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Abstract

This paper analyzes the effects of the green transformation on the German electricity sector with respect to the energy-political triangle. It focuses on how the development of renewable energies will affect security of electricity supply. In a cost-benefit analysis, the value of supply security is compared with its costs of provision. More specifically, the benefits of maintaining the present quality of electricity supply are the avoided social damages from electricity outages and are compared with the respective investment costs in the low- and medium-voltage distribution grid. It is shown that the transformation process towards a green and decentralized production structure will be costly for society, even though the costs can be reduced by different measures.

JEL Code: Q41, Q48, D61.
Keywords: Energy policy, cost-benefit analysis, value of supply security, value of lost load.

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1 Introduction

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

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

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

The economic literature, however, contains a wide range of papers that estimate the social value of supply security, which is often approximated by the (social) damages of outages (see, e.g., de Nooij et al. 2007; Ghajar and Billinton 2006; Willis and Garrod 1996) and is the approach taken here. The different estimation methods are described later in a separate section. The obtained results imply both technical and economic considerations. For example, de Nooij et al. (2010) and Munasinghe and Gellerson (1979) show how security standards based on estimating the value of supply security could replace those based on engineering practice. Thus, evaluating supply security can be seen as the first step in identifying socially optimal interruption levels (Baarsma and Hop 2009). Furthermore, it can be used in case of shortages to optimally allocate electricity (de Nooij et al. 2007; Serra and Fierro 1997; Forte et al. 1995). The present analysis combines technical and economic considerations such that the social welfare effects of the technically determined transition on the electricity market can be evaluated.

The analysis is based on the German electricity market, which in recent years has experienced a significant prioritization of environmental policy. The development of renewable energies is considered an appropriate way of reducing the country's CO_2-emissions. Therefore, renewable energy, as well as several energy efficiency goals for 2020, were defined in a national energy concept initiating a transition process on the electricity market. Unless electricity imports shall increase, the planned nuclear phase-out has put even more pressure on this project. After the transformation, the structure of the electricity market will be decentralized instead of centralized as it is currently. The renewable energies instrument designed to accomplish this transition is analyzed in this paper with respect to its effects on the energy-political benchmarks: First and foremost, the social welfare effects with respect to the supply security targets are analyzed in a cost-benefit framework based on the contributions of de Nooij et al. (2010) and Tishler et al. (2006). Then, the paper goes one step further than, to the author's knowledge, most supply security analyses by comparing the value of supply security with its costs of provision. Based on that comparison, conclusions are drawn with respect to the climate targets and their effects on electricity prices.

The paper is organized as follows. Section 2 analyzes targets and measures of the transformation process in the German electricity market and also in a European context with respect to the year 2020 from the perspective of the energy-political triangle. The cost-benefit analysis follows in Section 3. After presenting the methodological approach in Section 3.1, the necessary cost and benefit parameters are calculated in Sections 3.2 and 3.3. Then, in Section 3.4, the resulting net present value is derived. A discussion of other aspects of the analysis as well as the energy-political triangle follows in Section 4. Section 5 summarizes the results, draws conclusions, and discusses future research areas.

2 Targets and Measures

The structure of the analyzed problem is illustrated in Figure 2.1, where three policy levels can be distinguished: goals, indicators, and instruments. The energy-political triangle is the base of the analysis since it determines the goals, or targets, against which each policy instrument must be measured. But since these goals are stated in an abstract, sometimes even conflicting terminology, they are hardly testable. Thus, they are specified by three indicators, one for each goal, in the middle level. The indicators are precise and measurable parameters with which the effect of the instrument with regard to the specific goal can be tested. This interrelation between goals and indicators is illustrated by the dotted arrows in the figure. Finally, the upper level represents the policy instruments of interest in the present analysis; these are the development of renewable energies complemented by the second instrument, grid development. The solid arrows between the two upper levels point out the conceptual structure underlying the present paper, as will be explained in Section 3. The dashed arrows indicate other interrelations between the instruments and goals, respectively their indicators, that will be addressed in Section 4. The goals and indicators are next defined and explained in detail.

A primary target of energy policy is **environmental sustainability** of the electricity market. Environmentally unsound electricity production can have high social costs in form of external environmental damages.

Problems of internalization arise from the public good character, especially in an international context, or because damages may occur with delay (and therefore may appear less likely). The most prominent example is the climate change induced by anthropogenic greenhouse gas emissions. Growing awareness of future climate problems has put the reduction of anthropogenic CO_2-emissions at the center of attention.

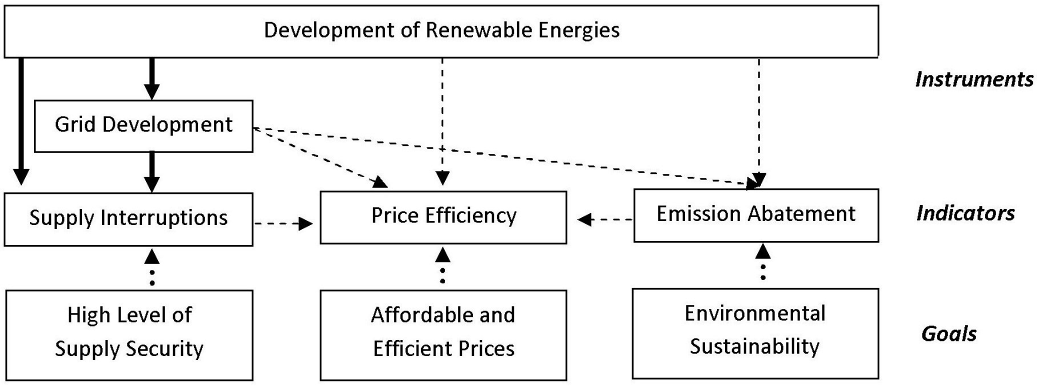

Figure 2.1: Structure of the problem

There is a vast range of legislation and regulation related to emissions reduction. For example, the European 20-20-20 targets to be reached by 2020 have been enacted (EC 2009a).[1] There are also national-level targets; for example, in Germany, a 40 percent reduction in greenhouse gases by 2020 and a reduction of at least 80 percent by 2050 with respect to the base year 1990 (BMWi and BMU 2010). Several measures have been designed to achieve these targets at both the national and international level, for example, the European emissions trading system (ETS) (EC 2009b) and the heavy promotion of renewable energies in Germany.[2]

Development of renewable energies is the German government's central instrument for reaching the environmental goals and thus is analyzed in this paper (see Figure 2.1). Accordingly, the success in CO_2-emissions abatement is used as an indicator of the instrument's utility with respect to the climate goals (see the target indicator in Figure 2.1).

The second energy-political goal is a **high level of security of electricity supply**. In this paper, the term "security of electricity supply" is used in a purely technical sense: a low level of supply security is associated with a high number of supply interruptions and is therefore costly for society. A reliable grid-bounded electricity supply can be seen as an important economic good, meaning that provision of the grid, a natural monopoly, is of particular importance. Moreover, the Energieinstitut (2012) report points out that households view provision of an interruption-free electricity supply as a duty of electricity companies (i.e., the government). Various

[1]The targets to be met by 2020 include "a reduction in EU greenhouse gas emissions of at least 20 percent below 1990 levels, 20 percent of EU energy consumption to come from renewable resources [and] a 20 percent reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency" (EC 2009b).

[2]The most important legislation is the German Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG) which came into law in 2000 and determines feed-in tariffs (§§16-22 EEG) for renewable energy electricity as well as feed-in priority (§5 EEG).

indices (VDE 2006) measure the technical supply security level (for an overview, see CEER 2008; VDE 2006). In general, the most important dimensions of technical (supply) security are frequency, duration, and extent of supply interruptions.[3]

Even though there are some substitution possibilities that may alleviate the consequences of supply interruptions, the damages incurred by a low level of technical supply security are substantial for an economy. In the case of firms, for example, damages arise due to interruption of work and production processes; in the case of households, damage manifests in the form of lost leisure time and also in the form of lost goods (de Nooij et al. 2007). From the government's perspective, lost tax revenues are one form of damage, but so is competitive disadvantage that arises due to supply interruptions. For a more detailed overview of damages caused by supply interruptions, see, frontier economics (2008), Bliem (2005), de Nooij et al. (2003), Wacker and Billinton (1989), and Munasinghe and Sanghvi (1988).[4]

This paper focuses on supply security problems that arise from the net integration of decentralized renewable energies (see Figure 3.1). The development of renewable energies leads to decentralized power production. To ensure a constant quality of structural supply security and to decrease the risk of network overload (i.e., the probability of a power outage), the grid must be appropriately designed. Consequently, grid development is a second energy-political instrument analyzed here (see Figure 2.1).[5] The suitable target indicator in this situation is the (cumulated) duration of supply interruptions (see Section 3.2.1). Moreover, the level of supply security in Germany is very high when looked at the international level.[6] Therefore, maintaining the status quo of supply security is often, and also in this paper, stated to be an energy-political minimum target.

Affordable and efficient electricity prices are the third dimension of the energy-political triangle. In industrialized countries, physical access to electricity is nearly universal. However, affordability is still an issue reflecting distributional effects of electricity prices. Efficient electricity prices are the second politically determined price goal. Obtaining efficient electricity prices is especially difficult since the electricity market faces different challenges, chiefly in regard to market power situations (since the provision of transmission technologies for electricity is a natural monopoly) or regulatory costs. Furthermore, from an energy policy perspective, it is important to consider the total social costs of electricity, including, for example, external costs like carbon

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

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

[5]For example, §9 Abs. 1 EEG describes the grid development obligation of system operators in the event of renewable energy capacity. On an international level, developing a European network system can be seen as a precondition for the Europe-wide development of renewable energies under the security constraint. For an overview of the different measures, see CEER (2008) or VDE (2006).

[6]An overview of the development of the supply security situation in Germany can be found in Table A1 of the Appendix.

emissions.

However, the price goals may be in conflict. For example, in the past few years, awareness regarding non-internalized carbon emissions of power production has increased. Internalizing this externality would improve efficiency (since prices should reflect the marginal social costs of electricity) but would increase electricity prices. Additionally, the internalization should take place in an international context to avoid competitive problems. In the following, the focus is more on the question of whether instruments increase the efficiency of electricity prices than on distributional issues, as shown in the price target indicator in Figure 2.1.

3 The Trade-Off between Green Policy and Supply Security

By means of a cost-benefit approach, the paper now analyzes the interrelation between renewable energies development and supply security targets regarding the distribution grid on the German electricity market.[7] The analysis is based on the transformation process between 2010 and 2020; estimations beyond 2020 entail too much uncertainty to be useful. The comparative static approach (indicated with the solid arrows in Figure 2.1) is explained in Section 3.1, followed by the quantitative evaluation of the discounted cash flows of the benefits (Section 3.2) and costs (Section 3.3) that will be compared in a net present value framework (Section 3.4).

3.1 Methodological Approach

Figure 3.1 shows and evaluates the interrelations between renewable energy and supply security goals on a social monetary cost basis: The upper quadrants illustrate the technical relations, which are valued on a social cost and benefit level in the lower quadrants.

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

In the two lower quadrants of the figure, the technical information from above is translated into social costs and benefits. The lower left-hand quadrant shows the associated social costs of accumulated investments for

[7]The paper analyzes network expansion of the low- and medium-voltage distribution grid. For a discussion of the planned expansion of the high- and maximum-voltage transmission network, see Section 4.

any given distribution grid development status in an upward-sloping curve.[8] The social damages of supply interruptions that result from any given level of supply security are illustrated as a downward-sloping curve in the lower right-hand quadrant: the higher the level of supply security, the lower are the social damages resulting from power outages.

As illustrated in Figure 3.1, the comparative statics of the cost-benefit analysis will be made in three steps. First, it is assumed that there is a centralized electricity production and a well-adapted grid structure, resulting in a high supply security level. Ceteris paribus, development of renewable energies in the second step will result in decentralized electricity production and thereby reduce the level of supply security. In step 3, investments in the grid are made in an effort to avoid increasing social interruption damages. In the cost-benefit analysis, investment costs are compared to avoided interruption damages, or social benefits, that are due to holding the level of supply security constant. All three steps are explained in more detail below.

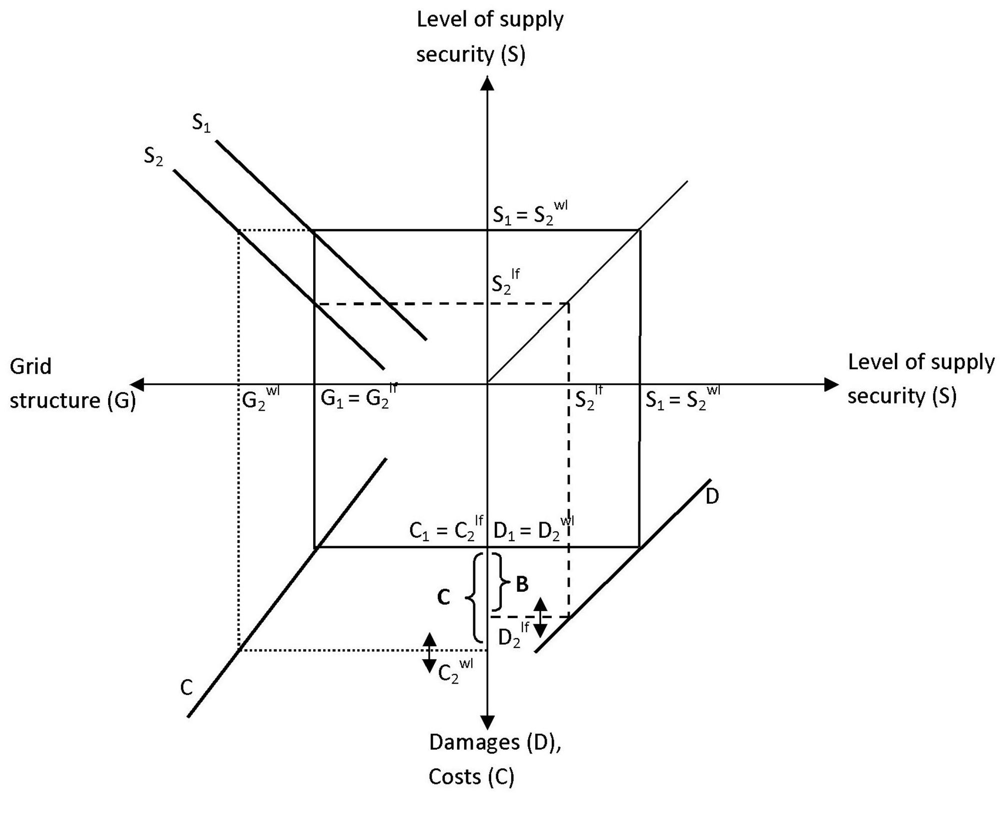

Figure 3.1: Grid structure vs. producer structure

The first step is illustrated in Figure 3.1 by solid lines that represent the basic situation on the electricity market. The top left-hand quadrant shows the initial grid development situation represented by the upper graph S_1. For a given producer structure, the initial grid status G_1 results in supply security level S_1. G_1 is associated with the respective accumulated investment costs C_1, as shown in the lower left-hand quadrant. Finally, the lower right-hand quadrant shows the social damages D_1 that result from the initial supply security level S_1.

[8] By assumption, current expenses, for example, maintenance costs, are not considered in this static framework.

In the basic situation, it is assumed that C_1 and D_1 coincide, indicating that costs and benefits in the initial electricity market situation are equal.

Growing awareness of climate problems has induced the government to encourage the development of renewable energies. The resulting consequences are examined in the second step, where new, deviating outcomes are shown with dashed lines. The renewables development can be understood as an external shock to the energy market that induces more decentralized power production.[9] Holding all else constant ("laissez-faire" situation, no investments in the grid structure), the producer structure works as a location parameter in the upper left-hand quadrant shifting S_1 downward to S_2; that is, no further investment is induced by renewables development (G_1=G_2^{lf} and C_1=C_2^{lf}). Consequently, the level of supply security decreases to S_2^{lf} and therefore the social damages increase to D_2^{lf}.

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

The difference between C_2^{wI} and C_1=C_2^{lf} in the lower left-hand quadrant represents the costs (C) of maintaining the basic level of supply security. The benefits (B), in terms of avoided interruption damages, are represented by the difference between D_1=D_2^{wI} and D_2^{lf} in the lower right-hand quadrant. The relative magnitude of benefits and costs (which depends on the relative slopes of the curves) determines whether the benefits of maintaining the basic level of supply security outweigh the costs.[10] A quantitative assessment of the costs and benefits is performed next.

3.2 The Benefits

Representing avoided (social) interruption damages ("B" in the lower right-hand quadrant of Figure 3.1), the benefits can be measured as the value of supply security (VoSS) approximated with the formula

$$VoSS[\frac{EUR}{a}] = SAIDI[\frac{min}{a}] * VoLL[\frac{EUR}{kWh}] * Load[\frac{kWh}{min}]. \quad (1)$$

The VoSS is the product of the SAIDI (System Average Interruption Duration Index), a reliability index that measures the level of supply security as the cumulated duration of supply interruptions in minutes per consumer

[9]This can lead, for any given distribution situation, to a reduction of structural supply security. The development of renewable energies tends to result in electricity being treated more like a common, tradable commodity, for example, transport is no longer unidirectional and supply and demand may be geographically separated (Energieinstitut 2012). This creates challenges to structural supply security if there has been a failure to develop the necessary grid capacities (and therefore grid redundancy decreases) (Energieinstitut 2012) and, consequently, may increase the number of outages.

[10]In Figure 3.1, aggregated effects correspond to marginal effects due to linear approximations. Because of high uncertainties both with regard to costs and supply interruption events (benefits), in the next sections, a marginal analysis is not useful for quantitative assessment.

and year (Consentec 2010), the VoLL (Value of Lost Load), which measures the damages of an electricity shortfall per unit of electricity lost, and the average (lost) load (consumption of electricity per minute) in each minute of interruption (see also, e.g., de Nooij et al. 2007; Bliem 2005). In the following sections, the different parameters are evaluated: first, the different SAIDI levels and then the valuation parameters VoLL and the average (lost) load.

3.2.1 The Level of Supply Security

In this paper, the level of supply security is approximated with the SAIDI, an internationally employed reliability index that is a part of the German Electricity Network Access Ordinance (Anreizregulierungsverordnung, ARegV; see also Federal Network Agency 2010); see §20 AregV.[11] The SAIDI describes the quality of supply security by measuring "the average amount of time per year that the power supply for a customer is interrupted" (CEER 2008). CEER (2008) calculates the SAIDI as

$$SAIDI = \sum \frac{N_i r_i}{N_T} \tag{2}$$

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

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

Since, by assumption, the SAIDI of the investment situation ($\mathrm{SAIDI}^{wI}_{2020}$) equals the initial SAIDI level (SAIDI_{2010}), it can be inferred from the Federal Network Agency (2012),

$$SAIDI^{wI}_{2020} = SAIDI_{2010} = 14,90\,\mathrm{min}\,. \tag{3}$$

In the following, the $\mathrm{SAIDI}^{lf}_{2}020$ will be estimated on the basis of the relation between the SAIDI and the structural parameter load density.[12] This relation is well-established, for example, in the German revenue cap regulation, and follows a strong nonlinear, negative (hyperbolic) functional form of

[11] SAIDI is an internationally employed DISQUAL index (UNIPEDE 1997). Weighted with the number of customers, it can also be found in the IEEE (Institute of Electrical and Electronics Engineers) Standard 1366.

[12] In this context, the load density is the quotient of the annual peak load and the geographical area. For a definition of geographical area, see StromNEV (German Electricity Network Fee Regulation Ordinance [Stromnetzentgeltverordnung]) §24 Abs.2.

$$SAIDI(LD) = \frac{a}{LD^c} + b \tag{4}$$

with the SAIDI in (min/a), the load or supply density (indicated as LD) in (kW/sqkm), and a, b, and c as constants (see Consentec 2010).[13] In the present paper, the parameter load density is used - with certain restrictions - as a proxy parameter to measure the suitability of the grid structure with respect to the producer structure.[14]

As an extension and elaboration of the top left-hand quadrant of Figure 3.1, Figure 3.2 illustrates the underlying considerations in forecasting SAIDI_{2020}^{lf} (note that the slopes of the graphs in both figures are reversed since $S = 1/SAIDI$): feeding in renewable energy and increasing energy efficiency lead to a sinking load density in 2020 compared to 2010.[15] The upper curve illustrates the negative relationship between load density and SAIDI, which is indicated by Equation (3) and shows that in the laissez-faire case without compensating network investments, the supply security in 2020 decreases from $SAIDI_{2010}$ to $SAIDI_{2020}^{lf}$. When there is sufficient network investment to maintain the former level of supply security, the curve shifts downward such that the level of supply security increases (the SAIDI decreases) for any given level of load density. The difference between these security levels is called ΔSAIDI and indicates the avoided changes in the level of supply security due to a network expansion parallel to the development of renewable power production. Consequently, ΔSAIDI refers to the difference between S_1=S_2^{wI} and S_2^{lf} in the top left-hand quadrant of Figure 3.1.

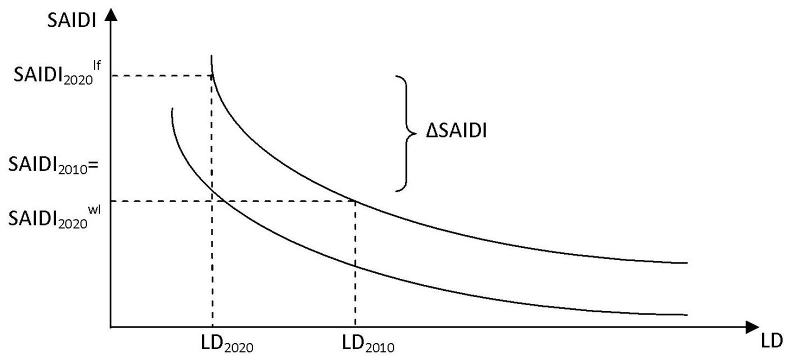

Figure 3.2: Estimation of the SAIDI

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

[14]Though Equation (4) doesn't necessarily meet the requirements of a precise prognosis, it clearly gives an idea of the magnitude of the change in the SAIDI level.

[15]A reason for the sinking load density due to the feeding in of renewable energy is that the grid will be used not more than simply unidirectional electricity transport (Energieinstitut 2012), which could even lead to a load reversal. For the year 2020, it can be assumed that other factors influencing the load density, such as a decreasing population, will not be much different from today.

The following calculations are based on the regression analysis of Consentec (2010).[16] They estimate the parameters of Equation (4) for the medium-voltage level as

$$SAIDI(LD) = \frac{1397}{LD^{0,8}} + 0,35. \tag{5}$$

Equation (5) is especially appropriate for estimating SAIDI^{lf}_{2020} since the grid situation of today that is captures is exactly the laissez-faire scenario of 2020: there is a change in load density, but the grid structure, indicated by the functional form of Equation (5), stays the same. Using Equation (5), SAIDI^{lf}_{2020} can be forecasted. For this purpose, forecasts of the load density for 2020 are needed. In the following, estimations of the annual peak load for the year 2020 made by the German energy agency (Dena 2010) are used to calculate the load density; these estimates are the best available to date as they show the largest range of estimates covering the forecasts of most other studies (see, e.g., BEE 2009).

The estimation results are presented in Table 3.1.[17] Depending on the underlying expectations about development of electricity demand, from 2010 to 2020, supply security will decrease from 14.90 minutes to about 20 minutes per customer and year. The difference of the SAIDIs, illustrated by ΔSAIDI in Figure 3.2, amounts to about 5 minutes per customer and year.

Year	Scenario	SAIDI_{2020}
2010	Experienced SAIDI	14.90
2020	Decreasing electricity demand	20.18
2020	Constant electricity demand	19.39

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

To translate the technical results into social monetary units and calculate the VoSS (Section 3.2.3), the SAIDIs will be multiplied by the value of a lost kWh, the VoLL, which is derived in the next section, and the average amount of electricity lost per minute of outage.

3.2.2 Value of Lost Load

Estimating the value a society places on a frictionless electricity supply is not straightforward. For one thing, being much lower than the economic value of a not delivered unit of electricity, the user price of electricity does not include the (marginal) damages of supply interruptions.[18] Moreover, an insurance system for power

[16]The supply interruptions data refer to §52 EnWG (Energiewirtschaftsgesetz [Law on Energy Management]) and anonymized data of the FNN interruptions statistics.

[17]Consentec (2010) emphasizes that for the considered range of load density values, the regression analysis is most exact for the medium-voltage level. However, load density is not a significant parameter for measuring supply security effects at the low-voltage level. Therefore, since the development of renewable energies is of prime importance for the low-voltage level, the SAIDI over the analyzed period is assumed to be constant. This is of minor importance for the present analysis since most interruptions take place in medium-voltage levels (Consentec 2010).

[18]One reason is that the end user electricity price partly consists of average costs, for example, the grid user fees, which are lower than the marginal costs. Moreover, it can be assumed that electricity prices do not siphon off the consumers' surplus, which would

interruptions reflecting a market price for supply security only exists partially and for only large end users (de Nooij et al. 2007; Bliem 2005).[19]

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

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

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

Another important method is the evaluation of revealed preferences. The behavior of households and firms with regard to investments in supply security, for example, buying backup generators or signing interruptible contracts, can be analyzed and used to calculate willingness to pay for supply security (de Nooij et al. 2007; Caves et al. 1992). However, one problem with this method is that measures taken to ensure supply may not be voluntary, but required by law, for example, in the case of a hospital.

The valuation method used in this paper is a macroeconomical production function approach.[20] Under this

include the value of a lost load.

[19] This is particularly interesting since, beside the public good character, the idea of insurance is especially important for electricity supply security.

[20] Consentec (2010) performs a similar calculation of the German VoLL for the year 2008; however, the results presented here were not influenced by the Consentec (2010) calculations.

approach, the VoLL answers the question of how much value added is produced with one kWh and thus approximately determines the foregone value added due to the electricity outage (opportunity costs concept; Willis and Garrod 1996). Then, the VoLL estimates the social "damage per unit of electricity [that is] not delivered" (de Nooij et al. 2003). In case of households, the damage is related to the consumers' value of leisure time. The VoLL is estimated using statistical data on electricity consumption and the value added of firms or, respectively, the value of private-life time of households (e.g., de Nooij et al. 2007; Tishler 1993; Munasinghe and Gellerson 1979). To evaluate the economy-wide outage damages, lost production can be calculated in each sector directly and then be aggregated with the value of lost leisure time of households to arrive at a total in a top-down fashion. There are several aggregation methods for evaluating production-side electricity outage damages. For example, linkages between sectors can be included using input-output-tables (Chen and Vella 1994). With regard to both firm and household estimations, an advantage of this method is the availability of empirical data. A problem is that because of the aggregation, some direct and indirect damages will not be taken into account and certain substitution and catch-up effects may be missed (Bliem 2005).

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

In the case of households, since they do not create economic value that can be related to electricity consumption, an alternative estimation method is needed. In the case of supply interruptions, the loss of private-life time (household activities and leisure time) is the most relevant damage to households (see Section 2). Therefore, in this paper, as in de Nooij et al. (2007) and Bliem (2005), on the basis of Becker (1965), the Munasinghe's model (1980) is used to estimate the costs of lost private-life time for households.[21] The basic assumption is that private-life time is a normal good with a decreasing utility in hours spent (see deSerpa 1971). Under the assumption of a well-functioning labor market, the optimal amount of working time is reached when the income generated by the last hour worked equals the value of an hour of private-life time (for a discussion, see de Nooij et al. 2007). Then, the marginal hour work has approximately the same value (utility) as the marginal hour of leisure time.[22] Additionally, since it is assumed that an interruption of the electricity supply leads to postponement of household activities, in accordance with Munasinghe (1980), a marginal hour of leisure has the same value as a marginal hour of household activities. In the following, the net marginal income is approximated by the average net income per hour.

The relevant data for calculating the value of time were collected from the German Federal Statistical Office. The interrelation between electricity dependence and duration of different activities is decisive in assessing substitution possibilities for households in case of outages. Most non-working time, except that spent sleeping,

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

[22]Other approaches exist that estimate the value of leisure time. For example, estimations based on observations of speeding behavior and speed limits can be found in Wolff (2011) or Ashenfelter and Greenstone (2004).

is used for leisure and household activities (see Table A2 in the Appendix) and most of these activities are at least partially electricity dependent and only partly substitutable. An overview of the electricity dependence of households can be found in Table A3 of the Appendix. Following Bliem (2005), a substitution possibility of 50 percent for private-life time is assumed, which means that in case of an outage, half the activities can be substituted without producing utility losses.

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

Scenario	Value of time (mio EUR)	Electricity Consumption (TWh) 2008-2010	VoLL (EUR per kWh)
Base scenario	2,106,028.64	139.9	15.05
Scenario less leisure time	2,039,245.55	139.9	14.58
Scenario lower tax burden	1,982,243.81	139.9	14.17

Table 3.2: Value of time, electricity consumption, and VoLL of households
Calculations are based on data from the Federal Statistical Office (2011a, 2011b, 2012a), Karl Bräuer Institut (2010), and BDEW (2011).

According to Table 3.2, the VoLL of households is estimated to be around 15 Euro per kWh. A sensitivity analysis in the form of two additional estimation scenarios confirms the robustness of the results: Assuming 10 percent less leisure time for non-working people (scenario "less leisure time") in comparison to the base scenario or assuming a lower accumulated income tax rate (scenario "lower tax burden") of 45 instead of 50 percent does not change the results much (see Table 3.2).[23]

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

[23] There are several reasons why these results could be to be over- or underestimations: On the one hand, better substitution possibilities or a higher variety of leisure activities could indicate an overestimation. On the other hand, the VoLL could also be underestimated since, in reality, a random hour of leisure is lost, an hour that could exceed the value of a marginal, or average, hour (see de Nooij et al. 2007; Becker 1965). Day and Reese (1992) give as an example an electricity interruption during a championship football game. Another example would be that most of the value added is produced during weekdays when the opportunity costs might be higher than implied by the average VoLL calculated above. However, even though the results lie in the middle range of the different VoLL estimates, as can be seen in Table A4 of the Appendix, they need to be viewed as conservative estimations because, for example, the VoLL of households increases with the duration of the outage (see Energieinstitut 2012), a fact not considered in the present analysis.

to the value added, that is, the higher the electricity intensity of a sector, the lower the VoLL.[24]

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

Table 3.3: Calculation of the economy-wide VoLL (average of the years 2008-2010)

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

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

Weighting the different VoLLs with the share of the sectoral value added and the share of the value of time with respect to the aggregated value leads to an overall (weighted average) VoLL of about 12.51 Euro per kWh.[25] Table 3.3 clearly shows that not only for the producing sectors, but also for households, the damages of a supply interruption far exceed the cost of electricity. A reason for this could be that in this non-marginal analysis, the difference between the end user electricity price and the VoLL reflects the consumers' surplus.[26]

3.2.3 Value of Supply Security

From the respective levels of SAIDI, the value of a lost unit of electricity (VoLL), and the amount of electricity (load) lost, the values of supply security (VoSS) can be calculated, as shown in Equation (1). The VoSS, which here is interpreted as the benefits (avoided social damages) due to grid investments made so as to hold constant the quality of supply (load and VoLL are assumed to be constant until 2020) arise from ΔSAIDI according to Figure 3.1: the technical results of the upper quadrants, which can be associated with ΔSAIDI, are weighted with economic values (see Equation (1)) as shown in the lower quadrants. The benefits occur in the difference between $D_1{=}D_2^{wI}$ and D_2^{lf}, indicated with "B" in the lower right-hand quadrant.

Differentiated for alternative demand scenarios, Table 3.4 shows the calculation of the benefits, ΔVoSS, for the year 2020 in current values. First, the table shows that a Germany-wide power outage of one minute leads on average to damages of about 12,064 TEUR. Multiplied by the respective SAIDIs, the social damages arising from power outages in the different years can be calculated. From that it follows that in 2010, the economic damages in Germany due to supply interruptions in the distribution grid amounted to 179,753.02 TEUR. In the

[24] This implies that, in line with Ramsey pricing, in case of supply shortages, consumers with the lowest price elasticity should be treated as the least important when it comes to allocating supply (de Nooij et al. 2007).

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

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

	Decreasing electricity demand scenario	Constant electricity demand scenario
Damages of one minute electricity outage (TEUR)	12,064	12,064
Damages of electricity outages per year (TEUR) $2010 = 2020^{wI}$ 2020^{lf}	 179,753.02 243,506.44	 179,753.02 233,886,23
Benefits of grid expansion (TEUR/a)	63,753.41	54,133.21

Table 3.4: Calculation of the benefits in 2020 current values

laissez-faire situation of the year 2020, the increasing SAIDI leads to higher economic damages from outages as can be seen in the next row of Table 3.4. In the "decreasing electricity demand" scenario, the damages are higher (243,506.44 TEUR) than in the "constant electricity demand" scenario (233,886.23 TEUR) resulting from the different SAIDI levels estimated (see Table 3.1).[27] The difference between the estimated damages with and without investments in supply security is the benefit in the year 2020, shown in the last row of Table 3.4, and amounts to 63,753.41, respectively 54,133.21 TEUR. These are the avoided damages since, due to grid development, the SAIDI level does not increase by another 5 minutes. To calculate the annual benefits between 2010 and 2020, it will be assumed that the load density for the different estimations of the ceteris paribus case develops linearly, resulting in the annual ΔSAIDI levels that will be used in Section 3.4.

3.3 The Costs

After calculating the benefits of maintaining the quality of supply security, the investment costs of the associated grid expansion are considered. Costs due to investments in the low and medium voltage distribution network arise mainly from the installation of open wires in the form of alignments and circuits, cables with the respective trenches as well as current transformers, transformer stations and local network stations (compact stations including transformers) (BET et al. 2011). The investment measures and costs in the electricity grid are illustrated in figure 3.1: The upper left-hand quadrant shows that the grid has to be developed by the amount of the difference between G_2^{wI}, the new level of grid structure, and G_1=G_2^{lf}, its previous level. Valuating the grid development in terms of costs directly leads to an increase in the accumulated grid investments from C_1=C_2^{lf}, the previous amount of aggregated investments into the grid structure, to G_2^{wI}, the respective new level. The total investment costs are indicated by "C" in the lower left-hand quadrant.

The considered investment costs are based on calculations of BET et al. (2011), which estimate, based on the technical guidelines, the amount of investment necessary due to the development of renewable electricity production in the low- and medium-voltage distribution grid (without maintenance and plant connection costs). On the basis of model net regions, BET et al. (2011) estimate the Germany-wide investment needed to ap-

[27] The demand scenarios refer to those assumed on the basis of Dena (2010) in Table 3.1.

propriately expand the network at the low- and medium-voltage level for two scenarios: the energy scenario (Prognos et al. 2010) developed for the government's energy initiative (BMWi and BMU 2010) and the BMU lead scenario developed by Nitsch et al. (2010). The individual components of the model net regions "are parameterized and estimated using conventional, standardized technique and planning principles."[28] The costs are summarized in Table 3.5.

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

Table 3.5: Costs of distribution grid development up to 2020
The distribution grid investment volume up to 2020 is calculated by BET et al. (2011)

In this paper, by assumption, the results are used as estimations of the costs incurred in holding the level of supply security at least constant under the new, decentralized producer structure. Table 3.5 shows the cost ranges: Depending on the scenario, the costs lie between 10 and 27 billion Euro.[29] In the following, it is assumed that the costs are incurred equally between 2010 and 2020. Therefore, the yearly costs are approximated as between 0.91 and 2.4 billion Euros in current values.

3.4 Calculation of the Net Present Value

The effects on supply security of the planned transformation process in the energy sector can be described in the following net present value framework. The sign of the net present value indicates the direction of the trade-off between the development of renewable energies and the supply security goals. The costs, indicated by "C", and the benefits, indicated by "B", can be compared graphically in the lower quadrants of Figure 3.1.

A simplifying assumption is that during the analyzed period of the transformation process, investments in development of the grid structure and renewable energy production go hand in hand. While the benefits from a constant quality of electricity supply increase during the period, the yearly costs are assumed to be constant. Additionally, as explained in Section 3.3, it is assumed that all the investment costs have to be paid by 2020. The discount rate is assumed to be 5 percent.

Table 3.6 shows the results of the cost-benefit analysis. The rows distinguish between the various cost scenarios, as done in Table 3.5. In the columns, the benefit scenarios are differentiated based on assumed development of electricity demand, as indicated in Table 3.4.[30] The negative net present values shown in Table 3.6 indicate

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

[29]The range of estimates is so large because the projections of installed capacity under the Energy Concept (BMWi and BMU 2010) and the Lead Scenario (Nitsch et al. 2010) vary so widely. This situation is especially due to different assumptions about the development of photovoltaic capacity in Germany (BET et al. 2011). In a sensitivity analysis, BET et al. (2011) show that the results are stable and that dimensioning the transformation levels does not influence the cost volume much.

[30]The present analysis is restricted to the period between 2010 and 2020 although transformation of the energy system will not be complete by the end of that period. Quantitative estimations of benefits and costs become increasingly difficult the longer the considered time span. This is mainly due to uncertainties beyond 2020 in regard to technological, climatic, and energy-political developments.

Cost scenarios \ Benefit scenarios	Constant demand	Decreasing demand
Energy concept (min)	-8,688,602.31	-8,683,459.24
Energy concept (max)	-11,305,122.79	-11,299,521.72
Lead scenario (min)	-18,282,510.74	-18,276,909.66
Lead scenario (max)	-23,515,551.69	-23,509,950.62

Table 3.6: Net present value (in TEUR)
Calculations are based on data from Tables 3.4 and 3.5.

that the transformation process will be costly in terms of supply security, although the magnitude of these costs depends on the underlying scenario.

4 Discussion

In the previous sections, the trade-off between the development of renewable energies and supply security was analyzed. Since the analysis is of a partial nature, other aspects must be taken into account to obtain a complete picture. This section extends the analysis to the context of both further considerations regarding the costs and benefits as well as price and climate goals.

First, the above analysis considers only the distribution grid. Extending the analysis to the transmission grid would increase both costs and benefits. Grid development costs due to renewable energies development would increase the price of electricity for households by about 1 ct. per kWh by 2020 (less for privileged electricity consumers), according to Dena (2011). Furthermore, the probability of system blackouts changes with transmission grid development (and to some extent also with distribution grid development): with higher network stability, the probability of such "low probability high impact" events can be reduced and supply security benefits increased.[31] Moreover, regarding investment in the distribution grid, BET et al. (2011) emphasize that their calculations need to be viewed as conservative. This is, on the one hand, because no optimization of the development measures has been done and, on the other hand, because grid operators can to some extent foresee from some of the repairs or replacements needed for the current grid due to the grid investments necessary for the green energy development. Considering these effects would reduce the investment costs reflected in the present analysis.

Second, ramifications of the considered time horizon must be discussed. It is possible that the positive effects of network investment will persist longer than the analyzed time horizon. Therefore, the benefits may have been underestimated. Additionally, considering a longer time horizon would decrease the annual investment cost of grid development and thereby increase the net present value. Nevertheless, the present analysis refrained from

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

examining the tran-formation process beyond 2020 since uncertainty about future developments is too high in the energy market and therefore not easily evaluated.

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

Fourth, the development of renewable energy avoids costs of ETS emission certificates (EUA, or EU-allowance, is an allowance unit of one ton of carbon dioxide) since the share of CO_2-emitting electricity production decreases with an increasing share of green electricity production. The effect indicating an overestimation of the costs can be roughly quantified at about 0.17 ct. per kWh in 2011.[32] Nevertheless, the EEG-induced (see Section 2) marginal abatement costs, distributed among the (non-privileged) end users as a renewable energies levy (EEG-Umlage), by far exceed the ETS-induced marginal abatement costs and therefore overcompensate for avoided certificate costs.[33] Also not included are the costs of the development and installation of storage and back-up technologies or the effects of phasing out nuclear energy. Consequently, further electricity price increases can be expected (see Erdmann 2011). Sinn (2012) points out that German renewable energies development creates welfare losses since it leads to a cost-inefficient abatement of CO_2. On the one hand, different feed-in tariffs for different technologies induce varying marginal abatement costs of CO_2-emissions. On the other hand, the German abatement is inefficiently high compared to other ETS countries' CO_2 abatement based on ETS certificate prices.

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

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

[33] In the year 2011, the apportionment costs were about 3.53 ct. per kWh. The renewable energies levy influences all non-privileged electricity consumers' prices and contains, among others, the difference in cost between the wholesale market prices of electricity and the feed-in tariffs of electricity. The renewable energies levy is expected to continue beyond the year 2020, even increasing until at least the middle of the decade (Nitsch et al. 2010). For the year 2013, the apportionment has already increased to 5.28 ct. per kWh.

Sixth, beside the absolute price effects, which are clearly in conflict with "affordability," the distributive consequences of the renewable energies development system need to be considered. Just to mention in this context is the most prominent distributive consequence regarding the renewable energies development in Germany: Many analyses, for example, Techert et al. (2012), show that the costs (e.g., EEG apportionment) are overproportionally borne by the low-income population, whereas the higher-income population profits from the high (relatively to the risk) green energy investment revenues (Gavel and Korte 2012).

Finally, the renewable energies instrument should be assessed with regard to its effectiveness in mitigating CO_2 since this is its primary aim. Much literature, for example, Sinn (2012), finds that the net effect of the EEG-implied emissions reduction is zero due to the interrelation of the EEG with the European emissions trading system (ETS). Since the latter covers almost 100 percent of European electricity production, a decreasing demand for emission certificates in Germany induced by renewable energies development reduces the European certificate prices and thereby increases the demand for certificates in other ETS countries by about the same amount. Based on this effect, Sinn (2012) emphasizes that other countries' CO_2-emissions are subsidized by Germany's abatement efforts.

5 Results and conclusions

In Germany, the development of renewable energies is almost unanimously believed by politicians and the public to be the most promising approach to reduce the country's CO_2-emissions and combat climate change. The present paper focuses on the welfare effects of maintaining the current level of supply security given the large-scale integration of green power into the energy system and quantifies the effects of the resulting trade-off. In a cost-benefit analysis, the discounted cash flows of the benefits of maintaining the high level of supply security and of the costs of grid investments are compared. The benefits were calculated as the avoided damages of a decreasing quality of supply security that would occur in case of a ceteris paribus development of renewable energies. They result from an increase in the average (per year) outage duration for each consumer served (SAIDI). The resulting lost load was evaluated with a production function approach. The investment costs of the associated grid expansion of the distribution grid are calculated by BET et al. (2011).

The net present value shows that the costs by far exceed the induced welfare gains of maintaining a constant supply security level. With regard to climate goals, the efficiency of the instrument is controversial since it induces different marginal abatement costs not only with respect to different green energies but also with regard to the abatement costs resulting from the European emissions trading system. Moreover, the mitigation effect on CO_2-emissions is doubtful due to the interrelation between the European emissions trading system (ETS) and the German renewable energies subsidy scheme (EEG). Finally, regarding the price target, mainly due to higher grid fees and the renewable energies levy, society suffers, not only in the matter of efficiency, but also with regard to the distributive goals. Thus, the analysis implies that the strong focus on the development of renewable energies in Germany, accompanied by a strict grid regulation, results in a triple trade-off with regard to environmental, price, and supply security considerations.

Nevertheless, the results cannot simply be dismissed as the "natural" outcome of a trilemma between different energy-political goals but as a specific consequence of a deliberately chosen energy-political strategy. For example, to reduce CO_2-emissions at the national level, choosing a more diversified set of instruments can to some extent result in welfare gains. Take the example of energy efficiency: if energy efficiency cannot be improved, the increasing use of renewable energy becomes much more expensive and the social costs of the transformation process increase. This may be because more back-up power has to be provided or because increasing energy efficiency decreases load density and therefore increases foregone interruption damages. Of course, also in this context, cost-benefit considerations are necessary to optimize the measures. Consider, for example, the possible consequences of a more economically (and less technically) oriented grid regulation. Regarding the negative net present value of the analysis, the question arises as to whether regulation may be too strict for socially optimal investment by network operators. Given the renewable energy development plans, more flexibility in the supply security goals (which are implied in the technical guidelines for the grid operators and can be interpreted as maintaining the current quality of supply security) could be welfare increasing. Moreover, regarding the welfare effects of delays in the (distribution) grid development, postponing grid development and therefore investment costs may, at least to some extent, be welfare enhancing in the analyzed situation.

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

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

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

There are several possible extensions of the approach taken in this paper. Since the present results indicate that incentive regulation and technical standards have to be sufficiently flexible to ensure efficient electricity market development, the role of regulation should be further analyzed as it is of great importance for the whole transformation process. Moreover, future research is especially needed on the relationship between the development of renewable energies and energy security. Also conceivable is an estimation based on an explanatory variable that could be used in addition to or instead of load density to estimate the relation between grid structure, production structure, and supply security. Finally, further research is needed with regard to the phasing out of nuclear energy and the resulting effects on supply security and emission reduction goals.

Appendix

The German SAIDI

Table A1 shows the supply security situation in Germany for previous years for the low- and medium-voltage level as well as aggregated over both voltage levels.[34] Duration and number of interruptions apply to the 48.8 million electricity consumers, firms and households, and are collected by the more than 800 German network operators in the low- and medium-voltage level (Federal Network Agency 2012). The quality of supply security in Germany is very high; in 2009, electricity in Germany was available for 99.9965 percent of the time (BDEW 2010).

[34] Longer time series of the German SAIDI were not available because publication of this information in Germany has been mandatory only since 2006 (§52 EnWG).

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

Table A1: Average unavailability (SAIDI) per customer and year
Source: Federal Network Agency (2012)

Value of Leisure Time

Table A2 shows the time spent on different daily activities for about 5,400 households and more than 12,000 persons between 2001 and 2002. It is differentiated between employed people, here, full-time workers, and unemployed people, here, retirees. The table makes clear that most non-working time, except then spent sleeping, is used for leisure and household activities.

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

Table A2: Average time organization per day 2001/2002 with selected activities in hours: minutes per day (Monday-Sunday)
[1]: full-time employed people; [2]: retirees
Source: Federal Statistical Office and BMFSFJ (2003)

Table A3 shows the extent to which household activities rely on electricity. The table reveals that the most important household and leisure activities are at least partially electricity dependent and only partly substitutable. Some leisure activities, but also general household activities, shown in Table A2, for instance, mass media or cooking, are even mostly electricity dependent with only limited substitution possibilities. Consequently, with regard to damages of supply interruptions, this means that the higher the electricity dependency and the lower the substitution possibilities, the higher are social damages.

Comparison of VoLL Analyses

Table A4 presents and compares the results from different VoLL estimates. It shows inflation-adjusted VoLLs in 2011 EUR values that were estimated for different countries with different methods (macroeconomic analysis,

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

Table A3: Electricity dependence of selected activities
Results are based on Bliem (2005) and de Nooij et al. (2007)

survey about willingness to pay, contingent valuation method, costs of back-up capacity, meta-analysis, choice experiment, shadow price of planned capacity). It must be kept in mind that a precise figure for the damages of a power outage is situation dependent and includes factors in addition to outage duration, sectors, regions, years, or time of day. Consequently, the VoLL cannot be seen as constant over time and between different electricity consumers. Therefore, for example, many authors differentiate the estimations with regard to interruption durations (see, e.g., Curtin and Doherty 2007), but an estimation of generic values is not possible due to the complexity of supply interruption situations (see also frontier economics 2008).The estimations in Table A4 therefore must be viewed as approximations or, at best, averages.

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

Method	Author(s)	Year	Region	VoLL [EUR/ kWh]
Macroeconomic Analysis	present paper[1]	2008-2010	Germany	Agriculture: 2.22 Industry: 2.81 Public Administration: 6.50 Trade and Services: 15.37 Transport: 7.61 Households: 13.61
Macroeconomic Analsis	Leahy at al. (2012)	2008	Republic of Ireland	Commerce: 13.2 Industry: 3.8 Households: 23.22
Macroeconomic Analysis	Tol (2007)	2005	Republic of Ireland	Average: 7.7 Agriculture: 5.8 Services: 11.6 Transport: 65.8 Residential sector: 63.9
Macroeconomic Analysis	de Nooij et al. (2007)	2001	Nether-lands	Agriculture: 4.61 Production: 2.21 Services: 9.39 Households: 19.37

Macroeconomic Analysis	Bliem (2005)	2004	Austria	Agriculture: 3.7 Construction industry: 48.1 Production: 2.4 Service: 10.5 Households: 18.1
Survey: Willingness to pay	CRA (2007)[2.3]	2007	Australia	Agriculture: 0.08 Commercial: 0.03 Industrial: 0.02 Residential: 0.01
Survey: Willingness to pay	Samdal et al. (2006)[4.5]	2001-2003	Norway	Agriculture: 2.84 Commercial: 18.77 Industry: 12.52 Residential: 1.52
Survey: Willingness to pay	Reichl et al. (2012)[8]	2008	Austria	Agriculture: 4.0 Construction Industry: 45.2 Production: 3.7 Households: 1.4
Survey: Mail-out and direct measurement	Electricity Authority New Zealand (2012)[2.6]	2010	New Zealand	Average: 12.51 - 26.65
Survey: Costs of backup capacity	Gilmore and Lave (2007)[7]	2004-2006	USA	Average: 22.80 - 25.48
Meta Analysis	frontier economics (2008)	2007	Germany	Average: 8.3 - 16.5
Shadow price of planned capacity	Curtin and Doherty (2007)[2]	2007	Ireland	Weighted average: 8.98

Table A4: Comparison of VoLL estimates
In EUR-values, inflation adjusted for 2011
[1] In nominal prices
[2] Interruption duration is 8 hours
[3] Exchange rate 2007: 1 AUD = 0.61159 EUR
[4] Annual average interruption duration is 1.3 hours
[5] Exchange rate 2003: 1 NOK = 0.12507 EUR
[6] In 2011 prices
[7] Exchange rate 2006: 1 USD = 0.79678 EUR
[8] Interruption duration is 12 hours in summer

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