_M\left(E_{R,1}^{a\sigma}\right) = -\frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}} \tag{4.17}$$

Knowing that $s_{R,1}, s_{D,1}, s_{D,2} > 0$, both a higher renewable electricity subsidy σ_1 as well as a higher levy on electricity consumption τ_1 reduce the permit price relative to its value without this policy. Concerning the subsidy, its tendency to decrease the permit price stems from the fact that it increases the quantity of renewable electricity, thereby decreasing the remaining demand for fossil electricity. The levy decreases the demand for electricity in general and for a given quantity of renewable electricity also the demand for fossil electricity in particular, which causes its dampening effect on the permit price.

Moreover, it can be seen from (4.17) that a high $s_{D,2}$, i.e. a steeply falling inverse demand function in country 2, leads to a stronger reduction in the permit price for any combination of σ_1 and τ_1. This fact will be discussed in more detail later and used to explain the effect on the consumer price in country 1.

THE CHANGE IN THE CONSUMER PRICE IN COUNTRY 1

In the next step, the impact of the unilateral levy-financed subsidy to renewable electricity on the consumer price in country 1 can be studied in more detail. The expression for the consumer prices in the two countries before and after the introduction policy of the policy were already derived above (see, (4.8), (4.10) and (4.11)). However, these all depend on the change in the permit price, which however has now also been determined. Thus, using the result for $\Delta p_M\left(E_{R,1}^{a\sigma}\right)$, the consumer price change in the policy implementing country 1 can be written as:

$$p_1(E_1^{a\sigma}) - p_1\left(E_1^{b\sigma}\right) = C'_{F,priv} + p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1 - C'_{F,priv} - p_{M,E_R=0} = \Delta p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1$$

$$\leftrightarrow \quad p_1(E_1^{a\sigma}) - p_1\left(E_1^{b\sigma}\right) = -\frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}} + \tau_1$$

$$\leftrightarrow \quad p_1(E_1^{a\sigma}) - p_1\left(E_1^{b\sigma}\right) = -s_{D,1} \cdot \frac{\sigma_1 - x_1 - \tau_1 \cdot \left(1 + \frac{s_{R,1}}{s_{D,2}}\right)}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}} \tag{4.18}$$

The main result of Chapter 3 was that even though consumers pay a levy on electricity consumption, the consumer price shrinks since the permit price decreases sufficiently to over-compensate the size of the unit levy. Whether this still is the case given that now two countries are modeled will be analyzed in the next subsection. However, it is useful to derive the condition that the consumer price in country 1 remains unchanged when the unilateral policy is implemented. This can be obtained by setting (4.18) equal to zero:

$$p_1(E_1^{a\sigma}) - p_1(E_1^{b\sigma}) = 0 \quad \rightarrow \quad \sigma_1 - x_1 - \tau_1 \cdot \left(1 + \frac{s_{R,1}}{s_{D,2}}\right) = 0$$

$$\leftrightarrow \quad \sigma_1 = x_1 + \tau_1 \cdot \left(1 + \frac{s_{R,1}}{s_{D,2}}\right) \tag{4.19}$$

Consequently, if (4.19) holds, the consumer price in country 1 is the same after the introduction of the subsidy as before. From (4.19) and (4.18) it can be seen that it would decrease if $\sigma_1 > x_1 + \tau_1 \cdot \left(1 + \frac{s_{R,1}}{s_{D,2}}\right)$ and increase in the opposite case. Hence, the question is whether such a combination of σ_1 and τ_1 is feasible given that a self-financing condition needs to be respected.

THE SELF-FINANCING CONDITION

To verify whether country 1 can implement a levy-financed subsidy to renewable electricity, which increases renewable electricity generation and at the same time reduces the domestic consumer price, again the self-financing condition needs to be formulated. As already introduced in Chapter 3, the subsidy expenditure needs to be financed by a unit levy on electricity consumption, τ_1, that is to be determined according to the following equation:

$$\tau_1 \cdot E_1^{a\sigma} = \sigma_1 \cdot E_{R,1}^{a\sigma} \tag{4.20}$$

where the left-hand-side corresponds to the levy revenue, being determined by τ_1 and the consumed quantity of electricity in country 1 after the scheme has been implemented $E_1^{a\sigma}$, and the right-hand-side the subsidy expenditure, which is σ_1 times the quantity of renewable electricity.

In the next step, the above derived expressions for $E_{R,1}^{a\sigma}$ and $E_1^{a\sigma}$ are substituted in the self-financing condition, whereby the sum of $E_1^{b\sigma}$ and $E_1^{a\sigma} - E_1^{b\sigma}$ (as derived in (4.14)) is used instead of $E_1^{a\sigma}$ itself for analytical convenience. Moreover, the expression derived for $\Delta p_M\left(E_{R,1}^{a\sigma}\right)$ in (4.17) is substituted. The resulting relationship between τ_1 and σ_1 classifies all possible combinations satisfying the self-financing condition (4.20). It is quadratic in both τ_1 and σ_1, therefore being more complex than its equivalent in Chapter 3, and can be written as:[9]

$$(4.20) \quad \leftrightarrow \quad \tau_1 \cdot \left(E_1^{b\sigma} + E_1^{a\sigma} - E_1^{b\sigma}\right) = \sigma_1 \cdot E_{R,1}^{a\sigma}$$

$$\leftrightarrow \quad \tau_1 \cdot \left(E_1^{b\sigma} - \frac{\Delta p_M\left(E_{R,1}\right) + \tau_1}{s_{D,1}}\right) = \sigma_1 \cdot \frac{\Delta p_M\left(E_{R,1}\right) + \sigma - x_1}{s_{R,1}}$$

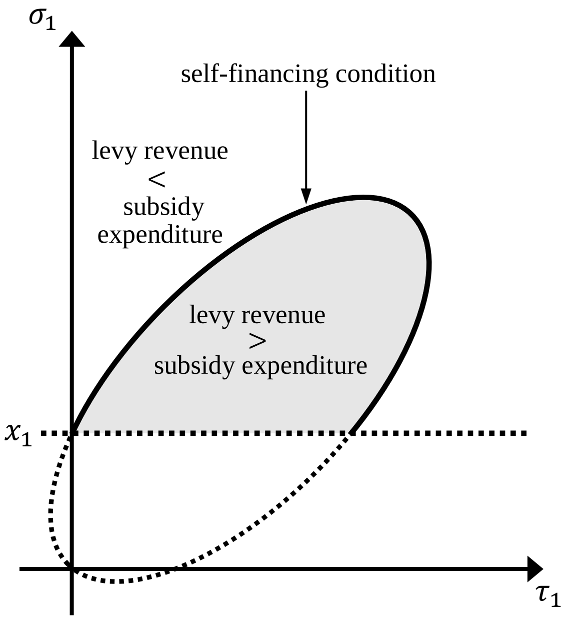
which can be simplified to:

$$\leftrightarrow \quad -(\tau_1)^2 \cdot \left(s_{D,2} + s_{R,1}\right) + \tau_1 \cdot \sigma_1 \cdot 2 \cdot s_{D,2} - (\sigma_1)^2 \cdot \left(s_{D,1} + s_{D,2}\right)$$
$$+\tau_1 \cdot \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right) + \sigma_1 \cdot x_1 \cdot \left(s_{D,1} + s_{D,2}\right) = 0 \qquad (4.21)$$

where $B = s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}$.

The characteristics of this equation will be studied as follows, the graph of which when drawn into a Cartesian coordinate system has the form of an ellipse (see Figure 4.6 for an example for the graphical representation of equation (4.21)). The focus will lie on the economic interpretations, whereby the mathematical details can be found in Appendix B.

Figure 4.6: Self-financing condition as an ellipse



Source: own illustration.

[9] See Appendix A for the derivation of equation (4.21).

The ellipse passes through $(\sigma_1, \tau_1) = (0,0)$ and $(\sigma_1, \tau_1) = (x_1, 0)$, which can be obtained by setting τ_1 equal to zero in (4.21) and solving for σ_1. The interpretation is as follows: a scheme with a zero subsidy and a zero levy evidently satisfies the financing condition; moreover, a subsidy equal to x_1 also does not lead to any additional renewable electricity, since x_1 is exactly the gap to the least costly renewable electricity unit, and is therefore also 'financeable' with a levy of zero. While the self-financing condition holds with equality on the boundary of the ellipse, any point in the interior of it implies that the levy revenue is larger than the subsidy expenditure, and vice-versa. This can be verified with the help of (4.21), but is also intuitive as, for example, moving to the right from $(\sigma_1, \tau_1) = (x_1, 0)$ means that levy revenue is generated, owing to the positive levy, whereas the subsidy expenditure remains zero since σ_1 does not increase above x_1.

Generally, only those combinations of σ_1 and τ_1 that imply $\sigma_1 \geq x_1$ and $\tau_1 \geq 0$, hold relevance when studying possible renewable energy support schemes, since only they would lead to a positive renewable electricity quantity in country 1. In fact, equation (4.21) and its graphical illustration in Figure 4.6 explain that there is a maximum subsidy that can be financed in country 1 by imposing the levy on domestic electricity consumption. The reason is that the levy creates a wedge between the domestic consumer price and the consumer price in country 2, which was already derived above. Hence as τ_1 increases, electricity becomes more expensive for domestic consumers whereas the consumer price in country 2 shrinks. Therefore, this process leads to increased electricity consumption in country, while it starts to decrease in country 1 at some size of τ_1. Thus, the relevant part of the self-financing condition as depicted in Figure 4.6 is analogous to the notion of the Laffer curve: as the levy increases, the base on which it is applied shrinks, eventually leading to a downward slope of the self-financing condition. Consequently, a the regulator in country 1 would only choose combinations of σ_1 and τ_1 on the upward sloping part.

Furthermore, the slope of the self-financing condition at $(\sigma_1, \tau_1) = (x_1, 0)$ is crucial for analyzing whether a subsidy scheme will lead to a lower consumer price in country 1 following the introduction of a subsidy scheme, which was certainly the case in Chapter 3. The slope can be determined by totally differentiating equation (4.21) and solving for

$d\sigma_1/d\tau_1$.[10] Hence, the slope of the ellipse shown in Figure 4.6, evaluated at $(\sigma_1, \tau_1) = (x, 0)$ is:

$$\left.\frac{d\sigma_1}{d\tau_1}\right|_{\substack{\tau_1=0\\ \sigma_1=x}} = \frac{s_{D,2}}{s_{D,1}+s_{D,2}} + \frac{B \cdot E_1^{b\sigma}}{x_1 \cdot \left(s_{D,1}+s_{D,2}\right)} \tag{4.22}$$

It is positive, but shrinking in x_1, which is intuitive since x_1 is the gap to the least costly renewable electricity unit, and the higher it is the larger the necessary per unit subsidy for achieving a given renewable electricity expansion, ceteris paribus. Consequently, more levy revenue is also required, implying a quicker increasing levy when σ_1 is raised beyond x_1, which is in line with the self-financing condition being flatter.

THE ZERO-CONSUMER-PRICE-CHANGE CONDITION

Combining the results derived thus far, it is possible to analyze whether the financing condition and zero-consumer-price-change condition as derived in (4.19) can be met simultaneously. If this is the case, country 1 could achieve some renewable electricity generation while the electricity price paid by domestic consumers at least remains unchanged.

In Figure 4.7 the same self-financing condition is drawn as in Figure 4.6. In addition, the zero-consumer-price-change condition, $\sigma_1 = x_1 + \tau_1 \cdot \left(1 + \frac{s_{R,1}}{s_{D,2}}\right)$, as derived in (4.19), is illustrated. It is a straight line, which as the self-financing condition also passes through $(\sigma_1, \tau_1) = (x_1, 0)$, and moreover has a positive slope of $1 + \frac{s_1^R}{|s_2^D|}$. The area above this straight line characterizes combinations of σ_1 and τ_1 that lead to a consumer price decrease, and vice-versa. This was already discussed below equation (4.19).

Given that the self-financing condition is concave at $(\sigma_1, \tau_1) = (x_1, 0)$ due to having the form of an ellipse, the sufficient condition for the consumer price in country 1 to increase following the implementation of the subsidy scheme involves the slope of the self-financing condition not being larger than $1 + \frac{s_1^R}{|s_2^D|}$ at $(\sigma_1, \tau_1) = (x_1, 0)$. Thus, it can be determined under which constellation the self-financing condition and the zero-consumer-

[10] See Appendix C for the derivation of equation (4.22).

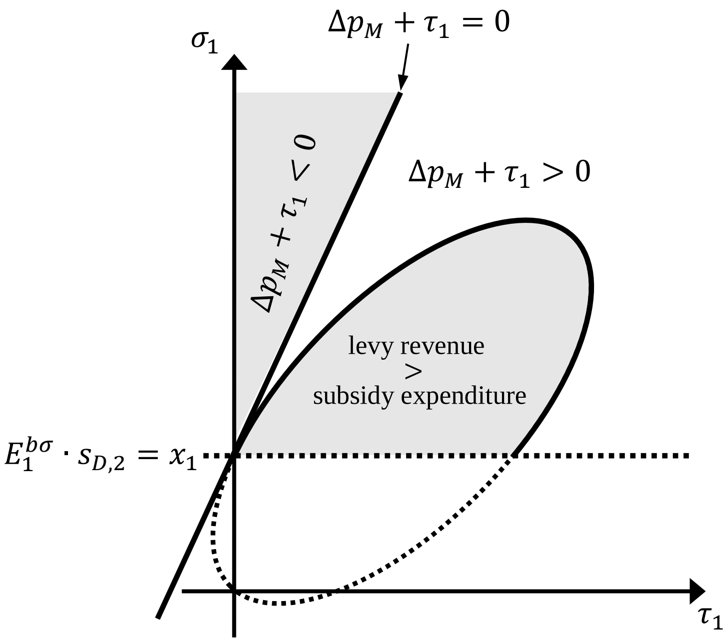
price-change condition have the same slope at $(\sigma_1, \tau_1) = (x_1, 0)$, meaning that if this is the case, any combination of σ_1 and τ_1 which respects the self-financing condition, i.e. is on the ellipse, implies an increase of the consumer price in country 1. Setting these two slopes at $(\sigma_1, \tau_1) = (x_1, 0)$ equal and simplifying yields:[11]

$$\frac{s_{D,2}}{s_{D,1} + s_{D,2}} + \frac{B \cdot E_1^{b\sigma}}{x_1 \cdot (s_{D,1} + s_{D,2})} = 1 + \frac{s_{R,1}}{s_{D,2}} \quad \leftrightarrow \quad x_1 = E_1^{b\sigma} \cdot s_{D,2} \tag{4.23}$$

where $B = s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}$ as defined above.

Thus, $x_1 = E_1^{b\sigma} \cdot s_{D,2}$ represents a case, in which the consumer price in country 1 increases certainly after the introduction of the levy-financed subsidy to renewable electricity, which is also illustrated in Figure 4.7. In fact, the consumer price in country 1 increases certainly when $x_1 \geq E_1^{b\sigma} \cdot s_{D,2}$, as will be discussed further below.

Figure 4.7: Increasing consumer price in country 1 owing to subsidizing renewable electricity



Source: own illustration.

In the case of $x_1 = E_1^{b\sigma} \cdot s_{D,2}$, the self-financing condition and the zero-consumer-price-change condition have the same slope at $(\sigma_1, \tau_1) = (x, 0)$, and hence any financeable

[11] See Appendix D for the derivation of equation (4.23).

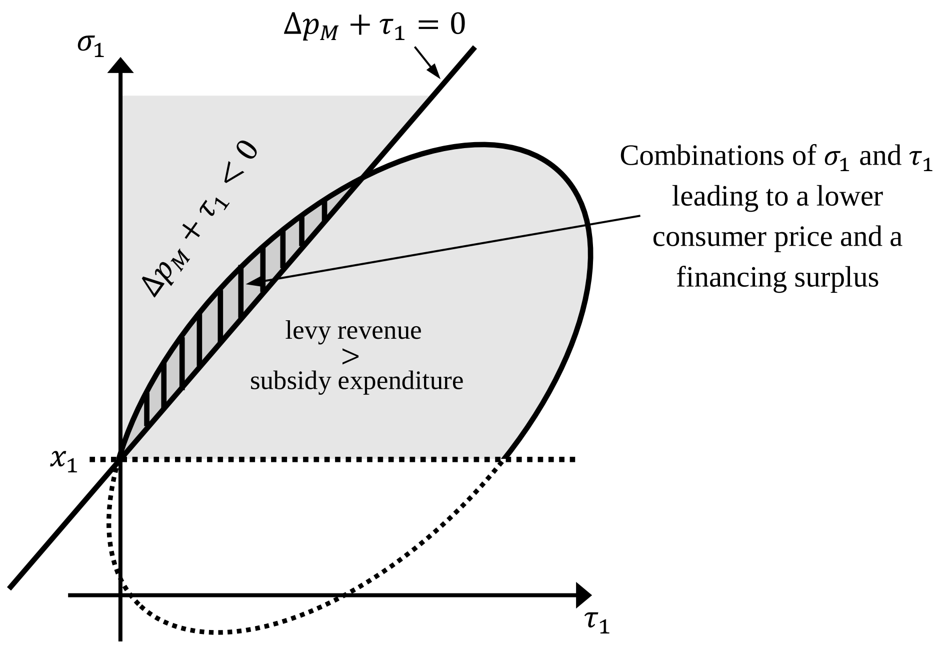
combination of $\sigma_1, \tau_1 > 0$ leads to a consumer price increase in country 1. Due to the downward sloping inverse demand function, an increase in the consumer price also is associated with a reduction of the consumed electricity quantity in country 1. This means that the consumer rent in country 1 decreases following the introduction of the subsidy scheme in such a constellation. On the other hand, since in total more electricity is being generated owing to the renewable electricity support in country 1, this outcome also implies that the electricity consumption in country 2 increases by the total renewable electricity generation, induced by the support in country 1, plus a share of the electricity originally consumed in country 1.

EXPLANATION OF THE RESULT

It is intuitive that x_1 and $s_{D,2}$, as well as $E_1^{b\sigma}$, are the crucial determinants of the burden on the electricity consumers in country 1, which implements the levy-financed subsidy scheme. When $x_1 > E_1^{b\sigma} \cdot s_{D,2}$, the zero-consumer-price-change condition is steeper than the self-financing condition at $(\sigma_1, \tau_1) = (x, 0)$, meaning that at any point to the upper-right the distance between these two is even larger than illustrated in Figure 4.7, and thus the consumer price increase in country 1 for any feasible combination of σ_1 and τ_1 being strictly positive. The interpretation is as follows: The more initially unprofitable the renewable electricity, i.e. the larger x_1 is, the more likely a consumer price increase, since the required subsidy per unit of renewable electricity is also large in this case. Moreover, a low initial electricity consumption in country 1, $E_1^{b\sigma}$, implies that also the initial base on which the levy can be imposed is small. Hence, to generate a certain levy revenue the unit levy needs to be larger, which naturally has the tendency of increasing the consumer price in this country.

Finally, $s_{D,2}$ is an important parameter for the strength of the reduction of the permit price when country 1 implements the support scheme. A high $s_{D,2}$, i.e. a steeply falling inverse demand function in country 2, implies a stronger decrease of the permit price for any combination of σ_1 and τ_1, which can also be seen from (4.17). This is intuitive and in line with the one-country model discussed in Chapter 3: if $s_{D,2}$ is large, then the additional demand for electricity by country 2 is small for a given consumer price change. Consequently, since the consumers in this country do not want to absorb the fossil electricity, which is not consumed in country 1 owing to the reduced demand because of the levy τ_1, at a moderately lower consumer price, the permit price needs to decrease more strongly for $\overline{E_F}$ yet to be consumed. In the limiting case with $s_{D,2} \to \infty$ (replicating the one-country analysis), the permit price would need to fall ceteris paribus by exactly the unit levy τ_1, as explained in Chapter 3. Hence, a large $s_{D,2}$ makes it more likely that consumers in country 1 will face a decreasing consumer price after its government has begun to support renewable electricity. On the other hand, if the electricity demand curve of country 2 is fairly flat, that is, $s_{D,2}$ is small, only a small effect on the permit price will be observed. The reason is that the electricity consumers in country 2 are willing to buy the electricity that is not demanded in country 1 owing to the levy, at a price that is not much lower than the initial consumer price. Thus, the permit price decreases only slightly and the consumer price increase in country 1 is more likely.

Figure 4.8: Negative effect on the consumer price of subsidizing renewable electricity



Source: own illustration.

In contrast to Figure 4.7, which is an example for a situation in which the consumer price in country 1 would certainly increase, Figure 4.8 offers an example, in which country 1 can achieve some expansion of renewable electricity while the consumer price decreases. The zero-consumer-price-change condition is flatter in Figure 4.8, which may be the case due to $s_{D,2}$ being larger. Hence, all combinations of σ_1 and τ_1, which lie on the left boundary of the shaded area imply that on the one hand the self-financing condition is respected and on the other hand the consumer price in country 1 decreases.

The results of this chapter can be summarized as follows: even though the permit price decreases by the same mechanism as in the one-country model when a country 1 subsidizes renewable electricity and imposes a levy on electricity consumption for its financing, it is now ambiguous whether this will impose a burden on domestic electricity consumers. Since only they contribute to the financing, the scheme particularly benefits electricity consumers in the other country, where electricity consumption increases. Thus, as more electricity is consumed abroad, an increasing consumer price in the renewable energy supporting country becomes a possible outcome, and occurs when renewable energy necessitates a high subsidy for becoming privately profitable and/or when foreign electricity consumers react strongly to changes in the electricity price. Therefore, despite the intuition provided in Chapter 3, this model explains why German electricity consumers might be suffering a burden owing to the extensive renewable energy support, while simultaneously describing that countries can appropriate rents by free-riding on the renewable energy policies of other countries with which they share a common electricity market.

The obtained results can be compared with Eichner and Pethig (2010), who argue that strategic incentives might represent the motive of countries to support renewable electricity. They derive that small countries with no effect on the permit price refrain from subsidizing renewable energy, whereas large countries impose a positive or negative subsidy on renewable energy in order to manipulate the permit price. Permit importing countries tend to subsidize renewable electricity in order to dampen the permit price, whereas permit exporting countries tend to tax renewable electricity in order to increase the price of the permits exported. Therefore, while Eichner and Pethig (2010) emphasize a different perspective than this chapter, it is also based on the possibility of a country manipulating the permit price.

4.5 IMPLICATIONS FOR ELECTRICITY TRADE FLOWS

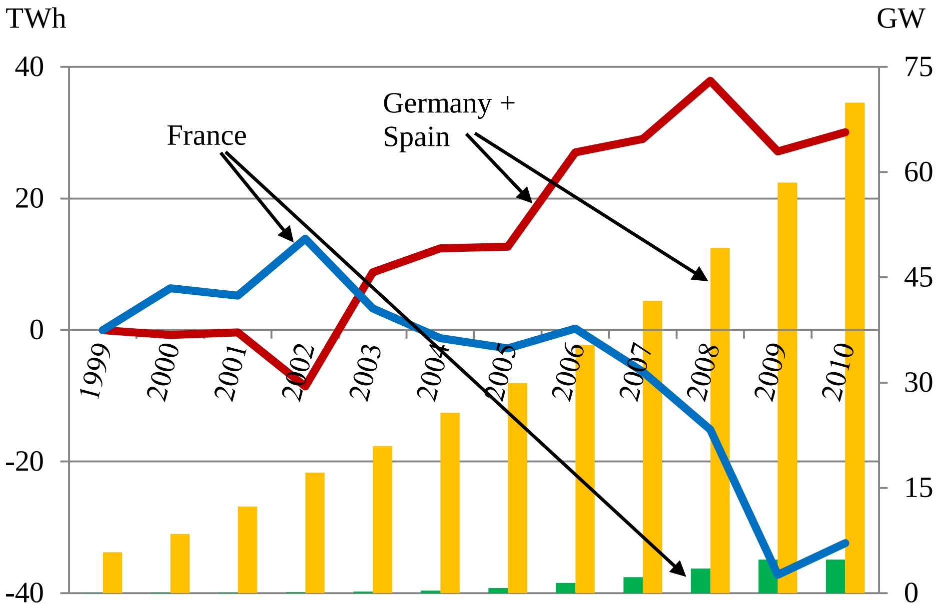
By unilaterally subsidizing renewable energy, this country increases the total electricity being generated; however, since only domestic consumers finance the subsidy by a levy the actual beneficiaries are foreign consumers, purchasing the electricity at a lower price and consequently increasing their consumption. In reality this increase in the other country's electricity consumption can occur in two ways. Firstly, for a given distribution of fossil energy power plants over these two countries, only the electricity trade flows would be affected. This is likely to be the adjustment in the short- to medium-run. Secondly, rather in the long-run, the distribution of conventional energy power plants over the two countries could change.

Thus, considering a time horizon of only a few years, a further implication of unilaterally supporting renewable energy as modeled in this chapter is the predicted increase of this country's net electricity exports. Interestingly, the model suggests that the subsidizing country may even export more than the full amount of the additional renewable electricity. Figure 4.9 aims to illustrate that those tendencies actually exist in Europe.

Note that Figure 4.9 shows the development of the net exports of Spain and Germany (red line, left axis) on one hand, and France (blue line, left axis) on the other. These are illustrated relative to the respective net exports in 1999 in the case of both curves, in order to have a common starting point. Moreover, note that the electricity trade is measured in physical units rather than value, which does not make a difference in the model yet matters in reality. Due to short-run fluctuations of the electricity price, a country that is a net exporter of electricity in quantity terms can also be net importer of electricity in value. However, these short-run effects are ignored in the model.

Spain, Germany and France have been chosen for two reasons. Firstly, the capacity for generating wind and solar electricity has strongly increased in Spain and Germany over the past decade, as shown by the yellow bars (right axis), whereas renewable energy policy in France was quite ineffective (cf. green bars, right axis). According to the model, a (unilateral) renewable energy expansion in Spain and Germany correlate with an increase in their net exports, which would be predicted to shrink in the case of France. Secondly, Spain and France as well as Germany and France share a common border, making the argument that these countries' electricity supplies affect each other more convincing.

Figure 4.9: Net exports of electricity relative to 1999 (curves, left axis), wind and solar electricity capacity (bars, right axis)



Source: Eurostat (nrg113a, nrg125).

Indeed, the stylized data suggests that the net exports of electricity of Spain and Germany have risen as their renewable electricity generating capacity increased. In contrast, the relatively large net exports of electricity of France in 1999 have shrunk by almost 20 TWh. However, despite the graph supporting the hypothesis of the model, this can serve only as a first indication, with further analysis necessary to fully validate the theoretical predictions.

4.6 Conclusions

As the slope of the demand curve in the country, which does not support renewable energy, affects the results derived in this chapter, it can be more generally discussed how $s_{D,2}$ can be interpreted. Whereas the analysis has thus far been interpreted as a two-country set-up, country 2 could also be interpreted as the sum of all other countries participating in the common electricity market, and $s_{D,2}$ would act as an indicator for the size of this country group. Total demand in a country stems from the aggregation of (homogeneous) household demands, a larger number of which could imply a lower $s_{D,2}$. Thus, $s_{D,2}$ could be high because country 2 is small; in contrast, a small $s_{D,2}$ could be interpreted as country 2 being relatively large. Since the result of the model was that a small $s_{D,2}$ increases the chance that the consumers in the renewable energy unilaterally supporting country will be burdened, one conclusion could be the following: a (small) single country is less likely able to introduce a renewable energy subsidy scheme that does not impose an additional burden on its consumers than (better) coordinated action.

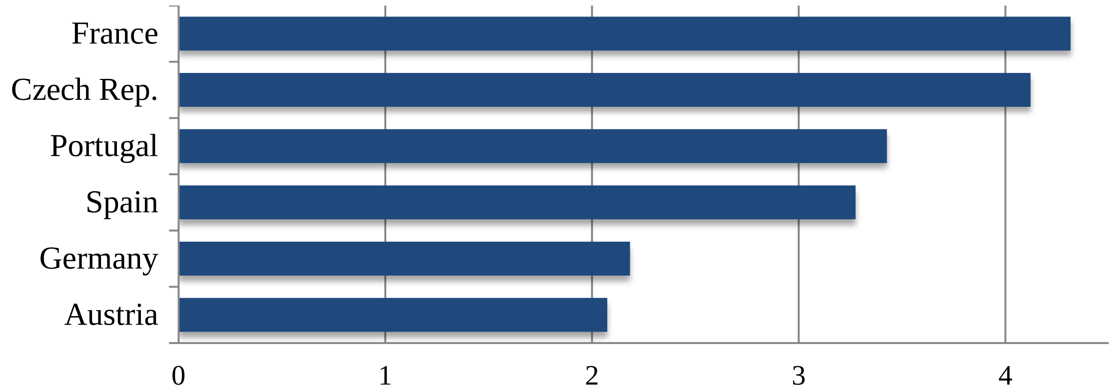
Nevertheless, in any case unilateral renewable energy support leads to a re-distribution of rents towards the electricity consumers in countries that have not introduced a subsidy scheme. Consequently, the model describes that countries can appropriate rents by free-riding on the renewable energy policies of those with which they share a common electricity market, whereas a full coordination of all countries brings the analysis back to the results obtained in Chapter 3. Concerning the normative basis for public policy interventions in the form of subsidizing renewable energy, the same arguments apply as in the conclusion of Chapter 3.

5. A new view on technology-specific feed-in tariffs

5.1 Plan of the chapter

The previous two chapters have mainly emphasized the distributional effects of a levy-financed renewable energy subsidy, and no difference was made between renewable energy technologies, such as wind energy and photovoltaic. In fact, all these alternative technologies were implicitly assumed to lie somewhere along the upward sloping marginal cost curve of renewable electricity, considering each as part of the continuum of possibilities for generating renewable electricity. Based upon this nature of interpretation, only a uniform subsidy for all available renewable energy technologies was studied in the previous chapters.

Figure 5.1: Ratio of the photovoltaic and onshore wind electricity feed-in tariff as of 2012[1]



[1] Since the feed-in tariffs in some countries differ according to the capacity of the respective facility, for instance, the highest possible feed-in tariff was always used for calculating the ratio, for simplicity reasons.
Source: RES LEGAL Europe, available at: http://www.res-legal.eu/compare-support-schemes/.

However, in reality support is differentiated between the renewable energy technologies, often being called ‘technology-specific feed-in tariffs’, in most countries that have a feed-in tariff scheme. The applied schemes typically favor less advanced technologies with a higher tariff: for example, photovoltaic electricity at one point time received a tariff in Germany six times higher than the respective compensation for wind electricity. Figure 5.1 summarizes the relationship between the feed-in tariffs for photovoltaic and onshore wind electricity in a stylized manner, specifically highlighting the ratio of the two feed-in tariffs while ignoring all other differences in the policy designs. It is notable that the feed-in tariff for photovoltaic is manifold higher in these countries, ranging from 2.1-times in Austria to

4.3-times in France. In Germany, despite having been significantly reduced it remains more than twice as high as the onshore wind electricity feed-in tariff.

Consequently, one may ask why governments favor photovoltaic over wind electricity. Both generate clean electricity while being based on an intermittent energy source, and subsequently there is no obvious reason to support photovoltaic more than wind electricity. However, economists and politicians have indeed produced a set of reasons to motivate and justify the differentiation of feed-in tariffs, with those potentially relevant arguments from an economic efficiency perspective summarized in two classes: static efficiency and dynamic efficiency. The next section will offer an intuitive interpretation of both, also citing the main doubts concerning why these arguments may be insufficient in explaining the actual support schemes.

The focus of the second part of this chapter lies on two alternative reasons favoring technology-specific support of renewable energy, one being a re-interpretation of the static efficiency concept, and the other extending this argument by including a distributional motive. In fact, these reasons may be stronger economic motives for technology-specific feed-in tariffs than those typically cited.

The analysis will assume that the climate change externality is internalized and the renewable energy target therefore constitutes only a political decision, itself reducing allocative efficiency.

5.2 EFFICIENCY REASONS IN FAVOR OF TECHNOLOGY-SPECIFIC FEED-IN TARIFFS

The efficiency of a technology-specific feed-in tariff scheme can be judged according to two basic concepts: static and dynamic efficiency. Without entering into great detail, the following subsections aim to explain both concepts briefly and intuitively. The discussion follows the previous assumption that society has decided to achieve a renewable energy target, which can only be achieved of policy supports renewable energy, and this is as such not being questioned.

STATIC EFFICIENCY

The concept of static efficiency ignores developments arising over the course of time. One particular dimension of static (production) efficiency is that goods within an economy should generally be produced at their lowest possible costs, as is typically assumed whenever a cost function is defined in an economic model. It implies that, if different ways exist to produce the same good, for the achievement of production efficiency the price of the good should be the same, independent of how it has been produced. This guarantees that the cheapest method of production will be applied, and therefore the costs for society will be minimized.

Considering society's problem of generating electricity, it is necessary to define the benefit of having renewable electricity. If the benefit is that a unit of electricity is being generated without adding carbon dioxide to the atmosphere – namely, if climate change is the motive – each unit of renewable electricity that contains this characteristic should receive the same price independent of the technology employed to generate it. A technology-specific feed-in tariff evidently violates static efficiency. Even if renewable electricity itself represents the aim of society, only uniform feed-in tariffs would lead to an efficient market outcome under these simplified assumptions.

However, it can also be argued that the social benefits and/or social costs of renewable electricity generated from different technologies are not uniform. To provide an example, renewable energy technologies may also have costs beyond the private costs of generating electricity, with one such possible reason being the noise of wind turbines. If it was not fully taken into account by their owners, regulation in the form of a lower feed-in tariff than for photovoltaic electricity, which does not have this externality, could be motivated. However, no study has found that such differences can actually justify manifold higher feed-in tariffs for photovoltaic electricity compared with wind electricity, as they can be observed in reality.

DYNAMIC EFFICIENCY

The concept of dynamic efficiency is more complex than the static efficiency consideration, requiring predictions about future developments of variables and thus naturally involving a higher degree of uncertainty. Generally, the idea of dynamic efficiency is concerned with the proper balancing of benefits and costs in the short-, medium- and long-run. Therefore, the technology that should be employed is not necessarily the least costly in the short-run, but rather the one that is most favorable when the effects on the long-run outcome are also considered. In the absence of externalities and other market failures, it is typically assumed that private markets achieve dynamic efficiency.

However, the following represents a prominent argument concerning the development of renewable energy, essentially describing a market failure: Suppose there are two alternative technologies, one of which is relatively cheaper in the short-run, but it has only little potential for cost reductions achieved by employing the technology. The other technology is less favorable in the short-run, yet has more potential for cost reduction and would therefore become cheaper in the long-run providing that investment in this technology has already occurred. Consequently, after balancing the costs in the short- and long-run, society's optimal choice could indeed be the initially more costly technology.

The market could fail to reach this allocation for a number of reasons, including an insufficient patent protection (or more generally, the existence of a positive externality due to knowledge spillovers), due to which firms have an insufficient incentive to develop the initially more expensive technology, even if they knew it would become superior in the future. Therefore, a support scheme with a uniform feed-in tariff could lead to a dynamically inefficient outcome in this example.

The example can be understood as an attempt to defend the use of technology-specific feed-in tariffs; however, its main purpose is actually to demonstrate the significant underlying uncertainty. Which technology represents the best overall choice for society is unknown, probably even more for the government than for the market participants. Therefore, if the development of a currently inferior technology leads to high additional costs in the short-run, such as in the case of photovoltaic, it is questionable whether society should select this path given the implied uncertainty (see, Yeh and Rubin, 2012, for a discussion of this uncertainty). While aware of the importance of this aspect, it is beyond the scope of this dissertation to evaluate how meaningful the use of technology-specific feed-in tariffs is for improving dynamic efficiency.

However, there is an intuitive reason in favor of technology-specific feed-in tariffs based on the notion of static efficiency. This will be presented in section 5.5, and extended by a further argument in section 5.6. Both can be derived from a simple theoretical model.

5.3 RENEWABLE ENERGY TARGETS IN THE EU

In sections 5.4 to 5.6, it will be assumed that policy has committed to achieving a fixed renewable energy target. This is the case in all EU countries, with a selection shown in Table 5.1.

In fact, EU countries have twice already formally committed to achieving a renewable energy target. The first such instance was specified in 2001, defining a target for renewable electricity for 2010. The second target was agreed in 2009, specifying how much renewable energy should be in terms of the share of total final energy consumption in 2020. As indicated in Table 5.1, the 2010 target was achieved by some countries and failed by others.

Table 5.1: Renewable energy targets in the EU (selection of countries)

	Share of renewable electricity in 1997	Target for 2010, as defined in 2001	Actual share of renewable electricity in 2010	Share of renewable energy in gross final energy consumption in 2005	Target for 2020, as defined in 2009
Belgium	1.1	6.0	6.8	2.2	13.0
Denmark	8.7	29.0	33.1	17.0	30.0
Germany	4.5	12.5	16.9	5.8	18.0
Greece	8.6	20.1	16.7	6.9	18.0
Spain	19.9	29.4	33.1	8.7	20.0
France	15.0	21.0	14.5	10.3	23.0
Ireland	3.6	13.2	12.8	3.1	16.0
Italy	16.0	25.0	22.2	5.2	17.0
Luxembourg	2.0	5.7	3.1	0.9	11.0
Netherlands	3.5	9.0	9.3	2.4	14.0
Austria	70.0	78.1	61.4	23.3	34.0
Portugal	38.5	39.0	50.0	20.5	31.0
Finland	24.7	31.5	26.5	28.5	38.0
Sweden	49.1	60.0	54.5	39.8	49.0
U. Kingdom	1.7	10.0	6.7	1.3	15.0

Source: Directive 2001/77/EC, Directive 2009/28/EC; Eurostat (nrg_ind_333a).

There are different policy paths that can be chosen by regulation in order to comply with the target, and each can be characterized under efficiency and distributional concerns. However, they all share the target acting as a constraint, whereas regulation is free to choose which other variable it wishes to maximize or minimize.

5.4 A MODEL FOR STUDYING TECHNOLOGY-SPECIFIC FEED-IN TARIFFS

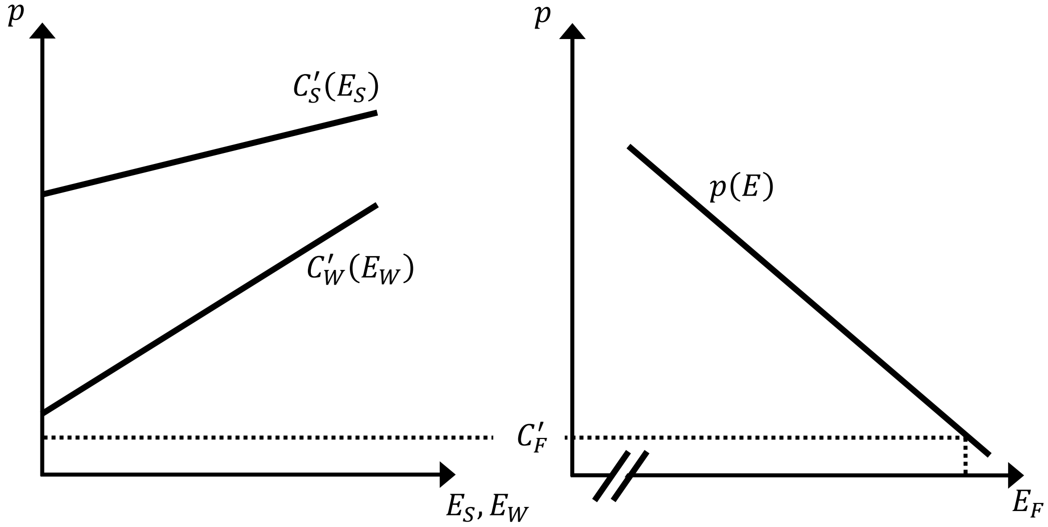
The electricity market as modeled in this chapter consists of a downward sloping inverse demand curve $p(E)$, where E denotes the consumed quantity of electricity, and the supply of electricity generated using renewable and fossil energy. More specifically, there are two renewable energy technologies – wind energy and photovoltaic – and fossil energy, with all three generating the homogenous good electricity. These three possibilities for generating electricity are modeled by representative agents, all of whom are assumed to behave competitively, thus taking the price of electricity as given.

As in the previous chapters, constant returns to scale and therefore a horizontal marginal cost curve will be assumed in the case of fossil electricity. The underlying reason is that a fossil energy power plant can be built many times at the same cost. As mentioned above, it is assumed that there is no non-internalized cost of fossil electricity and therefore C_F' denotes the private and social marginal cost of fossil electricity.

Wind and photovoltaic electricity generation both have an upward sloping marginal cost curve, labelled $C_i'(E_i)$ with $i = W, S$, where W stands for wind and S for solar photovoltaic and the electricity generation from photovoltaic and wind being denoted by E_S and E_W. The reason for this assumption is, as before, that the quality of available locations for the use of renewable energy decreases as the better ones gradually become occupied.

Suppose that electricity is initially only generated from fossil energy, which is the case if the marginal costs of wind and photovoltaic electricity are higher than C_F' even for the first units. The resulting allocation is illustrated in Figure 5.2, where it can be seen in the left diagram that electricity generation from photovoltaic and wind is zero, and fossil electricity, with the quantity being E_F, satisfies all demand (right diagram). The price of electricity is C_F', since the representative fossil electricity producer, setting the price equal to his marginal cost, is willing to supply any quantity at this price.

Figure 5.2: Market outcome without a support scheme for renewable energy



Source: own illustration.

Having specified the electricity market, the focus will now be on the renewable energy target, according to which the electricity output of renewable energy technologies is to be increased. Therefore, regulation implements a feed-in tariff p_W for a unit of wind electricity and a feed-in tariff p_S for a unit of photovoltaic electricity. Consequently, the representative producers of wind and photovoltaic electricity ($i = W, S$) solve the following problem:

$$\max_{E_i} \Pi_i = p_i \cdot E_i - C_i(E_i) \tag{5.1}$$

where Π_i denotes the profit, p_i the feed-in tariff and $C_i(E_i)$ the respective cost function. The first order condition is:

$$p_i = C_i'(E_i) \tag{5.2}$$

implying that the representative wind and photovoltaic producers choose a quantity, which equalizes the marginal cost with the feed-in tariff.

In the following, two cases will be distinguished regarding the maximization problem of the regulator. Firstly, regulation will maximize economic welfare consisting of the surplus of producers and consumers – given compliance with the renewable energy target. Subsequently, it will be considered how the problem changes when regulation minimizes the additional cost for electricity consumers. The difference between these two choices and the implication for the setting of the feed-in tariffs will be explained accordingly.

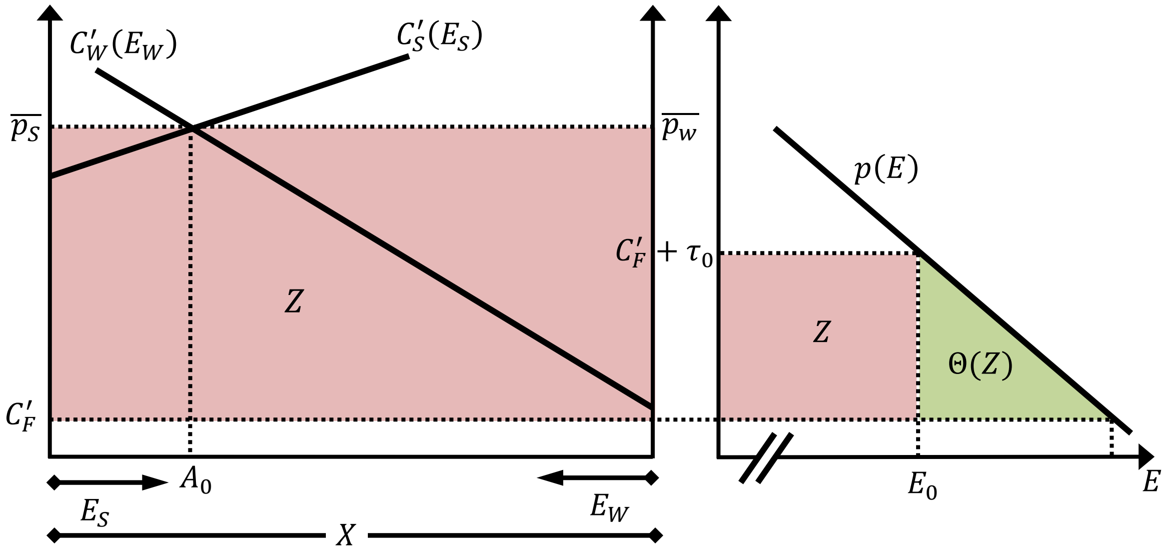
5.5 ALLOCATIVE EFFICIENCY-IMPROVING TECHNOLOGY-SPECIFIC FEED-IN TARIFFS

This section will study how a government committed to increasing the generation of renewable electricity to an amount of X should set the feed-in tariffs for wind and photovoltaic electricity in order to maximize total rents of producers and consumers. The total feed-in tariff expenditure needs to be financed by revenue from a unit levy on electricity consumption, which is denoted τ. Thus, the problem of the government is as illustrated in Figure 5.3, where the width of the left diagram is determined by the renewable energy target X. Given the increasing marginal cost curves of wind and photovoltaic electricity, one possibility to achieve the renewable electricity target is to pay a uniform feed-in tariff $\overline{p_S} = \overline{p_W}$ to both. The allocation in terms of the renewable electricity generation would be given by A_0 and suppose the unit levy on electricity consumption needed for the financing of the subsidy expenditure is τ_0. It will be explained in the following why this allocation does generally not satisfy (constrained) static efficiency.

Since the consumer price of electricity is C_F' before the introduction of the policy scheme, it increases because of it to $C_F' + \tau_0$, since the marginal cost of fossil electricity was assumed to be constant and assuming that some fossil electricity is still generated after the feed-in tariff scheme is in place. The unit levy τ is, as in the previous chapters, to be derived from a self-financing condition. The subsidy expenditure, which is implied by the feed-in tariffs is equal to $(p_W - C_F') \cdot E_W + (p_S - C_F') \cdot E_S \equiv Z$, and needs to be financed by a unit levy on electricity consumption, with its revenue being $\tau \cdot E$, where E is the consumed quantity of electricity. Thus, τ can be derived by dividing the subsidy expenditure by the total electricity consumption, given by E_0 in Figure 5.3, which also includes the renewable electricity quantity X.

In the right diagram in Figure 5.3 it can be seen that due to the higher consumer price and the downward sloping inverse demand curve less electricity is consumed than initially at the consumer price C_F'. Since C_F' is the social marginal cost of fossil electricity, an excess burden arises as the levy increases the consumer price even beyond this cost. The excess burden $\Theta(Z)$ grows as τ, the levy on electricity consumption, increases.

Figure 5.3: The renewable electricity target and the unit levy on electricity consumption



Source: own illustration.

Before solving the problem of the government concerning its choice of the feed-in tariffs, it is interesting to determine the producer and consumer rent before the introduction of the policy. Without the support to renewable electricity, only fossil electricity is generated and the producer surplus is zero as the marginal cost curve is horizontal. However, the consumer surplus is positive, equalling the area below the inverse demand curve $p(E)$ and above the market price which consumers pay for a unit of electricity C_F'. Given these initial rents, the feed-in tariff scheme to be implemented by the government can be evaluated in terms of how it changes the rents of the producers and consumers. Thus, a government which is committed to increasing the generation of renewable electricity to X solves the following problem in order to maximize total rents:

$$\max_{E_W, E_S} \; \underbrace{p_W(E_W) \cdot E_W + p_S(E_S) \cdot E_S - C_W(E_W) - C_S(E_S)}_{\textit{change in the producer surplus}}$$

$$\underbrace{-(p_W(E_W) - C_F') \cdot E_W - (p_S(E_S) - C_F') \cdot E_S - \Theta(Z)}_{\textit{change in the consumer surplus}} \tag{5.3}$$

subject to $E_W + E_S = X$. The first term in (5.1) is the change in the producer surplus, which is given by the total revenue which the producers of wind and photovoltaic electricity receive, $p_W \cdot E_W + p_S \cdot E_S$, minus their production cost for generating these quantities, $C_W(E_W) + C_S(E_S)$.

The second term in (5.1) gives the change in the consumer surplus, which has two components, and both are negative, meaning that the consumer surplus is reduced compared with the initial situation without the feed-in tariffs. One the one hand, the consumers have to pay the subsidy expenditure $Z = (p_W(E_W) - C_F') \cdot E_W + (p_S(E_S) - C_F') \cdot E_S$, which increases the consumer price via the unit levy τ. Note that $\frac{\partial Z}{\partial E_W} = p_W - C_F' + p_W' \cdot E_W$ and $\frac{\partial Z}{\partial E_S} = p_S - C_F' + p_S' \cdot E_S$, which will be used later. On the other hand, the consumer surplus is not only reduced by this amount, but also because of the excess burden Θ, which arises as the consumed quantity decreases. The excess burden increases as the subsidy expenditure Z grows (up to the maximum collectable levy revenue), i.e. $\partial\Theta/\partial Z > 0$, which can be seen in Figure 5.3.

Given that the feed-in tariff expenditure paid to the renewable electricity producers, $p_W(E_W) \cdot E_W + p_S(E_S) \cdot E_S$, only constitutes a re-distribution from consumers to the producers of renewable electricity, it is irrelevant for a total surplus maximizing regulator and thus cancels out in the objective function, as can be seen in (5.3). Hence, the objective function of the government is to:

$$\max_{E_W, E_S} \; -C_W(E_W) - C_S(E_S) + C_F' \cdot (E_W + E_S) - \Theta(Z) \tag{5.4}$$

subject to $X = E_W + E_S$. In fact, the objective function implies that the regulator aims to minimize the sum of the additional production costs when producing $E_W + E_S$ units of renewable rather than fossil electricity, given by $C_W(E_W) + C_S(E_S) - C_F' \cdot (E_W + E_S)$, and the excess burden arising from the levy on electricity consumption $\Theta(Z)$. The Lagrangian function for this maximization problem can be written as:

$$L = -C_W(E_W) - C_S(E_S) + C_F' \cdot (E_W + E_S) - \Theta(Z) + \lambda \cdot (X - E_W - E_S) \tag{5.5}$$

where λ is the Lagrange multiplier. The corresponding first order conditions are:

$$-C_W'(E_W) + C_F' - \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_W} = \lambda \tag{5.6}$$

$$-C_S'(E_S) + C_F' - \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_S} = \lambda \tag{5.7}$$

$$X - E_W - E_S = 0 \tag{5.8}$$

Note that throughout this chapter an interior solution, in which both wind and solar electricity ought to be employed, is supposed. Solving this system of equations yields a relation minimizing the social cost of achieving the renewable electricity target, which can be written as:

$$C_W'(E_W) + \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_W} = C_S'(E_S) + \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_S} \tag{5.9}$$

Using $\frac{\partial Z}{\partial E_W} = p_W - C_F' + p_W' \cdot E_W$ and $\frac{\partial Z}{\partial E_S} = p_S - C_F' + p_S' \cdot E_S$ and the fact that the competitively behaving representative wind and photovoltaic electricity producer set $p_W = C_W'(E_W)$ and $p_S = C_S'(E_S)$, respectively, when making their quantity choice (as derived in (5.2)), condition (5.9) can be written as:

$$p_W + \frac{\partial \Theta}{\partial Z} \cdot (p_W - C_F' + p_W' \cdot E_W) = p_S + \frac{\partial \Theta}{\partial Z} \cdot (p_S - C_F' + p_S' \cdot E_S)$$

$$\leftrightarrow \quad p_W \cdot \left(1 + \frac{\partial \Theta}{\partial Z} \cdot \left(1 + \frac{p_W' \cdot E_W}{p_W}\right)\right) = p_S \cdot \left(1 + \frac{\partial \Theta}{\partial Z} \cdot \left(1 + \frac{p_S' \cdot E_S}{p_S}\right)\right)$$

$$\leftrightarrow \quad p_W \cdot \left(1 + \frac{\partial \Theta}{\partial Z} \cdot \left(1 + \frac{1}{\eta_{E_W,p_W}}\right)\right) = p_S \cdot \left(1 + \frac{\partial \Theta}{\partial Z} \cdot \left(1 + \frac{1}{\eta_{E_S,p_S}}\right)\right) \tag{5.10}$$

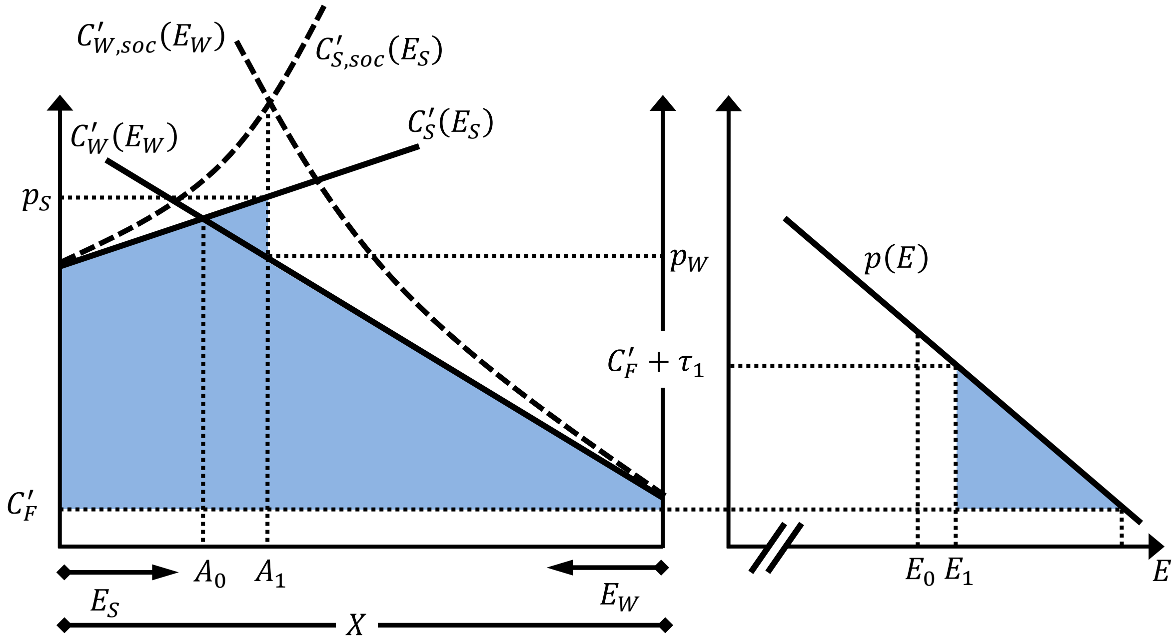
where η_{E_W,p_W} and η_{E_S,p_S} are the respective price elasticities of wind and photovoltaic electricity supply. This condition is analogous with the Amoroso-Robinson relation, which describes in its original form how the marginal revenue depends on the price and price elasticity of demand (see, Robinson, 1932). Therefore, when for the case of uniform feed-in tariffs the marginal excess burden caused by the alternative technologies differs due to non-identical price elasticities of supply, technology-specific feed-in tariffs are welfare enhancing.

The solution implies that not necessarily the private marginal costs, but rather the social marginal costs $C'_{i,soc}$ of wind and photovoltaic electricity should be equalized, whereby $C'_{W,soc}(E_W)$ is defined as $C'_W(E_W) + \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_W}$, and $C'_{S,soc}(E_S)$ is equal to $C'_S(E_S) + \frac{\partial \Theta}{\partial Z}\frac{\partial Z}{\partial E_S}$. Therefore, the social marginal cost of the two renewable energy technologies consists of the private marginal costs of generating electricity and the marginal excess burden. In fact, the derived expression is a re-formulation of the aforementioned static efficiency condition that emphasized the same good receiving the same price independent of how it has been produced. However, to achieve static efficiency in this case the feed-in tariffs possibly need to be differentiated to account for non-uniform costs beyond the private marginal costs of both technologies. The additional cost arises as an excess burden since a wedge between the consumer price and marginal cost of the fossil electricity is created owing to the unit levy on electricity consumption for the financing of the scheme.

The excess burden depends on the feed-in tariffs paid to the renewable electricity technologies, and also the quantity of electricity generated from each of them. Besides an increase in the feed-in tariff applying for the marginal electricity unit, it also affects the compensation of the intra-marginal units, which is driven by price discrimination not being possible within a technology and thus the marginal feed-in tariff expenditure is higher than the feed-in tariff itself. Hence, whenever the marginal feed-in tariff expenditures are not equal among the renewable energy technologies for a uniform feed-in tariff, a differentiation increases (static) allocative efficiency.

The result is illustrated in Figure 5.4, where the width of the left diagram is again determined by the renewable energy target X. In the selected example, the government should apply technology-specific feed-in tariffs to minimize the social cost of achieving the target, which implies choosing allocation A_1. This is the case despite the total cost of generating the amount of X from renewable energy, defined by the area below the marginal cost curves, not being minimized. For the latter to be the case, the marginal costs of generating wind and photovoltaic electricity would need to be equalized. However, the marginal expenditure for wind electricity would be higher than for photovoltaic electricity if the marginal costs were equalized, due to the higher quantity of wind electricity. Accordingly, the excess burden can be reduced by reducing the quantity of wind electricity and increasing the generation of photovoltaic electricity. Owing to the differentiation of the feeed-in tariffs the necessary levy on electricity consumption is now τ_1, whereas it would be $\tau_0 > \tau_1$ in the case of uniform feed-in tariffs (see, Figure 5.3).

Figure 5.4: Technology-specific feed-in tariffs for achieving constrained static efficiency



Source: own illustration.

5.6 The regulator as a monopsonistic buyer of renewable electricity

Suppose regulation does not aim to maximize welfare when achieving the renewable electricity target, but rather focuses on the surplus of consumers. There could be political economy reasons why this would be chosen as the objective function; moreover, it could also be important to minimize the levy on electricity consumption in order to ensure public support for the agenda.

In fact, regulation maximizing the consumer surplus while achieving a renewable energy target can be re-interpreted in the following way: Suppose consumers wish to purchase a certain amount of renewable electricity at minimal cost, with the two possibilities being wind and photovoltaic electricity. In order to achieve this aim, they appoint a regulator who sets the prices at which the consumers are willing to buy electricity from either technology. In order to minimize the expenditure of consumers, the prices are not set to equalize the marginal costs, but rather to equalize consumers' marginal expenditure on the two technologies, which can imply the need for choosing technology-specific feed-in tariffs.

As argued above, there is a reason for employing technology-specific feed-in tariffs when achieving a renewable electricity target despite regulation maximizing total rents. In the following, it will be shown that the necessary differentiation of the feed-in tariffs becomes even stronger if it predominantly cares about consumer welfare. This can be proven by again specifying the maximization problem solved by regulation, when it only considers the consumer surplus while ignoring the effects on the producer surplus:

$$\max_{E_W,E_S} \underbrace{-Z - \Theta(Z)}_{Change\ in\ CS} \tag{5.11}$$

subject to $E_W + E_S = X$, and where $Z = (p_W(E_W) - C_F') \cdot E_W + (p_S(E_S) - C_F') \cdot E_S$ as before. Thus, compared with the maximization problem defined in (5.3) the term concerning the producer surplus is missing, that is, the cost of generating renewable electricity no longer appears in the objective function. Instead, only the cost accruing to the electricity consumers is to be minimized. The Lagrangian function for this maximization problem is given by:

$$L = -Z - \Theta(Z) + \lambda \cdot (X - E_W - E_S) \tag{5.12}$$

with the new first order conditions:

$$p_W - C_F' + p_W' \cdot E_W + \frac{\partial\Theta}{\partial Z} \cdot (p_W - C_F' + p_W' \cdot E_W) = \lambda \tag{5.13}$$

$$p_S - C_F' + p_S' \cdot E_S + \frac{\partial\Theta}{\partial Z} \cdot (p_S - C_F' + p_S' \cdot E_S) = \lambda \tag{5.14}$$

$$X - E_W - E_S = 0 \tag{5.15}$$

where as before $\frac{\partial Z}{\partial E_W} = p_W - C_F' + p_W' \cdot E_W$ and $\frac{\partial Z}{\partial E_S} = p_S - C_F' + p_S' \cdot E_S$. The resulting relation for the feed-in tariffs now becomes:

$$\left(1 + \frac{\partial\Theta}{\partial Z}\right) \cdot (p_W + p_W' \cdot E_W) = \left(1 + \frac{\partial\Theta}{\partial Z}\right) \cdot (p_S + p_S' \cdot E_S) \tag{5.16}$$

alternatively:

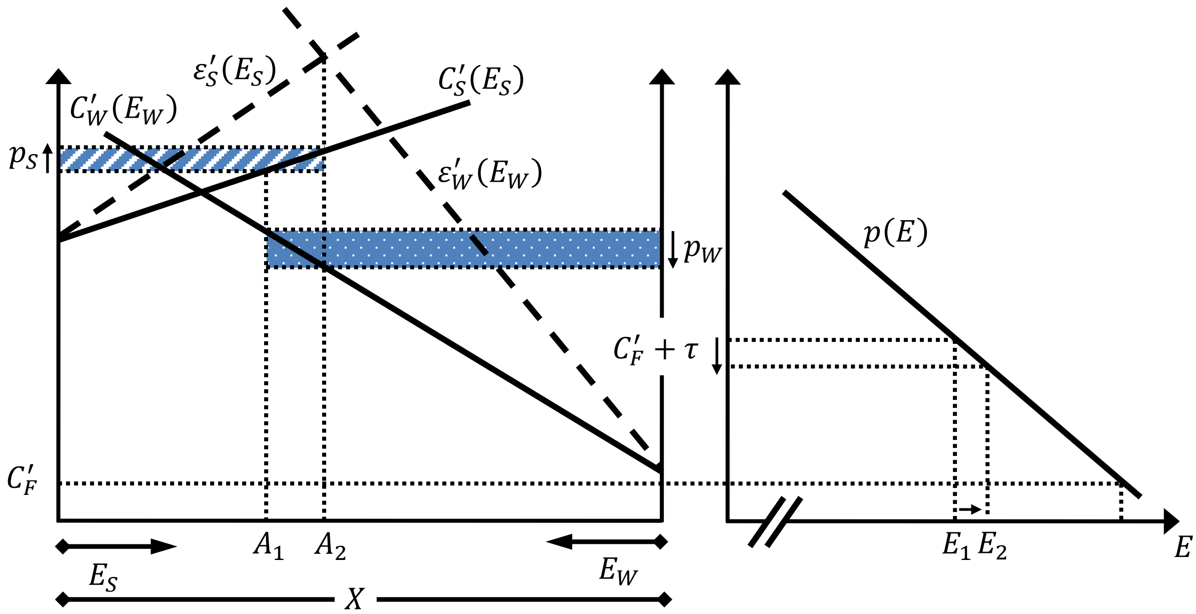
$$p_W + p_W' \cdot E_W = p_S + p_S' \cdot E_S$$

$$\leftrightarrow \qquad p_W \cdot \left(1 + \frac{p_W' \cdot E_W}{p_W}\right) = p_S \cdot \left(1 + \frac{p_S' \cdot E_S}{p_S}\right)$$

$$\leftrightarrow \qquad p_W \cdot \left(1 + \frac{1}{\eta_{E_W,p_W}}\right) = p_S \cdot \left(1 + \frac{1}{\eta_{E_S,p_S}}\right) \tag{5.17}$$

Equation (5.16) carries the basic intuition for the result: to minimize the cost for consumers, regulation equalizes the marginal consumer surplus reduction of both alternatives. This consists of the marginal expenditure ($p_i + p_i' \cdot E_i$) and the marginal excess burden which increases in the marginal expenditure. Consequently, equation (5.16) can be transformed to (5.17), according to which regulation must equalize the marginal expenditure when it acts as a monopsonistic buyer of wind and photovoltaic electricity.

Figure 5.5: Technology-specific feed-in tariffs for maximizing the consumer surplus



Source: own illustration.

Figure 5.5 illustrates the result for the same example as before. Allocation A_1 would be chosen by a total welfare maximizing government (that is constrained by the renewable electricity target), as opposed to allocation A_2 if it only maximizes the consumer surplus. By equalizing the marginal expenditure, denoted by ε_i', an even higher feed-in tariff for photovoltaic electricity is chosen, resulting in higher expenditure to the amount of the shaded rectangle in the left diagram. However, by reducing the feed-in tariff for wind electricity, consumers save an amount equal to the dotted rectangle. This results in a lower levy on electricity consumption and thus also implies a lower excess burden. Therefore, consumer surplus is higher compared to the allocation A_1, whereas the (not considered) producer surplus is lower in A_2 than in A_1.

5.7 Conclusions

In summarizing the main results of this chapter, two intuitive reasons for differentiating feed-in tariffs between renewable energy technologies can be concluded. Furthermore, in contrast to arguments related to the dynamic efficiency of renewable energy use, these do not require predictions about the future. The first reason for technology-specific feed-in tariffs is their enabling of society to achieve (constrained) static efficiency, whereby the constraint stems from an inefficiently high renewable energy target. The second motive is the maximization of the consumer rent, which implies an even stronger differentiation of the feed-in tariffs.

Interestingly, two different ways for extracting producer surplus have been considered in this chapter and in Chapter 3. Previously, it was the rent of the fossil electricity producers that could be transformed into levy revenue by reducing the value of the grandfathered emission permits, whereas this chapter has shown that the producer surplus of renewable electricity producers can be (partly) transformed into consumer surplus by differentiating the feed-in tariffs between the technologies.

6. Excessive nuclear risk-taking and the need of public policy

6.1 Plan of the chapter[12]

Topics thus far in this dissertation have focused on the use of renewable energy. However, another topic in the field of energy economics has recently attracted significant attention: nuclear energy. Due to the nuclear catastrophe in Japan in 2011, public awareness of the possibility of severe nuclear accidents has increased, and major political decisions have been taken. As briefly summarized in Chapter 1, Germany has decided to phase-out nuclear power even before the operating lifetimes of the existing nuclear power plants will be achieved. Despite the potential to write much about the process towards this decision and its impact on Germany’s electricity supply, the aim of this chapter is not to question it. Moreover, it also does not aim to generally argue in favour or against the use of nuclear power, but rather intends to apply a perspective in line Musgrave’s understanding of the role of public policy.

The purpose of this chapter is to outline and discuss one main economic problem concerning the use of nuclear power in an unbiased way, namely the safety of nuclear power reactors. It will be explained that owing to a market failure, the safety chosen by the nuclear power companies might be inefficiently low. Knowing that a market failure generally implies an inefficient allocation of resources, there are two channels by which the inefficiency can occur in such a case. Firstly, society might face an inefficiently high probability of a severe nuclear accident due to the insufficient level of safety. Secondly, if society is aware of the inefficiently high risk and thus chooses to phase-out nuclear power, it also misses the optimal allocation, whenever it would have been optimal to continue using nuclear power with the correctly selected safety level.

Therefore, this chapter provides guidance on what kind of public policy would be needed to ensure an efficient use of nuclear power, whereby society may still choose not to use nuclear power once an efficient safety level is achieved, for different reasons. After providing an introduction to the current state of nuclear energy use around the world, it will be derived that a negative externality arises and risk-taking of nuclear power companies (NPCs) is too excessive, both because of the existence of limited liability.

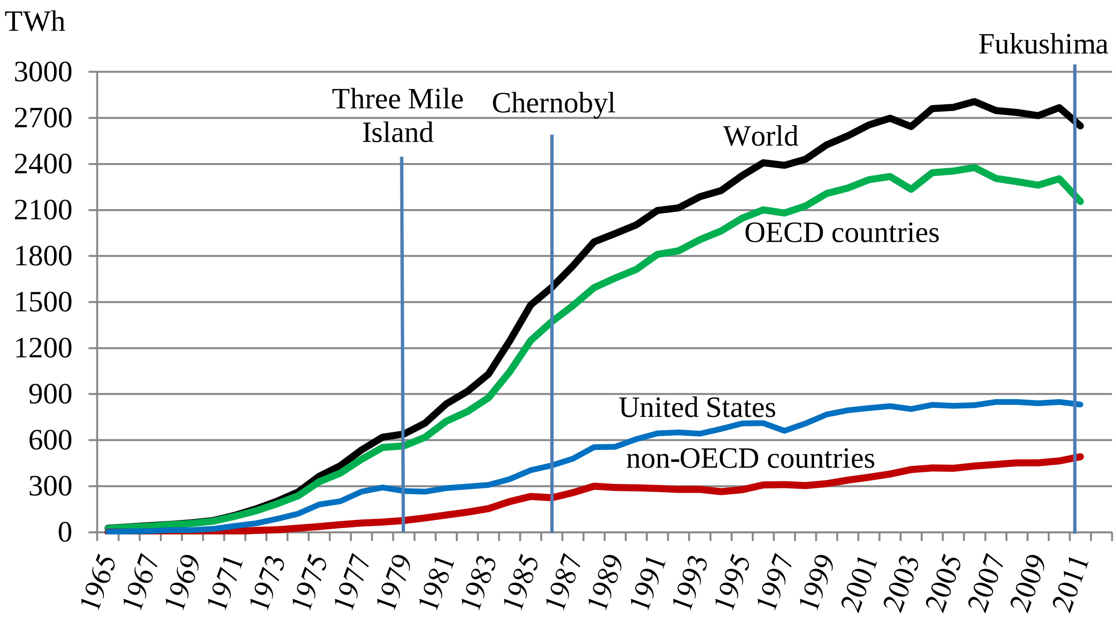
[12] The sections 6.3-6.8 are based on joint work with Jakob Eberl, cf. Eberl and Jus (2012).

Reviewing the current regulation and discussing possible regulatory instruments regarding their ability to deal with this problem, it will be concluded that neither current regulation nor those regulatory instruments in their pure form would be able to induce an efficient risk choice. Therefore, a new regulatory proposal will be presented and discussed in the final part.

6.2 NUCLEAR ENERGY USE AROUND THE WORLD

The commercial use of nuclear energy to generate electricity began in the 1950s, but only became an important component in the world's energy supply at the end of the 1960s. Of the two possibilities for exploiting nuclear energy, nuclear fission and nuclear fusion, only nuclear fission has been used commercially to date. Similar to fossil fuel power plants, nuclear fission reactors also typically generate electricity by heating water and using the steam to drive turbines. However, the source of the heat does not stem from the burning of a substance, rather from a (controlled) chain reaction in which atoms are split.

Figure 6.1: Nuclear electricity generation since 1965, by region



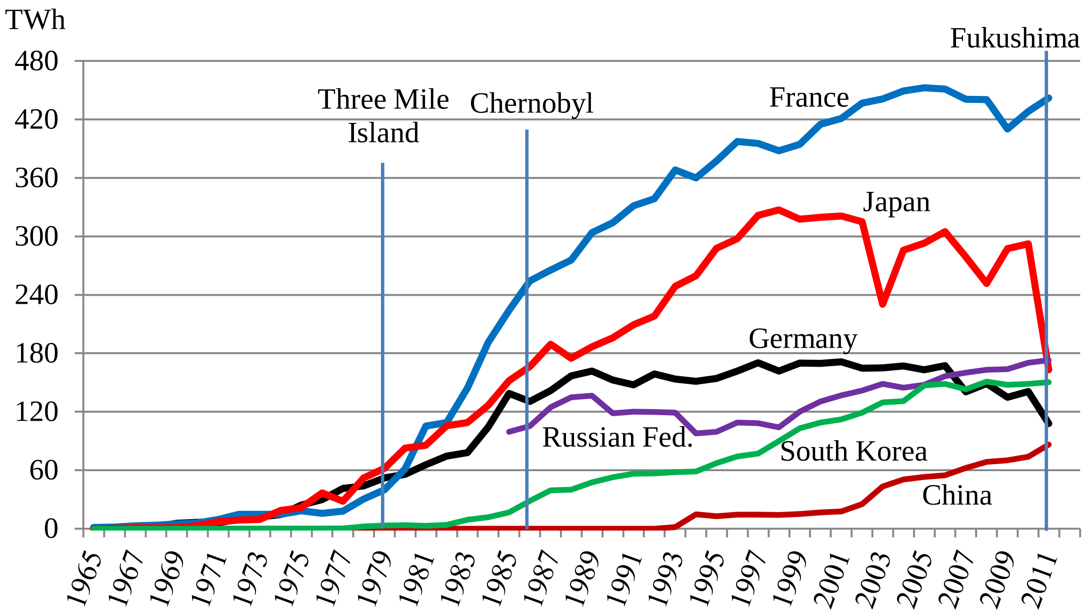
Source: BP Statistical Review of World Energy June 2012.

Figures 6.1 and 6.2 illustrate the development of nuclear electricity generation since 1965. The two major countries in terms of nuclear electricity generation are the United States and

France, accounting for almost 50 percent of the world's nuclear electricity generation in 2011.

Nuclear electricity has been losing relative importance in worldwide terms since the mid-1990s. Whereas it accounted for more than 17 percent of the world's electricity generation during the mid-1990s, its share declined to 13 percent in 2010 and only 12 percent in 2011. The reason for this relative decline can be found in its stagnation in the OECD countries, particularly Germany and Japan, whereas nuclear electricity generation is rapidly increasing in China and India, for example. The absolute decline in 2011 compared to 2010 is largely due to a strong decline in Germany (minus 32.6 TWh) and even more so in Japan (minus 129.5 TWh). Excluding those two countries, the rest of the world's nuclear electricity generation even increased by 42.6 TWh in 2011, relative to 2010.

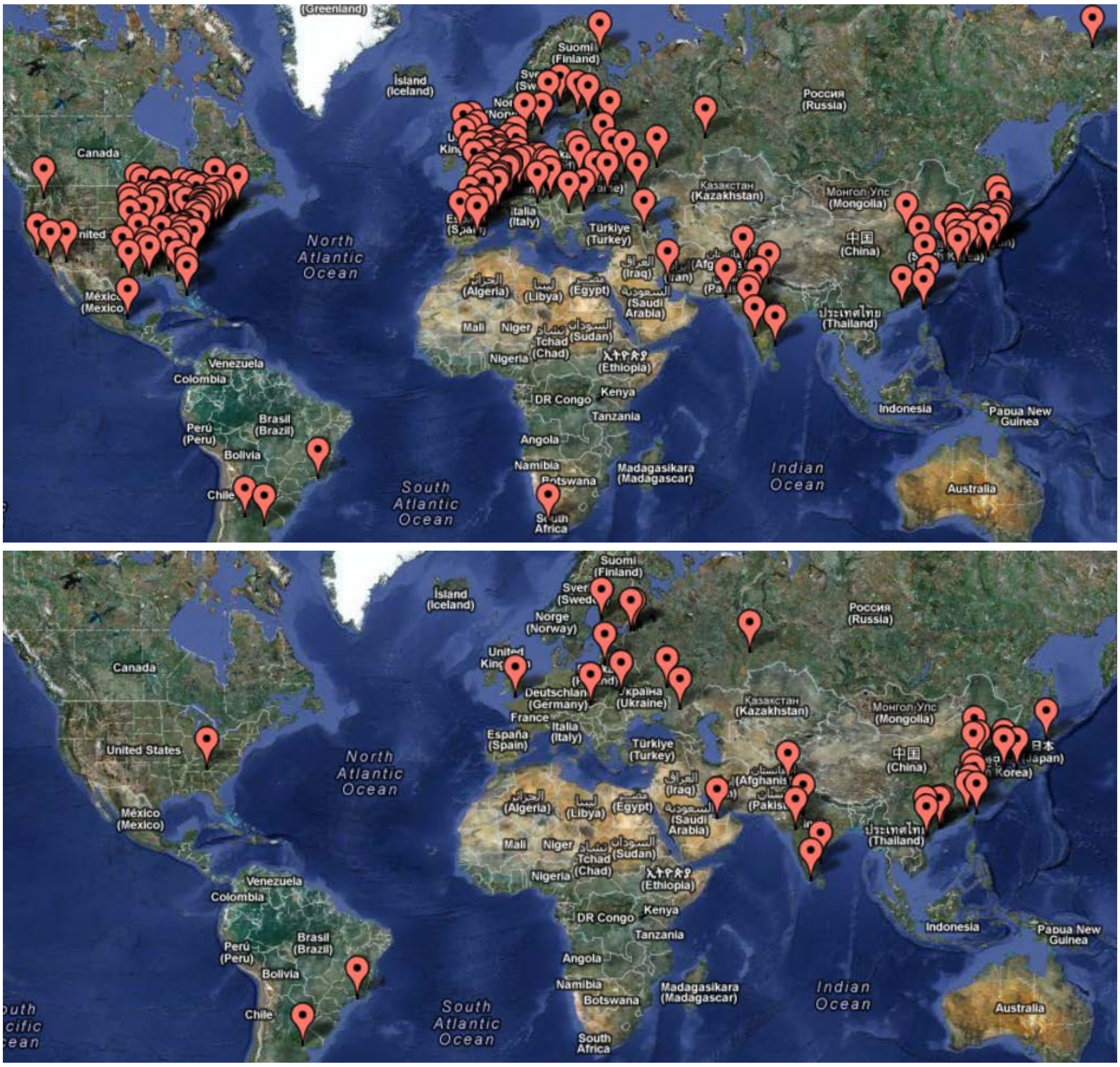
Figure 6.2: Nuclear electricity generation since 1965, by country



Source: BP Statistical Review of World Energy June 2012.

After the terrifying catastrophe in Japan in March 2011, a fundamental reassessment of nuclear risk generally occurred all around the world. As previously discussed, a complete phase-out was decided within a few months in Germany, according to which some nuclear power plants are supposed to be shut down even before their scheduled operational lifetime. Switzerland has also stated its ambition to phase-out the use of nuclear power, however only after the operational lifetime is achieved. Belgium, which had already set out and later abandoned a phase-out plan before the Fukushima catastrophe, is now aiming again to phase-out nuclear power by 2025. However, in the same course, the operation license for the Tihange 1 nuclear power reactor has been extended until 2025, having been originally supposed to end in 2015. In Japan, where all reactors were temporarily shut down for safety revisions, the Ōi nuclear power plant has been reconnected since July 2012. The "Energy & Environment Council" established by the Japanese cabinet office in July 2011 has recommended not building new nuclear power plants, whereas those existing are to be restarted once their safety has been assessed (see EEC, 2012).

Figure 6.3: Currently operating nuclear power reactors (upper map), nuclear power reactors currently under construction (lower map)



Source: World Nuclear Association Reactor Database, available at: http://world-nuclear.org/NuclearDatabase.

Most other nuclear power using countries have chosen to continue with their nuclear power plans for the time being, in the same vein as before the Fukushima accident. Moreover, many countries around the world are even currently expanding their civilian nuclear programs. The notion that nuclear fission will remain an important source of energy in the future is also found within the content of the Energy Roadmap 2050, published by the European Commission in December 2011. It emphasizes the current and future role of nuclear energy as an 'important part of Europe's power generation mix' considering it 'needed to provide a significant contribution in the energy transformation process' (see EC, 2011b).

As of December 2012, 437 nuclear reactors are operating worldwide, and another 64 are under construction. The list of countries with the most nuclear power reactors under construction is headed by China (27 reactors under construction), Russia (10) and India (7), but reactors are currently being built also in the European Union (France, Finland and Slovakia). The location of these reactors is illustrated in the lower map in Figure 6.3, whereas the upper map highlights all nuclear reactors in current operation. Moreover, there a large number of nuclear reactors planned or proposed all around the world. Thus, despite a general reassessment of nuclear risk after the Fukushima catastrophe, nuclear power is likely to remain (or become) a significant determinant of many countries' electricity supply.

6.3 THE TWO MAJOR PROBLEMS ASSOCIATED WITH THE USE OF NUCLEAR ENERGY

There are two major concerns regarding the use of nuclear fission for the generation of electricity: nuclear waste and the possibility of (severe) accidents, with both potentially leading to negative externalities if public policy does not implement proper regulation.

The handling of waste and the pollution of the environment are classical examples of negative externalities. Nuclear electricity producers would likely choose cheaper ways for dealing with nuclear waste if regulation did not demand certain rules to be respected. These cheaper ways would possibly imply higher costs for current society and/or future generations, which would not be taken into account in their full extent by today's profit maximizing NPCs. Therefore, the setting and enforcement of regulation is necessary for an efficient allocation to be achieved. Bearing this issue in mind, this chapter places a focus on the second problem, namely the issue of nuclear catastrophes.

Three terrifying events have occurred in the history of civilian nuclear energy use: the Three Mile Island accident in 1979, the Chernobyl disaster in 1986, and the Fukushima Dai-ichi catastrophe in 2011. Given the large number of nuclear reactors worldwide, the general probability of a severe accident occurring at a nuclear power reactor in a given year is microscopically small, yet, as the aforementioned catastrophes have proven, such risk does exist. There is currently no existing alternative that could generate sufficient amounts of electricity at low costs and without creating some sort of risk. The use of fossil energy causes climate change and also deaths in the mining and extraction industry, whereas the generation of renewable electricity is costly as such and suffers from the problem that electricity cannot yet be stored at reasonable costs. Therefore, the role of public policy should be to ensure that benefits and costs are fully taken into account by market participants, who would accordingly find efficient solutions for how to generate electricity.

With clean-up costs alone that could exceed JPY 20 trillion over the next ten years (cf. JCER, 2011), the Fukushima accident has reminded the world how strongly a society can be affected by the use of nuclear energy. At the same, it may be asked whether the NPCs actively influencing the probability of such an accident occurring are also those who bear the full costs in the unlikely yet existing case that it occurs. For example, Tokyo Electric Power Company (TEPCO) reported equity capital to the amount of JPY 2.47 trillion for March 2010, the last annual report published before the 2011 catastrophe (see TEPCO, 2011). This does not appear small at first glance; however, this amount only constitutes a small proportion of the actual costs of the Fukushima catastrophe, the remainder of which cannot be borne by TEPCO. Similarly, the liability of other NPCs around the world is limited de jure or de facto (by the equity capital of the company); see Table 6.1 for a brief overview.

This chapter argues that a main problem arises due to the existence of de facto or de jure limited liability of NPCs. The basic mechanism implies that an NPC cannot lose more than the legally defined liability capital, or in the worst case its equity capital, regardless of the higher damage of a nuclear accident. This reduces the incentive to invest in costly nuclear safety, thus leading to an inefficient safety level in nuclear reactors.

Table 6.1: *De facto* vs. *de jure* limited liability, selected countries and selected NPCs

Selection of countries with *de jure* limited liability[a]		Countries with *de facto* limited liability[b]		
China	RMB 300 million	Germany	E.ON	EUR 39.6 billion
Czech Republic	CZK 8 billion		RWE	EUR 9.9 billion
France	EUR 91 million		EnBW	EUR 6.1 billion
India	INR 5 billion		Vattenfall	SEK 138.9
United Kingdom	GBP 140 million	Japan	TEPCO	JPY 2.47[c] trillion
United States	USD 375 million	Switzerland	Axpo	CHF 7.6 billion

[a] right column: *de jure* national liability limitation; [b] right column: NPCs' equity capital in 2011; [c] as of March 2010;
Source: Eberl and Jus (2012).

The de jure limitations of nuclear liability have already existed for a long time, as will be emphasized in section 6.5. A major goal of nuclear liability regulation has been to protect NPCs against potentially ruinous claims. By introducing a limit up to which they can be made liable, liability is passed from the operator to a third party for any damage beyond this limit. In essence, this limitation has been justified by the social benefits of nuclear power, creating a tacit acceptance of nuclear risk by the society. At the same time, it has also increased the profitability of the nuclear industry, thereby fostering its development. The downside of this will be explained in the following section, which will outline the underlying theory and illustrate why the existence of limited liability leads to excessive risk-taking.

6.4 Limited liability and excessive nuclear risk-taking

Suppose a NPC maximizes its profit by choosing its nuclear power reactor's level of risk. It can build and operate a reactor with lower safety, thus reducing its costs (thereby increasing its profits), however this also leads to a higher probability of a catastrophic accident occurring. The maximization problem is:

$$\max_R \quad \big(1-p(R)\big)\cdot\big(E+\Pi(R)\big)+p(R)\ \cdot max(E-L,0)-E \tag{6.1}$$

where R is the level of risk chosen and $p(R)$, with $p'(R)>0$, is the probability of a catastrophic accident. Only a two-point distribution is considered for the sake of simplicity, meaning that if an accident occurs then the loss of the NPC is L. The variable Π denotes the profits of the NPC in the case that no accident occurs, and it is increasing in R as a lower level of safety is less costly providing no accident takes place. Finally, E is the equity capital of the NPC, which by the nature of a firm with limited liability, can at most be lost in case of an accident. Thus, in the case of no catastrophe the equity of the NPC remains within the firm, while additionally profits are generated. In the other state of the world, the wealth of the NPC is reduced to $E-L$ or zero, whichever of the two is larger.

Hence, there are two possible outcomes when a catastrophic accident occurs: the liable equity capital can be sufficient to cover the losses, or it can be lower than the resulting damage. Denoting by L_0 a possible damage for which holds that $E\geq L_0$, the maximization problem of the NPC becomes

$$\max_R \quad \big(1-p(R)\big)\cdot\big(E+\Pi(R)\big)+p(R)\ \cdot(E-L_0)-E \tag{6.2}$$

and the first order condition is:

$$\big(1-p(R^*)\big)\cdot\Pi'(R^*)-p'(R^*)\cdot(\Pi(R^*)+L_0)=0$$

$$\leftrightarrow \underbrace{\big(1-p(R^*)\big)\cdot\Pi'(R^*)}_{\substack{\text{benefit of a marginal}\\ \text{increase in risk}}}=\underbrace{p'(R^*)\cdot(\Pi(R^*)+E)+p'(R^*)\cdot(L_0-E)}_{\substack{\text{cost of a marginal}\\ \text{increase in risk}}} \tag{6.3}$$

Since all costs and benefits are fully taken into account by the NPS, the resulting risk choice R^* satisfies allocative efficiency (in the absence of other market failures), and can thus be regarded as the benchmark in the following.

In contrast to this case, suppose that the damage from a nuclear accident, now denoted by L_1, would exceed the equity capital of the NPC, that is, $E<L_1$. This is a realistic assumption as shown in the example of the Fukushima catastrophe. Since the NPC is a firm with limited liability, the maximization problem becomes

$$\max_R \quad \big(1-p(R)\big)\cdot\big(E+\Pi(R)\big)-E \tag{6.4}$$

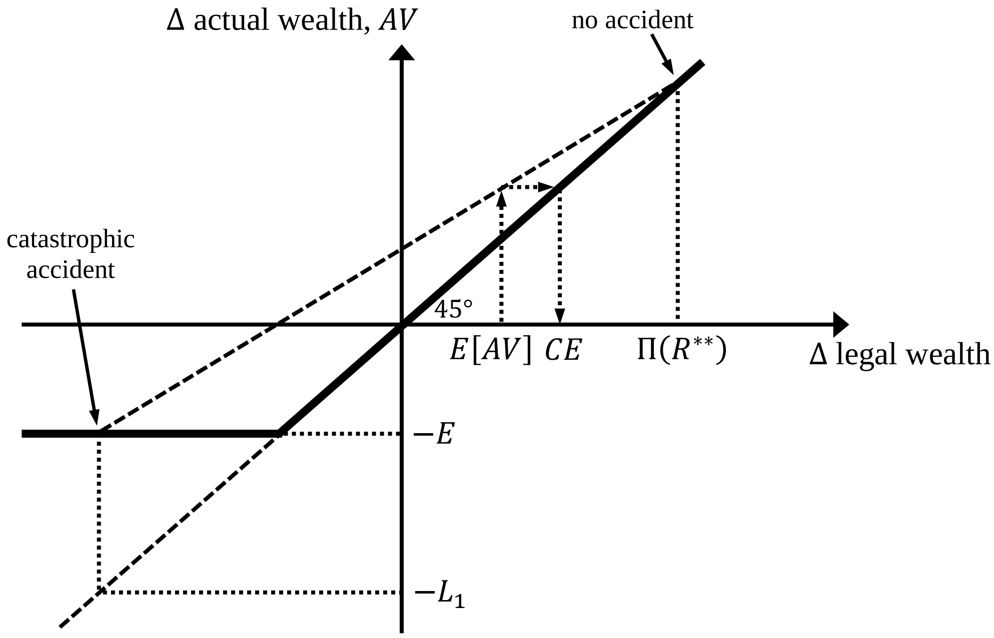
and the first order condition is:

$$\big(1 - p(R^{**})\big) \cdot \Pi'(R^{**}) - p'(R^{**}) \cdot \big(E + \Pi(R^{**})\big) = 0$$

$$\leftrightarrow \underbrace{\big(1 - p(R^{**})\big) \cdot \Pi'(R^{**})}_{\substack{\text{benefit of a marginal} \\ \text{increase in risk}}} = \underbrace{p'(R^{**}) \cdot (\Pi(R^{**}) + E)}_{\substack{\text{cost of a marginal} \\ \text{increase in risk} \\ \text{under binding limited liability}}} \tag{6.5}$$

where R^{**} is the risk-taking of the NPC under the assumptions made. The difference between this case and the previously derived efficient risk-taking is that under binding limited liability the term $p'(R) \cdot (L - E)$ no longer appears. The NPC can at most be made liable with the equity capital E, and thus does not consider any cost beyond E. According to Shavell (1986), in this case the NPC is 'judgment proof'.

Figure 6.4: The effect of limited liability on the NPC's risk preference



Source: cf. Sinn (1983) and Eberl and Jus (2012).

Figure 6.4 illustrates the underlying reasoning, whereby the change in the legal wealth of the NPC is shown on the horizontal axis, whereas the change in the actual wealth is on the vertical axis. The actual wealth can at most decline by E, whereas the legal wealth in the case of a severe accident with high damage can decrease by L_1. Thus, due to limited liability, the NPC's change in the actual profit is horizontal for any loss that is larger than its equity capital. It can be seen from Figure 6.4 that if the equity capital is sufficient to pay for the damage, the expected change in the legal wealth and the actual wealth coincide. However, if the potential loss exceeds the equity capital, the expected actual wealth is higher than the expected legal wealth. In such a case, an otherwise risk-neutral NPC strictly prefers the gamble between the two possible outcomes, which gives an expected change in the actual wealth of $E[AV]$, over a certain change in the legal wealth of the same amount. In fact, to be indifferent it would require a certain change in the legal wealth of CE, which is its certainty equivalent. Thus, given that the NPC operates under limited liability and potential losses can exceed its equity capital, an artificial risk-preference occurs. In terms of reactor safety, this means that the NPC chooses an inefficiently low level of care, as can also be seen from condition (6.5) in comparison with (6.3).

As explained in Sinn (1980, 1982. 1983), the underlying reason for the extensive risk preference is that the function describing the change in the actual wealth becomes de facto convex, indicating a risk-loving behaviour that can be interpreted as a preference of the NPC for choosing an inefficiently low safety. This argument is also discussed by Tyran and Zweifel (1993), Strand (1994) and Trebilcock and Winter (1997), with a review of other related literature provided by van’t Veld and Hutchinson (2009).

6.5 Liability regulation of the nuclear power industry around the world

The development of nuclear power liability regulation and its current state are briefly summarized in the following section, referring to Faure and Vanden Borre (2008) for an extensive analysis of international nuclear liability.

Passed in the United States in 1957, the Price-Anderson Act (cf. US NRC, 2012) was the first comprehensive nuclear liability law and has been central to the issue of liability in nuclear accidents. It has been repeatedly renewed (with amendments), most recently in 2005 for another 20 years, with the defined amount of an NPC’s liability gradually increasing over time. Today, coverage in the case of accident is provided by the nuclear industry itself on a two-tier basis. At the first layer, all NPCs are strictly and individually liable, required to purchase USD 375 million of liability coverage per reactor, provided by a private insurance pool. At the second layer, coverage is supplied by a mutual and solidary risk-sharing agreement among the NPCs. This risk-sharing pool is funded through retrospective payments in the case of a nuclear accident, which can reach up to

USD 112 million per reactor. In total, this two-tier system provides an aggregate sum of USD 12 billion of liability capital.

Liability regulation of the nuclear industry outside the United States is based on two conventions, the Paris Convention (NEA, 1960) and the Vienna Convention (IAEA, 1963), and on individual countries' national regulations. Whereas the Paris Convention covers European states, those from all over the world are party to the Vienna Convention. The national regulation in most countries that fall under one of these two conventions usually follow the proposed liability framework, with only few exceptions where the liability of NPCs is considerably higher than that demanded by the conventions.

The basic characteristics of the Paris Convention can be summarised as follows: (1) nuclear companies are strictly liable for any third-party damage, thus their liability is irrespective of their own fault;[13] (2) liability is fully channelled to the NPCs, thus only they can be sued; and (3) liability is limited to a pre-defined amount and a specified period of time within which claims can be made. More specifically, liability was originally supposed to be limited to a maximum SDR 15 million, whereas the minimum was supposed to be SDR 5 million;[14] however, national legislation has been allowed to provide for a higher, but necessarily limited, amount. Finally, (4) the liability has to be covered by mandatory insurance or some other financial security, to be held by the NPCs. The Paris Convention was amended in 1964, 1982 and in 2004, and according to the most recent amendment the minimum liability of nuclear operators is supposed to be raised to 700 million (cf. NEA, 2004, Art. 7). Moreover, the sentence excluding any liability for damage owing to 'a grave natural disaster of an exceptional character' has been removed (cf. NEA, 1960, and NEA, 2004). It was also the first amendment to allow the participation of countries with a de jure unlimited liability in place (Germany and Switzerland), thereby implicitly agreeing to this type of national liability legislation. However, the 2004 amendment is not yet in force as only Switzerland and Norway have ratified it to date.

In 1963, the Brussels Convention, supplementing the Paris Convention, introduced that in addition to the NPC, the state in which the nuclear accident occurs is also liable,

[13] Cf. Shavell (1980, 1982) for a comprehensive analysis of the incentives strict liability and negligence rules have on risk-taking.
[14] A Special Drawing Right (SDR) is a unit defined by the International Monetary Fund (IMF). As of March 2012, the value of one SDR equals USD 0.66, EUR 0.423, JPY 12.1, and GBP 0.111.

with a limit set at SDR 70 million. Moreover, all signatory states agreed to be jointly liable for claims, whereby each state is obliged to supply up to SDR 50 million.

Parallel to the Paris and Brussels conventions, the IAEA's 1963 Vienna Convention introduced a regulatory framework signed by 38 countries, including the Russian Federation, Ukraine, and Czech Republic, but also a large number of countries that do not even have a civilian nuclear program. It shares the basic principles of the Paris Convention, with the minimum liability of the NPCs initially only supposed to be USD 5 million. It was amended once in 1997, with the main difference being a seemingly higher minimum liability limit of NPCs in the amount at least of SDR 300 million. However, this may be reduced to SDR 150 million or only SDR 5 million, whereby the lower amounts are allowed if public funds are provided to cover the sum of SDR 300 million (cf. IAEA, 1997, Art. 7).

Following the 1986 nuclear accident at Chernobyl, efforts to clarify the applicability of the two 'competing' conventions have led to the establishment of a Joint Protocol, according to which only one of the two conventions shall apply to a nuclear accident, namely the one to which the country within whose territory the nuclear reactor is situated is party to (cf. NEA and IAEA, 1988).

The heterogeneity in national regulation stems from a few countries having substantially stricter rules than demanded by the conventions. For example, liability legislation in Germany far exceeds the requirements of the (amended) Paris Convention. Together with Japan and Switzerland, Germany is one of only three countries with a legally unlimited liability of NPCs. In order to ensure a desired minimum amount of financial security, it requires the amount of EUR 2.5 billion per reactor to be guaranteed by both a nuclear insurance pool and risk-sharing agreement between the NPCs. In addition to financial security, the European Union provides EUR 300 million in accordance with the Brussels Convention in case of an accident. For any loss exceeding the aggregate amount, the NPCs' liability is legally unlimited; however, this definition of unlimited liability only constitutes a legal property that cannot actually be sustained. In Switzerland, where NPCs are also de jure unlimitedly liable, they are required to hold financial security to the amount of CHF 1 billion. By contrast, the liability regulation of NPCs in France is weaker, with the liability of the state-owned NPC[15] being de jure limited to an amount of EUR 91 million (projected to increase to EUR 700 million, according to the 2004 amendment), which must be insured. This is also the case in the Czech Republic, where the de jure liability limit of CZK 8 billion necessitates insurance.

As they are not party to any international conventions and thus rely on their own arrangements, China, India and Japan occupy a special position in global nuclear liability legislation. China passed an interim law on nuclear liability in 1986, containing the basic properties of the international conventions. NPCs' liability limit was increased to RMB 300 million in 2007, above which the state is legally liable for up to RMB 800 million. However, this legal regime is under revision, with China aiming to modify its nuclear energy law along with its nuclear expansion (see WNA, 2012a). In 2010, the Indian government passed the so-called Nuclear Liability Act, which brings its liability regulation broadly in line with international conventions. The act renders NPCs liable for nuclear accidents up to an amount of INR 5 billion (although not exclusively).

NPCs' liability is strict, exclusive, and legally unlimited in Japan, and furthermore a financial security must be provided to the amount of JPY 120 billion. In addition, Japan's 1961 Act on Compensation for Nuclear Damage (cf. NSC of Japan, 1961) allows for an NPC to be relieved of liability in claims resulting from 'a grave natural disaster of an exceptional character', the relevance of which came into discussion after the Fukushima catastrophe. Regardless of this paragraph, the catastrophe has provided evidence that the costs of a large-scale nuclear accident can easily exceed the means of an NPC, and that society must eventually step in. Within this context, the Japanese government decided to provide financial assistance for compensation payments and clean-up costs, demanding an annual fee from TEPCO accordingly. The main reason for bailing TEPCO out was its essential role in maintaining adequate power supply and the need to ensure the safety of its other power plants. According to government estimates, TEPCO will be able to complete its repayments in 10 to 13 years, after which it is supposed to revert to being a fully private company with no government involvement (cf. WNA, 2012b).

The main insight gleaned from studying nuclear liability regulation around the world is that the liability for losses from catastrophic accidents is either de facto limited by

[15] As of August 2012, the French state holds 84.8 percent of the shares of Électricité de France (EdF), the owner of all French nuclear power plants.

the NPCs' equity capital (as in Germany, Switzerland and Japan) or de jure limited by national legislation (all other countries). Thus, some countries have chosen to limit NPCs' liability explicitly while firms in other countries are liable, at most, with their equity capital by their nature. As previously discussed, the consequences of limited liability become relevant in both cases. On this basis, the following section critically discusses the regulatory instruments that could be applied by a regulatory authority.

6.6 POLICY INSTRUMENTS WITH THE AIM OF ATTAINING THE OPTIMAL LEVEL OF SAFETY

Two schools of thought developed in the twentieth century could be applied in order to overcome the problem stemming from the existence of a negative externality, as described here. The first, the Coasian solution (drawing from Coase, 1960), would argue that defining property rights and letting the involved parties negotiate potential outcomes can solve the problem at hand. The other, the Pigouvian approach, calls for (stronger) government intervention through setting a price on the activity generating the externality (Pigou, 1920).

Applying the former framework to the nuclear industry, one could interpret a laissez-faire situation as a case in which the property rights for any potential damage are given to the NPC. In such a case, the NPC could choose any level of risk without being liable for the consequences. The defining of a liability limit is similar, with the only difference in property rights for a (small) share of the damage being given to the injured party. In line with Coase (1960), one could argue that negotiations between potential victims and the NPC could result in a Pareto-optimal level of risk-taking. However, this type of negotiation is hardly practicable since nuclear risk is dispersed over vastly many individuals, and moreover any attempt to specify private contracts over an efficient risk level would suffer from the public good problem (see, Sinn, 1983), in addition to other fundamental barriers such as incomplete information. Therefore, society is unable to obtain a contractual relationship with the NPC, and the NPC could thus not be forced to pay for a potential damage ex ante, whereas ex post liability is limited.

Therefore, Coasian irrelevance does not apply, and the risk allocation can be improved only if the government implements measures in representing the interest of society that increase the liability of the NPC or Pigouvian type of price mechanism on the activity that causes the externality, or both. Existing literature on the regulation of risk-taking in the nuclear power industry discusses several instruments that could be applied, which are reviewed and evaluated in the following sections, in terms of their ability to reduce the nuclear power company's incentives to take excessive risks.

SAFETY REGULATION

Recognizing that nuclear reactors are generally not sufficiently safe in theory, several papers propose the setting of safety standards or its joint use with other instruments (see, for example, Shavell, 1984, Kolstad et al., 1990, Schmitz, 2000). The setting of safety standards attempts to improve (or optimize) the level of precaution by defining a large set of measures to be implemented or followed by NPCs.

A repeated criticism of command-and-control measures set by a (central) regulatory authority is that this authority might only possess imperfect information and would therefore be unable to properly define safety regulation (see, for example, Baumol and Oates, 1971; Shavell, 1984). This may hold particularly strongly for the regulation of nuclear power, which by its nature requires an understanding of very complex processes. Trebilcock and Winter (1997) discuss the implications of this type of complexity for regulation, whereas Bredimas and Nuttall (2008) comprehensively analyse this issue in the context of several countries. Faure and Skogh (1992) also highlight that obtaining necessary information is difficult for a regulator, who thus might eventually depend on information provided by the nuclear industry itself. However, since the industry acts in its own interest, it is likely to provide inaccurate signals; in which case regulation may consequently become too lax in some respects and too strict in others.

In a very general sense, it is unclear whether a regulator is better able to achieve the proper level of care by setting safety standards, or alternatively whether (more) market-based instruments, proposed and discussed here later, are more effective. However, there are various other reasons why the efficient level of care cannot be implemented by safety regulation alone.

One such reason is that enforcement is not (or only incompletely) guaranteed, even when safety regulation is defined by law; see Downing and Watson (1974) for the first enforcement model in the context of environmental policy, and for related work, Harrington (1988), Kambhu (1989), and Wang et al. (2003). A second reason is that nuclear power plants are unequal and thus uniform safety regulation cannot perfectly internalize the externality; it may be too strict for some reactors or processes and too lax for others. Thirdly, as safety regulation also concerns the continual monitoring and reassessment of precautionary measures, it would need to closely follow technological progress to recognize potentially harmful developments and demand the quick implementation of new standards. However, given that even the ratification of the international conventions has taken many years (often five or more), it is doubtful whether a regulator is able to achieve this sufficiently well. Fourthly, regulatory competition between states may arise, resulting in inefficiently low safety standards. If a country demanded higher standards, the NPC might decide to build the reactor in a neighbouring country, which would harm the country with strict standards in several ways. This type of 'regulatory race to the bottom' was discussed in similar contexts by Wilson (1996), Wilson (1999), and Oates (2002).

Fifthly, complementing the initial argument in this subsection, the regulator might not have the incentive or ability to be sufficiently informed to elaborate a comprehensive and appropriate regulatory framework. Whereas Poterba and Rueben (1994) investigate wage differentials between public and private sector employees, in line with this Borjas (2003) finds that the public sector is unable to attract the labor force's most qualified individuals as it cannot compete with the private sector in wage terms. Finally, command-and-control measures are often accused of creating enormous inefficiencies. Taken to the extreme, scholars such as Coase (1960) have argued that direct regulation might not necessarily provide better results than leaving the problem to the market.

While often neglecting the problems discussed in the previous paragraph, safety and liability regulation are sometimes viewed as substitutes for correcting externalities. Consequently, the policy recommendation has involved choosing the instrument that causes the least administrative cost for achieving a given goal (for early discussions of related issues see, for example, Calabresi, 1970, and Wittman, 1977). However, in practice we observe that both instruments are often jointly used as in nuclear power regulation, for instance. Developing this observation, Shavell (1984), Kolstad et al. (1990) and Schmitz (2000) find that safety regulation and liability rules may be complementary as their joint use can correct the inefficiencies of using either of the two alone. Shavell (1984) argues that it is better to use both safety and liability regulation under asymmetric information and enforcement problems, where the regulatory standard can be set lower than if only safety regulation was used. Kolstad et al. (1990) and Schmitz (2000) argue similarly, whereby the former paper bases its reasoning on an imperfection in the definition of legal standards and the latter finds that wealth differences between firms do not change this result.

In line with these arguments, safety regulation is considered an important means of complementing liability regulation, particularly by defining a minimum level of precaution. If enforced, the setting of safety standards would guarantee a lower bound on the precautionary measures of an NPC, providing a basis for the application of other instruments. This potential advantage of safety regulation is further elaborated as follows, explaining under which conditions safety regulation would be neutral, beneficial or even harmful as a complement to the proposed new regulation.

MINIMUM EQUITY CAPITAL REQUIREMENTS

Defining minimum equity requirements (in equity-to-assets ratio terms) is a commonly used instrument to regulate the problem of limited liability in the banking sector (cf. Sinn, 2003). Despite the causes and consequences in the banking sector appearing to be very similar, there is one crucial difference in the nuclear industry: whereas a bank's maximum third-party loss is at maximum defined by the bank's liabilities (stated in the balance sheet), even under the assumption of perfectly correlated risks, the potentially catastrophic damages of a large-scale nuclear accident are not represented on an NPC's balance sheet. Therefore, even the requirement to finance all assets with 100 percent liable equity capital would not fully internalise excessive nuclear risk-taking (providing there are fewer assets than a potential catastrophic damage). However, this would lower the extent of the negative externality, given that the NPCs' de facto liability capital would increase.

MANDATORY INSURANCE

Among others, Trebilcock and Winter (1997) suggest mandatory liability insurance for reducing the incentives of excessive risk-taking. This proposal has been followed by several countries, where NPCs are required to cover a specified amount with insurance.

However, these amounts are tiny compared with the potential damage of a catastrophe, and thus the effectiveness is very limited in terms of setting incentives for improving safety. A more effective alternative would involve requiring the entire potential nuclear damage to be insured, thereby transferring the full risk from the NPC to a third party. It could be argued that this would induce an efficient outcome, as the NPC would have to pay a premium at least equal to the expected loss. Consequently, the insurer would punish the NPC for excessive risk-taking, which would become costly, and the negative externality would subsequently vanish.

However, imposing a full mandatory insurance for potential nuclear accidents entails several shortcomings. First of all, the insurability of catastrophic events – characterized by a low occurrence frequency, yet highly severe impacts – has generally been questioned within existing literature.[16] As a prime example, nuclear risk has been repeatedly regarded as non-actuarial (see, for example, Litzenberger et al., 1996; Kunreuther, 1997; Cutler and Zeckhauser, 1999; Radetzki and Radetzki, 2000).

However, the most important reason why mandatory insurance might not be a reasonable alternative is that the capital resources available to the insurance industry may also be insufficient to cover the damages of nuclear catastrophes. As insurance companies are similarly judgment-proof, they might not have the incentive to calculate and charge actuarially correct premiums (even if this were possible), but would also maximise their profits taking their own limited liability into account. In such a case, the insurance premiums charged upon the nuclear industry would not reflect the true expected loss, and consequently the effect of limited liability on risk-taking would only be shifted from one industry to another without solving the core problem.[17]

MUTUAL RISK-SHARING POOLS

In contrast to risk being transferred to a third party in the case of insurance, the risk in a mutual risk-sharing pool is shared among the risk-creating parties. Therefore, the NPCs agree on an ex post sharing of the costs of a catastrophic accident. Whereas insurance presumes an ex ante pricing of nuclear risk, mutual risk-sharing offers the particular

[16] This is the case for both natural and man-made catastrophes, to different extents. See, among others, Kunreuther (1997) and Cutler and Zeckhauser (1999).

[17] See Buck and Jus, 2009, for a similar argument concerning the possibility of securitization in the banking industry, which opens a channel for circumventing the introduction of stricter equity requirements on one layer of banking.

advantage that only paying the actual costs eliminates the need to estimate potential damages and probabilities in advance. Such advantages of mutual risk-sharing over insurance have been extensively discussed and emphasised by, among others, Skogh (1999), Faure (2004), Faure and Fiore (2008), and Skogh (2008), who elaborates on the theoretical foundation of mutual risk-sharing. Skogh (1999) explains why it is advisable for parties facing similar risks to share them in common pools. Furthermore, Faure (2004) investigates whether an extended mutual agreement between NPCs could serve as an alternative to the nuclear power liability regulation currently in place. Faure and Fiore (2008) discuss possible structures and the potential for a more comprehensive mutual risk-sharing agreement among Europe’s NPCs.

There are several examples of mutual risk-sharing agreements, for instance in the United States, the Nuclear Electric Insurance Limited (NEIL) and the Overseas NEIL (ONEIL), or in Europe, the European Mutual Association for the Nuclear Industry (EMANI) and the European Liability Insurance for the Nuclear Industry (ELINI). Mutual risk-sharing generally creates a collective responsibility for risk-taking; moreover making NPCs liable generates incentives to prevent accidents, which implies a reduction of excessive risk-taking. However, risk-sharing pools suffer from the fundamental problem of collective action: the higher the number of NPCs financing the pool, the stronger the tendency towards free-riding, as individual responsibility shrinks and peer-monitoring becomes more costly. Furthermore, the effectiveness of this type of regulation diminishes as an NPC’s share of the pool declines.

CATASTROPHE BONDS

Catastrophe (cat) bonds represent one means of spreading the risk of potentially large losses via financial instruments (namely via capital markets). A cat bond offers investors a return above the risk-free rate when a specified catastrophic event does not occur, but otherwise requires the sacrifice of interest or principal. The general idea of cat bonds is explained by Cummins and Weiss (2009), who also provide an overview of related literature.[18] Thus far, cat bonds have generally been employed by insurers as an alternative to traditional re-insurance, and by re-insurers usually in atomising the risk of natural

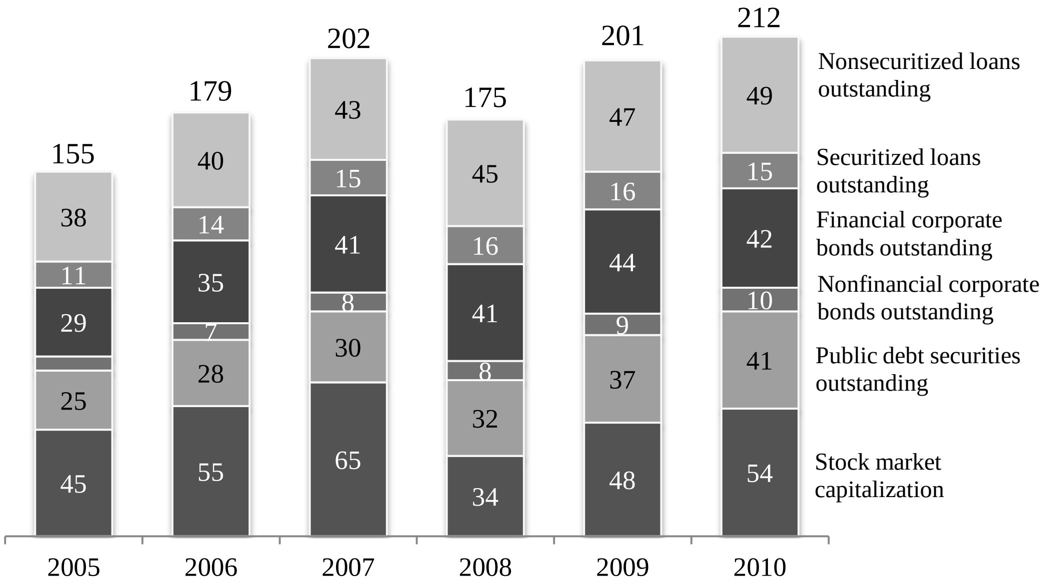
[18] For analyses of other private and alternative, arrangements for transferring risk, see Wagner, 1998; Radetzki and Radetzki, 2000.

catastrophes such as earthquakes or hurricanes (see Evans, 2011; for a comparison between cat bonds and re-insurance, see Gibson et al., 2007; Cummins, 2012). Mexico was the first sovereign to offer cat bonds, thereby protecting itself against the risk of natural catastrophes (see, for example, Cardenas et al., 2007; Michel-Kerjanet al., 2011). An overview of the development and current state of cat bond markets can be found in Cummins (2012) and Swiss Re (2012). It is evident that issuance volumes declined sharply in 2008 owing to the financial crisis, and have still not fully recovered. In 2011, they reached a volume of USD 5 billion.

Besides natural catastrophes, the idea of also employing cat bonds for nuclear accidents was discussed by Tyran and Zweifel (1993), offering a description of how to internalise environmental risks such as potential nuclear catastrophes via capital markets. They observe that NPCs could emit cat bonds, through which nuclear risk is spread among a large number of investors. The principal received for each cat bond issued is supposed to be placed in risk-free assets, for example certain treasury bonds. The spread between the cat bond interest and the interest on a risk-free bond represents the market assessment of the risk of a nuclear accident, if this is specified as the trigger for the cat bonds' default. Hence, as nuclear risk is priced by capital markets, risk-taking becomes costly for the NPCs. Consequently, NPCs taking excessive risk may either revise their strategy to reduce the premiums paid on cat bonds or even leave the market if this business becomes too costly for them. A further advantage of catastrophe bonds is that risks can be diversified internationally, thus diluting the strong impact on the economy where the accident occurs. Tyran and Zweifel (1993) argue that investors would have an incentive to remain well-informed and would on average estimate the risk correctly.

Leaving aside some well-known problems of cat bonds (such as high transactions costs), the main issue in the case of nuclear power is that NPCs would not voluntarily emit cat bonds. Paying a premium on cat bonds would imply additional costs and undermine the benefits of limited liability, and thus the regulatory authority would have to stipulate their emission. Despite the global cat bond market currently being relatively small, one could argue that if the supply of cat bonds was made perfectly inelastic by regulation, it would only be a matter of the price of the cat bonds for the demand to emerge.

Figure 6.5: Global stock of equity and debt outstanding in trillion US dollar, end-of-year, constant 2010 exchange rates



Source: Roxburgh et al. (2011)

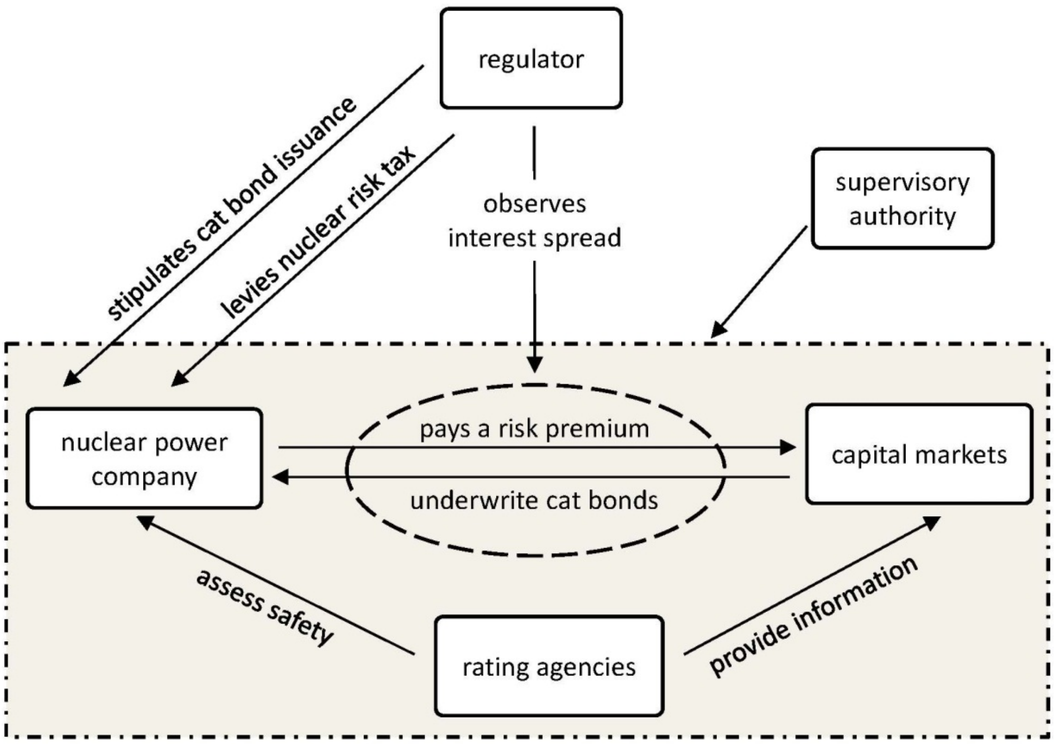
Concerning the externality from limited liability, a cat bond would achieve full effectiveness on risk-taking if any potential damage would need to be covered for every nuclear reactor. To cite an example, given the currently estimated damages of the Fukushima accident, suppose that the regulatory authority could demand an emission volume of USD 200 billion per reactor. This would likely outbalance any reasonable scope of the cat bond market given that there are more than 400 nuclear reactors operating worldwide, and therefore an amount in excess of USD 80 trillion would need to be invested in cat bonds. For the purpose of comparison, Figure 6.5 depicts the total global financial stock, measured as the sum of debt and equity outstanding, which constituted USD 212 trillion in 2010. Hence, the argument of a correct pricing of risk of even a large volume of cat bonds is likely to remain of a theoretical nature, given that a constraint on the properly functioning market size certainly exists in reality. Despite there being a surge for diversification and nuclear cat bonds offering the favourable property of generally not being affected by other shocks to the economy, a full coverage for all reactors appears impossible.

Therefore, although the idea of cat bonds sounds very promising, the nature of their implementation is highly open to debate. Demanding any smaller amount of cat bond emissions than potential damages would re-introduce the negative externality of limited liability partially. For this reason, the following section offers a proposal that partly relies on cat bonds and their favourable properties, and also has the potential to largely overcome the aforementioned market-size problem.

6.7 TAXING NUCLEAR RISK WITH THE HELP OF CAPITAL MARKETS

Having highlighted that current liability regulation might imply severe incentives for excessive risk-taking and reviewed various regulatory instruments, this section proposes a new method for the regulation of liability in the nuclear industry. This involves the major aim of internalising the externality of excessive risk-taking, which could be best accomplished by combining the strength of private markets with a Pigouvian-type of public intervention. The proposal demands using the ability of capital markets to evaluate risk-taking and society's reserve capacity to absorb high risks in order to achieve the desired level of nuclear reactor safety.

Figure 6.6: Schematic illustration of the proposed regulation



Source: Eberl and Jus (2012).

The basic idea can be summarized as a two-stage approach, depicted in Figure 6.6. In the first stage, by pricing a specified volume of cat bonds, capital markets provide an assessment of the risk stemming from each nuclear reactor. In the second stage, the regulatory authority employs this observable risk-assessment and intervenes by charging a Pigouvian tax equal to an actuarially fair premium, thereby – under ideal conditions – inducing the socially optimal level of risk-taking. Eventually, society adopts the role of an explicit insurer for nuclear risk. The main arguments in support of this solution are outlined below, prior to discussing the details relevant to its implementation.

This analysis has highlighted several issues prompting the conclusion that neither public safety regulation nor market-based instruments can solve the problem of excessive nuclear risk-taking in pure form alone. In contrast to Tyran and Zweifel (1993), the approach described in this section does not aim to establish comprehensive loss coverage on capital markets, rather it uses cat bond markets only for risk assessment and delegates any further responsibility to the regulator. Specifically, the proposal demands that NPCs are obliged to issue cat bonds for each reactor in a volume representing only a fraction of the potential costs of a large-scale accident. For example, an amount of USD 10 billion per nuclear reactor could be considered. Despite this seeming large at first glance, even if this was achieved for the 400-plus reactors worldwide, the total sum would only lead to a market size of just over USD 4 trillion, or around 30 percent relative to current US public debt. Given that the recent crises have revealed that investment portfolios were often not sufficiently diversified, it appears reasonable to assume that there might be sufficient demand for large amounts of cat bonds. From this perspective, the introduction of a cat bond model could be timely, since the inclusion of nuclear accident related securities would increase the portfolio diversification.

However, stipulating a cat bond issuance of some specified amount lower than the potential damage of a nuclear accident would not fully overcome the problem of excessive risk-taking, as outlined by previous arguments. However, capital market offers the crucial advantage of regulators being able to obtain an assessment of the probability of a catastrophe, given that the cat bond defaults when such an event occurs. Measured against a risk-free interest rate, the interest premium would exactly reflect the accident probability.

Alternatively, it could be measured against the safest reactor according to capital markets, which could represent a good approximation of the risk-free interest rate.

Naturally, there are certain problems to overcome, as discussed below; nevertheless, such a scheme would offer two particular advantages: (1) overcoming potential liquidity/capacity problems in capital markets, thus isolating the actual risk from other capital market imperfections; and (2) the risk assessment is transparent and the risks of various reactors comparable, as the cat bond issuance is reactor-specific.

It is disputable whether capital markets are able to properly evaluate the risks of nuclear power. Having failed to price a number of risks correctly in the recent past, it could be argued capital markets are generally likely to fail. On the contrary, one could, also argue that future assessment will be more cautious precisely because of these events, possibly even overestimating certain risks. While neither of them can be proven, it is important to note that even an incorrect risk-assessment by capital markets does not necessarily lead to an inefficiently low level of precaution. What matters is the pricing of safety differences and improvements, rather than the pricing of the level of safety. For instance, if a reactor is assessed as being relatively safe by capital markets, despite actually being rather unsafe, an incentive for safety improvements would still be set providing the NPC could sufficiently improve the conditions under which it can issue cat bonds. Under certain conditions (even in the case of the risk of nuclear power being under-priced), this may lead to an excessive level of safety if capital markets reduce the interest premium too generously when the NPC improves safety.

The correct assessment of safety differences and safety improvements can be largely reduced to the question of whether investors can obtain information at sufficiently low costs. If it is too costly for potential cat bond underwriters to acquire information about differences between reactors or safety changes in a specific reactor, capital markets would no longer be able to set adequate incentives. Thus, it is vitally important to establish a set of measures to make this market more efficient. As argued by Tyran and Zweifel (1993), (private) nuclear rating agencies could emerge, where moral hazard problems as discussed for existing rating agencies would need to be avoided (see, for instance, Bolton et al., 2012, Dittrich, 2007, and Pagano and Volpin, 2010). However, it would also be in the self-interest of the NPCs to provide information (for instance, by issuing reports) about the safety of their reactor and be as transparent as possible, since a lack of transparency could be interpreted as a sign of not being safe by financial markets.

Moreover, two reasons act in favour of believing that capital markets would not neglect the risks of nuclear accidents: on the one hand, the recent crises have sensitised investors that even highly improbable events may actually occur; and on the other hand, the Fukushima catastrophe itself has proven the specific risk of nuclear power. A similar argument was discussed by Dell'Ariccia et al. (2006), highlighting that the non-bailout of Russia in August 1998 has increased the cross-country spreads, sensitizing investors that such risks do exist. Furthermore, Cummins and Weiss (2009) argue that securities markets are more efficient than insurance markets in reducing information asymmetries and facilitating price formation.

Having outlined the first stage of the proposal, it is important to explain what the regulatory authority should do in the second stage. Once again, it shall be emphasised that a Coasian solution to the problem is not feasible, moreover that the regulator must intervene in a Pigouvian way if a full liability of NPCs is not implementable. Observing the reactor-specific interest premium of a cat bond over a risk-free bond, the regulator defines a tax for each nuclear power reactor to be paid by the NPC. The tax is proportional to the interest premium, and is thus lower for safer reactors and higher for those assessed as posing a higher risk. The regulator, representing society, subsequently becomes the insurer for nuclear risk by charging a premium that depends on actual risk, in return agreeing to absorb the costs of large-scale accidents. Under ideal conditions, this proposal fully overcomes the negative consequences of limited liability, as the reactor-specific risk becomes the crucial factor of tax paid by an NPC. Moreover, society has the capacity to absorb the costs of nuclear accidents better than privately owned companies (such as insurers). Societies have previously managed to overcome severe catastrophes and would also seek the best possible way to deal with a nuclear accident.

One notable aspect concerning this solution is whether an incentive to manipulate the cat bond market could exist. Since the cat bond issuance is supposed to be relatively small compared to the amount on which the Pigouvian tax is levied, an NPC could theoretically reduce its costs by engaging in (illegal) activities that drive the interest spread below its true level, thereby paying a smaller Pigouvian tax. Trivially, the incentive for manipulation depends on the costs of manipulation, namely on the supervisory power of the state and the size of the penalty if an NPC is caught cheating. It can be believed that the manipulating costs are reasonably high in the outlined case for two reasons: the market size to be manipulated would be comparably large, if the regulator demands issuance of cat bonds in the amount of, USD 10 billion for instance; and underwriters could be prohibited to buy a share of more than a few percent of the issued volume, thereby also reducing the possibility for manipulation.

Moreover, given that the transparency of the system is a crucial facet, a supervisory agency would be needed. Many lessons can be applied from the banking sector, which has established this type of supervision and is in the process of improving it after the emerging problems of the recent crisis.

The advantage of the outlined proposal is that nuclear power companies are internalising the social costs of their activity, and that society is fairly compensated on average for the risk it is taking over. This is all that can be demanded from an economic perspective, and it remains for the NPCs to decide whether it is still profitable to operate. Such a decision would likely also be influenced by developments in electricity prices, which could rise if an unsafe reactor had to close, thereby making safer ones sufficiently profitable despite the tax having to be paid. By the same token, renewable energy sources would also profit as nuclear power would become more costly through this proposal.

Evidently, no government can be forced to participate in such a regulation and adopt a Pigouvian nuclear risk tax in order to internalize the externality. However, it can be assumed that it should be in their interests to do so. Moreover, a lack of participation of some countries would not directly affect the effort undertaken by those participating countries, rendering this proposal different from climate change protocols in which the world climate is a global public good. The risk of nuclear catastrophes constitutes a rather regional or even local (if considering the most severe consequences) externality. Moreover, if a country is unwilling to charge the Pigouvian nuclear risk tax due to fearing the adverse effects for its nuclear industry, it could redistribute the collected revenues back to the nuclear industry on a lump-sum basis, thereby enhancing the safety level without harming the industry on average.

Moreover, cat bond issuance and the determination of the tax could be repeated according to a pre-defined schedule to offer NPCs the opportunity to improve their assessment and thus reduce the Pigouvian tax to be paid, for instance every two or three years. The maturity of the bonds could also be defined according to this schedule.

As previously argued in the subsection on safety regulation, the regulator's setting of standards represents a useful complement to this proposal: on the one hand, safety regulation provides information for potential underwriters as NPCs have to implement at least the safety level that is demanded, providing enforcement is guaranteed. Therefore, safety regulation that leads to a reduction of risk would be valued by capital markets and the interest premium would shrink accordingly. Owing the valuation by potential underwriters, if safety measures would have been implemented by the NPC anyway, safety regulation would be fully neutral. On the other hand, there are cases in which safety regulation would not be neutral, namely (1) if it demands a level of safety that is inefficiently high, or (2) if the standards are actually important yet would not be sufficiently priced by capital markets. The latter is the most important argument in favour of safety regulation, implying that a failure of capital markets to punish a lack of safety can be replaced by safety regulation. In this case, safety regulation improves allocative efficiency. However, the possibility exists that safety regulation stipulates measures for which the social costs are higher than the social benefits, in addition to the problems outlined in the respective section.

6.8 Conclusions

NPCs currently enjoy limited liability with respect to potential catastrophic nuclear accidents, which has been seen as necessary to protect them from ruinous claims and was considered essential for the development of this industry. However, it may be nowadays re-interpreted as a major source of excessively risky nuclear reactors. Given that the number of nuclear reactors worldwide is expected to rise over the coming decades, it is vitally important to discuss ways in which the use of nuclear power can be made safer. Several known instruments have been evaluated accordingly, concluding that each of these instruments either cannot be recommended in its pure form or is infeasible in reality.

Therefore, a new regulatory approach has been proposed, based on the general idea of catastrophe bonds that may be superior to the other instruments. The core of the proposal consists of a two-stage procedure: in the first stage, capital markets evaluate the risk stemming from each nuclear reactor via catastrophe bonds issued on a smaller scale than actually required to cover the potential losses, yet whose value can be used as an indicator for the riskiness of a reactor. In the second stage, the regulator uses this private risk assessment and intervenes by charging an actuarially fair premium, a Pigouvian nuclear risk tax that under ideal conditions would induce the optimal level of risk-taking. Society then acts as an explicit insurer for nuclear risk and is fairly compensated on average for the risk it is taking over.

The implementation of such a scheme would render the use of nuclear power (privately) more expensive, with the risk of accidents consequently also being priced. Some nuclear reactors (particularly the unsafe ones) may subsequently become unprofitable and could disappear from the market. Those that remain privately profitable are then also socially profitable according to the monetary risk imposed on society.

Neither the ethical nor the moral arguments against nuclear power have been considered at this stage; even after the optimal level of risk-taking being implemented, society may decide not to use nuclear power. However, this decision must not be taken on the basis of nuclear power plants that are too risky, given that the level of care satisfies allocative efficiency. Therefore, solving the problem of limited liability and excessive risk-taking is both an important element of the future use of nuclear power and a necessary basis for decisions regarding nuclear phase-outs.

Towards a better energy policy

It is typically fairly easy to derive general conditions for market equilibriums from economic models. However, the actual price leading to market clearing is unknown and cannot be determined given that full information about preferences, production and cost functions, etc., is not publicly available. Therefore, prices formed in markets “are an instrument of communication and guidance which embody more information than we directly have” (F. A. Hayek), representing the main reason for the superiority of markets over central planning in establishing efficient allocations. In fact, it is widely accepted that an equilibrium reached within a market free of market failure is efficient. Consequently, abstracting from distributive motives, public policy should not intervene in such a market, neither directly nor by influencing the price formation. As this argument generally holds for public policy, it should also form the basic foundation of any debate concerning energy policy.

However, it is doubtlessly true that markets, and particularly energy markets, often fail to reach efficiency, thereby affirming Musgrave’s conclusion that “public policy is needed to guide, correct, and supplement” the market mechanism. Nevertheless, before actually intervening, energy policy should very carefully explain the underlying market failure and present quantitative analysis of its importance. Accordingly, philosophical and ideological arguments should not serve as motives for subsidizing renewable energy or phasing-out nuclear power, for example. Consequently, energy policy more strongly based on the principles of welfare economics could avoid taking peculiar policy paths in the future, such as described in Chapter 1 for the case of Germany.

One market failure emphasized in Chapter 2 arises owing to the contribution to the climate change process being insufficiently accounted for when fossil energy is used. Public policy would ideally implement a (dynamically) correct pricing of the climate change externality, thereby establishing efficiency in absence of other market failures. If this is not feasible, a renewable energy subsidy can be efficiency improving, despite generally failing to reach the first best allocation. Moreover, this subsidy should not exceed the size of the climate change externality, which has already been quantified by a number of studies.

Another negative externality was discussed in Chapter 6. It arises owing to the existence of limited liability and can imply inefficiently excessive risk-taking within the nuclear industry. Once again, public policy is required for its correction. If the externality is caused by a de jure liability limitation, as is the case in most countries, the first step could involve abolishing this regulation. The remaining externality from the liability limitation by the nuclear power company's equity capital can be reduced through mandated catastrophe bonds and other policy instruments, yet cannot be completely resolved. Therefore, a new regulation is proposed in favor of using a market assessment of the specific nuclear risk for taxing nuclear power companies.

However, besides markets failing to achieve an efficient market outcome, this possibility also exists for governments, even when aware of the nature of the externality. Supporting this view, Milton Friedman once argued that 'the government solution to a problem is usually as bad as the problem'. Whilst this view is somewhat pessimistic, the possibility of public policy failure should be considered when debating about energy policy. Even if the market fails, a public policy intervention is evidently only justified when allocative efficiency can be improved.

Generally favoring photovoltaic over wind electricity, differentiated feed-in tariffs for renewable electricity are often considered as a policy failure resulting from an evident violation of the static efficiency condition. However, Chapter 5 shows that a government that has committed to an excessively strong renewable energy target, itself representing a policy failure and thus reducing efficiency, should generally select technology-specific feed-in tariffs to improve efficiency. This exemplifies that well-established arguments may need to be reconsidered if policy has left the efficient terrain.

Accordingly, the effects of different public policies on the electricity market need to be well understood in order to derive recommendations. For this reason, Chapter 3 and 4 analyze how the market outcome is changed when a government subsidizes renewable energy while also being part of an emission trading system. Removing itself from normative questions, the model explains that unilateral renewable energy policy implies a shifting of rents towards consumers in other countries. This can only be avoided by ensuring a stronger coordination of renewable energy policies between countries.

The models of electricity markets in this dissertation have not considered issues related to market power, however beyond externalities this is certainly the major motivation for government involvement, as market failure can also arise from strategic behavior. Accordingly, this represents one aspect in which the presented models can be further extended in the future. Moreover, it would be beneficial to empirically test the hypotheses developed in Chapter 4, and to evaluate the actual risk-taking of nuclear power companies discussed in Chapter 6.

Policy-oriented economic research is particularly important in a field when two factors simultaneously apply: the existence of market failure and its relevance for society. While the former was emphasized throughout this dissertation, the latter is also verified by my personal reflection that its writing process would have been much more difficult in the absence of electricity. Therefore, while this dissertation concludes, there is ample need for further research on electricity markets.

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Appendix

APPENDIX A: DERIVING EQUATION (4.21)

The self-financing condition is given by the following equation:

$$\tau_1 \cdot E_1^{a\sigma} = \sigma_1 \cdot E_{R,1}^{a\sigma} \qquad (A.1 = 4.20)$$

which can be written as:

$$\tau_1 \cdot \left(E_1^{b\sigma} + E_1^{a\sigma} - E_1^{b\sigma}\right) = \sigma_1 \cdot E_{R,1}^{a\sigma} \qquad (A.2)$$

Since,

$$E_1^{a\sigma} - E_1^{b\sigma} = -\frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1}{s_{D,1}} \qquad (A.3 = 4.14)$$

$$E_{R,1}^{a\sigma} = \frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \sigma - x_1}{s_{R,1}} \qquad (A.4 = 4.7)$$

equation $(A.2)$ becomes:

$$\tau_1 \cdot \left(E_1^{b\sigma} - \frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \tau_1}{s_{D,1}}\right) = \sigma_1 \cdot \frac{\Delta p_M\left(E_{R,1}^{a\sigma}\right) + \sigma - x_1}{s_{R,1}} \qquad (A.5)$$

which can be transformed to (4.21) in the following way:

$$(A.5) \quad \leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{\tau_1}{s_{D,1}} \cdot \Delta p_M\left(E_{R,1}^{a\sigma}\right) - \frac{(\tau_1)^2}{s_{D,1}} = \frac{\sigma_1}{s_{R,1}} \cdot \Delta p_M\left(E_{R,1}^{a\sigma}\right) + \frac{(\sigma_1)^2}{s_{R,1}} - \frac{\sigma_1 \cdot x_1}{s_{R,1}}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}} = \left(\frac{\sigma_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}\right) \cdot \Delta p_M\left(E_{R,1}^{a\sigma}\right)$$

where

$$\Delta p_M\left(E_{R,1}^{a\sigma}\right) = -\frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}} \qquad (A.6 = 4.17)$$

can be substituted:

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}} = -\left(\frac{\sigma_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}\right) \cdot \frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}} = -\left(\frac{\sigma_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}\right) \cdot \frac{s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1}{s_{R,1} + s_{D,1} + s_{R,1} \cdot \frac{s_{D,1}}{s_{D,2}}}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}}$$

$$= -\left(\frac{\sigma_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}\right) \cdot \frac{s_{D,1} \cdot s_{D,2} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot s_{D,2} \cdot \tau_1}{\underbrace{s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}}_{=B}}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}}$$

$$= -\left(\frac{\sigma_1}{s_{R,1}} + \frac{\tau_1}{s_{D,1}}\right) \cdot \left(s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1\right) \cdot \frac{s_{D,2}}{B}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}}$$

$$= -\left(\frac{\sigma_1 \cdot \left(s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1\right)}{s_{R,1}} + \frac{\tau_1 \cdot \left(s_{D,1} \cdot (\sigma_1 - x_1) + s_{R,1} \cdot \tau_1\right)}{s_{D,1}}\right) \cdot \frac{s_{D,2}}{B}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{(\sigma_1)^2}{s_{R,1}}$$

$$= -\left(\frac{s_{D,1}}{s_{R,1}} \cdot ((\sigma_1)^2 - \sigma_1 \cdot x_1) + \sigma_1 \cdot \tau_1 + \tau_1 \cdot \sigma_1 - \tau_1 \cdot x_1 + \frac{s_{R,1}}{s_{D,1}} \cdot (\tau_1)^2\right) \cdot \frac{s_{D,2}}{B}$$

$$\leftrightarrow \quad \tau_1 \cdot E_1^{b\sigma} - \frac{(\tau_1)^2}{s_{D,1}} + \frac{\sigma_1 \cdot x_1}{s_{R,1}} - \frac{s_{D,1}}{s_{R,1}} \cdot \sigma_1 \cdot x_1 \cdot \frac{s_{D,2}}{B} - \frac{1}{s_{R,1}} \cdot (\sigma_1)^2 + \frac{s_{D,1}}{s_{R,1}} \cdot (\sigma_1)^2 \cdot \frac{s_{D,2}}{B}$$

$$= -\left(2 \cdot \tau_1 \cdot \sigma_1 - \tau_1 \cdot x_1 + \frac{s_{R,1}}{s_{D,1}} \cdot (\tau_1)^2\right) \cdot \frac{s_{D,2}}{B}$$

$$\leftrightarrow \quad \tau_1 \cdot \left(E_1^{b\sigma} - x_1 \cdot \frac{s_{D,2}}{B}\right) + (\tau_1)^2 \cdot \left(\frac{s_{R,1}}{s_{D,1}} \cdot \frac{s_{D,2}}{B} - \frac{1}{s_{D,1}}\right) + \left(\frac{1}{s_{R,1}} - \frac{s_{D,1}}{s_{R,1}} \cdot \frac{s_{D,2}}{B}\right) \cdot \sigma_1 \cdot x_1$$

$$- \left(\frac{1}{s_{R,1}} - \frac{s_{D,1}}{s_{R,1}} \cdot \frac{s_{D,2}}{B}\right) \cdot (\sigma_1)^2 + (2 \cdot \tau_1 \cdot \sigma_1) \cdot \frac{s_{D,2}}{B} = 0$$

$$\leftrightarrow \quad \tau_1 \cdot \left(E_1^{b\sigma} \cdot B - x_1 \cdot s_{D,2}\right) + (\tau_1)^2 \cdot \left(\frac{s_{R,1} \cdot s_{D,2}}{s_{D,1}} - \frac{B}{s_{D,1}}\right) + \left(\frac{B}{s_{R,1}} - \frac{s_{D,1} \cdot s_{D,2}}{s_{R,1}}\right) \cdot \sigma_1 \cdot x_1$$
$$- \left(\frac{B}{s_{R,1}} - \frac{s_{D,1} \cdot s_{D,2}}{s_{R,1}}\right) \cdot (\sigma_1)^2 + (2 \cdot \tau_1 \cdot \sigma_1) \cdot s_{D,2} = 0$$

using $B = s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}$,

$$\leftrightarrow \quad \tau_1 \cdot \left(E_1^{b\sigma} \cdot B - x_1 \cdot s_{D,2}\right) - (\tau_1)^2 \cdot \left(s_{D,2} + s_{R,1}\right) + \left(s_{D,2} + s_{D,1}\right) \cdot \sigma_1 \cdot x_1$$
$$- \left(s_{D,2} + s_{D,1}\right) \cdot (\sigma_1)^2 + (2 \cdot \tau_1 \cdot \sigma_1) \cdot s_{D,2} = 0$$

$$\leftrightarrow \quad -(\tau_1)^2 \cdot \left(s_{D,2} + s_{R,1}\right) + \tau_1 \cdot \sigma_1 \cdot 2 \cdot s_{D,2} - (\sigma_1)^2 \cdot \left(s_{D,1} + s_{D,2}\right)$$
$$+\tau_1 \cdot \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right) + \sigma_1 \cdot x_1 \cdot \left(s_{D,1} + s_{D,2}\right) = 0 \qquad (A.7 = 4.21)$$

APPENDIX B: CHARACTERISTICS OF EQUATION (4.21)

The self-financing condition in country 1 is given by:

$$-(\tau_1)^2 \cdot \left(s_{D,2} + s_{R,1}\right) + \tau_1 \cdot \sigma_1 \cdot 2 \cdot s_{D,2} - (\sigma_1)^2 \cdot \left(s_{D,1} + s_{D,2}\right)$$
$$+\tau_1 \cdot \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right) + \sigma_1 \cdot x_1 \cdot \left(s_{D,1} + s_{D,2}\right) = 0 \qquad (A.8 = 4.21)$$

where $B = s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}$.

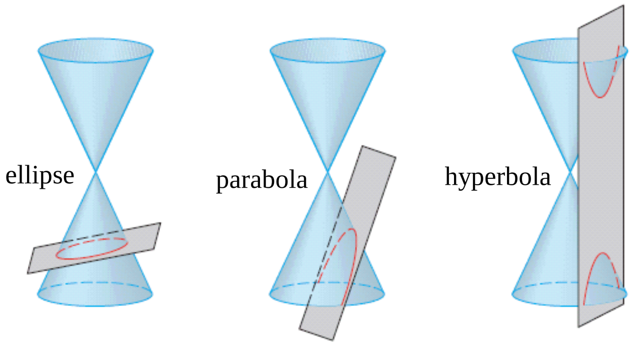
When drawn into a Cartesian coordinate system the graph of $(A.8)$ is a conic section, resulting from the intersection of a right-circular conical surface with a plane. As illustrated in Figure A.1, three types of conic sections exist, with all generally characterized by an equation of the form $a \cdot X^2 + b \cdot X \cdot Y + c \cdot Y^2 + d \cdot X + e \cdot Y + f = 0$ in the X-Y space, where the parameters a- f determine the actual shape.

The type of the conic section described by $(A.8)$ can be classified with the discriminant, which is given by $b^2 - 4 \cdot a \cdot c$ in the general case, and in the case of $(A.8)$ by:

$$\left(2 \cdot s_{D,2}\right)^2 - 4 \cdot \left(s_{D,2} + s_{R,1}\right) \cdot \left(s_{D,1} + s_{D,2}\right) = -\frac{4}{B} < 0 \qquad (A.9)$$

and as the discriminant is negative, $(A.8)$ is represented by an ellipse in the Cartesian coordinate system.

Figure A.1: Types of conic sections



Source: adopted from Jim Wilson, jwilson.coe.uga.edu, accessed on 23rd August, 2012.

Setting $\tau_1 = 0$ in $(A.8)$ yields:

$$-(\sigma_1)^2 + \sigma_1 \cdot x_1 = 0 \qquad (A.10)$$

showing, that the roots are $\{\sigma_1^* = 0, \sigma_1^{**} = x_1 > 0\}$. Moreover, setting $\sigma_1 = 0$ in $(A.8)$ yields:

$$-(\tau_1)^2 \cdot \left(s_{D,2} + s_{R,1}\right) + \tau_1 \cdot \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right) = 0 \qquad (A.11)$$

hence, the roots are $\left\{\tau_1^* = 0, \tau_2^{**} = \frac{B \cdot E_1^{b\sigma} - x_1 \cdot s_{D,2}}{s_{D,2} + s_{R,1}}\right\}$.

Appendix C: Deriving Equation (4.22)

Totally differentiating equation $(A.8 = 4.21)$, which is a function of σ_1 and τ_1, yields:

$$-2 \cdot \tau_1 \cdot \left(s_{D,2} + s_{R,1}\right) \cdot d\tau_1 + \sigma_1 \cdot 2 \cdot s_{D,2} \cdot d\tau_1 + \tau_1 \cdot 2 \cdot s_{D,2} \cdot d\sigma_1$$

$$-2 \cdot \sigma_1 \cdot \left(s_{D,1} + s_{D,2}\right) \cdot d\sigma_1 + \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right) \cdot d\tau_1$$

$$+x_1 \cdot \left(s_{D,1} + s_{D,2}\right) \cdot d\sigma_1 = 0 \qquad (A.12)$$

which can be solved for ${d\sigma_1}/{d\tau_1}$, to obtain the slope of the ellipse at any point:

$$(A.12) \quad \leftrightarrow \quad \left(-2 \cdot \tau_1 \cdot \left(s_{D,2} + s_{R,1}\right) + \sigma_1 \cdot 2 \cdot s_{D,2} + \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right)\right) \cdot d\tau_1$$

$$+ \left(\tau_1 \cdot 2 \cdot s_{D,2} - 2 \cdot \sigma_1 \cdot \left(s_{D,1} + s_{D,2}\right) + x_1 \cdot \left(s_{D,1} + s_{D,2}\right)\right) \cdot d\sigma_1 = 0$$

$$\leftrightarrow \quad \left(-2 \cdot \tau_1 \cdot \left(s_{D,2} + s_{R,1}\right) + \sigma_1 \cdot 2 \cdot s_{D,2} + \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right)\right) \cdot d\tau_1$$

$$= -\left(\tau_1 \cdot 2 \cdot s_{D,2} + (x_1 - 2 \cdot \sigma_1) \cdot \left(s_{D,1} + s_{D,2}\right)\right) \cdot d\sigma_1$$

$$\leftrightarrow \quad \frac{d\sigma_1}{d\tau_1} = \frac{\sigma_1 \cdot 2 \cdot s_{D,2} - 2 \cdot \tau_1 \cdot \left(s_{D,2} + s_{R,1}\right) + \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right)}{(2 \cdot \sigma_1 - x_1) \cdot \left(s_{D,1} + s_{D,2}\right) - \tau_1 \cdot 2 \cdot s_{D,2}} \qquad (A.13)$$

which when evaluated at $\tau_1 = 0$, and $\sigma_1 = x_1$ is equal to:

$$\left.\frac{d\sigma_1}{d\tau_1}\right|_{\substack{\tau_1=0 \\ \sigma_1=x}} = \frac{x_1 \cdot 2 \cdot s_{D,2} + \left(B \cdot E_1^{b\sigma} - s_{D,2} \cdot x_1\right)}{(2 \cdot x_1 - x_1) \cdot \left(s_{D,1} + s_{D,2}\right)}$$

$$\leftrightarrow \quad \left.\frac{d\sigma_1}{d\tau_1}\right|_{\substack{\tau_1=0 \\ \sigma_1=x}} = \frac{2 \cdot s_{D,2}}{s_{D,1} + s_{D,2}} + \frac{B \cdot E_1^{b\sigma}}{x_1 \cdot \left(s_{D,1} + s_{D,2}\right)} - \frac{s_{D,2}}{s_{D,1} + s_{D,2}}$$

$$\leftrightarrow \quad \left.\frac{d\sigma_1}{d\tau_1}\right|_{\substack{\tau_1=0 \\ \sigma_1=x}} = \frac{s_{D,2}}{s_{D,1} + s_{D,2}} + \frac{B \cdot E_1^{b\sigma}}{x_1 \cdot \left(s_{D,1} + s_{D,2}\right)} \qquad (A.14 = 4.22)$$

APPENDIX D: DERIVING EQUATION (4.23)

Setting the slopes of the self-financing condition at $(\sigma_1, \tau_1) = (x_1, 0)$ and the zero-consumer-price-change condition equal, yields:

$$\frac{s_{D,2}}{s_{D,1} + s_{D,2}} + \frac{B \cdot E_1^{b\sigma}}{x_1 \cdot \left(s_{D,1} + s_{D,2}\right)} = 1 + \frac{s_{R,1}}{s_{D,2}} \qquad (A.15)$$

which can be simplified to:

$$s_{D,2} + \frac{B \cdot E_1^{b\sigma}}{x_1} = s_{D,1} + s_{D,2} + \frac{s_{R,1} \cdot s_{D,1} + s_{R,1} \cdot s_{D,2}}{s_{D,2}}$$

$$\leftrightarrow \quad \frac{B \cdot E_1^{b\sigma}}{x_1} = \frac{s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1} + s_{R,1} \cdot s_{D,2}}{s_{D,2}}$$

and using $B = s_{R,1} \cdot s_{D,2} + s_{D,1} \cdot s_{D,2} + s_{R,1} \cdot s_{D,1}$:

$$\leftrightarrow \quad \frac{B \cdot E_1^{b\sigma}}{x_1} = \frac{B}{s_{D,2}}$$

$$\leftrightarrow \quad E_1^{b\sigma} \cdot s_{D,2} = x_1 \qquad (A.16 = 4.23)$$