Essays on the Economics of Energy Markets

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Security of Supply and Greenhouse Gas Abatement

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Abbreviations

ACPF	average costs of public funds
AGEB	Arbeitsgemeinschaft Energiebilanzen (Working Group Energy Balances)
AME	average marginal effects
bcm	billion cubic meters
BEI	Bremer Energie Institut (Energy Institute Bremen)
Benelux	Belgium, Netherlands, Luxembourg
BDH	Bundesindustrieverband Deutschland Haus-, Energie- und Umwelttechnik e.V. (Federal Industrial Association of Germany House, Energy and Environmental Technology)
BP	British Petrol
BPIE	Buildings Performance Institute Europe
CIEP	Clingendael International Energy Programme
CO_2-eq.	carbon dioxide equivalents
CV	compensating variation
DD	differences-in-differences
DDD	differences-in-differences-in-differences
DIscrHEat	Discrete Choice Heat Market Simulation Model
DIW	Deutsches Institut für Wirtschaftsforschung (German Institute of Economic Research)
e.g.	exempli gratia
EGM	European Gas Markets
ENTSOG	European Network of Transmission System Operators for Gas
ERGEG	European Regulators' Group for Electricity and Gas
EU	European Union
EUR	Euro
EWI	Energiewirtschaftliches Institut an der Universität zu Köln (Institute of Energy Economics at the University of Cologne)
FGLS	feasible generalzed least squares

FYROM	Former Yugoslav Republic of Macedonia
GDP	gross domestic product
GIE	Gas Infrastructure Europe
GmbH	Gesellschaft mit beschränkter Haftung (company with limited liability)
HDD	heating degree days
i.e.	id est
IEA	International Energy Agency
IGA	Intergovernmental Agreement
IGI	Interconnector Greece-Italy
IIA	Independence of Irrelevant Alternatives
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IWU	Institut Wohnen und Umwelt (Institute Habitation and Environment)
KfW	Kreditanstalt für Wiederaufbau (Reconstruction Credit Institute)
kwh	kilowatt hour
LNG	liquefied natural gas
MBtu	thousand British thermal units
MCPF	marginal costs of public funds
MEB	marginal excess burden
MWh	megawatt hour
mcm	million cubic meters
MCP	Mixed-Complementarity-Problem
m^2	square meter
m^2a	square meter year
NBP	National Balancing Point
NEEAP	National Energy Efficiency Action Plan
NGO	non-governmental organisation
OLS	ordinary least squares
OME	Observatoir Méditerranéen de l'Energie
PV	Political Stability and Absence of Violence/Terrorism
SOEP	Sozio-oekonomisches Panel (German Socio-Economic Panel Study)
SoS	security of supply
TAG	Trans Austria Gas Pipeline
TAP	Trans Adriatic Pipeline

TEN-E	Trans-European energy networks
TIGER	Transport Infrastructure for Gas with Enhanced Resolution
TSO	transmission system operator
TTF	Title Transfer Facility
UNCED	United Nations Conference on Environment and Development
UNECE	United Nations Economic Commission for Europe
UK	United Kingdom
UKERC	United Kingdom Energy Research Center
VA	Voice and Accountability
WGI	World Governance Indicators
WGV	working gas volume

Chapter 1

Introduction

1.1 Motivation

Energy is not only one of the major production factors of modern economies, but it is also a major driver of the well-being of society. The secure, economically efficient and environmentally sound provision of energy is a major objective of industrial nations in order to increase social welfare. Security of supply, competitiveness of economies and environmental sustainability in energy markets are the key points of the European climate and energy targets and are often referred to as the 'triangle of energy policy' (European Commission, 2010). In this day and age, energy generation requires resource- and capital-intense technologies. Therefore, the efficient provision of energy depends on an efficient deployment and allocation of these inputs as well as an efficient usage of the technologies.

In economic theory, perfect markets are considered to be able to attain an efficient allocation of goods. However, four standard causes of market failure may impede an efficient allocation: market power, incomplete information, externalities and public goods. All of these market failures are common issues in energy market analyses. The role of energy markets in providing both essential production factors and consumer goods indicates that market failures within energy markets may cause significant welfare losses and are thus an important economic subject to consider.

Market failures may counteract the objectives of the triangle of energy policy that industrial nations strive to achieve. In terms of energy security of supply (SoS), the pursued level may exceed the level that is provided from the plain market mechanism. Regarding the environmental sustainability of energy provision, externalities, such as greenhouse gas emissions, may occur that are not internalized by market players.

The economic energy market analyses conducted in the presented dissertation address these two topics in energy markets, namely security of supply and greenhouse gas abatement. The first part of the thesis presents two papers that pursue model-based analyses of SoS in the European natural gas market. These analyses are normative and holistic approaches that model the utilization of the European natural gas infrastructure based on the optimization of a social planner. Such an approach is indispensable in an intermeshed network, such as the European natural gas network, as the usage of infrastructure components has an impact on subsequent parts of the network.

The Russia-Ukraine gas dispute in January 2009 presented the importance of the holistic approach from the European Commission's position. The disruption of Russian natural gas supplies to Ukraine, coinciding with record low temperatures in many parts of Europe, had major impacts on the European gas market and resulted in a serious gas supply crisis. A total of twelve European member states were affected with the consequences of the supply disruptions differing for each particular member state. In general, the affected member states were deprived of 20% of their usual gas supply. Moreover, since many Eastern European countries mainly depend on Russian supplies and have limited storage capacities, they suffered major shortages to industrial consumers. The interruption could not be solely resolved by individual European companies or transmission system operators (TSOs) and the European Commission concluded that greater coordination of TSOs and policy interventions are crucial to aid future emergencies (European Commission, 2009). The European SoS Regulation (European Union, 2010), adopted in the aftermath of the supply crisis, aims to reduce the risks of disruptions and to enhance the cooperation on a European level. Moreover, the European support of the Nabucco pipeline project was a further attempt by the European Commission to increase the level of security of gas supply in Europe.

A second major reason for the European Union (EU)'s policy interventions is the ambitious climate and energy targets, the so-called '20-20-20' targets, which are to be reached by 2020. The objectives are the reduction of greenhouse gas emissions from 1990 levels by 20%, a rise in the share of EU energy consumption produced from renewable resources to 20%, and improvements in the EU's energy efficiency by 20%.

According to the IPCC (2001, 2007), greenhouse gas emissions may aggravate the effects of climate change as they cause increases in global average temperatures. Based on the assessment carried out by the IPCC (2001), Stern (2007) analyzes the economic impacts of climate change and reports that countries will be economically affected worldwide. Stern (2007) estimates that the dangers of unabated climate change will result in excess costs equivalent to 5-20% of global GDP each year depending on the range of potential risks considered. Thus, externalized greenhouse gas emissions reflect a 'public bad', characterized by non-excludability and non-rivalry concerning damage, and cause significant welfare losses in the case of overprovision.

The second part of the thesis thus seeks to shed light on greenhouse gas abatement potentials in the residential heating market, and to investigate the effectiveness of current policies. Economic agents are known to cause greenhouse gas emissions, so understanding their behavior is crucial to develop targeted abatement policies. Major greenhouse gas emitters include power generators, energy-intense industries and households. While the behavior of power generators and energy-intense industries is mainly driven by the objective of profit maximization, households may have diverse causes for their behavior. According to the European Commission (2012), 36% of greenhouse gas emissions in the European Union are caused by space and water heating, the majority of which is used by the residential sector. The emission level of the residential sector depends on the energy efficiency level and the type of energy carriers consumed in residential dwellings. How these standards are maintained is determined by the amount and frequency of investments in insulation measures and heating systems made by homeowners or landlords. Understanding the behavior of homeowners and landlords is thus important for evaluating policies in energy efficiency and for deriving greenhouse gas abatement potentials. Moreover, studying the impacts of policy interventions on consumer choices lays the groundwork for further improvements and developments of currently implemented policies.

In summary, the presented thesis analyzes two distinct economic subjects: security of supply in natural gas markets and greenhouse gas abatement potentials in the residential heating market. These subjects considered both reflect key points in the triangle of energy policy and are both associated with transnational market failures within energy markets. However, these two subjects require different perspectives when performing economic analyses. Security of supply analyses in an intermeshed network should be approached from a rather normative perspective of a social planner. On the contrary, the analyses of greenhouse gases emitted by households are dependent on positive analyses of consumer choices. Addressing these two perspectives thus requires tailored methodologies and modeling approaches, presented the following section.

1.2 Some conceptual foundations

The following sections provide a detailed description of the aforementioned normative and positive concepts and the applied and developed methodologies. In addition, advantages and limitations of the methodologies are discussed.

1.2.1 Normative security of supply analyses

Normative approaches define optimal economic solutions based on the current understanding of economic optimality. The first part of the dissertation conducts analyses based on a normative approach, which is the maximization of a social welfare function by a social planner.

More precisely, the security of supply analyses conducted in the first part of the thesis refer to scenarios of disrupted supply routes in the European natural gas network. The effects of these disruptions on the usage of other infrastructure components as well as on marginal supply costs are investigated. An adequate analysis of network effects and interdependencies requires a holistic perspective of the European natural gas market. Such an integrated, normative analysis can be conducted with the TIGER[1] model, which considers the European natural gas infrastructure to be one system optimized by a social planner.

1.2.1.1 The TIGER model

The security of supply analyses presented in the first part of the thesis are conducted with the TIGER model (see Figure 1.1), a European natural gas infrastructure and dispatch model, which has been developed by Lochner and Bothe (2007). The objective of the linear optimization in TIGER is to minimize the total costs of gas supply, while following given capacity constraints and meeting regionalized demand. The total costs include commodity, transportation, regasification and storage.[2]

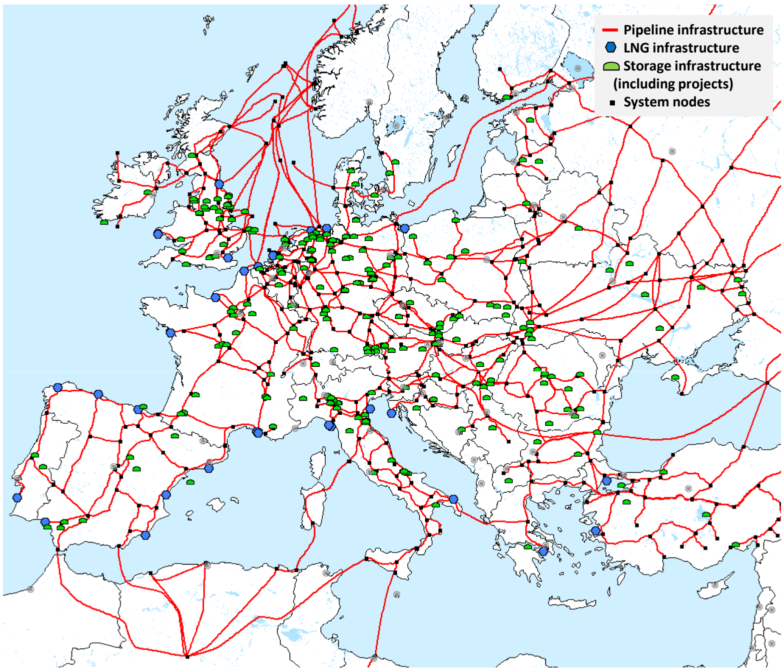


Figure 1.1: TIGER model
Source: EWI, illustration of selected pipeline and storage projects.

TIGER is a mathematical tool to compute an economically optimal dispatch of European natural gas transports given certain data assumptions. The economic idea behind the approach is the welfare maximization by a social planner that results in the same market outcome that would occur given perfect competition. The cost minimization approach can be interpreted as the minimization of the expenditure function of the social planner

[1] TIGER stands for Transport Infrastructure for Gas with Enhanced Resolution
[2] For more details on the objective function, constraints and data assumptions, see Appendix A.

to realize the optimal utilization of the gas infrastructure. The expenditure minimization is the dual problem of the primal problem of welfare maximization.

$$\begin{array}{llll} \text{Primal problem} & & \text{Dual problem} & \\ \text{maximize} & W = W(s) = s - d & \text{minimize} & C = C(s) = \int c(s)ds \\ \text{subject to} & \overline{C} \geq \int c(s)ds & \text{subject to} & \overline{W} \leq W(s) = s - d \\ & s \geq 0 & & s \geq 0 \end{array} \tag{1.1}$$

where W and C are the respective objective functions, d is the vector of demand parameters and s is the vector of optimization variables. The term $\int c(s)ds$ characterizes the total system costs and $c(s)$ are the respective marginal costs. The welfare function W maximizes demand satisfaction. The TIGER model assumes that demand is inelastic and that disruptions cause welfare losses which are larger than the costs of all supply options.[3] Figure 1.2 presents the optimization function. Increasing welfare, i.e. the area above the marginal supply cost curve $c(s)$, is equivalent to a minimization of total costs, i.e. the grey area below the marginal supply cost curve $c(s)$. Both is achieved by moving the marginal supply cost curve $c(s)$ downwards.

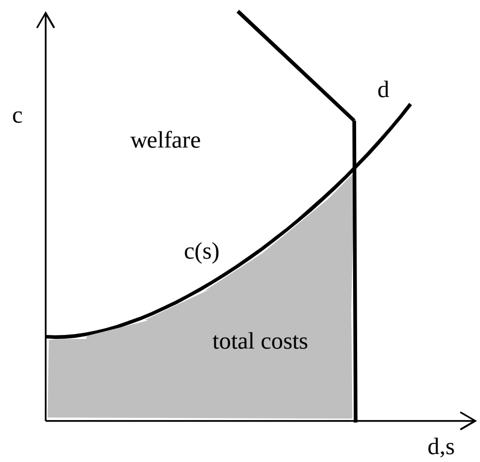


FIGURE 1.2: Duality and cost minimization

[3]This assumption is illustrated by the left bend of the demand curve in Figure 1.2 depicting the value of lost load.

For the two problems, we have the Lagrangian functions:

$$\begin{array}{ll} \text{Primal problem} & \text{Dual problem} \\ \text{max.} \quad \mathcal{L} = (s-d) + \lambda(\overline{C} - \int c(s)ds) & \text{min.} \quad \mathcal{L}^d = \int c(s)ds + \mu(\overline{W} - s + d) \\ \qquad s \geq 0 & \qquad s \geq 0 \end{array} \tag{1.2}$$

The solution of the maximization problem is:

$$\mu = c(s) \tag{1.3}$$

$$\lambda = \frac{1}{c(s)} \tag{1.4}$$

Regarding the standard microeconomic optimization problem and the application of Lagrange functions, the Lagrange multiplier reflects the shadow price at the optimal solution. The shadow price is the infinitesimal change in the objective function arising from an infinitesimal change in the constraint. In the primal problem, the shadow price is the marginal welfare of relaxing the constraint. Equivalently in the dual problem, the shadow price μ is the marginal social expenditure (or marginal total supply costs) of strengthening the constraint. Duality defines the relationship between these two constrained optimization problems by dictating that a) optimal supply quantities s^* are the same in both problems, b) $\overline{W} = W^*$, c) $\overline{C} = C^*$ and that d) the Lagrangian multipliers are reciprocal to each other ($\lambda = \frac{1}{\mu}$).

Shephard's Lemma defines the partial derivatives of the minimum of the total cost function (the social planner's expenditure function)[4]:

$$\frac{\partial C*}{\partial c(s^*)} = s \tag{1.5}$$

$$\text{and } \frac{\partial C^*}{\partial W^*} = \mu \tag{1.6}$$

Differentiating TIGER's cost minimization function with respect to the optimal welfare level W^* yields the shadow price μ or marginal supply costs $c(s)$. As $W^* = \overline{W}$ is the optimal degree of demand satisfaction, the Lagrangian multiplier μ identifies the amount of marginal social expenditure to meet an additional unit of demand. The model assumes maximum welfare to be reached when demand $d = s$ is satisfied. Disruption of demand is always assumed to be more expensive than the most expensive supply option.

Transposing the primal problem to the dual problem of expenditure minimization given a fixed level of utility has several advantages. One advantage of the dual problem is that the solution exhibits an upper bound for the optimal value of the objective function

[4]For details on duality, the Lagrange optimization approach and Shephard's Lemma see Chiang and Wainright (2005).

whereas the solution of the primal problem indicates a lower bound. Moreover, most algorithms are aligned at minimization problems.

Under a socially optimal planning or equivalently the assumption of perfect competition, the marginal costs can be interpreted as prices. The optimization in TIGER is conducted over several years, the social planner having perfect information and perfect foresight. Thus, the social planner knows which gas volumes and which infrastructure will be available. The optimization in TIGER accounts for further infrastructure constraints and provides the optimal solution based on given infrastructure assumptions. TIGER was specifically developed for the evaluation of existing assets, proposed projects, physical market integration and security of supply scenarios. The locational marginal supply costs (shadow prices) of TIGER are a helpful instrument for the identification of bottlenecks. In an optimal dispatch solution, the difference of marginal costs between two nodes in the system should not exceed the difference of supply costs between these nodes. A bottleneck occurs when there exists an insufficient transport capacity between the two nodes (see Dieckhöner et al. (2012), EWI (2010a), Lochner (2011a), Lochner and Dieckhöner (2008)).
In the security of supply analyses of disrupted routes (see Chapter 2 and Chapter 3), scenario comparisons including and excluding the disrupted routes enable the quantification of marginal supply cost differences as a measure for supply risks. Moreover, a specific variable in TIGER enables the identification of disrupted demand volumes in the event of a crisis. This variable allows for a cut in demand at costs that are significantly higher than the costs of the most expensive supply option. This enables the cost minimization problem to be solved, even if demand cannot be met.

1.2.1.2 Assumptions and caveats of TIGER

The linear programming approach of TIGER has several advantages. Following a normative approach, the interpretation of results is clear and identifies an optimal solution. If a solution to the optimization problem exists, then the minimal social expenditures are achieved. However, theoretically speaking, the solution is not necessarily unique. The transport volumes and the shadow prices do not need to be unique as long as the model achieves an equivalent total optimal solution. A strictly monotone total cost function would solve the problem and result in a unique solution. In practice, a wide range of sensitivity analyses and robustness checks have indicated that a clear supply-cost-based ranking concerning the production and the transport routes can be identified. These checks suggest that supply quantities and costs are strictly monotone.

A further major caveat alongside the normative approach is the assumption of perfect competition. The model does not take into account that market players, such as the few

major upstream suppliers, may exercise market power. However, this caveat is of less importance in optimal dispatch than in market price analysis.
The assumption of perfect information and perfect foresight in the normative approach is critical for security of supply analyses, as the model is able to anticipate a possible shock. Additional storage volumes may be available to guarantee supply in a shock situation. Combining two simulations, a first without a shock and a second, including the results of the first simulation before the shock, leads to more appropriate results.

Regarding data inputs, the analyses using TIGER are based on a large number of assumptions, especially concerning costs, capacities and demand. A unique database at The Institute of Energy Economics (EWI) covers these detailed assumptions. The data was gathered from public sources with due diligence and was edited with care. However, the heterogeneity of sources and the uncertainty regarding future infrastructure projects may restrict the data's validity, especially concerning future developments.

The model results concerning the optimal dispatch have been validated in the report EWI (2010a) and have been shown to adequately reflect actual gas flows. The differences between the actual and model-simulated gas flows could be attributed to inefficient capacity bookings or contract structures that are not considered by the model. As the purpose of the model is to perform a normative consideration, a validation is difficult. Moreover, the attempt of regulators to increase efficiency in the European gas market may further increase the overlap of model-simulated and actual gas flows in the future.

The results of TIGER require a careful evaluation with respect to its assumptions. Therefore, it is important to discuss some caveats concerning the interpretation of results. In the version of the TIGER model, as presented in this dissertation, additional investments are included exogenously and are therefore varied in different scenarios to analyze their impact. The bottlenecks identified indicate (temporary) impediments to price convergence and physical market integration between countries, and do not imply that additional investments to remove these bottlenecks are actually efficient from an economic perspective. Adding a marginal unit of capacity would only be efficient if marginal capacity costs were below marginal congestion costs. The calculation of the profitability of investments is not in the focus of the analyses conducted. To determine the full size of investment, endogenous modeling of investment decisions would be required in order to both capture interdependencies between investments and measure the lumpiness of investments. Lochner (2012) presents an extension of the TIGER model that includes endogenous investments.

In contrast to the modeling of investment decisions, the security of supply analyses presented in this thesis aim at identifying the short-run economic effects of disruption scenarios in terms of changes in marginal cost, demand curtailment and infrastructure usage. The results of Chapter 2 and Chapter 3 refer to the congestion that occurs in an efficient market. Potential additional congestion, as a consequence of market inefficiencies (i.e. in terms of capacity bookings and network charges), is not detected by the model approach. Thus, the normative approach indicates a lower bound for congestion and disruption volumes, i.e. where bottlenecks may occur despite efficient natural gas dispatch.

The assumption of inelastic demand requires careful interpretation. A quantification of the costs of demand disruptions in the model is not possible since in reality, the demand level would be reduced by consumers dependent on their substitution and curtailing cost potential. Moreover, the parameterization of developments in natural gas demand included in the analyses does not give enough regional detail to allow the identification of potential bottlenecks which may arise between balancing areas within countries. A Mixed-Complementarity-Problem (MCP) may account for elastic demand but would require a set definition of demand elasticities. For the purpose of security of supply analyses in natural gas markets, demand elasticities must vary by consumers and regions. Estimating and modeling the diverse European natural gas demand in detail is beyond the focus of this dissertation.

1.2.2 Positive analyses of consumer choices using microsimulation and econometrics

Contrary to the analyses in Part I, the two chapters of Part II are positive analyses investigating consumer choices on the micro-level. Greenhouse gas abatement potentials are mainly determined by investment choices made by energy consumers concerning long-term assets. Many energy-consuming technologies are capital-intense and therefore remain in the technology stock for a longer period of time. The energy efficiency level exhibited and the type of energy carrier used are determined by the investment decision and significantly affect the level of greenhouse gas emissions. Investment decisions in energy markets are made by different types of agents, such as power generators, firms or households. In particular the investment decision of households is not strictly driven by monetary objectives but also by non-monetary preferences. Major investment decisions of households concern investments in heating systems and in dwelling insulation. Hence, understanding household behavior is crucial for the development of targeted policies in greenhouse gas abatement.

1.2.2.1 Discrete Choice Heat Market Simulation Model

Econometric models are a useful method to analyze consumer choices such as households' decisions in heating systems as well as the resulting energy consumption and greenhouse gas emissions. A reduction of greenhouse gas emissions may be achieved by the introduction of policy measures that affect consumer choices. Understanding the effectivity of policy measures in terms of greenhouse gas abatement is crucial to estimate impacts on welfare. Incorporating the empirically estimated choice behavior, a microsimulation model enables the calculation of impacts of policy measures on consumer choices. The combined approach of econometric and microsimulation techniques is therefore an appropriate tool to investigate how policy measures may influence the investment decisions of households, the level of greenhouse gas abatement and the partial welfare effects.

The Discrete Choice Heat Market Simulation Model (DIscrHEat), which has jointly been developed by Harald Hecking an the author (Dieckhöner and Hecking, 2012), combines these two techniques. DIscrHEat is applied in Chapter 4 of Part II of the presented thesis to analyze consumer choices in heating systems and to derive microeconomic greenhouse gas abatement cost curves. The basic economic concepts of the model are presented in this section.

DIscrHEat is a dynamic simulation model for the German heat market of private households which simulates the development of the German residential heat market for the years 2010 to 2030 and uses the results of an empirical discrete choice estimation to describe the behavior of households regarding their heating system choice. The starting point of the model calculations is a detailed overview of the German building stock for private households in 2010. We distinguish single and multiple dwellings, as well as eight vintage classes. Each building class has an average net dwelling area and a specific heat energy demand, which varies depending on the actual insulation level. Additionally, data on the distribution of heating systems is included for each building class.

To simulate the future development of the German building stock (i.e. the newly-installed heating technologies), DIscrHEat accounts for new buildings and demolitions. Furthermore, it is assumed that a certain percentage of buildings is required to install a new heating system. Those modernization rates are given exogenously. Moreover, DIscrHEat is able to include diverse political measures like subsidies, taxes or standards. In terms of model output, DIscrHEat delivers results of newly installed heating systems for each modeling period, heat energy demand, final energy demand by energy carrier, primary energy demand and greenhouse gas emissions.

The discrete choice estimates of the households' choice behaviors are determined by using data from the actual heating choice made in 2010 and the according cost data for different heating systems. The econometric approach takes the observable costs (investment costs, operating costs and fuel costs) into account, as well as non-observable influences (switching costs or preferences), which affect the households' decisions.
The drivers of the technology diffusion in DIscrHEat are the estimated probabilities of the heating system choices for households. The estimation is based on a logit model,[5] according to McFadden (1974). The diffusion is characterized by the probability that household n chooses the technology j. The probability is the percentage of the utility

[5]For further detailed mathematical derivations, explanations of logit and conditional logit models see Train (2003).

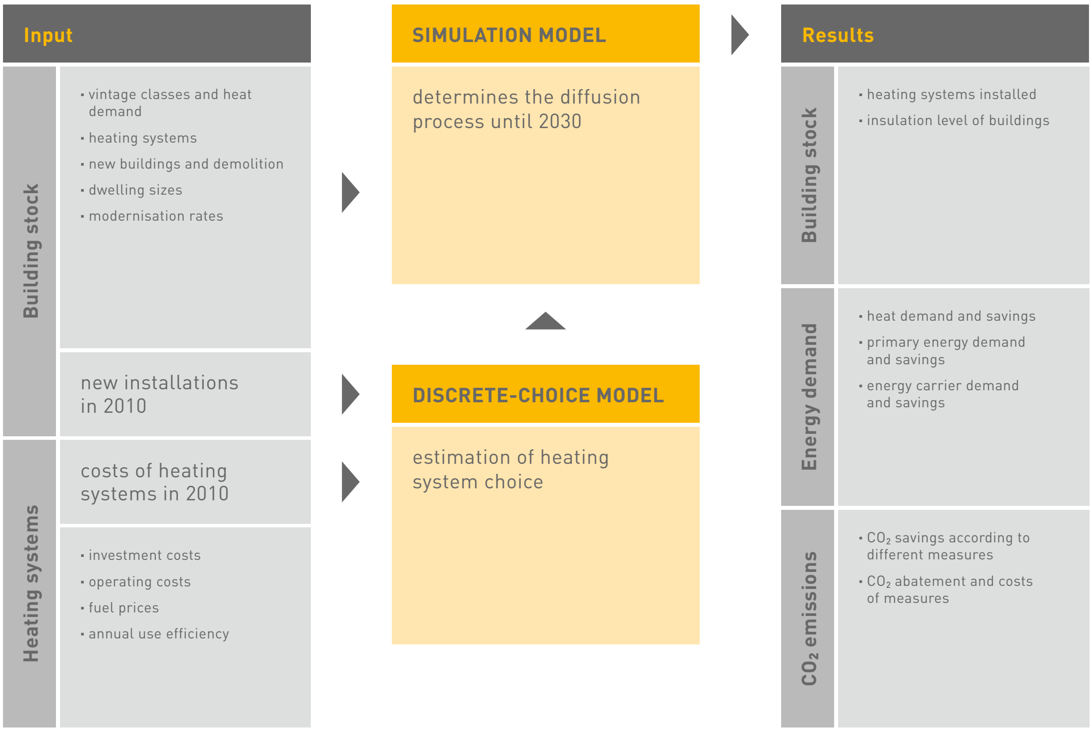


FIGURE 1.3: DIscrHEat model
Source: EWI.

$V_{n,i}$ of the chosen technology j relative to all possible technologies i (in exponents):

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} \tag{1.7}$$

If policy makers plan to facilitate the reduction of greenhouse gas emissions, they may want to influence the technology choice of households in order to increase the number of low-emission heating systems. One way to change the technology choice behavior of households is to introduce policy measures that affect the prices of the technologies. Such measures could be subsidies or taxes which may change the households' utilities and thus have partial welfare effects.

Based on Small and Rosen (1981) and McFadden (1999), the discrete choice approach can be used to measure partial welfare changes between technology diffusions with and without enforced policies. These partial welfare changes can be used to compute partial welfare losses, excluding the benefits from reducing greenhouse gas emissions. The partial welfare changes equal the changes in consumer surpluses in monetary units (i.e. the compensating variation) caused by different household choices. Then, the partial welfare losses indicate how much it would cost society to reduce a certain amount of greenhouse gas. To derive a microeconomic greenhouse gas abatement curve, the welfare effects, which result from a continuous variation of policy measures aiming at reducing greenhouse gas emissions, are measured.

A common instrument of welfare economics to measure the welfare effects of public polices is the compensating variation (CV) (Hicks (1942)). The CV equals the monetary compensation a household needs to get after a tax[6] introduction in order to counterbalance the price changes of the taxed goods (or technologies, in the specific case considered here). Figure 1.4 illustrates the concept: Before the introduction of a tax, a household maximizes its utility U_0 and chooses between two goods x and y given the budget constraint b_0. The optimal mix of x and y is achieved in point A, where the marginal rate of substitution (the slope of the indifference curve) equals the negative price relation of the goods (the slope of the budget constraint). The introduction of a tax that increases the price of good y moves the budget constraint left to b_1. The new optimal mix of goods consumed by the household is now in point B, which may imply an increase or decrease in the quantity of good x that is consumed, depending on the size of the income and substitution effect. Now, the utility level U_1 is lower than it was before the introduction of the tax. In order to measure the monetary compensation that is needed to keep the original utility level U_0 given the new price ratio, the point C is identified. For simplification, x is considered to be a numeraire good with a price equal to one. The point x^{max} indicates the maximum amount of x that can be consumed with budget b_0 and b_1, and x_{CV}^{max} is the maximum amount of x that can be consumed given the compensated budget constraint b_{CV}. Hence, we can measure the CV as $CV = x_{CV}^{max} - x^{max}$.

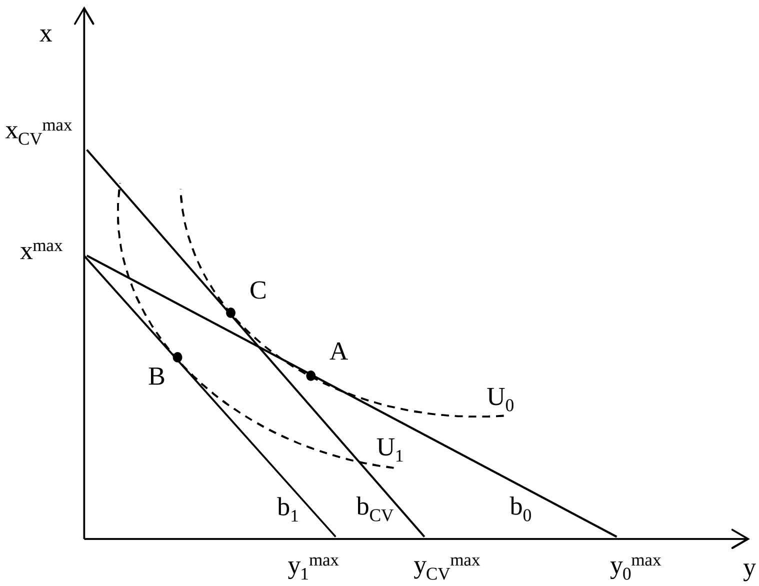


FIGURE 1.4: Compensating variation

[6]The focus is on taxes for illustrative purposes. The concept can also be applied to subsidies. See Chapter 4.

Following Small and Rosen (1981) and McFadden (1999), the CV of household n and the technologies j can be computed within the discrete choice framework:

$$CV_n = -\frac{1}{\beta} \left[ln \sum_j exp(V_{n,j}^{\text{policy}}) - ln \sum_j exp(V_{n,j}^{\text{no policy}}) \right] \tag{1.8}$$

The approach assumes a constant marginal utility of income denoted by $-\frac{1}{\beta}$. The utilities $V_{n,j}^{\text{policy}}$ and $V_{n,j}^{\text{no policy}}$ are the utility levels before and after the introduction of policy measures.

1.2.2.2 Assumptions and caveats of DIscrHEat

Due to its nature of being a microsimulation model and due to its bottom-up modeling procedure, DIscrHEat requires a wide range of data. The data have been gathered with due diligence and have been carefully evaluated; however the diversity of sources may affect consistency. The data is only based on public sources. A detailed overview of the database and the respective sources are provided in Appendix 4. Data have been gathered at the highest level of detail available. However, more detailed data concerning household characteristics and heating system choice would improve the modeling of heterogeneous households and would increase the accuracy of the model.

A further caveat of DIscrHEat is the validity of the assumptions concerning modernization rates. According to IWU / BEI (2010) and European Commission (2012) modernization rates in Germany and Europe remained low and relatively stable over the past decades. Based on these sources, DIscrHEat incorporates exogenous modernization rates because given data limits the feasibility of an empirical estimation of dynamic modernization rates.

Moreover, DIscrHEat assumes time-constant choice behavior of households based on a discrete choice estimation of past heating system choices. Changes in future preferences which require an adaption of the discrete choice estimates and are not considered by the changes in technology costs, are not included. In addition, available technologies remain constant over time. New technologies that are not known today but may be available in the future are not considered. Technological progress is only covered concerning cost assumptions.

Additionally, the discrete choice model incorporated in DIscrHEat has some caveats. A prominent assumption of discrete choice models is the Independence of Irrelevant Alternatives (IIA) assumption. IIA defines that the ratio of the logit probabilities for alternative technology choices does not depend on other excluded alternatives. Thus, unknown future technologies that are not considered in the model would violate the IIA assumption. Nonetheless, a major advantage of the IIA assumption is that relative probabilities within the subset of considered alternatives are unaffected by the existence and characteristics of alternatives outside the subset. Hence, the consistency of the estimator is not limited by the exclusion of alternative technologies.

One way to check if the IIA property holds is to test the hypothesis that the parameters estimated with all alternatives are similar to those parameters estimated with a subset of alternatives (Hausman and McFadden, 1984). We test IIA in Chapter 4 and show that it holds for our considered alternatives (see Appendix A).

A further caveat of the considered discrete choice approach is that it neglects price endogeneity (see Berry et al. (1995)). Nevertheless, price endogeneity is not considered. as it is assumed that energy prices are not determined by residential energy demand. The price of oil and gas is influenced by global supply and demand effects, as well as other sectors such as power generation, transport and industry sectors (rather than private households' heat demand).

The welfare measurement in terms of the compensating variation, based on the discrete choice estimation also requires certain assumptions. The most critical may be the assumption of homothetic preferences that accompanies the assumption of the constant marginal utility of income. As a consequence, income effects on welfare losses are not considered. No actual data is available that combines heating system choices and income information for the households considered. More detailed data, if available, could further improve the analysis. Relaxing the assumption of homothetic preferences and accounting for income effects in the technology choice of households and in the computation of the partial welfare effects to avoid a certain amount of greenhouse gases are all interesting topics that are open for further research. Torres et al. (2011) investigate the sensitivity of mistaken assumptions concerning the marginal utility of income and the impacts on the welfare measures in Monte Carlo experiments. They find that false assumptions regarding the marginal utility of income can amplify misspecification of the utility function. Throughout all misspecification cases analyzed, they find an underestimation in the compensating variation. Hence, the analyses conducted in Chapter 4 which assume a constant marginal utility of income and which tend to demonstrate that welfare losses are larger than technical costs, are rather conservative and may even underestimate the compensating variation and welfare losses.

1.2.2.3 Differences-in-differences-in-differences approach (DDD)

Chapter 5 analyzes the effectiveness of subsidies on household investments in energy efficiency, i.e. dwelling modernizations, regarding reductions in energy consumption. In order to appropriately identify the effects of the policies (the treatment effect), the heterogeneity of households, i.e. especially the differences between treated and non-treated households, should be taken into account.

Common quasi-experimental econometric techniques to evaluate public policies and to measure treatment effects though there may be biases between the treated subjects are the differences-in-differences (DD) and the differences-in-differences-in-differences (DDD) approaches. DD controls for these biases by comparing the post-treated group, the pre-treated group and another control group. Angrist and Pischke (2009), Imbens and Wooldridge (2009) and Wooldridge (2010) present comprehensive surveys on the DD and DDD approaches. One of the first economic analyses that used the DD approach is a study on the effects of minimum wages (Obenauer and von der Nienburg, 1915). The approach is exemplified using a simplification of the specific treatment problem in Chapter 5.

The paper presented in Chapter 5 examines the question whether a subsidy program to encourage investments in energy efficiency decreases energy consumption. For the specific case analyzed in Chapter 5, the term ‘treatment period’ describes a time period, in which a subsidy program for dwelling modernizations is in effect. No subsidies are provided during the non-treatment period. There is a panel of households i. Two groups of households ($B \in \{0,1\}$), a non-treated group ($B = 0$) and a treated group ($B = 1$), are considered. The non-treated group ($B = 0$) does not invest during the subsidy period. The treated-group ($B = 1$) makes dwelling modernizations during the subsidy period. Taking the difference between the energy consumption of the treated group before and after the treatment is not an accurate method of identifying the effect of the treatment, i.e. the effects of the subsidy on energy consumption. Dwelling modernizations in general, not only during the subsidy program period, may be a reason for the potential difference between the energy consumption of the treated group before and after the treatment. In order to control for the general impact of modernizations or general changes in energy consumption, we need a control group. We thus additionally differentiate between those households that have modernized ($M = 1$) and those that have not ($M = 0$).

Altogether, now we differentiate between non-treated households that have not modernized ($B = 0, M = 0$), non-treated households that have modernized ($B = 0, M = 1$), treated households that have not modernized ($B = 1, M = 0$), and treated households that have modernized ($B = 1, M = 1$).

To identify the treatment effect properly, we estimate:

$$y_i = \alpha + \beta_1 B_i + \beta_2 M_i + \beta_3 (B_i M_i) + \epsilon_i \tag{1.9}$$

where y is the energy consumption, B_i with ($B_i \in \{0,1\}$) is a dummy variable indicating whether a household i is part of the treatment group $B_i = 1$ or not $B_i = 0$, and M_i with $M_i \in \{0,1\}$ is a dummy indicating whether a household modernized ($M_i = 1$) or not. The estimate β_1 is the impact of the treated group and β_2 is the impact of modernizations on energy consumption.

$$\beta_1 = E(y|B=1) - E(y|B=0) \tag{1.10}$$

$$\beta_2 = E(y|M=1) - E(y|M=0) \tag{1.11}$$

The estimate β_3 is the interaction effect between modernizations and the treatment group, and quantifies the impact of modernizations made by the treated group.

$$\begin{aligned} \beta_3 = &(E(y|M=1, B=1) - E(y|M=0, B=1) \\ &- (E(y|M=1, B=0) - E(y|M=0, B=0)) \end{aligned} \tag{1.12}$$

The estimate β_3 is the differences-in-differences (DD) estimator, which controls for the modernizations and the treated group. DD can thus properly identify the impact of modernizations made during the treatment period on energy consumption.

Next, in the case of a potential landlord-tenant problem[7], it must be assumed that the subsidy program affects modernizations made by homeowners to a different extent than those made by landlords in tenant-occupied dwellings. In this case, the difference between households must be controlled for in order to differentiate between the effects of ones that live in owner-occupied and those that live in tenant-occupied dwellings. Therefore, the following differences-in-differences-in-differences (DDD) model is estimated:

$$y_i = \alpha + \beta_1 B_i + \beta_2 M_i + \beta_3(B_i M_i) + \beta_4(O_i) + \beta_5(B_i O_i) + \beta_6(M_i O_i) + \beta_7(B_i M_i O_i) + \epsilon_i \tag{1.13}$$

where $O_i \in \{0, 1\}$ and $O_i = 1$ indicates homeowners and $O_i = 0$ indicates tenants.
In this approach, the model additionally controls for the effect of owners in general (β_4), for owners that belong to the treatment group (β_5), for owners that modernized their dwellings (β_6) and for owners that modernized and are part of the treated group (β_7).

The differences-in-differences-in-differences (DDD) approach computes two DD estimators, i.e. for owners and tenants, and takes the difference between these two. The DDD estimator β_7 is given as the difference between the two DD estimators $DDD = DD_{owner} - DD_{tenant} = \beta^{DD}_{3,owner} - \beta^{DD}_{3,tenant}$:

$$\beta_7 = \beta^{DD}_{3,owner} - \beta^{DD}_{3,tenant} \tag{1.14}$$

[7] The landlord-tenant problem is a principal-agent problem that may occur in renting markets and may lead to underinvestment in tenant-occupied dwellings. The landlord-tenant problem characterizes barriers for landlords to include investment costs in the rent and thus, to realize appropriate investment returns. See Jaffe and Stavins (1994).

with

$$\beta^{DD}_{3,owner} = (E(y|M=1,B=1,O=1) - E(y|M=0,B=1,O=1)) - (E(y|M=1,B=0,O=1) - E(y|M=0,B=0,O=1)) \quad (1.15)$$

$$\beta^{DD}_{3,tenant} = (E(y|M=1,B=1,O=0) - E(y|M=0,B=1,O=0)) - (E(y|M=1,B=0,O=0) - E(y|M=0,B=0,O=0)) \quad (1.16)$$

The estimator β_3^{DD} refers to the estimator of the DD model presented in Equation 1.12. DDD is different from just adding a control group since it includes the interaction effects. By rearranging the terms in Equations 1.14, 1.15 and 1.16, the DDD estimator equivalently reflects the difference between the two DD estimators of the treated and non-treated group, controlling for modernizations and homeownership through the DD approach.

1.2.2.4 Assumptions and caveats of DDD

An important criterion for a good estimator is unbiasedness. For the DD estimator[8] to be unbiased the expected value must equal the real value, $E(\beta_3) = \beta_3$.
In addition, the following assumptions must hold for the DD estimator to be unbiased[9]:

- The model is correctly specified.
- The expected value of the error term is zero: $E(\epsilon_i) = 0$.
- The error term is uncorrelated with the variables in the equation:

$$cov(\epsilon_i, B_i) = 0 \quad (1.17)$$

$$cov(\epsilon_i, M_i) = 0 \quad (1.18)$$

$$cov(\epsilon_i, B_i \cdot M_i) = 0 \quad (1.19)$$

The assumption of Equation 1.19 is often referred to as the 'parallel trend assumption'. In the presented subsidy program analysis, the parallel trend assumption is the assumption that the modernization trend of treated and non-treated household is the same. If these two household groups have different modernization trends, the DD estimator is biased. Failing the parallel assumption is a common caveat in DD approaches. Nonetheless, this is often solved by identifying further pre-existing differences in trends.

[8] The focus on the DD estimator is only for illustrative purposes. However, the assumptions also hold for the DDD estimator.

[9] For the complete list of assumptions for an OLS estimator to be unbiased, see for instance van Auer (2005).

The more sophisticated approach, implemented in Chapter 5, supplementary controls for homeowners and applies the DDD model. Moreover, two treatment periods and thus two treated household groups are considered, as well as general time and regional trends.

A second major limitation that may affect the efficiency of the estimator and consistency of standard errors is serial correlation. A DD estimation may rely on observations of the same subject over several time periods. In this case, the dependent variables in DD estimation are typically highly serially correlated. Moreover, the treatment variable may change very little over the control groups. Using the usual ordinary-least-squares (OLS) estimators would thus result in underestimated standard errors. However, this limitation is addressed by introducing robust standard errors, clustered at the household level based on Huber (1967) and White (1980). Another possibility is to apply a feasible-generalized least-squares (FGLS) model[10], which accounts for serial correlation through its variance covariance matrix.[11] Both cluster-robust standard errors and the FGLS model are considered in the estimation strategy given in Chapter 5.

1.3 Thesis outline and contributions

The thesis comprises four essays on the economic effects of specific topics in energy markets. Each of the four essays is presented in a dedicated chapter within the thesis. The chapters are organized in two parts. Part I presents model-based analyses of European security of supply scenarios. Part II analyzes the impacts of public policies affecting consumer choices to promote energy efficiency and greenhouse gas abatement in the residential heating market. In the following, the content of each chapter is briefly summarized and the main results are outlined.

1.3.1 Security of supply effects of the Nabucco and South Stream projects

The paper presented in Chapter 2, Part I has solely been written by the author of the thesis and is published in Dieckhöner (2012b). It analyzes security of supply effects of the major pipeline projects Nabucco and South Stream. In addition to Nord Stream, these two pipeline projects have been announced to provide further gas supplies to Europe. This raises the questions whether and how these projects may contribute to the European Union's focus on security of supply. Applying the natural gas infrastructure model TIGER, this paper investigates the impact of these pipeline projects on southeastern Europe's gas supply. Gas flows and marginal cost prices are evaluated in general and considering the possibility of supply disruptions via Ukraine for the year 2020. The model results show a positive impact of these pipelines on security of supply despite few

[10]See Wooldridge (2010) for an overview of the FGLS model.
[11]For more details on the topic of serial correlation in DD models, see Bertrand et al. (2004).

consumer cut-offs that result from intra-European bottlenecks. South Stream is only highly utilized in case of a Ukraine crisis, supporting the idea that its main purpose is to bypass Ukraine.[12]

1.3.2 Civil unrests in North Africa – Risks for natural gas supply?

The analysis of the paper in Chapter 3, Part I has been conducted in co-authorship with Stefan Lochner and is published in Lochner and Dieckhöner (2012). The paper investigates the impacts of disruptions of gas supplies from North Africa to the European market. Such disruptions actually occurred during the uprising and military confrontation in Libya that began in February 2011. An analysis of how Europe has compensated for these missing gas volumes shows that this situation has not affected security of supply. However, the situation would change if the North African uprising was to spread to Algeria. Since Algeria is a much more important gas supplier to Europe than is Libya, more severe consequences would be likely. Applying the natural gas infrastructure model TIGER, we investigate the impact of supplier disruptions from both countries for a summer and winter period. Our analysis shows that disruptions in the low-demand summer months could be compensated for, mainly by LNG imports into several European countries. An investigation of a similar situation at the beginning of the winter shows that security of supply would be severely compromised and that disruptions to Italian consumers would be unavoidable. The analysis thereby highlights the importance of taking the political stability of supply countries into account when assessing the security of European gas imports.

1.3.3 Greenhouse gas abatement curves of the residential heating market

The paper in Chapter 4, Part II has been written in co-authorship with Harald Hecking (see Dieckhöner and Hecking (2012)). In this paper, we develop a microeconomic approach to deduce greenhouse gas abatement cost curves of the residential heating sector. By accounting for household behavior, we find that welfare-based abatement costs are generally higher than pure technical equipment costs. Our results are based on a microsimulation of private households' investment decision for heating systems until 2030. The households' investment behavior in the simulation is derived from a discrete choice estimation which allows investigating the welfare costs of different abatement policies in terms of the compensating variation and the excess burden. We simulate greenhouse gas abatements and welfare costs of carbon taxes and subsidies on heating system investments until 2030 to deduce abatement curves. Given utility maximizing households,

[12]This article is copyrighted and reprinted by permission from the International Association for Energy Economics. The article first appeared in The Energy Journal (Vol. 33, No. 3). Visit The Energy Journal online at http://www.iaee.org/en/publications/journal.aspx.

our results suggest a carbon tax to be the welfare efficient policy. Assuming behavioral misperceptions instead, a subsidy on investments may have lower marginal greenhouse gas abatement costs than a carbon tax.

1.3.4 Subsidizing investments in energy efficiency

The analysis presented in the paper in Chapter 5, Part II has solely been conducted by the author (see Dieckhöner (2012a)). Improving energy efficiency is one of the three pillars of the European energy and climate targets for 2020 and has led to the introduction of several policy measures to promote energy efficiency. The paper analyzes the effectiveness of subsidies in increasing energy efficiency in residential dwellings. An empirical analysis is conducted in which the effectiveness of subsidies on the number of dwelling modernizations is investigated. Next, the impact of renovations on energy consumption is analyzed using a differences-in-differences-in-differences approach for modernizations made in given subsidy program periods, as well as for ownership status and household types for more than 5000 German households between 1992 and 2010. By controlling for socio-economic status, dwelling characteristics and macro-indicators, it becomes apparent that homeowners invest significantly more and have significantly lower heating expenditures than their tenant counterparts. Thus, the landlord-tenant problem tends to broaden the energy efficiency gap. It is also found that the number of modernizations made by landlords does not increase with higher subsidies. However, the renovations made during the subsidy periods decrease the heating consumption of tenants. Given the conditions that homeowners already invest more in energy efficiency, they increase modernizations only slightly with increasing subsides. However, these modernizations during subsidy periods do not further decrease homeowners' energy consumption. Thus, the large part of the overall subsidies received by homeowners can be identified as windfall profits.

Part I

Model-based Analyses of Security of Supply in Natural Gas Markets

Chapter 2

Simulating security of supply of the Nabucco and South Stream projects for the European natural gas market[13]

Applying the natural gas infrastructure model TIGER, this paper investigates the impact of the Nabucco and South Stream pipeline projects on southeastern Europe's gas supply. Gas flows and marginal cost prices are evaluated in general and considering the possibility of supply disruptions via Ukraine for the year 2020. The results show a positive impact of these pipelines on security of supply despite few consumer cut-offs that result from intra-European bottlenecks. South Stream is only highly utilized in case of a Ukraine crisis, supporting the idea that its main purpose is to bypass Ukraine.

2.1 Introduction and Background

The declining European gas production will lead to an increasing dependence on imports (Capros et al., 2008, IEA, 2008). Several plans for major pipeline projects will be commissioned in the next decade to provide sufficient capacity for additional natural gas imports, and investments in interconnections among countries are planned to improve market integration. Moreover, several projects in focus should provide large-scale gas volumes from non-European gas producers to European regions. In addition to Nord Stream, which is online in 2011, the Nabucco and South Stream pipelines are the largest projects planned. Although both pipelines could enhance the security of the gas supply in the European Union (EU), they are expensive projects. The ambitious objectives of the EU in terms of the percentages of renewables in the energy mix by 2050 may lead to only a moderate growth in natural gas demand in the next decade and probably to a significant decrease by 2050. Natural gas demand for heating is even expected to decrease in northwestern Europe until 2030 through implementation of energy efficiency

[13]

measures in buildings (Capros et al., 2010). It follows that not all major pipeline projects may be essential for the security of supply in Europe, especially the Nabucco and South Stream projects, which are designed to supply southeastern Europe.

A quarter of Europe's gas demand is satisfied by imports from Russia, and 80 percent of these volumes are transported from Russia through pipelines via Ukraine (European Commission, 2006). The Russia-Ukraine gas dispute of January 2009 caused an unprecedented disruption of gas supplies to the EU, described as the worst gas crisis in International Energy Agency's (IEA) history (IEA, 2009). Disputes between Russia and Ukraine on the pricing of the commodity natural gas and its transit to the EU were recurrent during the past decade (Stern, 2009).

Because of these threats to the security of the natural gas supply, European policy will have to cope with several challenges. First, gas supply from non-European countries has to be secured. However, since importing a high proportion of gas volumes for the European market from one or only a few suppliers increases the risk of political pressure and price increases, supply sources and means of transport to different European regions should be diversified (European Commission, 2006, Reymond, 2007, Weisser, 2007). Political conflicts, such as the Russia-Ukraine crisis, could cause supply disruptions, and a halt to these transits has a significant impact on the European gas market, especially during times of high demand, such as the winter months. To secure gas supplies, additional gas infrastructure, that is, liquefied natural gas (LNG) import terminals, storage areas, and major import pipelines, will have to be built (Cayrade, 2004, Lise et al., 2008).

This paper investigates the effects of each of the Nabucco and South Stream pipeline projects on European natural gas supply security in general and with a particular focus on a Ukraine crisis simulation. The paper also analyzes the major supply risks associated with the EU's dependence on the main transit country, Ukraine, and the mitigating effects of Nabucco and South Stream and elaborates on the European gas infrastructure system's vulnerability, as well as its ability to respond and compensate. The scenarios are simulated with the European natural gas infrastructure and dispatch model TIGER from the Institute of Energy Economics, Cologne. The conclusions of the paper depend on these specific assumptions, in particular on assumptions on publicly announced infrastructure projects[14] and on demand projections. Possible effects of alternative assumptions are briefly discussed in the conclusion.

The next section provides a literature overview on issues related to the security of supply in the context of major European gas pipeline projects and describes the Nabucco and South Stream pipeline projects in detail. Their contribution to the two objectives of European security of gas supply – the security of natural gas imports and import diversification – is addressed. Section 2.3 describes the TIGER model which simulates

[14]The data on capacities based on current planning status is taken from ENTSOG (2009).

three infrastructure scenarios to analyze the effects of route diversification by Nabucco and South Stream in case of supply disruptions: a baseline scenario without either of the two pipeline projects, a scenario that implements only the Nabucco pipeline, and a scenario that implements only the South Stream pipeline. In section 2.4 the general effects of the Nabucco and South Stream pipeline projects – especially the effects on marginal supply costs – are analyzed for the year 2020 for a hypothetical peak winter day, when supply disruptions are most probable. Section 2.5 analyzes the impact of the two pipeline projects during a hypothetical Ukraine crisis on a peak winter day in 2020 on disruptions to consumers. Changes in marginal supply costs and gas flows for the three infrastructure scenarios in comparison to the results of the no-crisis simulation are presented. Section 2.6 concludes.

2.2 Security of natural gas supply and the Nabucco and the South Stream pipeline projects

2.2.1 Security of natural gas supply

The issue of security of supply in natural gas markets has been addressed by European energy policy (European Commission, 2000, 2006, European Union, 2004). Dimensions of security of supply cover a wide range of issues. Luciani (2004) defines security of supply as "the guarantee that all the gas volumes, demanded by non-interruptible (firms or protected) customers, will be available at a reasonable price" (Luciani, 2004, p. 2).

Thus, physical availability of natural gas and the price play significant roles in guaranteeing security of supply. However, defining a precise threshold for a threat of security of supply is a challenging task on which academics have not reached agreement. Many studies have addressed the issue of security of energy supply, albeit without a specific focus on natural gas (CIEP, 2004, Correlje and van der Linde, 2006). Gnansounou (2008) develops a composite energy vulnerability index to benchmark industrialized countries in a long-term security perspective regarding oil and gas supplies. Cabalu (2010) evaluates different gas supply security indicators. These cover gas intensity, net gas import dependency, a ratio of domestic gas production to total gas consumption and the geopolitical risk for Asian countries. Cabalu (2010) introduces a composite gas supply security index, based on Gnansounou's energy vulnerability index, that incorporates four of the presented indicators to analyze an overall security of natural gas supply measure for Asia. For the European market, Victor (2007) discusses aspects of global geopolitical security of supply for natural gas, but only a few studies focus on specific pipeline projects. Holz et al. (2009) analyze European gas supplies until 2025 using the strategic model GASMOD and find that pipeline availability remains a critical issue. Stern (2002) analyzes the impact of dependence on natural gas imports and the influence of liberalization on security of gas supply and recommends a policy framework to prevent disruptions to consumers. He analyzes European relationships with non-European gas-exporting countries and the influence of a liberalized European market on security of gas supply and differentiates between short-term and long-term adequacy of supply and infrastructure in the transport of gas to the demand regions. Stern (2002) also discusses operational issues, such as stresses of weather and other operational influences, and strategic security, such as catastrophic default of infrastructure or supply sources. Further, associated with import dependence Stern distinguishes among source dependence, transit dependence and facility dependence.

The current paper addresses transit dependence and facility dependence with a focus on the effects of the two pipeline projects, Nabucco and South Stream,[15] on security of supply. The major security of supply risks associated with the EU's dependence on the main transit country of Ukraine (transit dependence) are reflected in the results of the Ukraine crisis simulations in which the mitigating effects of the Nabucco and South Stream projects, the European gas infrastructure system's ability to respond and compensate, and its vulnerability (facility dependence) are analyzed.

Stern (2002) addresses the problem of attributing costs to events that have a low probability of occurrence but a high impact on supply and the difficulties for policy makers to balance costs and risks in order to find measures to cope with these events. This paper presents an approach to the analysis of such events.

2.2.2 The Nabucco project

According to Nabucco Gas Pipeline International GmbH (2010), the Nabucco project describes a gas pipeline connecting the Caspian region, the Middle East and Egypt via Turkey, Bulgaria, Romania, and Hungary with Austria and further on with the Central and Western European gas markets. The pipeline route with a length of approximately 3,300 km should start at the Georgian/Turkish and/or Iranian/Turkish border and run via Bulgaria, Romania and Hungary to Baumgarten, Austria. The pipeline's transport capacity is expected to amount to 31 bcm per year, and total investment costs are approximately 7.9 billion Euros. From an EU point of view the Nabucco project should present an opportunity to diversify gas supply options and to reduce the EU's dependence on Russia.[16] The Caspian region, especially Turkmenistan and Azerbaijan, and the Middle East-Egypt, Iran and Iraq, are discussed as supply sources for the project.

[15]Currently, there are three further "southern corridor" pipelines discussed, that could connect the Middle East or Caspian Region with Europe: The Trans Adriatic Pipeline (Trans Adriatic Pipeline, 2011), the Interconnection Turkey Greece Italy Pipeline (IGI Poseidon, 2011) and the recently announced South-East Europe Pipeline (Financial Times, 2011). These pipelines, however, connect only a part of the regions connected by Nabucco and South Stream.

[16]The Nabucco project is designated as of strategic importance by the European Union in the Trans-European Networks - Energy (TEN-E) program.

However, no supply contracts have yet been concluded, a fact that may affect the commissioning of the project. Problems that have arisen in the context of suppliers for the Nabucco pipeline are often discussed (Bilgin, 2007, 2009).

The Nabucco pipeline will be built only if sufficient volumes are contracted. The political risk of defaulted supply contracts is difficult to estimate and will depend on who the suppliers are. Turkey plays a major political role in the negotiations on supplies because it will need significant additional gas volumes in the future to meet projected rising demand (and the country neither has an own production nor sufficient gas storage) and because Turkey is the first transit country for the Nabucco pipeline. Turkey has already been negotiating with the EU on the volumes that should be withdrawn from Nabucco to satisfy the Turkish demand, and it has already signed and extended many of its gas contracts with its surrounding gas-producing neighbors. However, Turkey is interested in withdrawing as much Caspian and Middle Eastern gas as possible. Therefore, Turkey's geopolitical position could be both an opportunity and a threat for the EU.[17] Based on a geopolitical analysis, Bilgin (2009) recommends including at least two countries from the Middle East and Caspian regions as suppliers for the European gas market, which could be possible via Nabucco. Erdogdu (2010) analyzes strength and weaknesses of the Nabucco project with a focus on the policies of different countries involved and concludes that its realization largely depends on non-European actors and their interests.

In short, the Nabucco is an uncertain and cost-intensive project that could help to cope with the EU's security of supply challenges because it could provide significant gas volumes from non-European countries, it diversifies supply sources, and it diversifies supply routes that transit mainly European Member States.

2.2.3 The South Stream project

A number of routes for the pipeline are being discussed, including onshore sections across the Russian Federation and several European countries, as well as offshore gas pipelines via the Black Sea and the Adriatic Sea. South Stream is expected to provide a capacity of 63 bcm per year by 2016 and to diversify the Russian natural gas supply route to Europe, thereby strengthening European energy security (South Stream, 2010)[18]. The source of Russian gas for South Stream is as uncertain as the source for Nabucco. Natural gas production in the Volga Region is declining (Stern, 2005), and there will not be enough

[17] Kardaş (2011) analyzes actual political Turkish-EU relations in the context of the Nabucco Intergovernmental Agreement (IGA) and the discussion on Turkish-EU membership. He concludes that the latter has negatively affected an energy cooperation. However, he makes the point that the signing of the IGA in July 2009 gave indication for a better future energy cooperation. Turkey reduced its claims on access to Nabucco volumes and on discounted prices whereas the EU agreed on reverse flows on Nabuccco to Turkey and access to European gas stocks in case of emergency. Nonetheless, the future of Turkish-EU relations in terms of Nabucco remain uncertain.

[18] 50 percent of the South Stream AG is owned by Gazprom.

gas for 63 bcm to be exported per year. For the coming decades, large explored gas reserves in Russia are mainly in western Siberia and the Yamal Peninsula. Production in Yamal was approved to start in 2011 but is delayed because of the economic crisis and the uncertainty on European demand developments (Pirani, 2010). Russian exports to Europe are not likely to be much higher than 200 to 220 bcm in 2020 (Socor, 2009). Another issue is that this area is more than 3000 km away from the start of South Stream at Dzhubga. However, Russia is already importing Turkmeni gas and is also interested in purchasing gas from Shah Deniz II, an Azerbaijani gas field (Kupchinsky, 2009), which could also be used to supply South Stream. In addition, to avoid transit and political costs, Russia could also consider transporting its gas from the Yamal Peninsula to Europe via South Stream. However, Nord Stream, with 27 bcm (or 54 bcm after the expansion), seems to be a much cheaper option for Russia because of the higher costs of Caspian gas volumes and the long-distance of South Stream to future production regions. Moreover, Nord Stream avoids the Ukraine and other transit countries in transporting the gas farther on within Europe and even to southern Europe. Considering these circumstances, South Stream seems to be more a strategic option than a cost-efficient one for transporting Russian gas to Europe. Barysch (2010) states that it is a political project with the purpose to cut out transit countries like Ukraine and Belarus, and to prevent Nabucco which threatens Gazprom's monopoly.

About 80 percent of Russian gas exports go to Europe, and about 40 percent of EU imports stem from Russia (IEA, 2009). Therefore, each party is dependent on the other, which may lower the default risk for Europe and may be a lower risk than it would bear with contracts with Middle Eastern countries. However, South Stream does not support the EU's goal of diversifying supply sources. Moreover, although South Stream's planned extremely large capacity could be a strategic tool, it is not clear whether or how the pipeline could be completely filled.

In summary, South Stream offers the option to import large-scale (i.e., twice as much as Nabucco) gas volumes from non-European countries, gas transported via South Stream would have to be contracted with the mainly Russian state-owned natural gas company Gazprom, even if it originally stems from a Caspian country, and South Stream offers an alternative route to the existing routes from Russia.

In general, the development of the European gas market is very uncertain with several risks for the planning of pipeline constructions. In addition to the access to supply sources, European gas demand development in the context of the EU's ambitious climate change targets and the role of unconventional gas remain uncertain (Barysch, 2010).

2.3 Methodology

This section presents the framework and methodology for the model-based analysis that has been conducted to identify the impact of the two pipeline projects Nabucco and South Stream on security of natural gas supply. Thereby, importance of the routes and capacities of these two projects for security of supply is identified. Regarding that both pipelines are major import routes in addition to the old-established route via Ukraine, which is fraught with risk, their impact on security of natural gas supply in case of a hypothetical Ukraine crisis is analyzed.

2.3.1 The TIGER-model

Different types of natural gas market models are presented in literature. Theoretical natural gas transport optimization models include those presented by de Wolf and Smeers (1996), de Wolf and Smeers (2000), Ehrhardt and Steinbach (2004), Ehrhardt and Steinbach (2005) and van der Hoeven (2004). Midthun et al. (2009) present a modeling framework for analyzing natural gas markets that accounts for further technological issues related to gas transportation – primarily the relationship between flow and pressure. The mixed-complementarity models presented by Gabriel et al. (2005), Gabriel and Smeers (2005) and Holz et al. (2009) focus mainly on modeling competition and agents with focus on natural gas trade determining supply volumes to the European market in different types of competitive environments.

The results presented in this paper for the year 2020 are based on simulations with the natural gas infrastructure model TIGER (Transport Infrastructure for Gas with Enhanced Resolution). Developed by Lochner and Bothe (2007), it enables an integrated evaluation of the utilization of gas infrastructure components – pipelines, storages and terminals – and their interaction. Therefore, the model can be used for a comprehensive analysis of the short-term supply situation and gas flows within the European long distance transmission grid.

TIGER's focus is on the optimal dispatch within the European gas infrastructure system.[19] The results of the TIGER model thus represent the first best distribution of natural gas and utilization of infrastructure components within Europe assuming that the European Commission's regulative objective to achieve an efficient functioning of the natural gas transport infrastructure within the next decades is accomplished.[20]

[19] A similar modeling approach for the US market is presented by Ellison (2007).

[20] Fast steps into this direction have already been made by introducing and revising Gas Market Directives (European Union, 1998, 2003, 2009). A model validation presented in EWI (2010a) shows that the model can adequately reflect real flows apart from minor deviations. Efficient swaps in the model's pipeline system reflect the higher willingness to pay in regions where supply shortages occur in comparison to regions where supply is still adequate. In an efficient transport sector contracted volumes will be resold to regions with a higher willingness to pay, if sufficient transport capacity is available.

Maximum supply volumes to the European market, demand developments as well as capacity and start-off dates of existing infrastructure and infrastructure projects are exogenous to the model. The results cover flows in the pipeline system, the utilization of pipelines, LNG terminals, and the system of storage. The infrastructure components are considered with respect to integration, and effects on marginal supply costs. (See Figure 2.1 for an overview of the model.)

The marginal supply costs or nodal prices (Lochner, 2009, 2011a) quantify how much it would cost to meet an additional unit of demand at a specific node in terms of determining the next cost-optimal solution to satisfy this additional unit. Within the linear optimization framework, the marginal supply costs represent the shadow costs on each node's balance constraint for each period. They indicate the marginal system cost of supplying one additional cubic meter of natural gas to a specific node at a certain point in time. These additional cost estimates thus cover the sum of all costs such as production, commodity, transport, regasification or storage costs that are accumulated in the cost-minimal solution to meet the node-specific additional unit of demand. Hence, they also account for opportunity costs. In a perfectly competitive and efficiently organized gas transport market, the marginal supply costs at each node in the system should be equal to a theoretical wholesale price at that node. Therefore, an analysis of changes in marginal supply cost indicates the effects the simulated scenarios could have on market prices in a perfectly competitive market. If there is a disruption in supply, the marginal supply cost estimator rises towards infinity within the model.[21] Based on marginal supply costs and disruptions computed, the model gives an indication where additional infrastructure might be needed as a starting point for further cost-benefit analyses.

[21] A detailed description of the objective function, the main constraints, the computation of marginal supply costs, a list of all cost components, their sources and application in the model is presented in the Appendix.

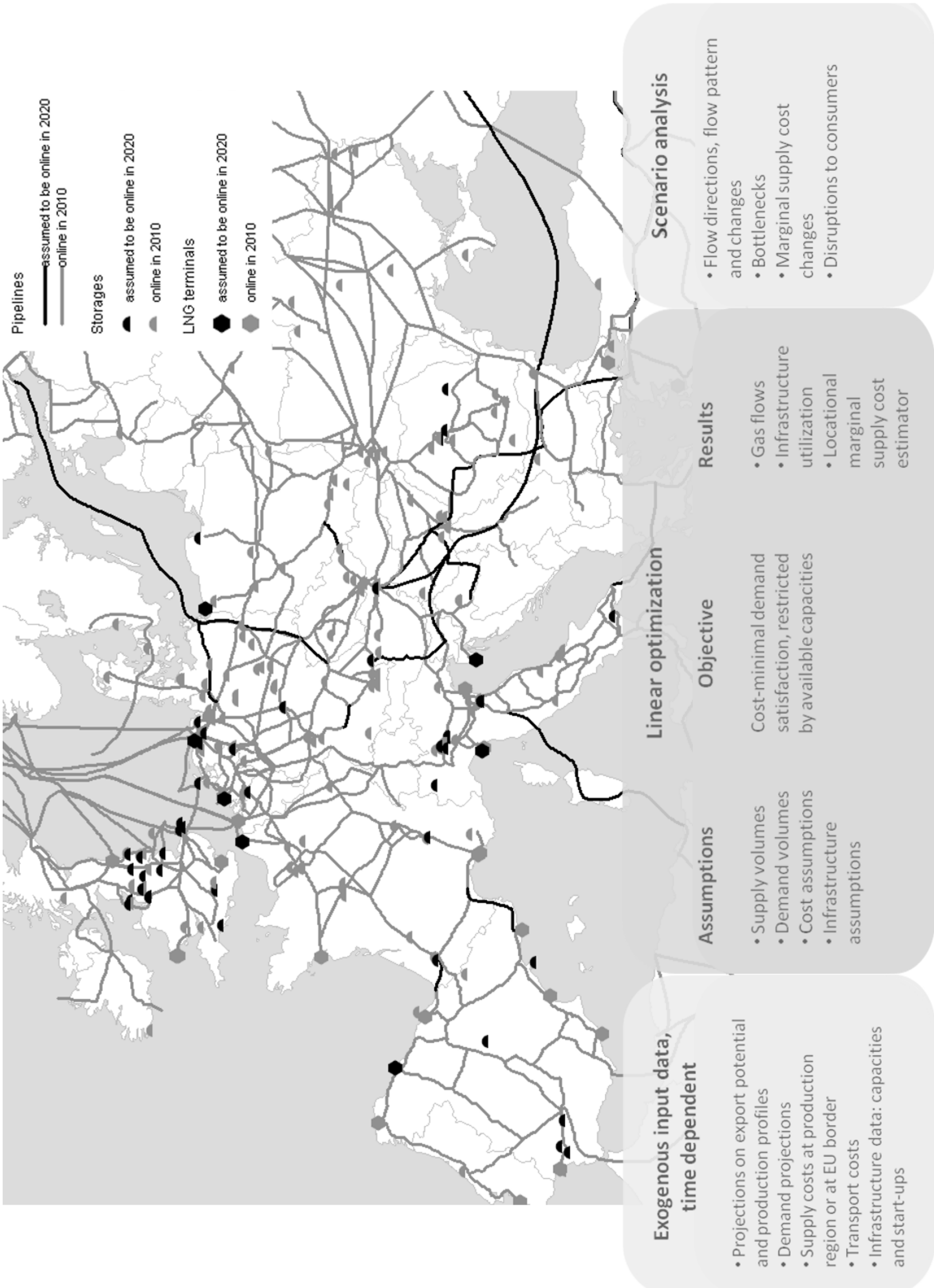


FIGURE 2.1: TIGER-model composition

2.3.2 Data assumptions

Demand, supply and infrastructure assumptions are based on EWI (2010a).[22] The demand scenario used is the EWI/ERGEG demand scenario, which is based on Capros et al. (2008) and adapted to the economic crisis from 2009 on. The peak day demand assumptions applied are published in the Ten Year Network Development Plan of the European Network of Transmission System Operators (ENTSOG, 2009). This is the highest possible daily demand level published and reflects a worst case scenario in terms of security of supply. In terms of pipeline projects in general – new pipelines, expansions and reverse flow projects – the scheduled projects are included based on EWI (2010a) which are those projects that the European regulators considered likely. With respect to the several intra-European pipeline projects and planned expansions of interconnector capacities between countries, those published in ENTSOG (2009), slightly adapted according to EWI (2010a), are implemented in the simulations. Table 2.1 gives an overview of European demand, the maximum pipeline import volumes, as well as the aggregated European production and infrastructure capacities that are available in 2010 and that are assumed to be online in 2020. The upper limit of pipeline import volumes available to the European market is either predefined by pipeline capacity restrictions or by the maximum export potential of the producer country.[23]

TABLE 2.1: European gas market in 2010 and assumptions for 2020

in billion cubic meter	**2010**	**2020**
Demand	489.1	533.31
Upper limit imports*	374,86	548.81/579.81**
from Russia	197.15	201.48
from Norway	121.22	112.82
from Algeria	45.40	55.35
from Caspian Region	0.99***	18
from Middle East		15.5/46.5**
from Lybia	10.10	9.9
LNG import capacity	164.92	279.02
European production capacity	190.61	124.7
Storage working gas volume	85.17	140.39

Gas Infrastructure Europe (GIE), BP (2011), Eurostat (2010), and EWI (2010).
All data refers to EU-27.
Data for 2020 sum up model inputs.
*Imports are restricted either by export potential or pipeline capacities.
LNG imports are only constrained by the capacity of regasification terminals (LNG import capacity).
**Only in Nabucco Scenario, based on the assumption that capacity to Turkey is extended then.
***From Caspian and/or Middle East.

[22]For a detailed overview of additional primary sources applied in EWI (2010a), the parameterization, the cost assumptions of the model, and the respective data sources, see Appendix A.3.

[23]More details on these assumptions, see EWI (2010a).

2.3.3 Scenarios

To analyze the impact of the two pipeline projects three different scenarios are simulated:

- The Baseline Scenario uses the assumptions listed above and includes one line of Nord Stream with an annual capacity of 27.5 bcm.
- The Nabucco Scenario is based on the Baseline Scenario, but it also assumes the Nabucco pipeline will provide an additional 31 bcm in 2020. The route of Nabucco, based on data published by Nabucco Gas Pipeline International GmbH (2010), runs from Turkey via Bulgaria, Romania and Hungary to Baumgarten, Austria with several connections to the national grids that allow for withdrawal and consumption of Nabucco gas along the way.
- The South Stream Scenario incorporates the South Stream pipeline instead of the Nabucco pipeline, but it otherwise makes the same assumptions as the Baseline Scenario. The pipeline's route is implemented as published by South Stream (2010) from Russia via the Black Sea to Bulgaria and from there on with two different onshore connections: one via Serbia, Hungary and Slovenia to Arnoldstein in Southern Austria and the other via Serbia and Hungary to Baumgarten, Austria. A pipeline connecting Greece and Italy is included based on EWI (2010a). A third route of South Stream via Greece to Brindisi, Italy is assumed to be unlikely if the pipeline connecting Greece and Italy is commissioned. It is thus not implemented in the simulations.

The three infrastructure scenarios are first simulated allowing for supplies via Ukraine in order to generate some general results and to establish a basis for comparison of the simulation of a hypothetical Ukraine crisis. The evaluations presented in the following section are based on simulated daily gas flows.

2.4 Results of no-crisis simulation for 2020

This section first presents general results on security of natural gas supply in Europe based on the Baseline Scenario. Second, the Nabucco and South Stream Scenario are compared with the Baseline Scenario. The results of the three infrastructure variations focus on a peak winter day in 2020, i.e. the day with the highest demand and therefore the strongest impact on security of supply.

2.4.1 Baseline Scenario results of no-crisis simulation

Increasing import dependency has a crucial impact on security of natural gas supply in Europe in the next decade which is shown in Figure 2.2 presenting the supply mix for 2009 and the simulated supply mix for 2020. Russia's role as a major exporter to the European Union increases. Russia covers additional 11.5 percentage points of European gas supplies in 2020.

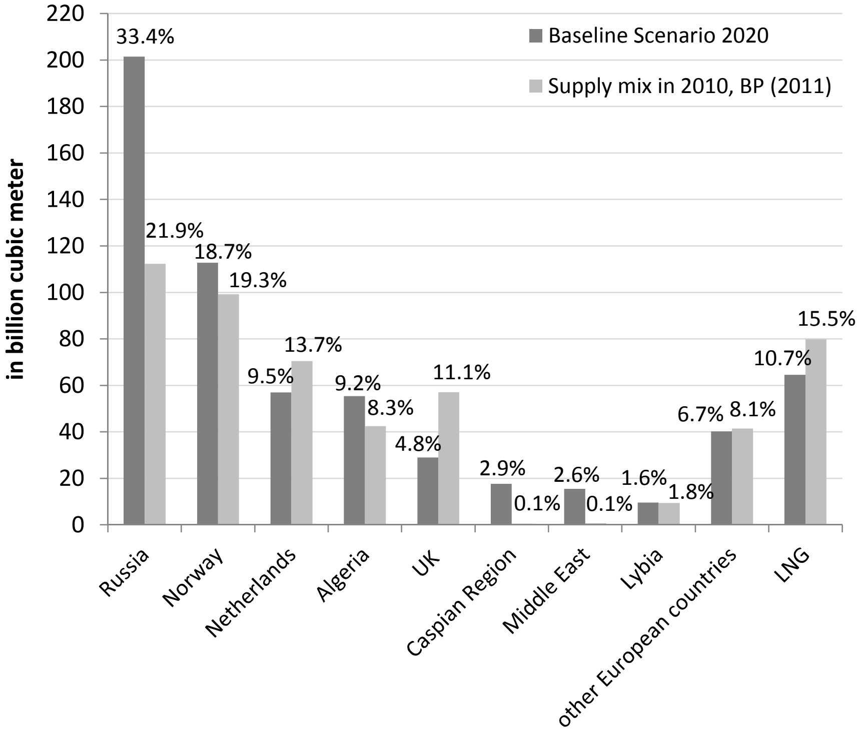


FIGURE 2.2: Supply mix in 2020

These additional Russian volumes are mainly transported via the Nord Stream pipeline (27.5 bcm in 2020), the Yamal pipeline via Belarus and Poland (about 32 bcm) and via Ukraine. European production decreases especially in the UK, where production is at 11.1 percent in 2009 and decreases to only 4.8 percent of EU-27 gas supply in 2020. Thus, intra-European gas flows from the production regions in the UK and the Netherlands are decreasing and flows on all new and existing pipeline import routes are increasing. Nord Stream causes a reduction of flows via the Czech Republic in comparison to 2010. In 2020, the additional volumes sent via Ukraine are transported further on to Hungary, Slovakia and Austria, to meet higher demand in this region.

The Baltic region, eastern Europe and Italy exhibit low marginal supply costs in comparison to Western Europe in 2020 (see Table 2.2). Western European countries are distant from non-European gas producers and the marginal unit of natural gas supplied to this region is comparatively cost-intensive because the incurred costs cover either additional transport costs or relatively high LNG import costs. In the Balkan region bottlenecks occurring on the peak day, the worst case scenario in terms of security of supply, lead to disruptions to consumers. These occur because of a lack of interconnector capacities to the adjacent countries relative to the high level of demand. The only import pipeline from Bulgaria to Former Yugoslavian Republic of Macedonia (FYROM) provides an average daily capacity of 2.6 million cubic meters per day (mcm/d), which is not sufficient to meet the Macedonian peak demand of 3 mcm/d assumed for 2020 by ENTSOG (2009). The same holds for the interconnector from Serbia to Bosnia and Herzegovina with 1.9 mcm/d compared with a peak demand of 2 mcm/d, and the Serbian demand of 20 mcm/d, which is significantly higher than the assumed cross-border capacity of about 13 mcm/d from Hungary, and about 4.3 mcm/d from Romania.

Table 2.2: Overview marginal supply costs - South Stream and Nabucco in comparison to Baseline Scenario

	Marginal supply costs on peak day in EUR/MWh					**Peak day**
Country*	Baseline	Nabucco	% Change to Baseline	South Stream	% Change to Baseline	**demand (in mcm)**
AT	21.56	20.97	-2.71%	21.62	0.27%	**86**
BA**	peak day disruption	peak day disruption	peak day disruption	peak day disruption	peak day disruption	**2**
BE	22.61	22.53	-0.37%	22.63	0.07%	**182**
BG	20.87	19.97	-4.32%	21.09	1.07%	**15**
CH**	22.51	21.99	-2.30%	22.62	0.51%	**23**
CS**	peak day disruption	peak day disruption	peak day disruption	21,59	prevention of disruption	**20**
CZ	21.17	20.47	-3.29%	21.47	1.43%	**71**
DE	21.80	21.39	-1.90%	21.77	-0.14%	**500**
EE	18.46	17.73	-3.95%	19.27	4.41%	**3**
ES	22.06	22.08	0.07%	22.07	0.04%	**294**
FI	18.53	17.80	-3.93%	19.35	4.39%	**24**
FR	22.79	22.77	-0.09%	22.76	-0.12%	**417**
GB	22.32	22.06	-1.19%	22.23	-0.44%	**483**
GR	21.62	21.81	0.89%	21.51	-0.47%	**35**
HR	21.66	21.08	-2.68%	21.71	0.25%	**37**
HU	21.61	20.30	-6.10%	21.50	-0.55%	**99**
IE	22.81	22.53	-1.22%	22.71	-0.44%	**28**
IT	20.26	19.80	-2.28%	20.34	0.42%	**433**
LT	19.66	18.96	-3.53%	20.06	2.05%	**14**
LU	22.72	22.60	-0.55%	22.75	0.11%	**7**
LV	18.82	18.10	-3.82%	19.55	3.90%	**8**
MK**	peak day disruption	peak day disruption	peak day disruption	peak day disruption	peak day disruption	**3**
NL	22.32	22.25	-0.33%	22.32	-0.03%	**431**
PL	20.62	19.93	-3.38%	20.74	0.57%	**85**
PT	21.89	21.88	-0.08%	21.88	-0.06%	**32**
RO	20.24	19.65	-2.91%	20.61	1.80%	**90**
SI	21.74	21.18	-2.58%	21.82	0.37%	**9**
SK	20.78	20.08	-3.36%	21.15	1.79%	**40**
EU-27 averages weighted by demand	**21.79**	**21.48**	**-1.39%**	**21.81**	**0.10%**	

*ISO Country Codes

**Non-EU and disrupted countries not included in averages.

2.4.2 Nabucco and South Stream Scenario results of no-crisis simulation

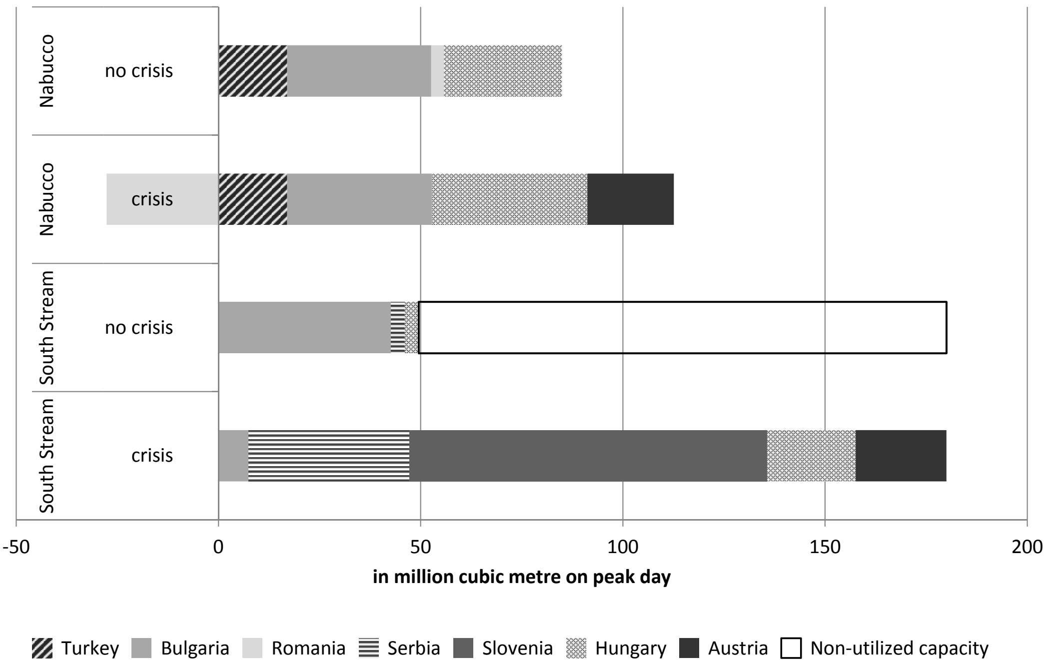
The inclusion of Nabucco and South Stream in the simulation changes gas flows on major import routes. Flows on Nabucco push Russian volumes further to the West and cause a higher utilization of the routes via Ukraine and Slovakia. On the contrary, South Stream takes over volumes from these routes and sends them directly to Bulgaria. In the Baseline Scenario these volumes are transported via Ukraine and further on to Romania and Bulgaria. Figure 2.3 shows the gas volumes transported to the European market by Nabucco and South Stream sorted by the countries where these volumes are withdrawn and consumed. Nabucco and South Stream volumes remain in eastern Europe.

Based on the cost-minimizing simulation of a peak-day scenario without crisis, Nabucco brings more gas to the European market than does South Stream. Nabucco volumes provide main supplies to Bulgaria and Hungary, as well as Turkey, and minor volumes are withdrawn in Romania. These volumes reduce marginal supply costs significantly in eastern Europe, especially in Hungary and Bulgaria (see Table 2.2). Only minor marginal supply cost decreases of around one percent can be observed in Western Europe. Belgium, Netherlands, Luxembourg (Benelux countries), France, Spain and Portugal are not significantly affected by the commissioning of Nabucco. On average, marginal supply costs decrease by 1.4 percent within EU-27.

South Stream only transports natural gas to Bulgaria and minor gas volumes to Serbia and Hungary (see Figure 2.3). In opposition to the Nabucco, Scenario disruptions in Serbia are avoided in the South Stream Scenario, which simultaneously causes slight average marginal supply cost increases (0.1 percent, see Table 2.2) in the European Union, especially in Romania, Bulgaria, Slovakia and the Czech Republic because of the rerouting of Russian volumes.

However, the disruptions in the Balkan countries Bosnia and Herzegovina and the FYROM cannot be prevented on a peak winter day even with the inclusion of Nabucco and South Stream because both pipelines bypass this region.

In summary, Nabucco and South Stream provide additional capacity and another option to transport gas to the European market, so they both improve the supply situation in terms of changes in marginal supply costs or the avoidance of disruptions, which are observed only in eastern and central Europe. Significant effects for Western Europe occur neither in the South Stream nor the Nabucco Scenarios.



The negative values in the Nabucco crisis scenario indicate injections into the pipeline in Romania.

FIGURE 2.3: Withdrawal of gas volumes along the route

2.5 Results of Ukraine crisis simulation for 2020

Since about 80 percent of Russian gas to the European Union is currently transported via Ukraine, a supply disruption on this route is the most threatening scenario for the European gas supply. Therefore, the effects of a disruption of four weeks of gas imports via Ukraine on the locational marginal cost price estimators are evaluated for the Baseline Scenario. Subsequently, the effects of the inclusion of the Nabucco pipeline or the South Stream pipeline are investigated. The analysis of the simulation results is carried out as a comparison of the three infrastructure scenarios.

2.5.1 Baseline Scenario results of Ukraine crisis simulation

A disruption of gas supplies via Ukraine causes major gas flow changes mainly in eastern Europe. Natural gas is withdrawn from storages in eastern Germany and partly transported to Poland, the Czech Republic and further on to the gas hub in Baumgarten, Austria. Storages in southern Germany provide volumes for Austria and volumes from western German storages are partly sent further on to Switzerland. Volumes withdrawn in northern Italy remain in the domestic market. (See Figure 2.4 for the additional volumes withdrawn from storages during the crisis.)

The respective changes in marginal supply costs analyzed result from a simulation with a stoppage of gas supplies via Ukraine in comparison to a scenario without such a crisis. On a peak winter day, the simulated four-week stoppage in gas supplies via Ukraine leads to disruptions to consumers and significant effects on marginal supply costs in large parts of southeastern Europe. For the Baseline Scenario presented in Table 2.3, given the planned pipeline infrastructure expansions, a peak day scenario itself would already cause disruptions in a no-crisis simulation (see section 2.4). These peak day disruptions are aggravated in a crisis simulation. Without a Ukraine crisis only 4 percent of peak day demand is disrupted in Bosnia and Herzegovina, 17 percent in Serbia and 27 percent in Macedonia, which increase to a complete disruption of peak day demand in Bosnia and Herzegovina and Macedonia during a Ukraine crisis. In addition, in a Ukraine crisis simulation, between 15 to 27 percent of consumers in Romania, Bulgaria and Hungary are also cut off from gas supplies (see Table 2.3 and Table 2.4).

In Croatia, no consumers are disrupted. However, marginal supply costs indicate that disruptions would occur at the margin if demand increases only slightly. Increases in marginal supply costs of more than 3 percent occur in eastern Europe, while Germany, the Benelux countries and Poland are confronted with slight changes in marginal costs that result from the compensation through German storage volumes (see Figure 2.4). Western European countries, which are supplied by Norwegian and Algerian pipeline gas as well as LNG imports (i.e. UK, Ireland, Switzerland, Italy, Portugal, France and Spain) are not significantly affected by the crisis.

In the Baltic countries, Finland and Estonia, marginal supply costs even decrease by more than 40 percent in the crisis simulation. Because of the cut-off of Russian volumes to Western Europe via Ukraine and the available Russian export potential, these countries receive additional Russian volumes. In contrast to marginal costs being driven by expensive storage withdrawals in a no-crisis simulation, these additional Russian volumes lead to significant reductions in marginal supply costs.

TABLE 2.3: Change of marginal supply costs during crisis

Country*	% change Baseline	% change Nabucco	% change South Stream
AT	4.23%	4.52%	1.28%
BA	peak day disruption	peak day disruption	peak day disruption
BE	1.41%	0.53%	0.48%
BG	crisis disruption	marginal crisis disruption	-1.92%
CH	0.58%	0.02%	0.03%
CS	peak day disruption	peak day disruption	-1.87%
CZ	3.09%	4.74%	0.70%
DE	1.31%	1.42%	0.37%
EE	-42.94%	-40.59%	-7.01%
ES	-0.14%	0.07%	-0.03%
FI	-42.44%	-40.08%	-6.99%
FR	-0.02%	-0.11%	0.00%
GB	0.18%	-1.06%	0.00%
GR	crisis disruption	crisis disruption	-1.34%
HR	marginal crisis disruption	3.37%	-0.55%
HU	crisis disruption	crisis disruption	-0.07%
IT	0.19%	0.31%	0.00%
IE	0.72%	0.37%	0.10%
LT	-9.22%	-9.38%	-7.42%
LU	1.80%	0.73%	0.69%
LV	-5.86%	-5.78%	-5.81%
MK	peak day disruption	peak day disruption	peak day disruption
NL	1.37%	0.34%	0.47%
PL	1.13%	2.66%	0.01%
PT	0.03%	0.11%	-0.02%
RO	crisis disruption	marginal crisis disruption	crisis disruption
SI	4.33%	0.00%	0.64%
SK	8.39%	0.00%	3.89%

The wording "marginal crisis disruption" indicates that no volumes are disrupted, but an additional unit would be.
Therefore, no marginal supply costs can be computed.
*ISO Country Codes

TABLE 2.4: Disrupted volumes during crisis

in million cubic meter on peak day	**Baseline**				**Nabucco**				**South Stream**			
Country*	**no disruption**		**disruption**		**no disruption**		**disruption**		**no disruption**		**disruption**	
BA	0.08	4.00 %	2.00	100.00%	0.08	4.00%	2.00	100.00%	0.08	4.00%	0.08	4.00%
BG	0.00	0.00%	3.98	26.51%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
CS	3.42	17.11%	4.00	20.00%	3.42	17.11%	4.00	20.00%	0.00	0.00%	0.00	0.00%
GR	0.00	0.00%	5.25	15.00%	0.00	0.00%	2.38	6.81%	0.00	0.00%	0.00	0.00%
HU	0.00	0.00%	26.83	27.10%	0.00	0.00%	8.31	8.40%	0.00	0.00%	0.00	0.00%
MK	0.81	26.96%	3.00	100.00%	0.81	26.96%	0.81	26.96%	0.81	26.96%	0.81	26.96%
RO	0.00	0.00%	13.52	15.02%	0.00	0.00%	0.00	0.00%	0.00	0.00%	9.20	10.22%
Sum	**4.31**		**58.57**		**4.31**		**17.51**		**0.89**		**10.09**	

The percentages indicate proportions of peak day demand.
*ISO Country Codes

2.5.2 Nabucco and South Stream Scenario results of Ukraine crisis simulation

The compensation for the missing Ukraine transits causes overall changes in the utilization of infrastructure components and gas flows. The differences of supply volumes between the crisis and the no-crisis scenario are presented in Figure 2.4. The compensation within the applied overall optimization framework could even reduce the utilization of alternative infrastructure to the Ukraine route, which is indicated by the negative bars. Therefore, including all changes between the crisis and no-crisis scenarios, the net length of the bar in Figure 2.4 reflects the aggregated compensated or disrupted volumes via Ukraine for each of the three infrastructure scenarios.

These aggregated volumes differ because the utilization of the Ukrainian routes in a no-crisis simulation varies depending on the major pipeline available to supply the European market. Without a Ukraine crisis South Stream already takes over some of the volumes that are transported via Ukraine in the Baseline Scenario. Thus, in the South Stream Scenario, given that Ukraine transits were already lower than in the Baseline Scenario, the missing volume – about 77 mcm/d less than in the Baseline Scenario – must be substituted if there is a supply disruption via Ukraine. Rerouting of Russian gas volumes and only a small proportion of withdrawal from storage in Germany and other European countries can then substitute for the missing Ukrainian volumes. Rerouting here turns the volumes that have been transported via Ukraine in the no-crisis simulation to another route from Russia in a crisis simulation.[24] Thus, less west-to-east gas flows take place with South Stream than in the Baseline Scenario and no significant gas flow changes occur in western Europe.

Because of several bottlenecks in southeastern Europe, 15 million cubic meters (mcm) less LNG are imported into the Krk terminal in Croatia and 13 mcm less gas is withdrawn from eastern European storage on the peak day during the simulated Ukraine crisis. These supply reductions are also compensated by additional supplies via South Stream.

[24] These routes could be Nord Stream, the Yamal route via Belarus and Poland to Germany, Blue Stream or South Stream depending on the Scenario. In the South Stream Scenario, Russian gas is rerouted via South Stream because Nord Stream and the Yamal route are completely utilized.

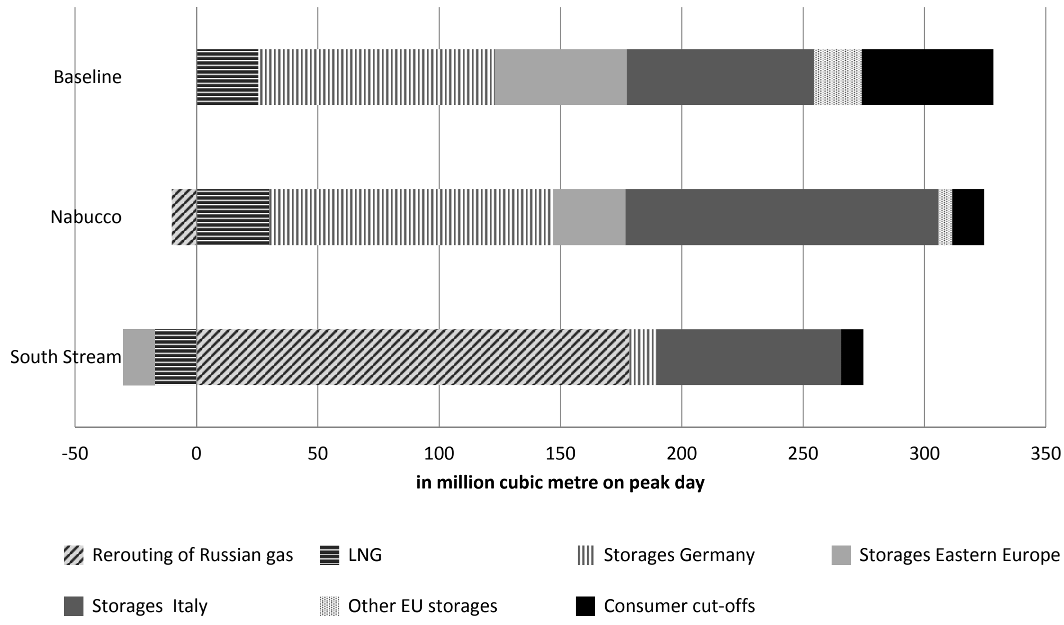


FIGURE 2.4: Differences regarding supply volumes between crisis- and no-crisis simulation

The net length of the bars – positive part less the negative part – indicates the sum of the missing Ukraine transits and how these are compensated.

South Stream being only poorly utilized in a no-crisis simulation offers generous redundant capacity during a crisis simulation (see Figure 2.3 on page 38). During a halt of gas supplies via Ukraine, gas transported on South Stream more than triples on a peak demand day, which demonstrates the extent of redundant capacity available. Because of this alternative supply option, gas flows in west Europe remain mainly unaffected by the crisis except for north Italy where the missing volumes are compensated for by storage withdrawals and South Stream supplies. South Stream then provides less volumes for the Bulgarian market, but significant volumes for the Serbian, Slovenian, Hungarian and Austrian market. It eliminates persistent supply disruptions in Serbia; avoids the crisis-induced disruptions that occurred in the Baseline Scenario in Bulgaria, Greece and Hungary; and reduces increases in marginal supply cost significantly in Slovakia, Croatia, Austria and Germany.

Disruptions to consumers can be observed in Romania due to a lack of pipeline capacity from Hungary to Romania and South Stream bypassing Romania,[25] although large volumes are transported to neighboring Bulgaria. But the disruptions in Romania are reduced from 15 to 10 percent of peak day demand in comparison to the Baseline Scenario. Referring to the mitigating effects these extra volumes have on the marginal

[25]Gazprom and Romania have started negotiations on Romania joining the South Stream pipeline network. A feasibility study will be worked out, but it is not yet clear whether this could result in a different route that excludes Bulgaria. (Euractiv.com, 2010)

supply costs and on disruptions to consumers, South Stream's large-scale capacity has a significant impact on security of supply in terms of transit country risks. So it significantly reduces the dependence on Ukraine. However, based on cost-minimization, even in a peak day scenario South Stream is poorly utilized if other transport options from Russia are available.

By contrast, gas volumes transported via Nabucco do not have a crowding-out effect on Ukraine transits in a no-crisis simulation, so the missing Ukraine volumes are much greater during a crisis simulation. These missing volumes are mainly compensated for by withdrawals from storage in eastern Europe, Germany, Italy and other European countries. Germany, which has the largest storage working gas volumes in Europe, with more than 25 bcm, provides additional volumes during the crisis to be transported east. Nabucco provides additional volumes for Italy and Austria, which in addition receive some volumes from northern Italian storages during the crisis. In comparison to the Baseline Scenario more German storage volumes can therefore be sent to northeastern Europe. In the Nabucco Scenario, in the simulated crisis on a peak day, 10 mcm less volume than in the no-crisis simulation is rerouted from Russia, that is, transported on a route other than the Ukraine route (Blue Stream in this case). The simulated Ukraine crisis causes a bottleneck in the interconnector from Turkey to Bulgaria, which results in this decrease in Blue Stream flows. Again subtracting these negative volumes from the positive bar for the Nabucco Scenario mirrors the missing Ukraine volumes (see Figure 2.4).

During the halt of Ukrainian transits, Nabucco gas supplies to Bulgaria and Turkey remain the same as in the no-crisis simulation, and additional volumes are transported to Hungary and Austria (see Figure 2.3 on page 38). These additional volumes are mainly injected in Romania, as Nabucco is already completely utilized from the start of the pipeline in a simulation without a crisis. Since some volumes are consumed in Bulgaria, capacity is then available in Romania. The gas volumes injected into the pipeline are withdrawn from storage in Romania, mainly to reduce disruptions in Hungary and to mitigate increases in marginal supply costs in Austria. Introducing the Nabucco pipeline does not reduce the peak day disruptions that result in Serbia, Bosnia and Herzegovina[26]. However, during the simulated Ukraine crisis, disruptions in Bulgaria, Romania and parts of Greece are avoided such that only increases in marginal supply costs occur, rather than consumer cut-offs. In addition, disruptions in FYROM are reduced from a 100 percent in the Baseline Scenario during the Ukraine crisis to the peak day disruption level of 27 percent. However, the improvement of market integration with Nabucco leads to minor increases in marginal supply costs in Austria, Czech Republic, Poland and

[26]The Bosnian natural gas company BH-Gas has already shown interest in extending its gas supplies through connections to major pipeline projects. It has asked Turkey's Bota to help it connect to the planned Nabucco and TAP pipelines in an effort to diversify its gas supplies (Balkans.com Business News (2010)).

Northern Germany over the marginal supply costs in the Baseline Scenario. Again, it is cost-efficient, within this modeling framework, to accept these slight increases in order to prevent disruptions to customers in other regions.[27]

Additional consumer cut-offs caused by the Ukraine crisis on the peak day are reduced by both South Stream and Nabucco. In the Baseline Scenario about 54 mcm are additionally cut off during the crisis, but only about 13 mcm are additionally cut off with Nabucco included, and South Stream's extensive capacity further reduces the disruptions to about 9 mcm. (See Figure 2.4. These numbers reflect the differences between the crisis and no-crisis scenarios in Table 2.4.)

2.6 Conclusion

The Nabucco and South Stream Pipelines are often discussed in the context of security of European gas supply. The results of the simulations with the TIGER model show that security of supply in Eastern Europe increases with the inclusion of either Nabucco or South Stream based on assumptions covering currently publicly announced infrastructure plans. Nabucco reduces marginal supply costs in many Eastern European countries and South Stream prevents disruptions to consumers in Serbia that occur in the Baseline Scenario. However, consumer cut-offs in some Balkan countries cannot be avoided by either Nabucco or South Stream because these cut-offs occur as a result of insufficient interconnector capacity. These results are conditional on the specific assumptions.[28] Additional not yet announced interconnector capacity expansions that may occur during the interim would mitigate or even prevent these consumer-cut-offs. The same holds for a lower demand scenario whereas significantly higher demand could even worsen the disruptions.

Without either Nabucco or South Stream, the European market is strongly dependent on transits and on a functioning pipeline system in Ukraine. Not even flexible LNG imports can reduce this dependence because of the bottlenecks that occur in the European pipeline system during a halt of Ukraine transits.

Generally, the inclusion of Nabucco and South Stream in model simulations of a Ukraine crisis both increases security of supply and leads to a reduction of disruptions to consumers and to lesser price increases. The impact of these improvements varies significantly over different European regions and is most effective in southeastern Europe. Nabucco prevents disruptions in Bulgaria and Romania and South Stream in Hungary, Serbia and Bulgaria. However, not all disruptions within the European market can

[27] These effects reflect a higher willingness to pay in regions confronted with supply shortages.

[28] Bottlenecks identified in the paper that might lead to disruptions refer to congestion which occurs in an efficiently working market. Potential additional bottlenecks as a consequence of market inefficiencies are not detected by the modeling approach.

be avoided by these pipeline projects because of intra-European bottlenecks. Persistent disruptions remain in Bosnia and Herzegovina and Former Yugoslavian Republic of Macedonia. These results are based on assumptions on significant demand increases in this region and publicly announced plans on infrastructure developments. A connection of South Stream to Romania or (reverse flow) capacity from Hungary to Romania could mitigate disruptions to consumers there. The same holds for a connection of Nabucco to the Serbian market or a better integration of the Hungarian and Serbian market. Moreover, because of the significantly lower capacity of Nabucco, additional LNG volumes imported into Croatia would be needed to eliminate disruptions in Hungary and Serbia, but these volumes could be transported only if bottlenecks in Croatia were removed. The effects of the pipeline projects in Western Europe are small.

Based on cost-minimization, the model results show that South Stream, which is poorly utilized even on a peak winter day in a no-crisis simulation, supplies primarily Bulgaria. However, South Stream offers redundant capacity in a crisis simulation to reroute Ukraine transits during the simulated halt of supplies via Ukraine. In the crisis simulation, South Stream is highly utilized, so it would be built primarily to bypass Ukraine. Both pipeline projects enable a diversification of supply routes especially with respect to the main routes via Ukraine and, if implemented, should contribute to securing gas supplies. However, only Nabucco would reduce the dependency on Russian gas, assuming adequate alternative suppliers in the Middle East and Caspian region were available to provide gas for the pipeline, and would support a diversification of supply sources.

In summary, Nabucco and South Stream provide additional large-scale pipeline capacity in southeastern Europe, but they also increase security of supply by extending supply options and mitigating the effects of potential supply disruptions via Ukraine in this region. However, the attribution of relevant costs, apart from relative changes in short-term marginal supply costs, and the probability of events that have high impact on security of supply are not evaluated.

The determination of the optimal security of supply level by comparing marginal costs of investments into the Nabucco and South Stream pipeline with marginal benefits of additional security of supply provided remains open for further research. For measuring these benefits a detailed investigation on country-specific demand profiles and elasticities is needed, especially because of the uncertain demand developments in the EU within the next decades. Moreover, an efficiency analysis of a potential investment in the Nabucco and South Stream pipeline projects would complement a long-term economic analysis of security of supply.

Chapter 3

Civil unrest in North Africa – Risks for natural gas supply?[29]

In this paper, we analyze the impacts of civil unrests in North Africa on European security of natural gas supplies. Applying the natural gas infrastructure model TIGER, we investigate the impact of supply disruptions from Algeria and Libya for a summer and winter period. Our analysis shows that disruptions in the low-demand summer months could be compensated for by LNG imports. An investigation of a similar situation at the beginning of the winter shows that disruptions to Italian consumers would be unavoidable. The analysis thereby highlights the importance of taking the political stability of supply countries into account when assessing the security of European gas imports.

3.1 Introduction

The political uprising in Libya at the beginning of 2011 has severely affected the country's pipeline exports to Europe. The Greenstream pipeline from Libya, which supplies around nine billion cubic meters (bcm) of natural gas to Italy each year, stopped operations on 22 February 2011 and deprived the Italian gas market of significant volumes for eight months.

This article analyses the current and potential effects on the European gas market of supply disruptions in North Africa. In general, the European Union imports 10 bcm annually from Libya and another 54 bcm from Algeria which together amount to about 13 percent of EU gas consumption and 28 percent of non-European imports (or, taking into account Norway, 20 percent of non-EU imports). (All figures are for 2010 and based on BP (2011).) However, Europe's dependence on North Africa differs significantly between countries and is higher for Southern European countries. The only pipeline from Libya to Europe, Greenstream, supplies about 10 percent of Italian gas

[29]The paper is a joint work of Stefan Lochner and the author and is published in Lochner and Dieckhöner (2012).

consumption. Another 25 percent of Italian gas demand are provided via the Trans-Mediterranean pipeline (Transmed) from Algeria. The Maghreb-Europe pipeline as a link from Algeria via Morocco to Spain delivers about 20 percent of Spanish gas demand; a new line directly from Algeria to Southern Spain, the Medgaz pipeline which started operating in 2011, can supply an additional 8 bcm per year (see the gas flow map in Figure 3.4 for the different supply routes to Southern Europe).[30] In addition to these pipeline supplies, North Africa is also a relevant supplier of liquefied natural gas (LNG) to the global market. Algeria exported about 20 bcm in 2010, most of which arrived in the EU (BP, 2011).[31] Therefore, North African countries are important suppliers for the European natural gas market. The current civil unrests in this region and a potential spread to Algeria might have a significant impact on the security of natural gas supplies.

This article offers a in-depth analysis of short-term security of supply threats arising from the current instability in North Africa. In the next section, it is discussed how the prolonged disruption of natural gas supplies from Libya suggests a different threat to European security of natural gas supplies than the ones observed in Eastern Europe in the past. It not only concerns a different route and region but it is also due to a different cause: domestic political uprisings leading to civil-war-like unrest and, in the case of Libya, outside military intervention and war. Security of supply is discussed in the context of the existing literature. To document the events in Libya in 2011, Section 3.3 describes the reaction of the gas market and how consequences to consumers were avoided. Extending our perspective to the more important North African supply country to Europe, Algeria, we apply a European infrastructure and dispatch model (presented in Section 3.4) to simulate crisis scenarios for supply disruptions from North Africa. Results focusing on necessary gas flow diversions and potential consequences to consumers in Europe are presented in Section 3.5. Section 3.6 offers some concluding remarks and policy implications.

3.2 Security of European natural gas supply and political stability of supplier countries

Previous research on security of natural gas supply can be categorized into issues of technical infrastructure facility maintenance on the one hand and a more economic perspective regarding the provision of the commodity natural gas on the other hand.

[30] With the first line of Nord Stream providing an additional capacity of 27.5 billion cubic meters annually from Russia to Germany since 2011 and with a second line of that volume that should be in operation in 2012, another major supply option is available especially to Northwestern Europe.

[31] Libya is only a minor LNG exporter (less than 0.5 bcm in 2010). The other North African LNG exporter, Egypt, exported close to 10 bcm in 2010: 50 percent to Europe, the rest to North America and the Asia-Pacific market.

Literature on the latter thereby distinguishes between different causes of potential insecurities. Because of its decreasing indigenous production, the European natural gas market is increasingly dependent on supplies from non-European countries with different political systems. Therefore, types of security of European natural gas supplies in economic terms are firstly, the very long-term view of the range of reserves and resources (Costantini et al., 2007), the mid-term availability of suppliers to the European market (Holz et al., 2009), their bargaining power and aspects of global geopolitical security of supply (Victor, 2010) and last the analysis of short-term disruptions due to political disputes such as between Russia and transit countries like Ukraine (Bettzüge and Lochner, 2009, Dieckhöner, 2012b, EWI, 2010a, Lochner, 2011b, Monforti and Szikszai, 2010). Although the long-term uncertainty arising from political instability is also an issue, the immediate consequences of the situation in North Africa fall into the short-term supply security category.

However, they have a different cause compared to previous events. The economic disputes seen in the past were in general resolved after a couple of weeks. Suppliers like Russian state-owned Gazprom, or the transit countries, have a strong incentive not to harm the relationship with its main consumption region, i.e. the European Union. This does not hold for political conflicts such as those that started this year in North African countries where severe civil unrests and fundamental political regime changes take place: The relationships with natural gas consumers in foreign countries may not be of importance to the different stakeholders in a politically motivated civil war. Nevertheless, the consumer countries might be significantly affected by this supply risk.

This type of risk has rarely been discussed in the academic literature in the past as most of the literature focuses on security of supply in general or the risks associated with transits of Russian gas.

There are some contributions that address North Africa in the terms of security of natural gas supplies. Algeria' role as a major supplier is, for instance, analyzed within different frameworks. Egging et al. (2008) develop a mixed-complementarity model for the European natural gas market where Algeria is a major supplier. Darbouche (2011) discusses Algerian export strategies in the medium term with a focus on how reliable production targets are – and comes to the conclusion that these may have to be revised downwards until 2015. Lise et al. (2008) analyze long term gas supply security in Europe with their market equilibrium model GASTALE. Within their study, they analyze the impact of a disruption of supplies from Algeria for 2020 on demand and prices. They find that only Southern European countries are significantly affected, i.e. Italy and Spain. These countries have to rely on LNG in this case, which results in significant price increases. The results of the large-scale study by EWI (2010a) are similar for 2019. However, the study focuses on a four week disruption which is only found to be critical for Spain if sufficient substituting LNG volumes cannot be procured in the short term. With respect to the crisis in Libya in 2011, Lochner and Dieckhöner (2011) offer a qualitative discussion of the lessons for EU security of supply legislation and show that a Libya-only disruption is not critical for security of supply.

Weisser (2007) and Stern (2002) define security of supply dependence and provide a differentiation of the type of dependence for natural gas. These definitions cover source, transit and facility dependence and structural risks of natural gas supplies. According to Weisser (2007) and Stern (2002) risks to these dependences could be triggered by drivers such as natural catastrophes, political conflicts, terrorism, wars and civil unrests. Thus, the stability of the mainly non-Western countries, where most of Europe's natural gas imports come from, could have an impact on security of natural gas supplies.

According to the Worldwide Governance Indicators (WGI) for Political Stability and Voice and Accountability[32] published by the The World Bank Group (2010), the two major supplier countries to the European market, Russia and Algeria, exhibit negative values in a range from -2 to -1 whereas European countries have mainly positive indicator values even for Romania, which is the country with the lowest value (see Figure 3.1).

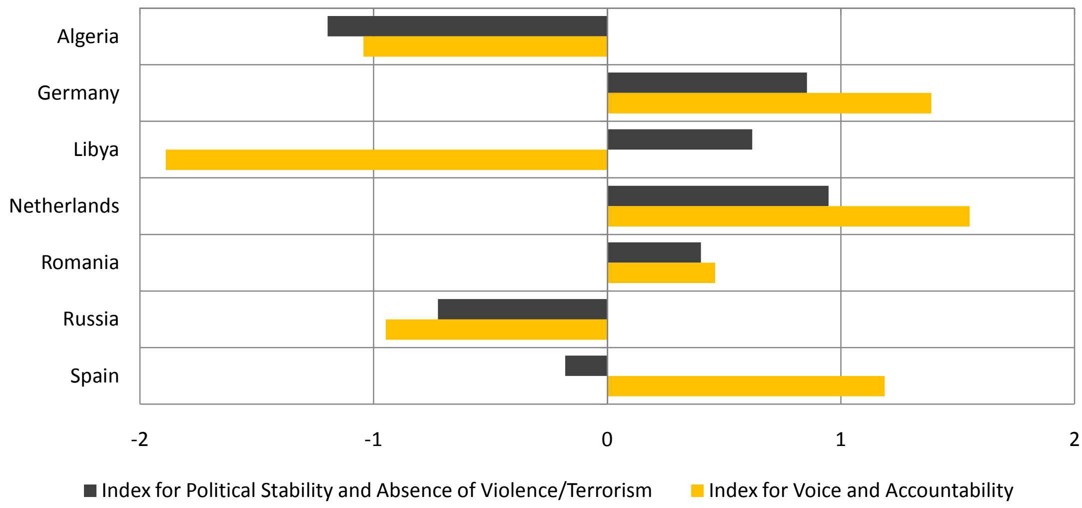


FIGURE 3.1: Worldwide Governance Indicators

The very low value of the 'Voice and Accountability Index' for Libya in 2009 gives an indication to the limited rights of Libya's citizens at that time and reflects the risk

[32]The indicators are computed including several hundred individual variables from different analyses and surveys of a variety of public and private institutions as well as NGOs. The indicators listed in Figure 3.1 reflect "The process by which governments are selected, monitored, and replaced: 1. Voice and Accountability (VA) – capturing perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media. 2. Political Stability and Absence of Violence/Terrorism (PV) – capturing perceptions of the likelihood that the government will be destabilized or overthrown by unconstitutional or violent means, including politically-motivated violence and terrorism" (Kaufmann et al., 2010). The higher the index value of a country, the more pronounced is the respective characteristic.

for civil uprisings. These eventually started at the beginning of February and severely impacted the country's pipeline exports to Europe. However, two more things need to be noted. First, a strong dictatorship suppressing its citizens and not being held accountable for its actions can still be politically stable - as Libya has been for more than 40 years. Therefore, drawing conclusions from any such index needs to be treated with caution. Second, measuring political stability is equally difficult, even more so as political stability can be interpreted differently in different countries. As also illustrated in Figure 3.1, the WGI indicators present Libya to be more politically stable than Algeria - and more surprisingly, also more stable than EU member states Romania and Spain.

Turning back to natural gas supplies, however, it can be concluded that two of the main suppliers (Russia and Algeria) are not highly rated with respect to political stability and voice and accountability – the latter also holds true for Libya. Hence, there appear to be significant short-term security of supply risks from political conflicts.

Because of political uprisings in Libya, the Greenstream pipeline was not in operation between February 22 and October 13, 2011. The disruption deprived the Italian gas market of large volumes. While the consequences to Europe were limited (Lochner and Dieckhöner, 2011), a spread of the uprisings in North Africa to other countries could worsen the situation for Europe. Therefore, even if the part of North African supplies delivered as liquefied natural gas may be substituted by LNG from other sources in the currently well supplied global gas market, these type of disruptions could be a severe risk to natural gas supplies.

Within the security of natural gas supply regulation of the European Union (2010), clear preventive measures for enhancing security of supply are defined. One of the most prominent pillars of the regulation is that the infrastructure of each European country must be able to compensate a disruption of the most important infrastructure component for 30 days in times of a demand level of a 1 out of 20 winter. These conditions are mainly deduced from the transit country risk discussion after the repeated gas dispute between Russia and Ukraine in January 2009. So far, no significant disruption occurred due to prolonged political conflicts. But depending on the importance of the involved countries for European natural gas supplies and the duration of the conflict, this might have severe affects on natural gas consumers in Europe.

As the role of and the potential short-term insecurity arising from the dependence on Russia have been discussed in the literature, especially in the context of transit disruption, this article focuses on the different type of risk associated with natural gas supplies from North Africa. The impact of disruptions caused by the recent turmoils in Libya and by hypothetically similar events in Algeria on security of European natural gas supplies are thus analyzed in the next sections.

3.3 Libyan gas export disruption in 2011

Following the fall of the regime in Tunisia and the departure of Egyptian president Mubarak in January and early February 2011, the unrest in the Arab world spread to Libya. The military started violent crackdowns on mostly peaceful protests on February 15. More demonstrations in the following days were met by increased violence; armed protesters also started to attack government buildings in a number of cities across the country. The situation quickly escalated into a civil war-like confrontation between reform-oriented protesters and the Gaddafi regime and its supporters. As a consequence, international corporations in the country's oil and gas exploration sector started to wind down operations and withdraw their international staff from the country.[33]

On February 22, Libyan pipeline gas exports to Italy came to a halt. Nevertheless, the consequences for the Italian gas market were limited. There were no disruptions to consumers; even price spikes at the Italian natural gas trading points did not occur. The high flexibility of European natural gas transmission system - and the end of the winter implying declining demand - meant that natural gas supply shortfalls from Italy were rather easily compensated by additional volumes from other sources as illustrated in Figure 3.2.

The 25 million cubic meter (mcm) per day usually imported via the Greenstream pipeline from Libya, were mainly compensated by a simultaneous increase in imports via the TAG pipeline from Austria. This pipeline mainly carries Russian gas via Ukraine, Slovenia and Austria to Italy. Although it was not possible for Russia to instantaneously increase exports to Italy - it takes about two weeks for Russian gas volumes to be transported all the way to Italy - the country made up most of the shortfalls over the following months. In the short term, Algerian gas exports remained at a relatively high level and additional natural gas was withdrawn from storages in Italy (and possibly also Austria explaining the speedy increase of deliveries on the TAG route). All other volumes supplied to the Italian market (domestic gas production, LNG imports, imports via Switzerland) remained at the normal level. It is also evident from Figure 3.2 that the availability of natural gas was sufficient to even start the refilling of storages for the following winter (negative storage withdrawals in Figure 3.2) by April 2011.

Table 3.1 further illustrates how volumes were compensated over the whole seven months until the start of the next winter (October 1) compared to the previous year. (Supplies slowly resumed on October 13th, 2011.) Almost 80 percent of the missing imports from Libya were compensated by additional Russian gas volumes. As demand was actually 1.7 billion cubic meter (bcm) lower, storage injections between March and September 2011 were higher than in the previous year. This also partially compensated

[33] For a detailed discussion of the events in Libya in spring 2011, see for instance Institute for Security Studies (2011).

the higher storage withdrawals in the first weeks of the disruption in February. Again, all other volumes into the market were basically at the level of the 2010 summer.

Table 3.1: Italian gas balance from March to September

Import pipeline / country	2010 [bcm]	2011 [bcm]	Difference / Change [bcm]	[mcm/day]	[%]
Transmed (Algeria)	13.64	12.40	-1.23	-5.8	-9%
Greenstream (Libya)	5.06	0.00	-5.06	-23.6	-100%
Transitgas (Switzerland*)	5.48	7.05	+1.57	+7.4	+29%
TAG (Austria**)	9.95	13.93	+3.98	+18.6	+40%
Gorizia (border Slovenia)	0.07	0.07	-0.00	-0.0	-2%
LNG imports	5.22	5.21	-0.01	-0.1	-0%
Italian Production	4.84	4.77	-0.06	-0.3	-1%
Storage Balance***	-6.53	-7.37	-0.84	-3.9	+13%
Total	37.73	36.07	-1.66	-7.7	-4%

Source: Own calculations based on SnamReteGas.
*Import route for Norwegian and Dutch gas volumes.
**Import route for Russian gas volumes.
***Negative: injection into storage.

However, these findings do not allow the conclusion that the European gas market in general and the Italian market specifically are not vulnerable with respect to North African and Libyan gas supply disruptions. Firstly, the disruptions occurred at the end of the winter. Supplies recommenced before the next winter. As evident from Figure 3.2, significant storage withdrawals of between 80 and 125 mcm per day were required during the first days of the disruption to compensate the shortfall. Normally, withdrawals of such volumes only happen on individual cold days in January or early February. If a disruption were to happen earlier in winter, storages might deplete quickly causing shortages at the end of the winter. The majority of the disruption in this case affected the low demand summer months. Secondly, the conflict in Libya affected a relevant but not the most important North African gas exporter to Europe. Algerian gas volumes have a much higher market share in the Italian and Spanish gas market. A disruption of exports could potentially cause more concerns for consumers.

Therefore, the model based analysis at the focus of this paper aims to identify critical situations for the European gas market which could arise from unstable situations in North Africa. This mainly concerns the export of gas by pipeline. LNG volumes in general can be compensated easier as in a sufficiently flexible global LNG market, additional cargoes would be diverted to Europe if European wholesale prices were to rise as a consequence of a crisis in North Africa. Hence, the focus of the analysis is on Libyan and Algerian pipeline exports. The model applied to do so is presented in the following section.

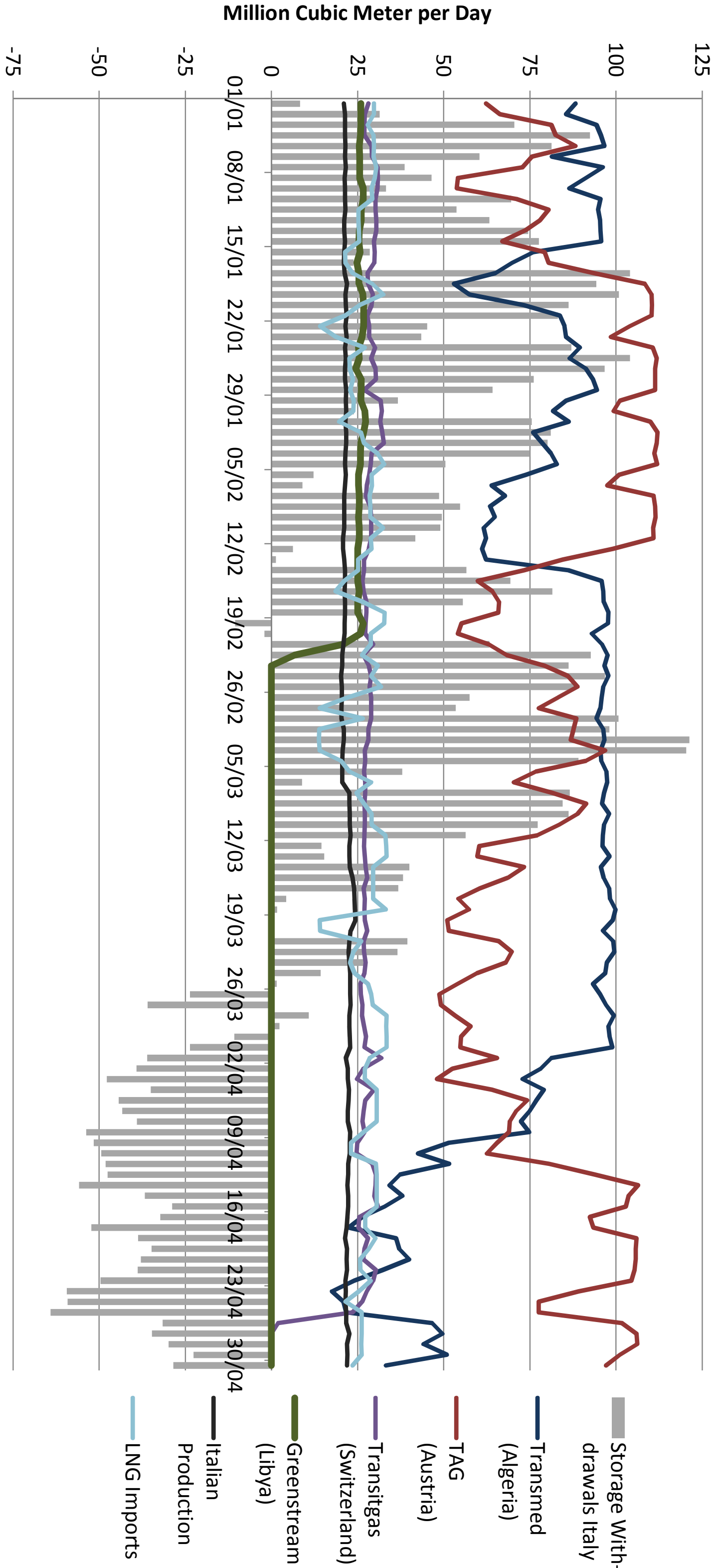


FIGURE 3.2: Italian pipeline imports January to April 2011

3.4 Model-based analysis of potential future disruptions

Methodologically, we apply a natural gas infrastructure and dispatch model of the European gas market presented in Lochner and Bothe (2007) and Lochner (2011a). It is a linear optimization model minimizing the total cost of gas supply in the European gas market taking into account the relevant technical constraints of the infrastructure and assuming an efficient utilization of infrastructure assets. The integrated consideration of the gas infrastructure components, i.e. pipelines, storages and terminals, allows evaluations of interdependencies and of the effects of single events on the system as a whole. Thus, the model is well suited for comprehensive analyses of the supply situation and gas flows within the European long distance transmission grid - and has been used in academic and applied research in this capacity.

The model's cost-minimization approach is based on the assumptions of a perfectly competitive and efficient organization (regulation) of the gas transportation market. It does not account for institutions, agents or contractual relations. Hence, it offers a benchmark of a first-best utilization of the infrastructure. A mathematical description of the model is provided in the Appendix A. On the input side, the model is fed with assumptions on supply, demand and the infrastructure in place (with a high level of spatial detail, see Figure 3.3). Supply is injected into the pipeline grid at the respective system entry points (or via LNG vessels at the terminals), the network is used to distribute the gas spatially – with storage as an intertemporal connection allowing gas from one period to the other.

Demand assumptions are assigned to the respective nodes (natural gas sinks) were the commodity has to be transported to. Outputs include the utilization of all considered infrastructure assets in each time period, gas flows in the system and locational marginal supply costs. In modeling terms, these marginal supply costs are the dual variable on the energy balance constraint. They indicate how much it costs to supply an additional unit of gas to the respective node and can, hence, be interpreted as an indicator for the price in a competitive market (see Section 3.5.3). The model is a stochastic one (see Appendix A) which, in simultaneously computed scenarios, accounts for uncertainty with respect to temperatures (which influence household gas demand for space heating) and the reliability of supply (supply disruption from North Africa or not). Presented results in the following section refer to the median temperature case.[34]

Numerical assumptions refer to a simulation of the year 2011. The demand projection is based on Capros et al. (2010); the availability of supply volumes on EWI (2010a). The infrastructure available is the one in place in 2011 according to the database by GIE (2010). On the demand side, we do not include an elasticity of demand to enable

[34]The stochastic modeling reflects a number of scenarios. Interpreting the distribution of results is not relevant for the context of this paper. We therefore evaluate the median demand scenario which can be interpreted as the expected value given the temperature uncertainty.

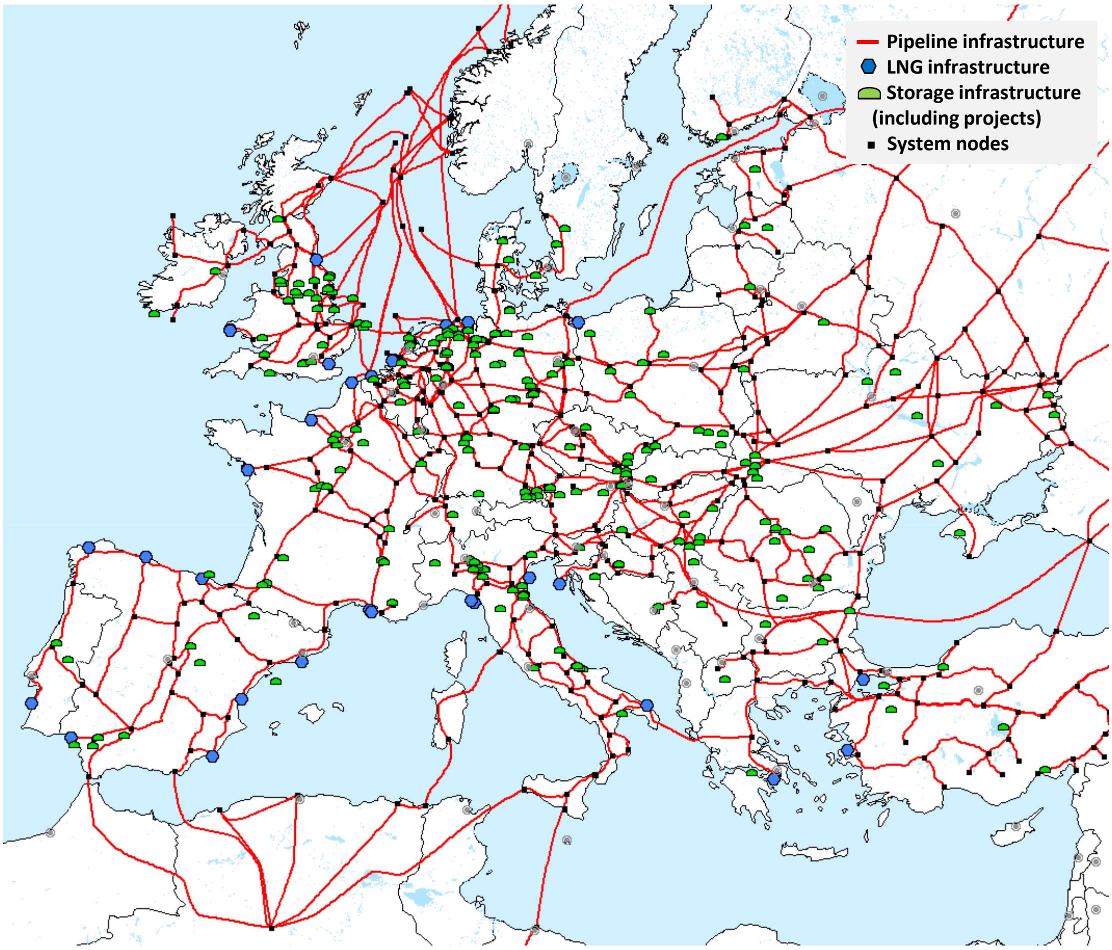


Figure 3.3: Modeled infrastructure elements in Europe

the identification of all supply short-falls. From a modeling perspective, we include a threshold price of 55 EUR/MBtu at which demand is reduced (based on the value of lost load according to UKERC, 2009). Hence, the model always aims to supply consumers with natural gas up to this (prohibitively high) marginal cost of gas provision. If that is not possible, demand is curtailed and the price indicator in the model simulations jumps to around 55 EUR/MBtu (which equals around 180 EUR/MWh).

We investigate nine scenarios which differ with respect to the affected country and the duration of the disruption. Regarding the supplier countries, pipeline export disruptions from Libya, from Algeria or from both countries are varied. The duration and timing of the crisis is modified for 8 months in summer (March to October as in Libya in 2011), for 8 months in winter (September to April) and for one whole year. The specification of these scenarios is listed in Table 3.2; additionally a Reference scenario (Sc.0) without any pipeline supply disruption is modeled as a benchmark for comparisons.

As mentioned in Section 3.3, we do not explicitly consider the effects of the disruptions to the global LNG market. These might arise as production stops in North

TABLE 3.2: Scenarios

Affected time / country	Libya	Algeria	Libya & Algeria
March to October	Sc.1a Libya summer	Sc.2a Algeria summer	Sc.3a Maghreb summer
September to April	Sc.1b Libya winter	Sc.2b Algeria winter	Sc.3b Maghreb winter
one year starting in March	Sc.1c Libya 1year	Sc.2c Algeria 1year	Sc.3c Maghreb 1year

Sc.0: Reference scenario without any disruption.

Africa would also affect the region's LNG exports (from Algeria and Egypt). However, in today's large and liquid LNG market, we presume such volumes could be substituted by LNG imports from other countries such as Qatar, Nigeria and Trinidad and Tobago. While there might be a few concerns in very short-term (the time it takes to organize diversions and physically get them to Europe), this cannot expected to be the case in the long term: Algeria makes up only 6.4 percent of the global LNG market of 298 bcm in 2010 (BP, 2011).

3.5 Results

The aforementioned scenarios are simulated with the model and analyzed with respect to the impact of the supply disruptions. Thereby, we focus on consequences to consumers in term of wholesale price effects and supply cut-offs. In addition, the gas market's reaction, i.e. how volumes are replaced, is evaluated.

3.5.1 Diversion of gas flows

In a competitive gas market, price signals indicate supply shortfalls. If the disruption of imports causes a deficit of natural gas in one region, the wholesale price in that region would increase and attract additional gas shipments from other regions.

Such gas market reactions could, for instance, be observed when Ukraine transits from Russia were interrupted in 2009 (Lochner, 2011b) or during the Libyan civil war and export disruption in the summer of 2011 (see Section 3.3). If the Libyan supply disruption would extend into high-demand winter, such gas flow diversions would need to intensify; the same holds true if the larger supplier Algeria were affected. The average daily flow diversions for the Algerian summer and winter disruptions (Scenarios 2a and 2b) and a Libyan disruption into winter (Sc. 1c) are displayed in Table 3.3.

Three findings become obvious concerning security of natural gas supplies to Italy in these scenarios. First, the compensation of an Algerian gas supply shortfall in summer (Sc.2a) is compensated similar to the Libyan shortfall of 2011: The majority of additional volumes comes via the TAG pipeline from Austria. As more natural gas from Algeria needs to be replaced (as was the case from Libya), additional volumes come via Switzerland and further LNG cargoes are landed in Italy. Second, this rise of imports

Table 3.3: Compensation of shortfalls of Algerian or Libyan supplies to Italy

Source of gas	Sc.1b Libya winter		Sc.2a Algeria summer		Sc.2b Algeria winter	
TAG (Austria)	+1.4	(+1%)	+33.7	(+56%)	+1.5	(+1%)
Transitgas (Switzerland)	+13.2	(+269%)	+19.9	(+302%)	+39.9	(+813%)
Gorizia (border Slovenia)	+0.1	(+16%)	+0.9		+3.1	(+358%)
Transmed (Algeria)	+0.7	(+1%)	-81.4	(-100%)	-89.7	(-100%)
Greenstream (Libya)	-16.3	(-100%)	+6.8	(+45%)	+5.7	(+35%)
LNG imports	+0.8	(+3%)	+16.3	(+115%)	+2.0	(+7%)
Storage Balance	0.0		-4.1	(-11%)	-23.9	(-35%)
Italian Production	0.0		0.0		0.0	
Demand Curtailment	0.0		0.0		+14.3	

Difference to Sc.0 Reference in million cubic meter (mcm)/day.
Please note that no percentage values are provided, when values are zero in Sc.0 Reference.

of Russian gas via the Transgas-TAG route via Slovakia and Austria in summer in Scenario 2a, which helped to reduce the deficit of the Libyan supply disruption in 2011 (see Section 3.3), may not be possible in winter (Sc.1b and Sc.2b). Export and transit pipelines for Russian gas are higher utilized in winter for supplies to other European countries. The Transgas(-TAG) route also supplies the Czech Republic, Austria, Southern Germany and France. Hence, there is not sufficient capacity for increasing flows to Italy. Instead, other gas sources and routes need to be tapped in order to supply Italy in winter. Third, this effect is largely compensated by increases in the flows via Switzerland to Italy. This route (from Germany) via Switzerland, thereby, usually transports Norwegian and Dutch gas to Italy. As in the case of Russian import pipelines, natural gas production facilities in these countries are usually highly utilized in winter making output increases difficult. However, additional volumes can be brought into the Swiss and German markets for supply to Italy. These include LNG imported in the Netherlands, France or the UK. As of the winter 2011/2012, the Nord Stream pipeline as a new route also enables the delivery of Russian gas directly to Germany. Although these volumes are unlikely to be transported all the way through Germany and Switzerland to Italy, they improve the supply situation in Germany and free up additional volumes of Norwegian and Dutch gas for transport to Italy. Thus, in high-demand winter, only limited additional volumes can be brought into Italy via Austria in case of a supply disruption from North Africa. The route via Switzerland offers some free capacities, LNG imports in Northwestern Europe and Russian gas deliveries via Nord Stream into Germany can increase the availability of alternative supplies. Nevertheless, not all consumers in Italy can be supplied at all times and some demand curtailments is necessary if Algerian exports cease for a prolonged time period in winter (see also Section 3.5.2).

For the other country receiving pipeline gas from North Africa, Spain, demand curtailment is not necessary at any point due to the sufficient LNG import capacities, provided that LNG cargoes can be contracted (see Table 3.4). We assume that the global LNG market is sufficiently well supplied in order to provide additional LNG cargoes. In the Libya supply disruption (Sc.1a-1c), effects to the country are limited: Some additional LNG is imported and transported to France (especially in winter). These volumes compensate France for the aforementioned diversions of Russian gas to Italy in this case. However, this effect is very small. When Algerian pipeline exports are disrupted, either in summer, in winter or for one year, the missing volumes of about 56 mcm per day[35] are entirely compensated by additional LNG imports. This is possible as the country has sufficient LNG import capacities. In fact, as the Algeria disruption implies shortages of pipeline gas in Western and Central Europe, Spanish exports to France actually rise, especially in winter. As in Scenarios 1a-c, LNG import capacities in Spain can contribute to supplying additional gas volumes to other countries in the North, i.e. France. Significant volumes are then also diverted from France towards Italy (see previous paragraph).

Table 3.4: Trade balance Iberian Peninsula across scenarios

Scenario [all values in mcm/day]	Imports from Algeria	LNG	Exports to France
Sc.0 Reference	56.2	65.1	7.0
Difference to Reference:			
Sc.1a Libya summer	+0.1	-0.1	0.0
Sc.1b Libya winter	+0.7	0.0	+0.7
Sc.1c Libya 1year	+0.7	-0.2	+0.5
Sc.2a Algeria summer	-56.9	+59.0	+2.2
Sc.2b Algeria winter	-55.6	+55.8	+0.2
Sc.2c Algeria 1year	-56.2	+58.6	+2.6
Sc.3a Maghreb summer	-56.9	+63.5	+6.7
Sc.3b Maghreb winter	-55.6	+55.8	+0.2
Sc.3c Maghreb 1year	-56.2	+61.6	+5.5

This effect further increases if pipeline exports from the whole Maghreb region come to a stop. Then, LNG imports increase by up to 63 mcm/day for further exports via France to the other regions affected by shortages from Maghrebian supply. Demand curtailment in Spain is not necessary at any point because of sufficient LNG import capacities.

Figure 3.4[36] displays the diversion of gas flows for this extreme scenario (Sc.3c) of no pipeline exports from the Maghreb region in a whole year. Generally, the illustration in Figure 3.4 confirms the previous observations in the different scenarios, which are more pronounced when total exports from the region stop for one year: The total net-export from Spain to France increases by 2.2 bcm. In Italy, 12 and 16 bcm are additionally imported via Austria/Slovenia and Switzerland respectively. The additional LNG imports

[35] Please note that the year 2011/2012 is the basis of our simulation, i.e. the Reference parameterization includes the new Medgaz pipeline from Algeria to Southern Spain.

[36] The pipelines with increasing and decreasing gas flows of more than 1 bcm/year are visualized in different colors and LNG terminals are colored where imports rise. Pipelines with only small changes in gas flows are in a transparent color.

in Italy can only amount to 2.9 bcm due to capacity restrictions. The gas delivered via Austria is largely Russian gas. The volumes that are supplied via Switzerland are additional LNG volumes imported in the Netherlands, France and the UK. Other changes in flows allow these volumes to get to Italy: Interconnector flows from the UK via Belgium to Germany increase while flows in the other direction (Norwegian and Dutch gas to the UK) decrease. Hence, more gas is available in Germany for transports south. In addition, gas from French LNG import terminals is transported to Switzerland.

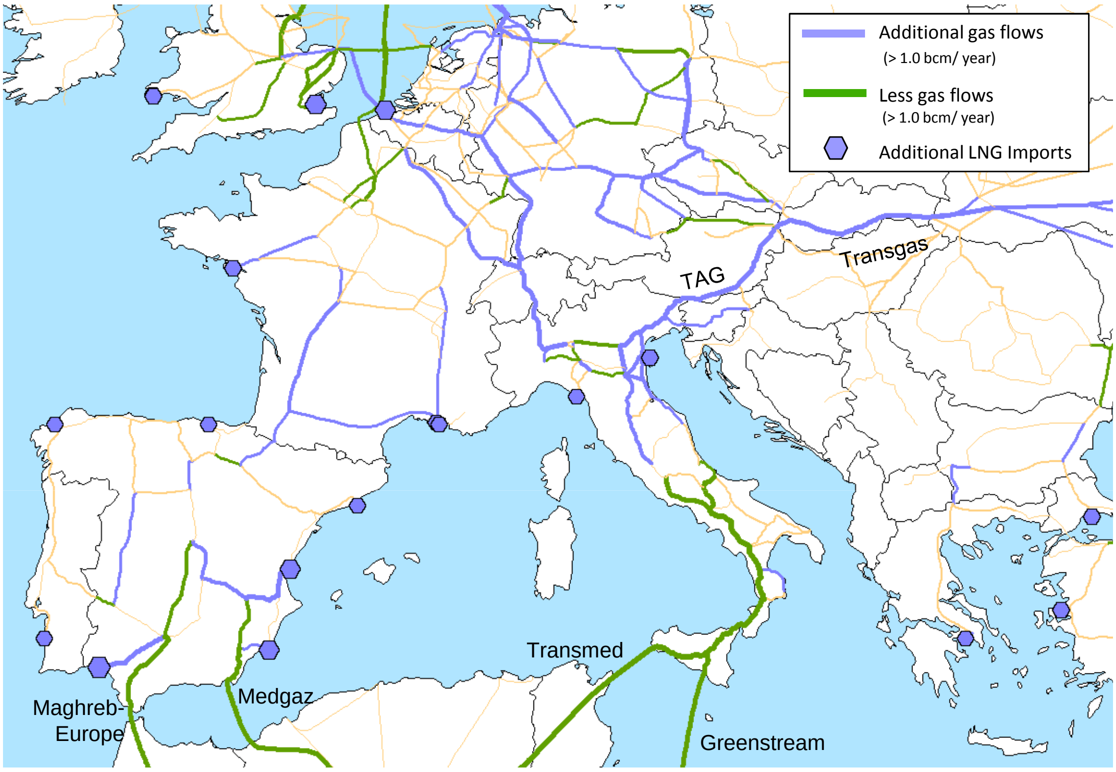


Figure 3.4: Gas flow changes Maghreb 1 year disruption vs. Reference Scenario

As the results on gas flows in this subsection have shown, the events in Southern Europe have pronounced impacts on gas flows over most of Central and Western Europe. The applied model helps to understand these interdependencies and can contribute to improving concepts dealing with the mitigation of consequences from supply crisis. Nevertheless, as the discussion in the next section shows, severe supply disruptions, for instance from Algeria, can not be resolved with gas flow diversions alone. In this case, consequences to gas consumers are unavoidable.

3.5.2 Demand curtailment

The most severe consequence to consumers arises from demand curtailment if price inelastic demand exceeds supply. The model was programmed to first reduce industrial gas consumption, so it would do so in Switzerland before, for instance, reducing supply to Italian households. Table 3.5 shows how much consumption cannot be met by supply in the disruption scenarios. The scenarios which reflect a disruption of supplies from Libya only (Sc.1a-c) are not listed in Table 3.5 as no demand curtailments take place. This reflects the observations from reality. Supply to consumers was secure at all times in summer (Section 3.3) and the observable but moderate price reactions for the winter futures did not indicate that the situation may become very problematic when demand is higher[37].

TABLE 3.5: Demand curtailment in disruption scenarios

Country [values in mcm]	Demand in 2011	Sc.2b Algeria winter	Sc.2c Algeria 1year	Sc.3b Maghreb winter	Sc.3c Maghreb 1year
Italy	80,424	726	1,236	3,900	4,978
Switzerland	3,420	78	118	527	744
Spain	37,045	0	0	0	0
Slovenia	1,096	16	19	91	115
Croatia	3,471	52	60	337	410

The situation is different in the case of an Algerian disruption. While such a scenario could be compensated in summer months - as discussed in the previous section, there are sufficient excess capacities on the Russian import route and demand is lower in summer - this is not possible in winter. As shown in Table 3.3, spare capacity on the TAG route via Austria only allows minimal supply increases. Similarly, LNG import terminals operate close to the capacity restriction according to our simulation enabling supply increases of only about 7 percent. The additional volumes procured in Northwestern Europe may then not be sufficient in winter. In the simulation with temperature-dependent, stochastic demand, the expected demand curtailment necessary in Italy is then 726 mcm (Sc.2b) over the whole winter (November to February). However, not only Italy is affected. The market is very well integrated with the Swiss natural gas market, so price spikes in Italy due to demand-supply gaps result in price spikes in Switzerland as a result of the efficient market hypothesis. Hence, demand curtailment might also take place there. The same holds true for Slovenia and Croatia, which are well integrated with Italy physically and which receive the same supplies via the TAG route (which might be delivered to Italy in the crisis). Total expected demand curtailment outside Italy amounts to another 146 mcm over the whole winter in Scenario 2b. This value even rises to almost 200 mcm if Algerian supplies stop for a whole year (Sc.2c).

In the event of a Maghrebian crisis affecting both Algerian and Libya, demand curtailment cannot be avoided, even if the winter turns out to be a rather warm one.

[37]Future prices for the 2011/2012 winter in Italy were 21 percent higher than the average of the NBP, TTF, Zeebrugge prices as it was unclear at the time whether supplies would have resumed by then (ICIS Heren European Gas Markets EGM 18.14 28 July 2011, page 13). In the previous winter (2010/2011), there was no persistent difference between prices at the different European hubs.

Expected demand curtailment in Italy is 3.9 bcm if the crisis only affects the winter. If it lasted through summer, so that storage facilities cannot be properly filled before the winter, the expected value for Italy is 1 bcm higher. In all affected countries, expected demand curtailment exceeds 6 bcm according to the model simulations.

Table 3.5, however, also shows the aforementioned comfortable situation of Spain. Sufficient redundant capacities for LNG deliveries ensure that demand cut-offs are not necessary, even in a prolonged crisis in the Maghreb region. However, consequences to consumers do not need to be limited to demand curtailment. Another effect potentially affecting all of Europe are price spikes.

3.5.3 Price effects

In our model, we measure price increases as the change in marginal supply costs. In a competitive market, marginal costs are identical to prices. Nevertheless, as the full price-demand curve is unknown (and we use inelastic demand), these marginal supply costs should only be used as indicators for wholesale prices. In our network, such a locational marginal prices (or nodal price, see Lochner, 2011a)), is calculated for each point in the system (node). For the evaluations in this section, we select representative ones for the directly affected countries Italy and Spain. Additionally, to gain a perspective on the price effects in the rest of Europe, the price estimators for the UK and Germany are also discussed. It needs to be stressed that the focus of our analysis is on pipeline supply disruptions. Hence, it is assumed that neither potential Algerian LNG export disruptions nor the increase in European LNG demand in the scenarios have an impact on the global LNG price. While this is a simplifying assumption, it helps to illustrate the effects of the dependencies arising from pipeline supplies alone. While price effects may, thus, be underestimated, it becomes clear what the effects on top of any LNG price effect – which is beyond the scope of this article to measure – would be. The price increases on the days with the highest prices in the respective scenario relative to the prices in the Reference scenario are illustrated in Figure 3.5 (please note the log-scale).

Regarding the supply disruption from Libya, our model confirms the insignificant price effect observed in reality: Only when the supply disruption lasts for one year, locational marginal supply costs exceed the ones in the Reference scenario by about 25 percent in Italy. Due to the high level of physical market integration in the European gas market, the same increases can also be observed for all the other countries in Figure 3.5. This is a consequence of sufficient transport capacities being in place and the perfect competition assumption: Arbitrage causes prices to increase in Spain, Germany and the UK as well.

The situation is significantly different for a supply disruption from Algeria. Again, if it were to happen only in summer (and end by October), marginal supply costs would only increase mildly by about 5 percent in all countries. However, supply disruptions in winter or for the duration of one year, which would lead to demand curtailment for consumers in the countries listed in Table 3.5, would also cause price spikes in Italy. The marginal supply cost peak in the modeling environment is thereby determined by the assumed demand curtailment price (value of lost load assumption). Interestingly, the price spike in Italy also translates to price spikes in Germany - but not the UK and Spain. In Germany, demand curtailment is not necessary and the transport pipeline to Switzerland and Italy would be congested most of the time due to the high import demand in Southern Europe. However, when the line is not congested, there is a significant demand for transports from Germany towards Italy, so arbitrage, again, leads to an albeit smaller price spike in Germany and Central Europe. This causes significant congestion from the LNG terminals in Spain and Northwestern Europe (where additional imports take place, see Figure 3.4) towards Germany. All pipelines into Germany would be heavily congested. This congestion prohibits arbitrage and price formation takes place separately: Price formation in Germany and Italy is impacted by demand curtailment in Southern Europe. The one in the West and Northwest is not and LNG becomes the price setting supplier. The situation for supply disruptions from the whole Maghreb region is almost identical to the Algeria only case.

Hence, we can conclude that price effects in a rather small crisis (Libya) are limited. If they happen in a prolonged disruption, sufficient infrastructure and arbitrage cause them to spread across Europe. In severe disruptions in winter, demand curtailment causes price spikes and congestion. Congestion causes separate price formation in the different European markets with Central Europe being more effected by events in the South than Northwestern Europe or the Iberian Peninsula. The latter, in general, is well protected from price spikes if the global LNG market is sufficiently well supplied.

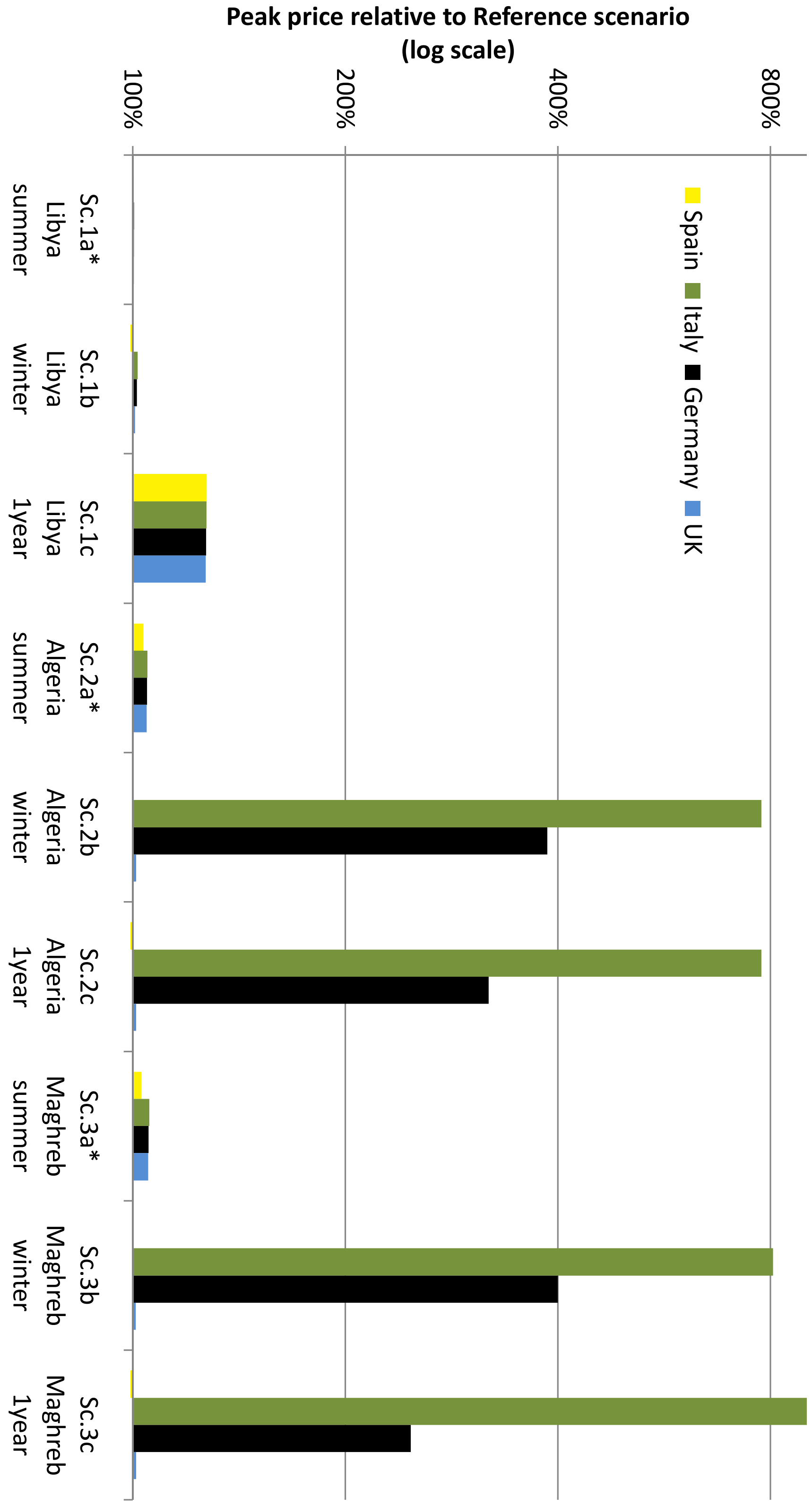


FIGURE 3.5: Modeled price effects in selected countries from pipeline disruptions

3.6 Conclusion

The natural gas export disruptions during the civil unrest in Libya in 2011 demonstrated a potential threat to security of supply neglected in most analyses of European security of natural gas supply. A civil war may last for a prolonged time period and economic interests regarding current and potential future gas sales take a back seat. Hence, exports may be disrupted for several months or even longer. Especially for grid-bound pipeline exports, the transport infrastructure usually does not exhibit sufficient redundancies to compensate disruptions. Therefore, assessments of security of supply as the ones obligatory for EU member states need to take this potential risk into account. Measuring the arising risks or the probability of a disruption is difficult. The World Bank Governance Indicator for political stability presented in this paper ranked Libya to be relatively stable. However, the Voice and Accountability Index exhibits almost the worst value for the ability of citizens to participate in politics. The fact that a civil uprising happened, and that two other large exporters to Europe (Algeria and Russia) exhibit a potential for civil unrests (according to both World Bank Governance Indicators), is not only a cause for concern but also illustrates the importance of taking political stability into account.

In our model-based analysis for North Africa, we find that the threat from civil unrest in Algeria would be much larger than the minor consequences felt in Europe from the Libyan supply disruption. While most missing volumes in the summer of 2011 could be replaced by Russian gas, this is no longer possible in high-demand winter when Russian gas is already consumed elsewhere. The main compensation of the missing volumes would then have to come from LNG imports into terminals all over Europe and especially in Northwestern Europe from where these volumes would be routed to Italy via Germany and Switzerland. Nevertheless, a globally well supplied LNG market would not be able to compensate all missing imports from Algeria due to infrastructure bottlenecks between the import terminals in Northwestern Europe and Southern Europe. Some demand curtailment to consumers in Italy and potentially some neighboring countries would be unavoidable in winter; price effects are also felt in Central Europe. The other larger importer of Algerian gas, Spain, is, however, in a much better position. Sufficient redundant import capacities, especially on the LNG side, ensure a steady supply of gas to the market under the assumption that the LNG market is sufficiently flexible.

Part II

Consumer Choices, Energy Efficiency and Greenhouse Gas Abatement Policies

Chapter 4

Greenhouse gas abatement curves of the residential heating market – a microeconomic approach[38]

In this paper, we develop a microeconomic approach to deduce greenhouse gas abatement cost curves of the residential heating sector. By accounting for household behavior, we find that welfare-based abatement costs are generally higher than pure technical equipment costs. Our results are based on a microsimulation of private households' investment decision for heating systems until 2030. The households' investment behavior in the simulation is derived from a discrete choice estimation which allows investigating the welfare costs of different abatement policies in terms of the compensating variation and the excess burden. We simulate greenhouse gas abatements and welfare costs of carbon taxes and subsidies on heating system investments until 2030 to deduce abatement curves. Given utility maximizing households, our results suggest a carbon tax to be the welfare efficient policy. Assuming behavioral misperceptions instead, a subsidy on investments might have lower marginal greenhouse gas abatement costs than a carbon tax.

4.1 Introduction and Background

The social costs of greenhouse gas emissions as a global externality are more and more spotlighted in the worldwide public discussion. Since the UNCED[39] in Rio de Janeiro 1992, but latest since the Stern Review (Stern, 2007) and the IPCC report on climate change in 2007 (IPCC, 2007), politicians, engineers, ecologists and economists argue about optimal strategies of greenhouse gas avoidance. Consequently, national objectives and policies for greenhouse gas abatement have been introduced in the last years. Besides the emissions produced by major polluters such as the energy sector, a significant part of

[38]The paper is a joint work of Harald Hecking and the author (see Dieckhöner and Hecking (2012)).
[39]United Nations Conference on Environment and Development

overall emissions stem from small emittents such as households. Hence, the achievement of reduction objectives strongly depends on the behavior of economic agents.
The heating sector is thereby a good example. In the discussion of greenhouse gas abatement, heat provision in residential buildings is often tagged the sleeping giant. Besides enhancing thermal insulation, the replacement of inefficient and carbon intense heating systems holds a huge potential of emission reduction. However, there is no easy wake-up call: the total greenhouse gas emissions in the residential sector is the aggregated result of millions of households' individual decisions on heating systems and building insulation. Thereby, each one faces different investment costs, habits, preferences and therefore motivation to reduce his building's greenhouse gas footprint. Subsidies and carbon taxes are two prominent policy measures to incentivize greenhouse gas reduction in the residential sector. However, either strategy imposes costs: not solely monetary for technical equipment, but also in terms of welfare losses due to tax and subsidy distortions. Thus, to quantify total social costs of emission reduction, our paper aims at deducing a welfare-based greenhouse gas abatement cost curve of the residential heating sector, thereby accounting for costs and households' behavior and preferences.

Several studies have already addressed pollution abatement curves based on welfare effects of environmental taxes using a general-equilibrium approach (Ballard and Medema, 1993, Bovenberg and Goulder, 1996). In addition to these studies on the macro level, among the analyses on the micro-level most studies are mainly technical thereby focusing on the technical equipment costs (Kavgic et al., 2010, Swan and Ugursal, 2009). One example of such technology-based approach is a recently published study by McKinsey & Company, Inc. (2009), which identifies significant energy savings with low costs for society. Huntington (2011) discusses the overestimation of the reduction potential in the McKinsey & Company, Inc. (2009) study, which results from assuming adoption rates of technologies of 100%. In an aggregated approach Huntington (2011) shows that accounting for the households' behavior and their reactions on policy measures would revise the greenhouse gas abatement curves downwards as well as by including policy costs. There are microeconomic analyses that investigate the impact of environmental policies: Tra (2010) evaluates the benefits of air quality improvements in a discrete choice locational equilibrium model that accounts for welfare impacts of policy interventions in a microeconomic context. However, to date there are few attempts to derive microeconomic greenhouse gas abatement curves that account for the behavior of economic agents. Our paper fills this gap.

In the light of current literature, our paper contributes to public economics, the analytical and the numerical literature in two ways: First, it extends earlier work by being the first paper to derive a greenhouse gas abatement cost curve based on household behavior and welfare losses on externalities in a microeconomic setting. We have chosen this approach because the abatement potential of many externalities depends on the behavior of microeconomic agents. Second, the paper investigates the impact of carbon taxes and subsidies numerically. Here we expand on the analytical work by developing a numerical microsimulation model based on an empirical discrete choice estimation. Microsimulation models are a useful tool to analyze the diffusion of technologies and the impact of environmental policies. Kazimi (1997) uses a microsimulation model to investigate the effects of vehicle price changes in emissions in the Los Angeles area. She applies a microsimulation model which – similar to our model DIscrHEat – also incorporates the results of a discrete choice estimation.

The use of the numerical model enables us to derive specific greenhouse gas abatement cost curves and analyze the welfare effects of different policies. Our paper thus combines the strengths of analytical and numerical approaches: in a stylized analytical model we present a microeconomic approach of how to derive a greenhouse gas abatement curve based on welfare measurement in discrete choice models. Our numerical model based on empirical household behavior allows to derive greenhouse gas abatement curves of specific policies and to explore their mechanisms in a more realistic setting.

To conduct our analysis, we choose Germany as exemplary case for two reasons: first, the insulation level of domestic buildings is already very high and further insulation is very cost-intense in terms of greenhouse gas abatement compared to the installation of new heating systems (Buildings Performance Institute Europe (BPIE), 2011, International Energy Agency (IEA), 2011). Second, since more than 90% of all residential buildings are heated decentrally, the households' individual heating system decisions have a strong impact on the total greenhouse gas emissions. Both aspects underline the importance to account for the household's decision behavior on investment in heating systems.[40]

We first derive analytically how the adoption of technologies takes place based on household behavior in a theoretical discrete choice framework.[41] We show how this diffusion process is affected by public policies and its impact on greenhouse gas abatement. The discrete choice approach further allows for the derivation of different welfare measures such as the compensating variation and excess burden (Diamond and McFadden, 1974, McFadden, 1999, Small and Rosen, 1981), which we use to derive welfare based greenhouse gas abatement curves. Second, given this setting, we develop DIscrHEat, an economic microsimulation model of the German heat market for the years 2010 to 2030. Its core idea is to simulate the households' decision behavior on a new heating system. In the current market for heating systems, we observe that the heating system decision is based not only on observable heating system costs, but as well on hidden factors such as non-observable costs and preferences. To account for both aspects, we

[40]Because greenhouse gas abatement costs for insulation measures are so high in Germany, for simplification, we exclude the households' decisions on thermal insulation from our analysis.

[41]See for Train (2003) for an overview of discrete choice approaches on which we base our framework.

choose a discrete choice model estimated with current domestic investments into heating systems and their respective observable costs. We then apply our simulation model to investigate the impact of different greenhouse gas abatement policies on newly installed heating systems and greenhouse gas abatement until 2030: e.g. a carbon tax increases the observable costs of carbon intense technologies, thereby c.p. reducing their installations and consequently carbon emissions. Applying the approach of Small and Rosen (1981) and McFadden (1999), we derive the welfare costs of policy measures in terms of excess burden in our numerical framework. From that we deduce welfare-based greenhouse gas abatement curves of the investigated policies, thereby accounting for household behavior.

Our results confirm the implications of Huntington's paper suggesting that welfare-based greenhouse gas abatement curves run above technical cost curves. Thus, accounting for the behavior of households and their reactions on policy measures implies greater costs for society than pure technical equipment costs. Second, despite a flat curve of marginal excess burden of greenhouse gas abatement, the marginal costs of public funds might increase very steeply getting closer to the peak of the Laffer curve. This indicates the limits on an implementable level of a carbon tax rate in reality. Third, our results suggest that in most cases a carbon tax causes less welfare losses than subsidies on technology investments. However, in case of behavioral misperceptions or credit barriers, subsidies on investments might be reasonable.

The paper is organized as follows: The next sections 4.2 and 4.3 provide a brief overview of previous research and presents the theoretical approach to the derivation of microeconomic greenhouse gas abatement cost curves. Section 4.4 describes the microsimulation model DIscrHEat and the different policy scenarios we consider. Section 4.5 presents our results, first, in Section 4.5.1 on the effects of the policies on greenhouse gas abatement and the diffusion of technologies. Second, Section 4.5.2 presents the welfare impacts of the different policies to derive greenhouse gas abatement cost curves in 4.5.3. Section 4.6 concludes.

4.2 Previous research

There are two strands of literature which are related to our paper. The first strand is on energy demand modeling in general. There are a variety of studies that model the energy demand of the private sector and that identify drivers of energy consumption and energy efficiency. Swan and Ugursal (2009) and Kavgic et al. (2010) give an overview of different bottom-up models and models to analyze residential energy consumption, i.e. mainly technology-based energy demand modeling approaches. These bottom-up models are based on extensive disaggregated data and components that influence energy demand on an individual detailed level. This model type is often applied to identify cost-efficient technology options for achieving certain greenhouse gas emission abatement targets. There are also a variety of top-down models that focus on rather macroeconomic relationships. These models use aggregated empirical data to investigate the interrelation of the energy sector and the economy as a whole by variables like GDP, income, temperature and prices of energy carriers. Mansur et al. (2008) analyze the impact of climate change on energy demand and welfare in the US applying a discrete-continuous model of fuel choice and energy consumption. They find a potential increase of American energy expenditures and welfare losses caused by temperature rise. Madlener (1996) provides an overview of the different time-series based methodologies applied to analyze residential energy demand. Rehdanz (2007) examines the determinants of household expenditures on space heating and hot water supply in Germany based on panel data and covers a number of socio-economic characteristics of households along with dwelling characteristics. Braun (2010) examines building, socio-economic and regional characteristics in a discrete choice model focusing on space heating technologies applied by households but not on the heating system choice in terms of new heating system installations. Michelsen and Madlener (2012) conduct a survey about heating system installations to analyze the influence of preferences about residential heating system specific attributes on the adoption decision in a discrete choice estimation.

The second strand of related literature focuses on numerical approaches to the deduction of greenhouse gas abatement costs. The literature on greenhouse gas abatement modeling can be categorized into general equilibrium modeling approaches and technical models. Bovenberg and Goulder (1996) develop an emission abatement curve based on marginal welfare costs in a general equilibrium setting. Nordhaus (2011) and Pearce (2003) determine different social damage costs of greenhouse gas. Morris et al. (2008) apply a general equilibrium model to compute marginal abatement costs and marginal welfare costs for different greenhouse gas prices. They argue that the marginal abatement costs in their model reflect the shadow prices on the greenhouse gas constraint on certain countries or sectors. This is interpretable as a price that would be obtained under an allowance market that developed under a cap and trade system. They come to the conclusion that these marginal abatement costs are not closely related to the marginal welfare costs. The marginal abatement costs of their model vary over countries and are sometimes above and sometimes below the marginal welfare costs and therefore they conclude that they should not be used to derive estimates of welfare change.

A recent study on greenhouse gas abatement curves on the micro-level has been published by McKinsey & Company, Inc. (2009) which establishes a cost-efficient greenhouse gas abatement curve for different energy efficiency measures. Huntington (2011) discusses the overestimation of the reduction potential in the McKinsey & Company, Inc. (2009) study. According to Huntington (2011), McKinsey & Company, Inc. (2009) neglect the real behavior of private households assuming adoption rates of technologies of 100%. In reality, a new technology might not be cost-efficient for everyone even if it is cost-efficient for the average consumer. In addition, the adoption and diffusion of technologies proceeds slowly in general. Huntington (2011) also mentions the exclusion of the households' reactions to the introduction of policy measures and the exclusion of policy costs in the McKinsey & Company, Inc. (2009) study. Introducing basic assumptions to these additional costs and impacts on the greenhouse gas abatement curve, Huntington (2011) revises the curve to highlight implications for policymakers if they base their decisions on a what he calls "out-of-pocket" technology based cost curve.

4.3 Theoretical approach

Energy efficiency and greenhouse gas abatement policies can have different impacts and purposes. They can either try to influence the number of low emission investments made by trying to incentivize the household to invest earlier or more often; or they try to make the household investing in less greenhouse-gas-intense technologies. We focus on the latter.

Diffusion process of technologies

We have different representative household categories n ($n \in \{1, ..., N\}$) that have to install a new greenhouse-gas-emitting technology j ($j \in$ {1,...,J}) as the previous system has to be replaced due to break-down.[42] Each alternative technology causes different amounts of greenhouse gas emissions. The probability $P_{n,j}$ that a representative household n chooses a technology j is a function of the total annual system costs $c_{n,j}$[43] and some household specific characteristics z_n:

$$P_{n,j} = f(c_{n,j}, z_n) \tag{4.1}$$

The total annual system costs $c_{n,j}$ are a function of the investment costs $i_{n,j}$, the energy consumption $e_{n,j}$, the energy price p_j and two policy measures that we model: Carbon taxes T_j, which are derived from a Pigovian carbon tax τ[44], and subsidies on the

[42]This is a realistic assumption for heating systems as shown in IWU / BEI (2010), but also holds for expensive building insulation or other investments into energy efficiency.

[43]We do not consider the impact of policy measures on the number of investments, but only on the structure of heating system choices. Therefore, the total annual system costs are relevant and not a differentiation between investment costs and future energy savings. Based on IWU / BEI (2010), we argue that households only change their heating system when it is broken. Finding out reasons for this behavior is open for further research.

[44]In our heat market microsimulation model, the Pigovian carbon tax τ times a conversion factor CF_j, times the total heat demand TD_n of a household and divided by the annual use efficiency of a heating

investment S_j:

$$c_{n,j} = f(i_{n,j}, e_{n,j}, p_j, T_j, S_j) \tag{4.2}$$

Based on the alternative-specific conditional logit model, first presented by McFadden (1976, 1974), the indirect utility $U_{n,j}$ of household n that chooses between different technologies j is given by:

$$U_{n,j} = V_{n,j} + \epsilon_{n,j} \tag{4.3}$$

$V_{n,j}$ is the observable utility of the household whereas $\epsilon_{n,j}$ captures further factors that influence the utility but are not in $V_{n,j}$.

$V_{n,j}$ is:

$$V_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_j z_n \tag{4.4}$$

with α_j being alternative-specific constants that give an extra value to each technology. β represents the negative total annual system cost impact and γ_j is a vector of technology-specific impact on the household characteristics. We get:

$$U_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_j z_n + \epsilon_{n,j} \tag{4.5}$$

The choice of a household can be described as a dummy variable $y_{n,j}$:

$$y_{n,j} = \begin{cases} 1, \text{if} \quad U_{n,j} > U_{n,i} \quad \forall i \neq j \\ 0, \text{else} \end{cases} \tag{4.6}$$

system AE_j results in T_j. CF_j indicates the amount of greenhouse gas emissions per kilowatt hour of the different energy carriers.

The choice probability that determines the diffusion process of a technology is defined as:

$$\begin{aligned} P_{n,j} &= Prob(y_{n,j} = 1) = Prob(U_{n,j} - U_{n,i} > 0, \quad \forall i \neq j) \\ &= Prob(\epsilon_{n,i} - \epsilon_{n,j} < V_{n,j} - V_{n,i}, \quad \forall i \neq j) \end{aligned} \tag{4.7}$$

where $\epsilon_{n,i}, \epsilon_{n,j} \sim \textit{iid extreme value}, \quad \epsilon_{n,i} - \epsilon_{n,j}$ has a logistic distribution[45] and only the difference between two utility levels has an impact on the choice probability and not the absolute utility level.
The probability that household n chooses alternative j is[46]:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} = \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_j z_n}}{\sum_i e^{\alpha_i + \beta c_{n,i} + \gamma_i z_n}} \tag{4.8}$$

This determines the proportion of installations of technology j among the new systems chosen by household type n.

Own cost changes and those of alternative heating systems affect the choice probabilities of a heating system. These cost impacts on the choice probability of a heating system can be described in terms of elasticities. The elasticity of a household's choice probability with respect to heating costs of the system j that he chooses is given by:

$$\frac{\partial P_{n,j}}{\partial c_{n,j}} \frac{c_{n,j}}{P_{n,j}} = \beta(1 - P_{n,j})c_{n,j} < 0 \tag{4.9}$$

which is negative because of the negative cost impact $\beta < 0$.

The elasticity of a household's choice probability for j with respect to heating costs of an alternative system i is given by:

$$\frac{\partial P_{n,j}}{\partial c_{n,i}} \frac{c_{n,i}}{P_{n,j}} = -\beta P_{n,i} c_{n,i} > 0 \tag{4.10}$$

with $i \neq j$.

[45]The logit model with its elasticities are a standard approach to model the diffusion of technologies. See for instance Geroski (2000).

[46]For detailed mathematical derivations and explanations of logit and conditional logit models see McFadden (1974) and Train (2003).

The effects of the model are ceteris paribus and allow for the computation of own and cross cost elasticities on the diffusion rates of the different technologies, i.e. the choice probabilities of an alternative, keeping all values fixed. The changes in the total greenhouse gas emission level are determined by the diffusion process.

The elasticities account for the cost effect β on the technology choice. An advantage of the inclusion of $P_{n,j}$ in the elasticities is that changes of $P_{n,j}$ depend on the current level of $P_{n,j}$.[47] The restricted substitution pattern of the choice probability holds on the individual level and is much more flexible on the aggregated level over all household types. On the aggregated level, the substitution pattern also accounts for the heterogeneity of households.

Welfare effects of different policies

The aggregated net utility in our model over all households that change their technology and install a new one in period (year) $y \in 2010, ..., 2030$ is defined as follows:

$$U^{aggr.} = nC + \sum_{n=1,j=1}^{N,J} y_{n,j} V_{n,j} \tag{4.11}$$

C is a constant positive utility level that is assumed to be the same for all household types n and indicates the minimum utility of a new technology. $nC \geq \sum_{n=1,j=1}^{N,J} y_{n,j} V_{n,j}$ by definition because a new technology needs to be installed when the old one is broken and thus is assumed to imply a higher utility than costs. The utility $V_{n,j}$ is negative because it indicates the cost impact of the essential new systems on the aggregated utility. As for the welfare analysis only the differences between two aggregated utilities with different policies are of importance, we can neglect the constant C from now on.

When we introduce a carbon tax which increases the costs of greenhouse-gas-intense

[47] Analyzing the development of the German heat market over the last 60 years indicates that this is a realistic assumption and that changes resulting from the cost advantages of new heating systems take place only inertially and based on the number of heating systems of that type that are already installed (BDH, 2010), (IWU / BEI, 2010). The inertia of the heating system stock results from the long life spans of the heating systems and the fact that heaters are only exchanged when they are broken. Adoption rates of heating systems that already have a large market share are much higher. The proportional substitution pattern of conditional logit models is often criticized. In the case of the homogeneous good heat, it seems however to be appropriate. See for instance Train (2003) for a detailed discussion of the substitution patterns of logit models.

systems to incentivize investments into the lower-emission technologies, the relative annual costs of the different heating systems change. This leads to different investment decisions. The introduction of such policies, which are not lump-sum, cause welfare losses even if the tax revenues are redistributed lump-sum. The households that have to modernize their systems are elastic but not completely elastic as presented in the previous section. For simplification, we assume that the supply function is completely elastic.[48] Then, the welfare loss, i.e. the excess burden, is the difference between the tax revenue and the aggregated compensating variation over all households. The compensated variation of the introduction of a tax indicates how much the government needs to pay the households to compensate the resulting price increase and keep their original utility level. For a subsidy, the compensating variation reflects the willingness to pay of the households to keep the subsidy. Therefore, for both cases, the tax revenue, which could be redistributed to the respective households and the subsidy expenditure of the government which could be collected from consumers via a lump-sum tax, must be compared with the respective compensating variation.

The compensating variation CV_n is determined for each period y by an equation based on McFadden (1999) which is a generalization of the compensating variation of logit models introduced by Small and Rosen (1981).[49]

To determine the difference in consumer surpluses of the two scenarios with and without policy measures, we get:

$$\int_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} = \left[\ln \sum_j \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_j z_n}}{-\beta} \right]_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} \tag{4.12}$$

[48]This assumptions leads to an underestimation of the excess burden. It means that the investment costs of heating systems and energy prices are not influenced by demand changes of the residential heating sector. We assume that the residential sector demand is too small to have an impact on energy prices. The producers of heating systems in Germany sell all types of heaters. Thus, they do not depend on a specific system and would adapt their product composition according to the changing demand conditions.

[49]Tra (2010) provides an application of this discrete choice equilibrium framework to the valuation of environmental changes.

The amount of money that is needed to keep the original utility level and compensate for the additional costs CV_n caused of the policy measures is then computed as follows:

$$\ln \sum_j \frac{e^{\alpha_j + \beta(c_{n,j}^{\text{policy}} - CV_n) + \gamma_j z_n}}{-\beta} = \ln \sum_j \frac{e^{\alpha_j + \beta c_{n,j}^{\text{no policy}} + \gamma_j z_n}}{-\beta} \tag{4.13}$$

where $c_{n,j}^{\text{policy}}$ indicates the respective total annual heating costs of household n with heating system j including a tax or subsidy and $c_{n,j}^{\text{no policy}}$ describes these costs without any policy measures.

To compute the compensating variation per dwelling type n the formula by Small and Rosen (1981) can be applied[50]:

$$\begin{aligned} CV_n &= \\ &\frac{1}{-\beta} \quad \left[ln \textstyle\sum_j exp(V_{n,j}^{\text{policy}}) - ln \textstyle\sum_j exp(V_{n,j}^{\text{no policy}}) \right] \end{aligned} \tag{4.14}$$

We have to account for the number of households belonging to the same group with the same building characteristics (H_n) which have to install a new heating system. Thus, the aggregated compensating variation is:

$$CV = \sum_{n=1}^{N} H_n CV_n \tag{4.15}$$

Finally, we define the excess burden EB for each period y following Diamond and McFadden (1974):

$$EB^{tax} = CV^{tax} - T \tag{4.16}$$

[50]See the Appendix for a more detailed derivation. This approach assumes a constant marginal utility of income denoted by $\frac{1}{\beta}$. Torres et al. (2011) investigate the sensitivity of mistaken assumptions about the marginal utility of income and their impacts on the welfare measures in Monte Carlo experiments. They find that mistaken assumptions about the marginal utility of income can amplify misspecification of the utility function. However, throughout all misspecification cases analyzed, they find an underestimation of the compensating variation (referred to as 'compensating surplus' in their paper). Thus, the analysis conducted in this paper assuming a constant marginal utility of income is conservative and might even underestimate the compensating variation (and excess burden).

where T indicates the overall tax income in this period with:

$$T = \sum_{n \in N, j \in J} H_n P_{n,j} T_j \tag{4.17}$$

We consider a carbon tax T_j which equals a carbon tax τ in Euro per tons greenhouse-gas-equivalent times a conversion factor that converts τ into T_j accounting for the greenhouse gas emissions of the different systems.

The excess burden of a subsidy is determined similarly:

$$EB^{sub} = S - CV^{sub} \tag{4.18}$$

with

$$S = \sum_{n \in N, j \in J} H_n P_{n,j} S_j \tag{4.19}$$

If we assume behavioral misperception to be the cause for the household choices, the compensating variation based on utility might not be an adequate measure.[51] Therefore, we also compute total heating system cost differences that result from the introduction of greenhouse gas abatement policies. We take the total annual heating costs over all households and heating systems:

$$c = \sum_{n \in N, j \in J} H_n P_{n,j} c_{n,j} \tag{4.20}$$

In case of a carbon tax, the total heating system cost differences (CD) are the following:

$$CD^{tax} = (c^{\text{policy}} - c^{\text{no policy}}) - T \tag{4.21}$$

Again, we assume that the tax income is redistributed lump-sum. For a subsidy we get:

$$CD^{sub} = S - (c^{\text{no policy}} - c^{\text{policy}}) \tag{4.22}$$

[51] The utility maximizing approach to model the diffusion process is still appropriate as long as the misperception and household preferences cannot be affected by public policies. However, in this case the evaluation of the compensating variation does not reflect real consumer losses and society's costs.

Microeconomic greenhouse gas abatement curve

The excess burden EB changes with different tax rates T_j (equivalently for changes in the subsidy levels S_j). dEB covers the changes in welfare losses of an additional unit increase of the tax rate (or subsidy):

$$dEB^{\text{tax}} = \sum_{n \in N, j \in J} \left[\left(\underbrace{\frac{\partial EB}{\partial CV_n}}_{(+)} \underbrace{\frac{\partial CV_n}{\partial V_{n,j}^{\text{policy}}}}_{(-)} \underbrace{\frac{\partial V_{n,j}^{\text{policy}}}{\partial c_{n,j}}}_{(-)} \underbrace{\frac{\partial c_{n,j}}{\partial T_j}}_{(+)} - \underbrace{\frac{\partial T}{\partial T_j}}_{(+/-)} \right) dT_j \right] \tag{4.23}$$

The signs in brackets below the derivatives indicate their direction such that (+) indicates a positive and (−) a negative derivative.

$$\frac{\partial T}{\partial T_j} = \sum_{n \in N} \left[\underbrace{H_n P_{n,j}}_{(+)} + \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}} \frac{\partial c_{n,j}}{\partial T_j} H_n T_j}_{(-)} \right] \tag{4.24}$$

The first part of the equation indicates the positive impact of the increasing tax rate on the total tax income T whereas the second part displays the negative impact of the decreasing tax base. Hence, $\frac{\partial T}{\partial T_j}$ is positive for the increasing part of the Laffer curve and negative for the decreasing part.
$\frac{\partial T}{\partial T_j} < \frac{\partial EB}{\partial CV_n} \frac{\partial CV_n}{\partial V_{n,j}^{\text{policy}}} \frac{\partial V_{n,j}^{\text{policy}}}{\partial c_{n,j}} \frac{\partial c_{n,j}}{\partial T_j}$ (see Auerbach and Feldstein (1985)). Thus, $dEB > 0$ when the tax rates are increasing ($dT_j > 0$).

For the change of total subsidy spending in S_j, we would have:

$$\frac{\partial S}{\partial S_j} = \sum_{n \in N} \left[\underbrace{H_n P_{n,j}}_{(+)} + \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}} \frac{\partial c_{n,j}}{\partial S_j} H_n S_j}_{(+)} \right] \tag{4.25}$$

as the subsidy increases the costs decrease ($\frac{\partial c_{n,j}}{\partial S_j} < 0$) and the installation rate $P_{n,j}$ of the technology j increases through decreasing costs. Adapting equation 4.23 accounting for equation 4.18 we would get $dEB^{\text{sub}} > 0$ for $dS_j > 0$.

In the case of behavioral misperceptions, the changes in the total annual heating costs might be more appropriate to be considered than dEB:

$$dCD^{\text{tax}} = \sum_{n \in N, j \in J} \left[\left(\underbrace{\frac{\partial c_{n,j}}{\partial T_j}}_{(+)} - \underbrace{\frac{\partial T}{\partial T_j}}_{(+/-)} \right) dT_j \right] \tag{4.26}$$

The amount of greenhouse gas emissions $CO2_{n,j}$ that is consumed by household n who installs a new technology is determined by the proportion of installations $P_{n,j}$.

$$CO2_{n,j} = f(P_{n,j}) \tag{4.27}$$

where $f(P_{n,j})$ is a linear function that transfers the energy consumed by the chosen technology into greenhouse gas emissions. Besides the new technologies, the technology stock (i.e. the currently installed heating systems) ST also emits greenhouse gas. Thus, the aggregated greenhouse gas emissions over all households sum up to:

$$CO2 = \sum_{n,j} f(P_{n,j}) + ST \tag{4.28}$$

We analyze the impact of a carbon tax and investment subsidies on the diffusion process and on greenhouse gas abatement. We assume that the emissions of the stock are not targeted by the policies. Introducing a new policy $T_j, T_i \quad \forall i \neq j$ (or $S_j, S_i \quad \forall i \neq j$) thus leads to the following change of total greenhouse gas emissions:

$$dCO2 = \sum_{n,j} \left[\left(\underbrace{\frac{\partial f(P_{n,j})}{\partial P_{n,j}}}_{(+)} \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,j}}}_{(-)} \underbrace{\frac{\partial c_{n,j}}{\partial T_j}}_{(+)} \right) dT_j + \sum_i \left(\underbrace{\frac{\partial f(P_{n,j})}{\partial P_{n,j}}}_{(+)} \underbrace{\frac{\partial P_{n,j}}{\partial c_{n,i}}}_{(+)} \underbrace{\frac{\partial c_{n,i}}{\partial T_i}}_{(+)} \right) dT_i \right] \tag{4.29}$$

and equivalently for S_j, S_i with $\frac{\partial c_{n,j}}{\partial S_j} < 0$ and $\frac{\partial c_{n,i}}{\partial S_i} < 0 \quad \forall i \neq j$.

The greenhouse gas abatement $-dCO2$ is increasing with an increasing tax rate $dT_j > 0$ (or with a decreasing subsidy $dS_j < 0$) of the carbon-intense system j. The greenhouse gas abatement $dCO2$ is decreasing with the increasing tax rates $dT_i > 0$ (or the decreasing subsidy $dS_i < 0$) of the alternatives i. Setting a Pigovian tax τ with $\frac{dT_i}{dT_j}$ being constant would therefore lead to $-dCO2 < 0$.

$\frac{\partial f(P_{n,j})}{\partial P_{n,j}}$, $\frac{\partial c_{n,j}}{\partial T_j}$ and $\frac{\partial c_{n,i}}{\partial T_i}$ are constants due to the respective linear relations. Thus, the changes in the total greenhouse gas emission level are determined by the impact of the cost changes on the diffusion of technologies $\frac{\partial P_{n,j}}{\partial c_{n,j}} < 0$ and $\frac{\partial P_{n,j}}{\partial c_{n,i}} > 0$.

The marginal excess burden dEB and the marginal greenhouse gas abatement $dCO2$ of introducing abatement policies enable to display a microeconomic greenhouse gas abatement curve that accounts for the reaction of households and the resulting diffusion process of technologies as well as marginal welfare losses. In case of behavioral misperceptions dCD might be considered instead of dEB.

4.4 Data and Methodology

4.4.1 Microsimulation using DIscrHEat

We developed the model DIscrHEat (DIscrete choice HEat market simulation model) which is a dynamic simulation model for the German heat market of private households. It simulates the development of installed heating systems and insulation levels of German dwellings in five-year intervals until 2030. Starting point of the model calculations is a detailed overview of the current German building stock of private households in 2010. We distinguish single and multiple dwellings and six vintage classes. Each of those building classes has an average net dwelling area and a specific heat energy demand (kWh/m^2a). Additionally, we include data on the distribution of heating systems in each building class.

To simulate the future development of the German building stock (i.e. the installed heating technologies and the buildings' insulation level), DIscrHEat accounts for new buildings and demolitions. Furthermore, we assume that a certain percentage of buildings has to install a new heating system. Those modernization rates are given exogenously. IWU / BEI (2010) show that in Germany, investments into new heaters mostly take place when mendings or replacements need to be done. Therefore, we assume that heater replacements only take place according to empirical rates of the last years based on IWU / BEI (2010).

The household's decision for a new heating technology is modeled by the approach presented in Section 4.3 which is included in DIscrHEat. The econometric model (alternative specific conditional logit model) estimates the household's choice behavior by using data on the actual heating choice in 2010 and the according cost data of different heating systems. Using this approach allows to take into account not only the observable costs (investment costs, operating costs and fuel costs) but as well non-observable influences (switching costs or preferences) on the household's decision based on empirical data. (See Appendix for the model and estimation results.)

4.4.2 Policy scenarios

Based on our simulation model results of three greenhouse gas abatement policies, we analyze the diffusion process of newly installed heating systems until 2030. We simulate a scenario without any policies as reference. In a first policy scenario, we introduce a Pigovian carbon tax as it is the first best policy measure if households are utility maximizing. We increase the carbon tax gradually to achieve higher levels of greenhouse gas abatement.[52] We consider a carbon tax t_j in $Euro/kWh$ which equals a carbon tax τ in Euro per tons CO_2-equivalent times the conversion factor CF_j that converts τ into t_j accounting for the amount of CO_2-equivalents in the different energy carriers.[53] In case of a carbon tax all households of the stock that have a heat pump, a gas or an oil heater are thus affected by such a tax and not only the households that have to make the decision on their heating system, i.e. have to modernize it. However, we assume that the households of the building stock that do not have to change their heating system due to break-down are inelastic to price changes. They neither change their heating system as a result of the tax nor do they change their energy consumption behavior for heating. Thus, their compensating variation is equal to the tax revenue that they generate. In terms of the welfare changes of the introduction of a tax or subsidy only the households who modernize their heating system are relevant.

In addition, we simulate two different subsidy regimes, which both provide subsidies on newly installed heating systems reducing the investment costs of the respective systems.

[52] For the assumed emissions of the energy carriers, see Table B.3. We assume that no tax is levied on biomass.

[53] See Table B.3 in the Appendix.

For the first subsidy scenario (subsidy I), we implement a simplified version of the German subsidy system with subsidies on heat pump and biomass heaters. Thereby, subsidies on biomass are significantly larger. The second subsidy scenario (subsidy II) is a hypothetical policy scenario. It provides the same level of subsidies on heat pumps as on biomass heaters and additionally a low subsidy on gas heating systems. We choose this parameterization subsidizing heat pumps and natural gas heaters relatively more than in the German system because marginal abatement costs of biomass heaters are the highest. Contrarily, biomass heaters are highly subsidized in the German system. Like this we can generate a subsidy based greenhouse gas abatement curve that generates lower welfare losses for the first major part of abatement units (see Table B.4 for the subsidy levels). For both subsidy scenarios we increase these subsidies proportionally to effectuate higher greenhouse gas abatement.

Since the heat market and in particular the installation of heating technologies only changes inertially, we focus on the total modeling period and aggregate all greenhouse gas emission reductions until 2030. We compute the final values of the tax income and subsidy expenses and excess burdens in 2030 based on an interest rate of 6% that has been applied throughout the model.

4.5 Results

4.5.1 Greenhouse gas abatement policies and diffusion of heating systems

To evaluate the three policy scenarios, we first investigate the diffusion process of the newly installed heating systems in this section. Figure 4.1 presents the mechanism of our simulation approach exemplarily for the carbon tax: in each policy scenario we increase taxes and subsidies proportionally which leads to different amounts of greenhouse gas abatement. Until 2030, about 300 million tons of greenhouse gas abatement are already achieved in the reference scenario without any policies. The accumulated tons of CO_2 abatement correspond to a decrease from 134 million tons greenhouse gas emissions in 2010 to 105 million tons in 2030 in the reference scenario without policy measures. These reductions are achieved because of the assumed increases in annual use efficiencies of the heating systems over time, the diffusion of the recent non-fossil heating technologies heat pump and biomass, the demolition of old insufficiently insulated buildings and the construction of well-insulated new buildings. Additional greenhouse gas abatement then requires policy intervention. The additional greenhouse gas avoidance achieved by policy measures is slightly increasing with the proportional increase of the tax rate (as in Figure 4.1) or a subsidy. At levels between 700 and 800 million tons of accumulated CO_2-equivalent (CO_2-eq.) abatement no additional volumes can be reduced. This corresponds to emissions between 64 and 56 million CO_2-eq. in 2030 in comparison to 104 million tons in the reference scenario, i.e. a maximum decrease by 39% to 47%. A carbon tax rate of 100 Euro per tons CO_2-equivalent (t CO_2-eq.) leads to an accumulated greenhouse gas abatement of about 330 million tons until 2030 (or a level of 102 million tons in 2030). 30 million additional tons of accumulated greenhouse gas abatement are therefore achieved by the carbon tax of 100 Euro per t CO_2-eq. A 420 Euro per t CO_2-eq. carbon tax results in an additional reduction of accumulated 200 million t CO_2-eq. until 2030 (see Figure 4.1).

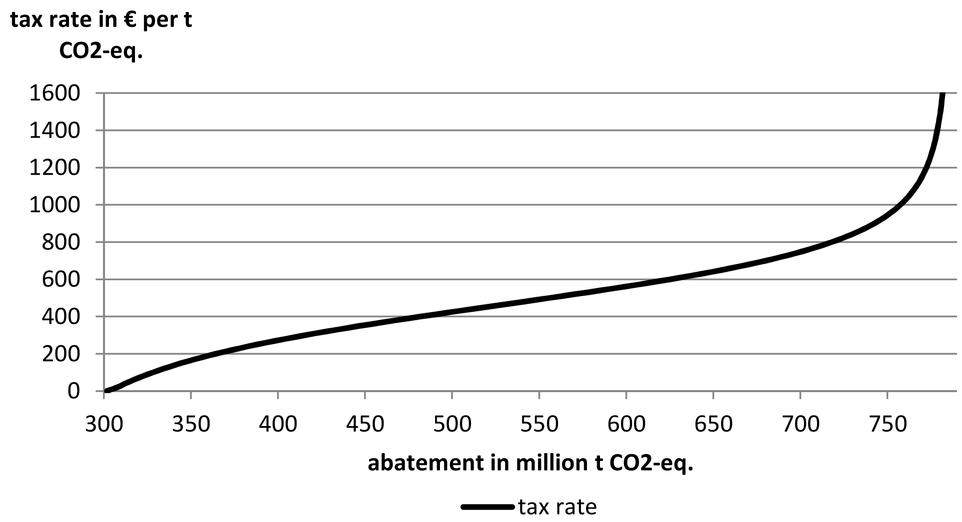


Figure 4.1: Tax rate, subsidy level and resulting greenhouse gas abatement

Figure 4.2 presents the effects on the government's budget of introducing all three different policies. For abatement levels above 500 million tons of accumulated CO_2-eq. expenses for the subsidies increase overproportionally and are significantly higher than the tax revenue that is generated by a carbon tax. At about the same abatement level, the tax revenue starts to decrease indicating the falling part of the Laffer curve. This is where the shrinking tax base, i.e. mainly fossil heating systems disappearing in the building stock, reduces the revenue more than the increasing tax rate adds to the revenue.

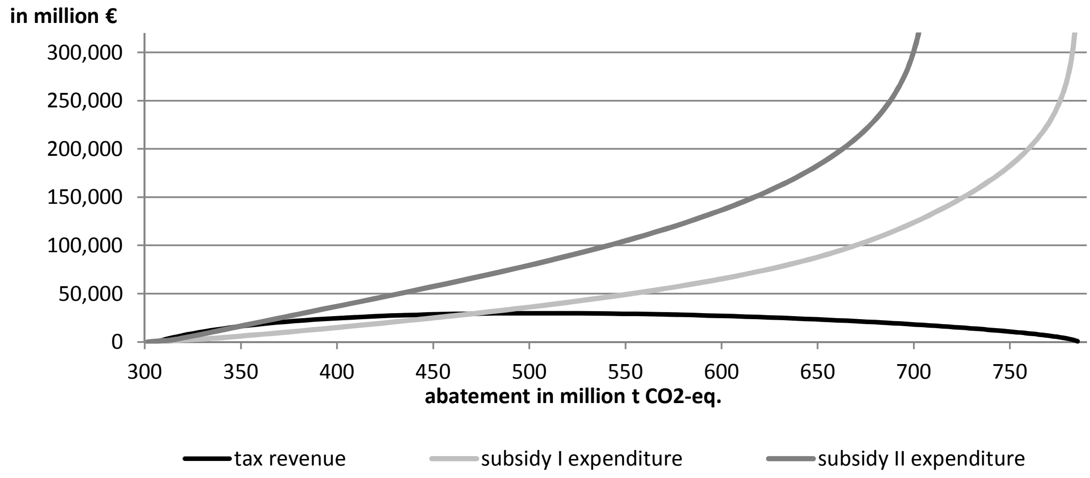


FIGURE 4.2: Tax revenue and subsidy expenditure

The diffusion of heating systems and the resulting accumulated amounts of greenhouse gas abatement until 2030 in the three policy scenarios are illustrated in Figure 4.3. The increasing greenhouse gas reduction amounts thereby result from increasing taxes or subsidies. The high subsidy on the investment costs of biomass heaters in comparison to the subsidy on investments into heat pumps leads to lower installation rates of heat pumps in the subsidy I scenario compared to the tax scenario. The diffusion resulting from the Pigovian tax indicates that heat pumps would be more greenhouse gas abatement cost efficient than biomass heaters for a further reduction of CO_2-eq. of 300 million tons to 550 million tons of greenhouse gas abatement. The subsidy II scenario causes a slightly slower reduction of gas heatings and keeps heat pumps and not only biomass heaters in the market. This is a result of the constant relative subsidy levels for heat pumps and biomass heatings. In this scenario 709 million tons of accumulated greenhouse gas abatement is the maximum that could be achieved because for additional reductions of CO_2-eq. biomass heaters need to be installed instead of heat pumps. In the tax and subsidy I scenario this abatement limit is at accumulated 786 million tons CO_2-eq.[54]

[54]Please note that very high tax and subsidy levels, especially on the downward-sloping part of the Laffer curve, would not be politically implementable because of their government budget effect. Moreover, such high relative cost changes would probably change household behavior and make them install new heating systems before they are broken.

The abatement level is higher as all installations of the greenhouse-gas-emitting heating systems oil, gas and heat pump are completely phased out in favor of biomass heaters.

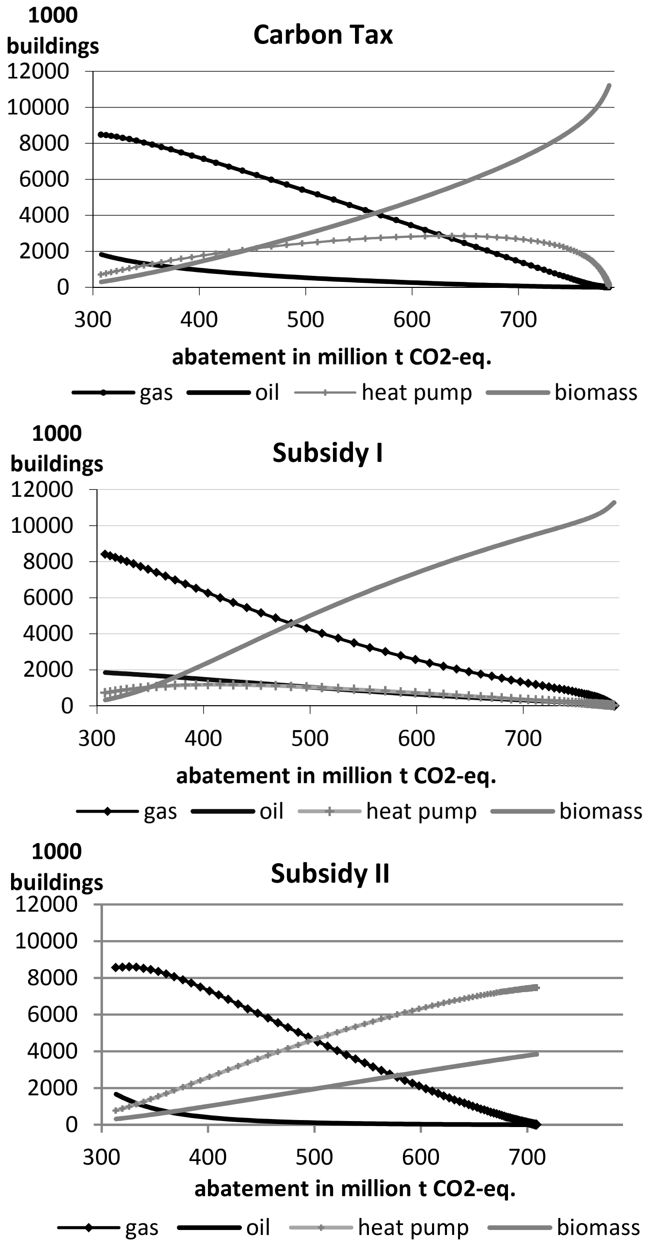


FIGURE 4.3: Installed heating systems in 2030 depending on CO_2 reduction and policy measures

4.5.2 Welfare analysis

In this section, we compare different welfare measures of the three policies in relation to the accumulated greenhouse gas abatement. We compute the accumulated excess burden and heating system cost differences over time, i.e. their net future values, given a discount rate of 6%.[55]

Figure 4.4 presents the different accumulated welfare measures, i.e. the excess burden and (total) heating system cost differences of the three policy measures. The excess burden is thereby always significantly larger than the heating system cost difference and increases much stronger.

The carbon tax thereby leads to a significantly lower excess burden for all greenhouse gas reductions than the subsidies on investments and is therefore the more efficient policy. If we cannot observe all costs and impacts determining the heating system choice of households, the determination of an investment subsidy that is equivalent to a Pigovian carbon tax is impossible and thus always leads to larger distortions on the household choice. Thus, a subsidy on the heating investment causes a higher excess burden than a carbon tax as it affects the price of the "bad" greenhouse gas directly. We could therefore identify the first best carbon tax as the lower bound for CO2 abatement. Assuming that administration costs would be the same or even higher, other policy measures would lead to higher distortions and welfare costs. However, in case of an energy efficiency gap, Allcott and Greenstone (2012) point out that if investment inefficiencies exist, subsidies for energy efficient capital stock might have greater benefits than costs. Applied to the public good of greenhouse gas abatement in our case, this could mean that in case of financing constraints, a subsidy as a second best policy could help to reduce this problem and get households to invest in less CO2-intense heating systems. Thus, in reality welfare losses of optimal greenhouse gas abatement policies might lay somewhere between the first best Pigovian tax and the subsidy curve.

[55]Please note that the formulae presented in the previous section refer to the excess burden and heating system cost differences for one period.

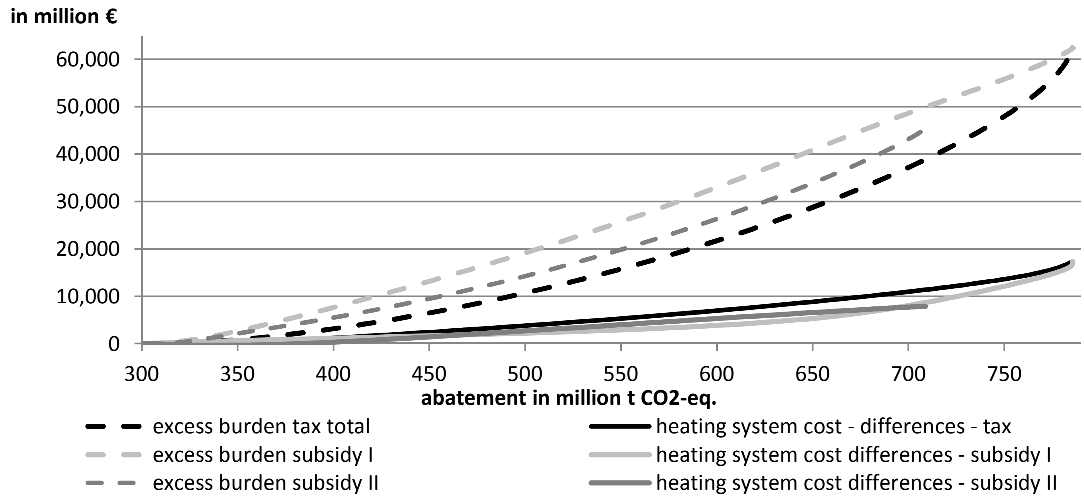


FIGURE 4.4: Tax, subsidy and excess burdens depending on CO_2 reduction based

The accumulated heating system cost differences are significantly lower than the excess burdens of all policies. These curves are still based on the diffusion process of the heating systems accounting for household behavior as before but they neglect the losses in consumer utility and focus on pure heating system costs spent. Technology based approaches to determine greenhouse gas abatement curves would neglect household behavior, which leads to even lower plain technology costs. However, a comparison of the curves in Figure 4.4 already shows, that a plain heating system cost consideration underestimates costs that incur for households and thus society. The cost differences caused by the subsidies are even below the carbon tax.

We further analyze different welfare measures relative to the greenhouse gas abatement level achieved by a Pigovian carbon tax and subsidies on heating system investments to investigate the marginal costs of greenhouse gas abatement. We define the following measures based on Auerbach and Feldstein (1985), Baumol (1972), Mayshar (1990):

- The average costs of public funds in Figure 4.5 equal the compensating variation of a policy measure relative to the tax revenue T generated: $ACPF = \frac{CV}{T}$. $1 - ACPF$ thus indicates the level of excess burden caused in percent of tax revenue.

- The marginal costs of public funds are the marginal compensating variation per marginal additional tax revenue T generated: $MCPF = \frac{\Delta CV}{\Delta T}$. $MCPF$ measures the additional welfare loss in raising the total tax income. $1 - MCPF$ thus indicates the marginal level of excess burden caused in percent of an additional tax revenue unit. The different levels of $MCPF$ for different CO_2 abatement levels are shown in Figure 4.5.

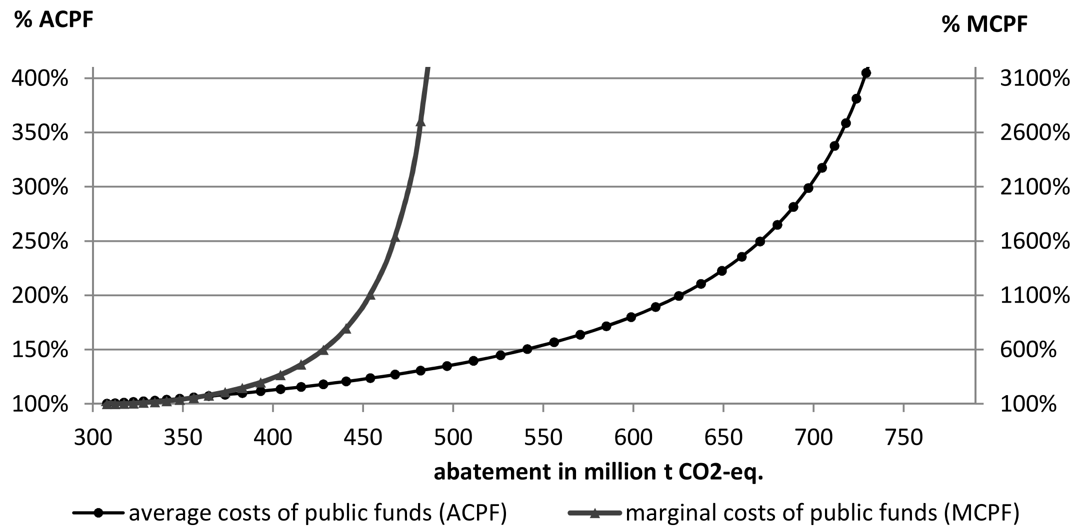


FIGURE 4.5: Marginal and average cost of public funds per CO_2 abatement level

The ACPF are increasing slightly whereas the MCPF first increase slowly, but getting closer to an abatement level of 450 million t CO_2-eq., the MCPF increases significantly. At this abatement level, the slope of the tax revenue curve is already close to zero in Figure 4.4 indicating that the tax base, i.e. mainly the oil and gas heaters, is decreasing significantly. This is also shown in Figure 4.3. Further greenhouse gas abatement is thus very costly for society because large amounts have already been reduced and additional welfare losses are comparatively high relative to the additional tax revenue generated. Up to a level of 430 million t of accumulated CO_2-eq. abatement, the MCPF remains below 1500% and the ACPF below approximately 120%. Thus, at this point the excess burden of an additional accumulated greenhouse gas reduction of 130 million t CO_2-eq. amounts to approximately 20% of the total tax revenue generated and the generation of a marginal tax income unit causes additional welfare losses of 1500% of the additional tax revenue generated. In summary, accounting for the quantity effects or the decreasing tax base of the carbon tax, i.e. the decreasing number of oil and gas heaters, the MCPF indicate that the additional welfare losses relative to tax revenue generated increase significantly for accumulated abatement levels of 450 t CO_2-eq. until 2030 or total annual greenhouse gas emissions of 92 million tons in 2030. Hence, referring to Figue

4.1 we can conclude that tax rates above 350 per t CO_2-eq. cause immense marginal costs of public funds and thus seem politically rather unrealistic.

4.5.3 Welfare-based greenhouse gas abatement curves

For the derivation of greenhouse gas abatement curves we use the marginal excess burden for different greenhouse gas abatement amounts for the three policy measures. The results are presented in Figure 4.6. To derive a greenhouse gas abatement curve based on welfare losses in our partial analysis, we compute the marginal excess burden per additional unit of greenhouse gas reduction: $MEB = \frac{dEB}{-dCO2}$. In Figure 4.6, per greenhouse gas abatement level $-dCO2$ on the abscissa an additional unit of abatement $-dCO2$ would cause an additional excess burden of MEB. The marginal excess burden of the carbon tax is significantly lower than the marginal excess burden of the subsidy throughout all realistic abatement levels up to 450 million t CO_2-eq. The MEB of subsidy I is decreasing at very high abatement levels because multiple dwellings mainly start switching their heating systems at very high subsidy levels in this policy regime.

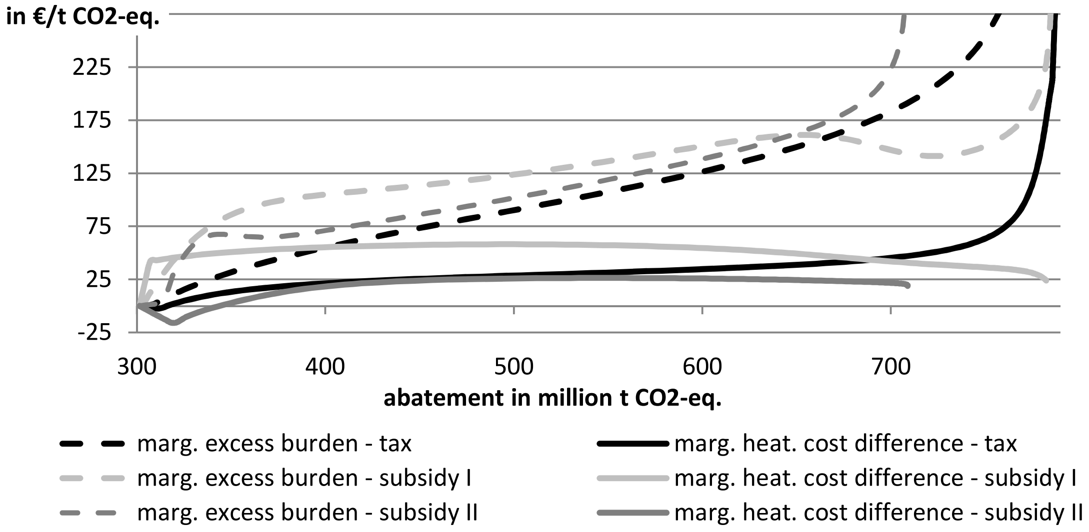


FIGURE 4.6: Marginal excess burden of greenhouse gas reduction

The marginal cost difference curves ($MCD = \frac{dCD}{-dCO2}$), which include solely the monetary heating system costs instead of the utility, are also displayed in Figure 4.6. These marginal cost difference curves reflect the additional heating system costs of a unit of greenhouse gas reduction at the different abatement levels already achieved. The curves indicate that the cost based curves are again significantly below the welfare loss based curves. These marginal heating system cost differences of subsidy I are also significantly higher than those of a carbon tax (for abatement levels up to 700 million t CO_2-eq.). Contrarily, the marginal cost difference of subsidy II are lower indicating that in case of behavioral misperceptions, for which a utility-based measure is not appropriate, subsidies might be effective. However, Figure 4.2 indicates that such a policy requires a large budget to finance the subsidy expenses. A policy that changes household behavior could then be more appropriate.

In general, the welfare based greenhouse gas abatement curve might overestimate the abatement costs assuming that households do not change their behavioral patterns until 2030. If one assumes that the households' cost elasticities might change over time and that more households might switch to a less carbon intense heating system over time bearing less non-observed costs, the abatement curve might be somewhere between the cost-based and utility-based abatement curves. However, in comparison to pure technology based curves, these curves account for households' reactions to policy measures and policy costs that society would have to bear.

4.6 Conclusion

Analytically, we derive a welfare based greenhouse gas abatement curve, thereby taking into account household behavior and cost effects of policy measures. We implement the theory into the behavioral micro-simulation heat market model DIscrHEat and use the model to derive an abatement curve based on household preferences and welfare losses for the German residential heating market: based on a discrete choice estimation of the heating system choice of households in 2010, we simulate the diffusion of heating systems until 2030 with and without policy measures to finally derive the compensating variation, excess burden and heating system cost differences in relation to greenhouse gas abatement. In comparison to technology-based abatement curves, this approach takes household investment behavior in heating technologies into account as well as welfare costs of policy measures.

Our microeconomic analysis provides a partial analysis of welfare based greenhouse gas abatement costs in the context of optimal abatement strategies. Analyzing these costs and options of greenhouse gas abatement is of major importance in the residential heat market and also holds for other sectors, where the behavior of economic agents affects the greenhouse gas reduction potential and the implied welfare costs. Implementing certain policies to give incentives for greenhouse gas reduction needs to account for the behavior of economic agents whose elasticities determine the welfare costs and thus the costs society would have to bear in order to achieve certain abatement objectives.

Based on our model results for the German residential heating market we conclude that a carbon tax is more efficient than subsidies on heating system investments in most cases. A subsidy on investments might cause lower abatement costs in case of behavioral misperceptions, but this policy requires very high subsidies (and lump-sum taxes) and precise information on household investment behavior into heating systems. Hence, such a policy seems rather not implementable in reality. The subsidy regime currently implemented by the German government that subsidizes expensive biomass heaters to a large extent reflects a suboptimal design: For the first affordable section of greenhouse gas abatement units, the curves of this policy regime run above carbon tax curves and the alternative subsidy regime curves. The alternative subsidy regime promotes heat pumps and natural gas systems more than the German regime. In summary, regarding policies that change heating system choices through relative costs, a carbon tax is optimal. However, if financing constraints for households exist, subsidies on new heating system installations might be reasonable.

In our model, household preferences and cost elasticities remain constant over time and the policy measures that we introduce are assumed to not affect the preferences. There are alternative policy measures that might change the household behavior over time and might impact abatement curves. These could be information campaigns or letters sent to households that compare their energy behavior with others[56]. The evaluation of the greenhouse gas abatement potential and costs of such policy measures remains open for further research.

The partial analysis of the paper does not cover additional welfare effects of the policy measures caused by cutting other taxes at the same time (see the analyses of the double dividend hypothesis for Bovenberg and de Mooij (1994), Goulder (1995) and Fullerton and Metcalf (1998)). In addition, environmental policies might have redistributive effects

[56] Allcott (2011) evaluates such a program for the electricity use of households and finds a significant decrease in energy consumption.

which might need to be included in the welfare analysis of different policy measures if equity or equality are highly valued by society (see Cremer et al. (2003) and Llavador et al. (2011)). This type of analyses are beyond the scope of our paper.

The results of our paper have implications to policy makers: Understanding how households react to different policies to derive microeconomic greenhouse gas abatement curves is crucial for developing targeted policies and for achieving abatement objectives.

Chapter 5

Does subsidizing investments in energy efficiency reduce energy consumption? Evidence from Germany.[57]

The paper empirically analyzes the effectiveness of subsidies in increasing energy efficiency in German residential dwellings. In a first step, the impact of subsidies on the number of dwelling modernizations is investigated. Next, the impact of renovations on energy consumption is analyzed using a differences-in-differences-in-differences approach. It becomes apparent that the landlord-tenant problem tends to broaden the energy efficiency gap. It is also found that the number of modernizations made by landlords does not increase with higher subsidies. However, the renovations made during the subsidy periods decrease the heating consumption of tenants. Given the condition that homeowners already invest more in energy efficiency, they increase modernizations only slightly with increasing subsidies. Nonetheless, these modernizations during subsidy periods do not further decrease homeowners' energy consumption and the large part of the overall subsidies received by homeowners can be identified as windfall profits.

5.1 Introduction and Background

The promotion of energy efficiency in the residential sector has already been addressed in public policies for several decades. Reasons for the attention have been diverse. High prices of heating energy during the oil crises, fossil fuel depletion and the reduction of

[57] This chapter includes the working paper Dieckhöner (2012a).

greenhouse gas emissions following the UNCED[58] in Rio de Janeiro 1992 are common explanations. More recently, the Stern Review (Stern, 2007) and the IPCC reports on climate change in 2001 and 2007 (IPCC, 2001, 2007) have increased awareness. In the current European political debate, the curtailment of energy consumption, especially of fossil fuels, and the abatement of greenhouse gas emissions are major objectives of European energy policy. The EU is aiming to cut 20% of Europe's annual primary energy consumption by 2020 (European Commission, 2011).

The European Commission estimated buildings to cause 40% of final energy consumption and 36% of greenhouse gas emissions in the European Union, mainly caused by space and water heating (European Commission, 2012). Major energy savings can only be achieved by increasing energy efficiency, requiring significant investments. Improvements of the level of energy efficiency of buildings, such as improvements in heat insulation, imply high initial investment costs for households. These high investment costs are associated with three major obstacles for reaching the policy objectives of energy savings in residential dwellings. First, households may underinvest causing the cost-minimizing level of investment in energy efficiency to deviate from realized investments, often referred to as the 'energy efficiency gap'(Allcott and Greenstone, 2012). These underinvestments may be a result of hyperbolic discounting, major credit constraints or specific information asymmetries. Second, inefficiently high energy consumption may occur, despite investments in energy efficiency, referred to as the rebound effect. Third, the principal-agent problem between landlords and tenants reduces incentives to invest in energy efficiency improvements. This so-called landlord-tenant problem (Jaffe and Stavins, 1994) characterizes barriers for landlords to ensure appropriate investment returns by including investment costs in the rent.

Therefore, an evaluation of policy measures to enhance energy efficiency in residential dwellings should consider both the impacts on investments and on energy consumption. Subsidies being prominent policy measures may give incentives for investments in energy efficiency, e.g. by reducing credit constraints, which may result in a larger number of renovations (quantity effect). In addition, or alternatively, subsidies may increase the degree of energy efficiency that is achieved through the subsidized investments (quality

[58]United Nations Conference on Environment and Development

effect). Hence, the comprehensive research question may be raised whether subsidies have such a quantity and/or quality effect. The presented paper attempts to analyze both effects by performing a twofold analysis to investigate how subsidies can promote investments in energy efficiency and reduce energy consumption. Moreover, specific attention should be given to the landlord-tenant problem when considering residential dwellings. Thus, the paper raises further questions of how the landlord-tenant problem affects heating energy consumption and how the policy measures work given different owner and landlord investment and owner and tenant energy consumption behavior.

Germany is an important subject to consider since Germany has highly ambitious national objectives concerning greenhouse gas reductions and improvements in energy efficiency. Germany set a target of 40% reduction and voluntarily aims at outperforming the EU targets of 20% greenhouse gas abatement until 2020 relative to the levels of 1990 (The Federal Environment Agency (Umweltbundesamt), 2007). In fact, the German government spent more than 6.5 billion Euros between 1996 and 2002 and an additional 31.5 billion Euros between 2003 and 2010 to promote investments in energy efficiency in residential dwellings in Western Germany (KfW (Kreditanstalt für Wiederaufbau), 2012). Moreover, Germany has a high proportion of households that live in rented dwellings and therefore may be strongly affected by the landlord-tenant problem.[59]

Therefore, using detailed micro-data on dwelling modernizations and heating expenditures, as well as socio-economic and dwelling characteristics of more than 5000 German households for the period 1992–2010, the impact of policy measures on investments in energy efficiency and their impact on energy expenditures are investigated in the presented paper. The analysis is performed by assessing the standard policies used to increase investments in energy efficiency, i.e. lump-sum subsidies and subsidized credits. The empirical analysis proceeds in two steps. In the first step, the effects of the subsidies on the probability of dwelling modernizations are analyzed, controlling for household and dwelling characteristics. In a second step, the empirical analysis investigates the impacts of dwelling modernizations made during the periods of the subsidy program on heating expenditures. In this analysis, a differences-in-differences-in-differences approach is

[59]The proportion of German households that rented is more than 50% compared to less than 30% in the United Kingdom or even less than 20% in eastern European countries (Eurostat, 2010).

applied to control for the difference between owner- and tenant-occupied dwellings, the heterogeneity of households and modernization trends.

The major empirical findings of the paper show that subsidies spent on dwelling modernizations only have a slight impact on the probability of renovations, i.e. a slight quantity effect, and only in owner-occupied dwellings. However, referring to the quality effect, the investments made during the subsidy period only reduce energy consumption in tenant-occupied buildings excluding the effect of the generally lower energy expenditures of homeowners. In summary, the empirical results show that subsidies have only a minor quantity and no quality effect in owner-occupied dwellings and thus reveal that subsidy payments for owners are mostly windfall profits. There is no quantity effect on modernizations in tenant-occupied dwellings and quality effects are small. Moreover, the results provide evidence for the landlord-tenant problem and the lack of investments in tenant-occupied dwellings. Tenants live in significantly less insulated homes and consume more heating energy per square meter.

The next section provides a literature overview and Section 5.3 presents the hypotheses of the estimations. Section 5.4 describes the database. In addition to the socio-economic and dwelling characteristics, policy variables are included in the analysis, reflecting the subsidies spent for housing reconstructions. The estimation strategy is presented in Section 5.5 as well as the applied differences-in-differences-in-differences approach used to analyze the impacts of the investments made during the subsidy program periods, while controlling for homeownership. Section 5.6 provides evidence of the effects of policy measures and further variables on the probability of dwelling modernizations. Furthermore, Section 5.6 discusses the empirical results on the determinants of heating energy and warm water expenditures and the impact of investments made during the subsidy program periods in owner- and tenant-occupied dwellings. Section 5.7 concludes the analysis.

5.2 Literature overview

A broad range of literature analyzes the determinants of energy consumption: Baker et al. (1989) investigate the determinants of electricity and gas demand for households during the period 1972 to 1983, accounting for socio-economic characteristics such as ownership, household size and income, as well as details of the dwelling such as the number of rooms. They find that energy consumption increases with income and that the price sensitivity of households is higher for families with children and lower income. Meier and Rehdanz (2010) investigate determinants of residential space heating expenditures in the UK in a panel data analysis of more than 5000 households for the years 1991 to 2005. They analyze socio-economic factors, building characteristics, heating technologies and weather conditions, and derive price and income elasticities both for different types of British households and for Britain as a whole. They find that owner-occupied and tenant-occupied households react differently to changes in income and prices. Brounen et al. (2012) investigate the impact of dwelling and socio-demographic household characteristics on residential energy use in a cross-sectional estimation. The study shows that residential gas consumption is mostly determined by structural dwelling characteristics, such as the vintage class, building type and characteristics of the dwelling. They evaluate that well-insulated homes may reduce natural gas consumption, primarily for heating, by 12%.

Several studies have identified the need and obstacles for energy efficiency policies caused by underinvestment, the rebound effect and the landlord-tenant problem. Allcott and Greenstone (2012) present an overview of reasons for underinvestment in energy efficiency measures, often referred to as the 'energy efficiency gap' and provide a survey on the relevant literature. They identify two major market failures that need to be addressed by energy efficiency policies: the internalization of environmental externalities (such as greenhouse gas emissions) and the mitigation of investment inefficiencies. Similarly, Train (1985) shows that consumers may base their investment decisions on excessive discount rates and undervalue future benefits from energy savings.

Subsequent to dwelling modernizations as a result of lower expenditures for energy, households may increase their consumption, resulting in the so-called 'rebound effect' and counteracting energy conservation objectives. Greening et al. (2000) present different studies which analyze the rebound effect and find different magnitudes of the resulting behavioral response, depending on the deviating definitions and different empirical analyses. Furthermore, for energy end uses, they conclude that the range of estimates for the size of the rebound effect is low to moderate. Allcott (2011) shows that providing information to consumers about their energy consumption and the consumption of similar households gives an incentive to reduce energy consumption.

The landlord-tenant problem, i.e. that the investor is not the person who pays the energy expenditures, may limit investments in energy efficiency (see Jaffe and Stavins (1994)). With a low ownership rate, the German housing market is an interesting case. Regarding the impact of ownership status, Gebhardt (2012) empirically evaluates whether the allocation of asset ownership (with the risk of expropriation) effects relationship-specific investments. In an empirical analysis of the German housing market, he finds evidence of more frequent relationship-specific investments, such as bathroom renovations, if the occupant is protected against expropriation, which is the case for homeowners. Gebhardt (2012) concludes that renovations are significantly dependent on the ownership status and his model predicts underinvestment in rental housing. Hence, the heating energy consumption of households that own their dwelling may deviate significantly from that of tenants. Rehdanz (2007) also reveals differences in owner- and tenant-occupied dwellings. She examines the determinants of household expenditures on heating and warm water supply in Germany. She includes a variety of socio-economic and dwelling characteristics in her analysis. In addition, Rehdanz (2007) finds a significant difference between the effects of energy price increases for owners and tenants, and concludes that owners are more likely to have installed energy-efficient heating and hot water supply systems.

While the aforementioned studies have identified the need for policy interventions to promote energy savings, several other papers have gone further and analyzed the impact of policy measures on energy conservation. Hassett and Metcalf (1995) investigate the effects of energy tax credits on residential energy conservation, controlling for unobserved heterogeneity of energy saving tastes. They analyze panel data on individual tax returns for residential conservation investments to measure the impact of tax policies on the probability of making these investments. They find that a 10 percentage point decrease in the tax paid on investment in energy efficiency would lead to a 24% increase in the probability of investments. Eichholtz et al. (2010) show that 'green ratings' significantly increase rents and selling prices of office buildings. Eichholtz et al. (2012) however show that this only holds among green buildings. Brounen and Kok (2011) find that consumers capitalize on information collected from energy performance certificates in the housing market and take it into account when considering the price of their prospective home. They also show that adoption rates of energy labels implemented by the European Union are low and that European policy needs to further stimulate their dissemination. Allcott and Mullainathan (2010) reason that understanding the behavior of households is crucial for the design of effective policies to reduce energy consumption. They argue that policies need to consider insights from the behavioral sciences rather than focusing solely on price changes (e.g., subsidies for energy-efficient goods) and information disclosure (e.g., through energy-use labels).

Allcott and Greenstone (2012), Allcott et al. (2012) and Heutel (2011) investigate the effectiveness of a subsidy theoretically. Allcott and Greenstone (2012) argue that if energy is priced below social cost and neither a feasible Pigovian tax nor effective information disclosure policies are available, subsidies and standards may be a second best approach. Subsidies (and standards) may cause higher welfare costs for mainly two reasons: First, subsidies change prices for all households equally despite the heterogeneity of household preferences. Second, subsidies do not price the usage of energy and may therefore rarely be targeted. Most probably, the greenhouse gas abatement level achieved by a subsidy would be higher or lower than the one achieved by a Pigovian tax. Thus, marginal abatement costs of subsidies would vary among households and would rarely equal marginal damage costs. However, Allcott and Greenstone (2012) discuss that subsidies may increase welfare by reducing credit barriers. Moreover, Allcott et al. (2012) and Heutel (2011) argue that a subsidy or standard may be optimal in addressing hyperbolic discounting or undervaluation of energy savings in contrast to a Pigouvian tax.

In summary, the majority of previous studies focus on the determinants of residential energy consumption. However, energy consumption could only significantly be reduced through investments in energy efficiency. Several studies analyze the effects of policy measures on investments in energy efficiency. The potential positive effects of subsidies on energy conservation are theoretically discussed in the literature. The presented paper contributes to the existing literature by providing evidence for the effectiveness of subsidies in an empirical analysis investigating quantity and quality effects of subsidies on investments in energy efficiency. Moreover, the impact of the landlord-tenant problem and differences between the effects of subsidies on investments in owner- and tenant-occupied dwellings have not been investigated so far. The presented paper thus attempts to fill a gap in the existing literature by empirically analyzing the different effectiveness of subsidies in owner- and tenant-occupied dwellings.

5.3 Hypotheses

An important instrument of the German National Energy Efficiency Action Plan (NEEAP) (Federal Ministry of Economic Affairs and Technology, 2007) to achieve the ambitious German greenhouse gas reduction targets are subsidies on investments in energy efficiency. The presented paper investigates the impact of these subsidy programs on investments in energy efficiency and on energy consumption by examining three hypotheses.

The theoretical considerations of Allcott and Greenstone (2012) and Allcott et al. (2012) have shown that subsidies may overcome credit barriers or other barriers such as hyperbolic discounting or asymmetric information problems and may increase energy conservation. Thus, the German subsidies may reduce the costs of investments in energy efficiency and hence energy consumption. These energy savings may be achieved by two effects of the subsidies. The subsidies may give incentives for more households to invest in energy efficiency, or the subsidies may increase the level of energy efficiency realized through the subsidized investments. Therefore, the following two hypotheses are evaluated:

Hypothesis 1: Subsidies may increase the number of dwelling modernizations (quantity effect).

Hypothesis 2: Subsidies may decrease energy consumption by increasing the quality of investments in energy efficiency (quality effect).

The existing literature has presented differences in investments in owner and tenant-occupied dwellings (Gebhardt, 2012) and in the energy consumption of owners and tenants (Rehdanz, 2007). Thus, the landlord-tenant problem is assumed to have significant impacts on investments in energy efficiency and thus may also have impacts on subsidized investments.

Hypothesis 3: Renovation frequency and energy consumption are different in tenant- and owner-occupied dwellings as well as the effects of subsidies.

Section 5.6 investigates these hypotheses in two empirical analyses.[60] The next section presents the database for these analyses.

5.4 Data and descriptive statistics

5.4.1 Sources and variables

The data used for the empirical analyses of this paper are provided by the German Socio-Economic Panel Survey (SOEP).[61] The survey is a representative and longitudinal study of private households, carried out by the German Institute for Economic Research (DIW Berlin), and includes data on household composition, occupational biographies, employment, earnings, housing, health and satisfaction indicators. The survey started in 1984 and covers nearly 11,000 households and more than 20,000 persons for each year. The data is collected by the fieldwork organization TNS Infratest Sozialforschung, which surveys the same households every year. The sample applied in this study ranges from the year 1992 to 2010 and covers more than 5000 households per year. Only data for Western Germany is used, as the structure and development of the Eastern German residential building sector is quite different than the Western German sector, especially during the first decade after the reunification. Significant amounts of money and different types of subsidies were transferred to the East after the reunification in 1990. Due to both the different types of implemented policies and the fast structural changes of the

[60] The hypotheses are illustrated in a simple theoretical model based on Allcott and Greenstone (2012) in C.1 in the Appendix.

[61] Wagner et al. (2007) provide a detailed description of the panel survey.

building sector in Eastern Germany, consistent impacts cannot be identified between Eastern and Western Germany. Hence, Western Germany is taken as the focus of the analysis.

The presented paper uses SOEP data on the household and dwelling characteristics. The economic situation of households is given in terms of disposable income and heating and warm water expenditures. Table 5.1 provides an overview of all variables included in the estimations. In the dataset, data on whether households made major dwelling renovations or installed new windows, which improve the state of dwelling, are covered. The two variables are combined to make the variable *dwelling modernizations*.

The variable *log. of heating expenditures per* m^2 is the logarithm of average annual heating expenditures per dwelling size. Controlling for the gas price increases, the average heating expenditure in the sample is 12.20 Euros per m^2 for an average dwelling size of 103.93 m^2 over the years 1992–2010. For owner-occupied dwellings the average heating expenditure amounts to 10.50 Euros per m^2 for an average dwelling size of 125.39 m^2. The average heating expenditure of tenant-occupied dwellings is 14.26 Euros per m^2 for an average dwelling size of 78.08 m^2.

The socio-economic (household) variables included are the logarithm of monthly disposable household income (*log. of adj. income*) and a categorial variable for different household compositions (*household type*), which increases with an increasing number of household members. A dummy variable (*owner-occupied*) indicating whether the dwelling is owner- or tenant-occupied is also included.

Variables representing dwelling characteristics used in the analyses are the *number of relocations*, i.e. how often a household relocated, the number of rooms (*room*), a categorical variable for construction periods (*construction period*), and the condition of the dwelling (*need of renovation*), which is a categorical variable from 1 to 4 with 1 indicating a good status and 4 the need for renovation. The status of the dwelling has been evaluated by the interviewed household member.

Based on the variable *dwelling modernizations*, additional variables are generated. The variable *modernized* indicates whether a household's dwelling has been modernized in previous periods. The variables *treated household group 1* and *treated household group 2* indicate the types of households that made investments during the subsidy periods

Table 5.1: Overview of variables

Name	Description
dependent	
dwelling modernizations	1 if household installed new window or made other major modernizations in previous year, 0 else
log. heat. exp. per m^2	logarithm of average annual heating and warm water expenditure per m^2
independent	
household characteristics:	
owner-occupied	1 if household is owner of the dwelling, 0 else
log. of adj. income	logarithm of disposable monthly household income
household type	categorial variable with
1	one person household
2	childless couple
3	single parent
4	couple with children $\leq$ 16 years
5	couple with children $>$ 16 years
6	couple with children $\leq$ and $>$ 16 years
7	multiple generation household
8	other combination
dwelling characteristics:	
construction period	categorial variable with
1	built before 1918
2	built in 1918–1948
3	built in 1949–1971
4	built in 1972–1980
5	built in 1981–1990
6	built in 1991–2000
7	built in 2001–2010
number of relocations	number of relocations between 1992–2010
room	number of rooms $> 6m^2$
need of renovation	condition of dwelling (1–4; 1 good, 4 renovation necessary)
modernized	1 if dwelling has been modernized, 0 else
treated household group 1	1 for households that modernized between 1996 and 2002, 0 else
treated household group 2	1 for households that modernized between 2003 and 2010, 0 else
macro-indicators:	
subsidy ratio	average subsidy as a proportion of average modernization spendings by program (interest rate reductions, or lump-sum subsidies)
log. of gas price	logarithm of gas price index for residential heating (2005 = log(100))
HDD	heating degree days published by ECA&D
year dummies	year dummies for each other year between 1992 and 2010
state dummies	state dummies for ten different states

1 and 2. The subsidy period 1 indicates the years 1996–2002 and the subsidy period 2 covers the years 2003–2010.

In addition, macro-data is added, i.e. non-individual data such as heating-degree-days (*HDD*, published by Klein Tank et al. (2002)[62]) and the variable *log. of gas price*, i.e. logarithm of the annual natural gas prices index for households (published by the German Statistical Office). Only prices of gas are included as input data, since approximately 70% of all households used natural gas for heating during the time period considered and the heating systems of the single households cannot be differentiated by energy carriers. An additional 17% to 27% of all households in Germany had oil heaters.[63] As most households heat with natural gas, and as oil and gas prices are highly correlated, the gas price is assumed to be a good proxy for a heating energy price.

To cover policy impacts on the macro-level[64], annual subsidies alloted to households for dwelling modernizations (published in the subsidy reports of KfW (Kreditanstalt für Wiederaufbau) (2012)[65] are used. The subsidies are provided to households through different KfW building renovation programs primarily via direct subsidies on investment interest rates.[66]

Including these total subsidies may cause endogeneity problems. A high relative frequency of modernizations due to other reasons than the subsidies may lead to a large number of applications for a subsidy and thus increase total subsidies spent. To ascertain that causality is vice versa and to check whether increasing subsidies cause a higher probability of dwelling modernization, a subsidy ratio indicating the subsidized proportion of dwelling modernization spendings is included in the analysis. The variable *subsidy ratio* is the average subsidy divided by the average modernization expenditure in residential dwellings during a sub-program period.[67] Data on modernization expenditures of residential dwellings is provided by the German Statistical Office (DESTATIS).

[62]Heating degree days $= \sum_i^I (17°C - T_i)$, with T_i equaling the daily mean temperature at day i.

[63]See BDH (2010) for a distribution of heating systems in the German building stock.

[64]Micro-data for subsidies for energetic building modernizations received by households are not covered by the SOEP.

[65]KfW stands for Kreditanstalt für Wiederaufbau (Reconstruction Credit Institute)) and is a German government-owned development bank.

[66]For further details on the subsidy programs see Section C.3 in Appendix C.

[67]An average of the program periods is used to account for the different time lags between approval of the subsidy and the completion of the renovation.

Two main program periods are differentiated. The first program period of the CO_2-reduction programs is 1996–2002 and the second program period is 2003–2010 when the dwelling modernization program provided additional subsidies. The CO_2-reduction program has been modified in 2001 and the dwelling modernization program has been adapted in 2005. Therefore, the subsidy ratio varies over the years 1996–2000, 2001–2002, 2003–2004, 2005–2010 and over the ten different Western German states[68]. Figure 5.1 shows the development of the subsidy ratio for the states and years covered in the analysis. Moreover, dummies for the ten different states as well as year dummies for the years 1992–2010 are included.

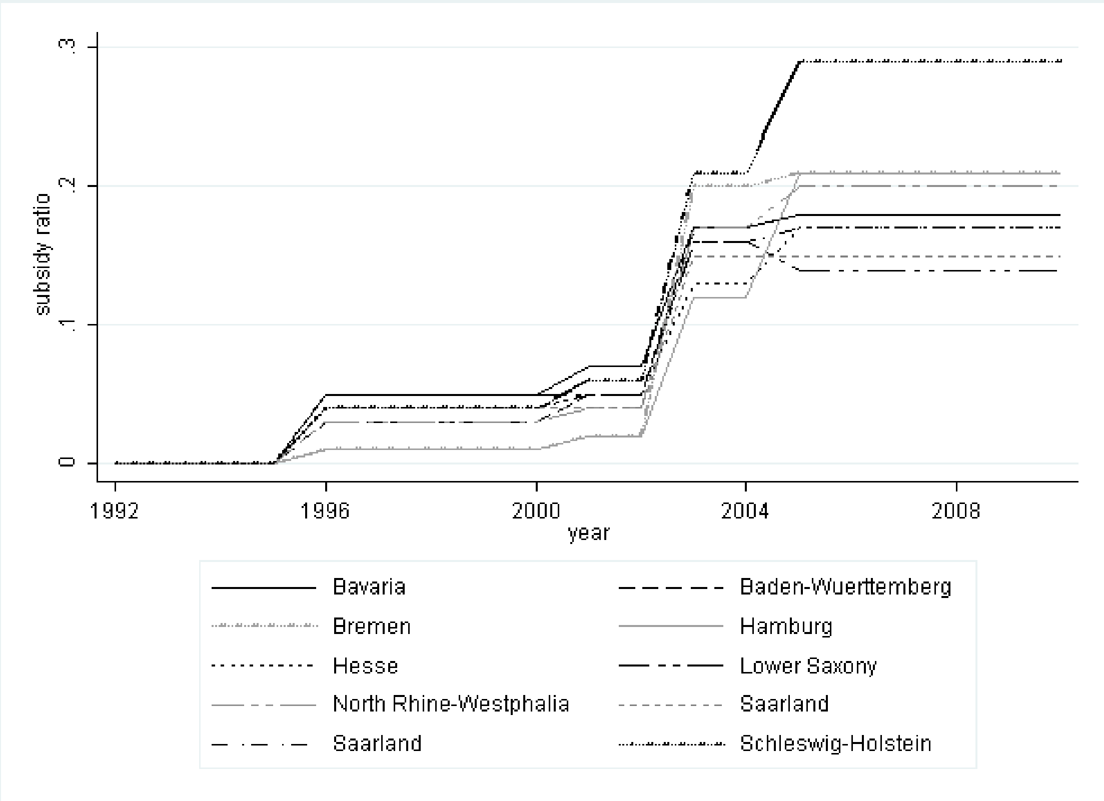


FIGURE 5.1: Average subsidies per state

5.4.2 Heating expenditure and dwelling modernization

Germany is a special case concerning the tenancy structure of dwellings. Only about 50% of the dwellings are actually owned by the residents (see Figure 5.2). Renovations in rented dwellings are made by landlords. Several studies have shown the importance of

[68]The states included are Baden-Wuerttemberg, Bavaria, Bremen, Hamburg, Hesse, Lower Saxony, North Rhine-Westphalia, Rhineland-Palatinate, Saarland and Schleswig-Holstein. Berlin is excluded because of the aforementioned potential impacts of the reunification.

accounting for the ownership status to explain investments and renovations (Gebhardt, 2012), as well as heating expenditures (Rehdanz, 2007), in German dwellings.

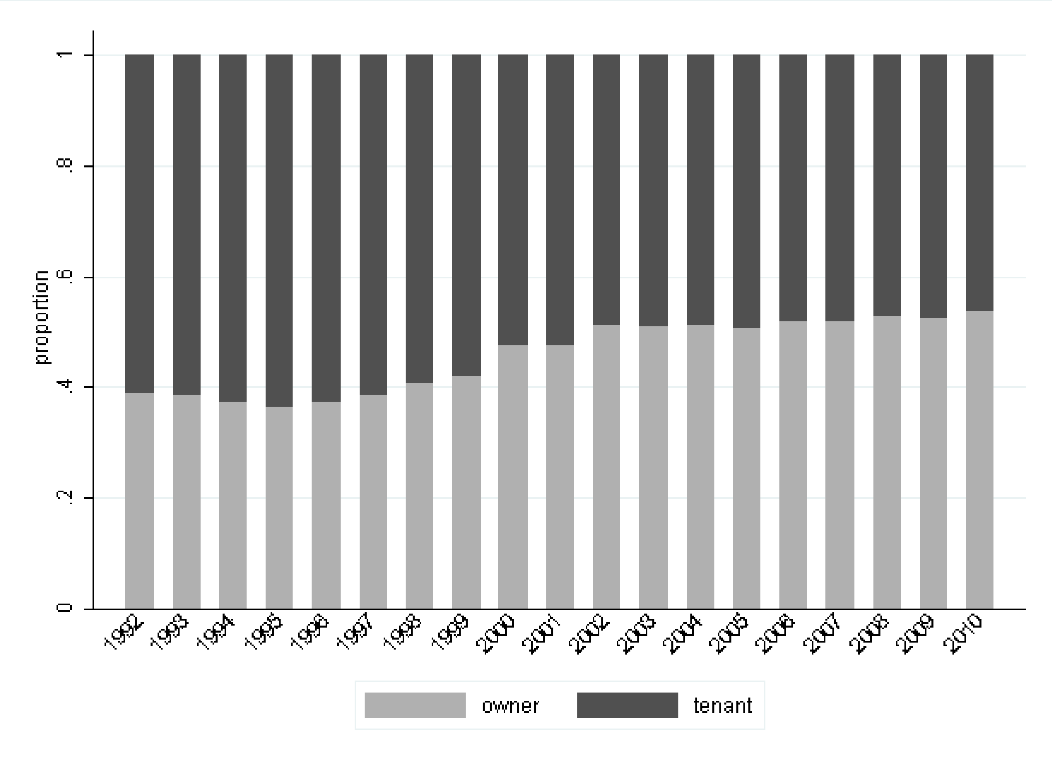


FIGURE 5.2: Percentage of households with owners or tenants in Western Germany

Figure 5.3 shows the development of the average heating expenditure per square meter between 1992 and 2010 for all households together and for owners and tenants separately. The level of the average heating expenditure of an owner is far below the average tenant's expenditure. However, the development of the heating expenditure follows a similar pattern for owners and tenants. Heating expenditure decreased after 1996 and increased again consistently from 2000 onwards. The development of the gas price index (2005 = 100) indicates that increases in heating expenditures mainly result from increases in gas price increases.

Figure 5.4 shows the subsidy ratio of 1-7% percent for renovation spendings in the first program phase until 2002. The subsidy ratio increases significantly to 12-29% during the second period reaching the peak after 2003. Figure 5.4 also depicts the share of dwellings that are modernized in a respective year as well as real heating expenditures for owners and tenants separately. The share of modernized dwellings is relatively stable between 1996 and 1999, decreases in 2000 and increases constantly after 2003, indicating

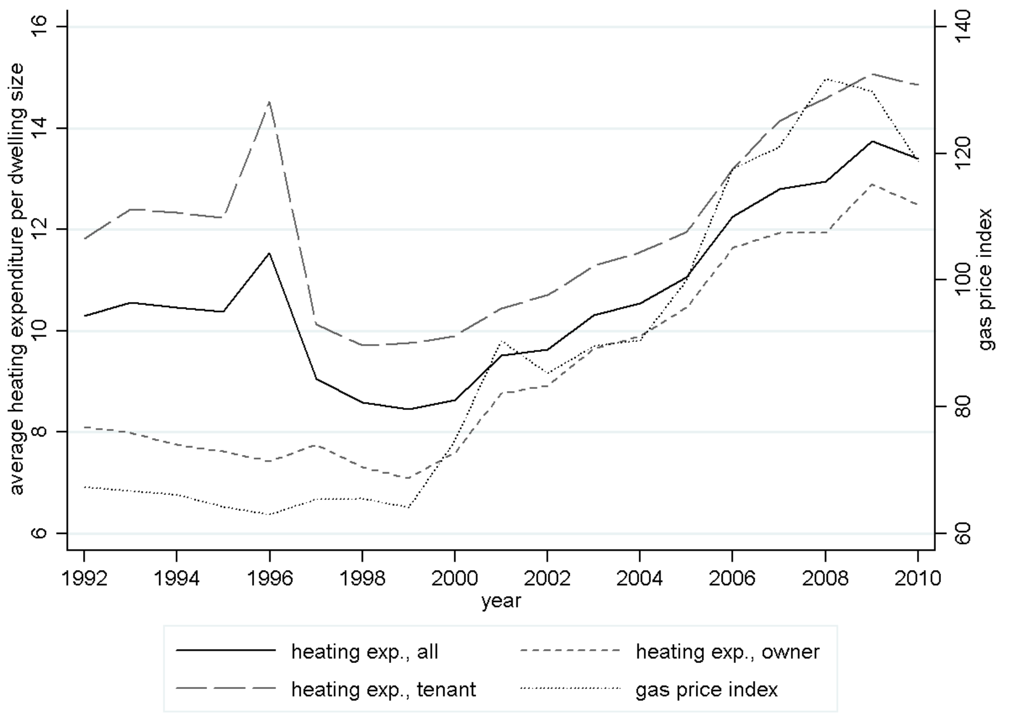


FIGURE 5.3: Heating expenditure and gas price development

a quantity effect of the subsidy, i.e. that the subsidy may have a positive impact on the number of renovations. Moreover, the real heating expenditures, i.e. accounting for changes in gas price levels, follow almost the opposite pattern over time. Figure 5.4 shows a strong decrease in real heating expenditures between 1996 and 2000, and a continuing decrease after 2003. Thus, it is worth analyzing if the subsidies effectively promote dwelling modernization and cause lower heating energy consumption (Hypothesis 1 and Hypothesis 2).

Furthermore, the proportion of modernizations made in owner-occupied dwellings is considerably higher than in tenant-occupied dwellings. Gebhardt (2012) shows that renovations are more frequent if the occupant owns the dwelling (as observed in the data) and in turn cause lower heating expenditures for owners. The difference in modernizations made in owner- and tenant-occupied dwellings and the lower energy expenditures for owners indicating lower insulation give reason to Hypothesis 3. The landlord-tenant problem may broaden the energy efficiency gap and impact the effectiveness of the subsidies.

A comparison of the disposable income of owners and tenants, as presented in the

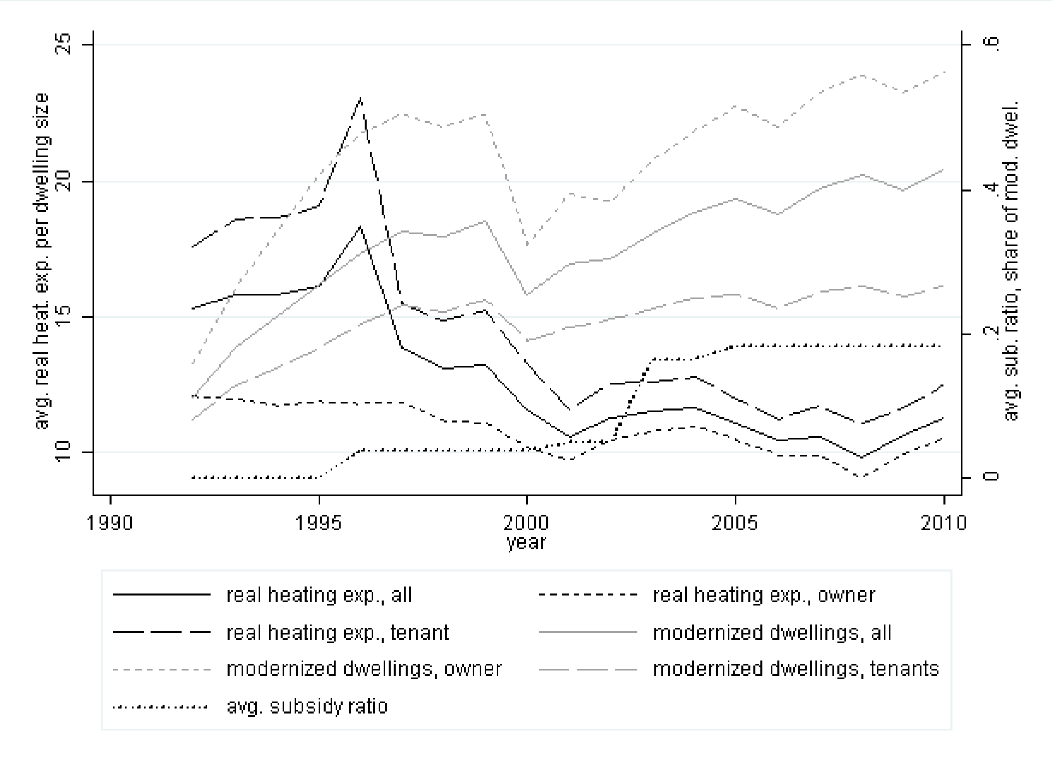


Figure 5.4: Average subsidy payments for different treatment periods and real heating expenditure

boxplots in Figure 5.5, reveals that the disposable income of owners tends to be significantly greater than that of tenants. Over all years, 75% of the tenants have less disposable income than the average owner. Baker et al. (1989) also find a significant correlation between homeownership and income.

In a functioning renting market, a landlord would modernize a dwelling as long as the rent could adapt according to the tenant's payment abilities. The income of a tenant thus may indicate a potential credit barrier to investments in energy efficiency. On the contrary, the high income of owners and the high proportion of subsidies received by owners – more than 50% of all subsidies in 2009[69] – may give reason to analyze whether subsidies may be a windfall in case of a high a priori willingness to pay.

[69]See Clausnitzer et al. (2010).

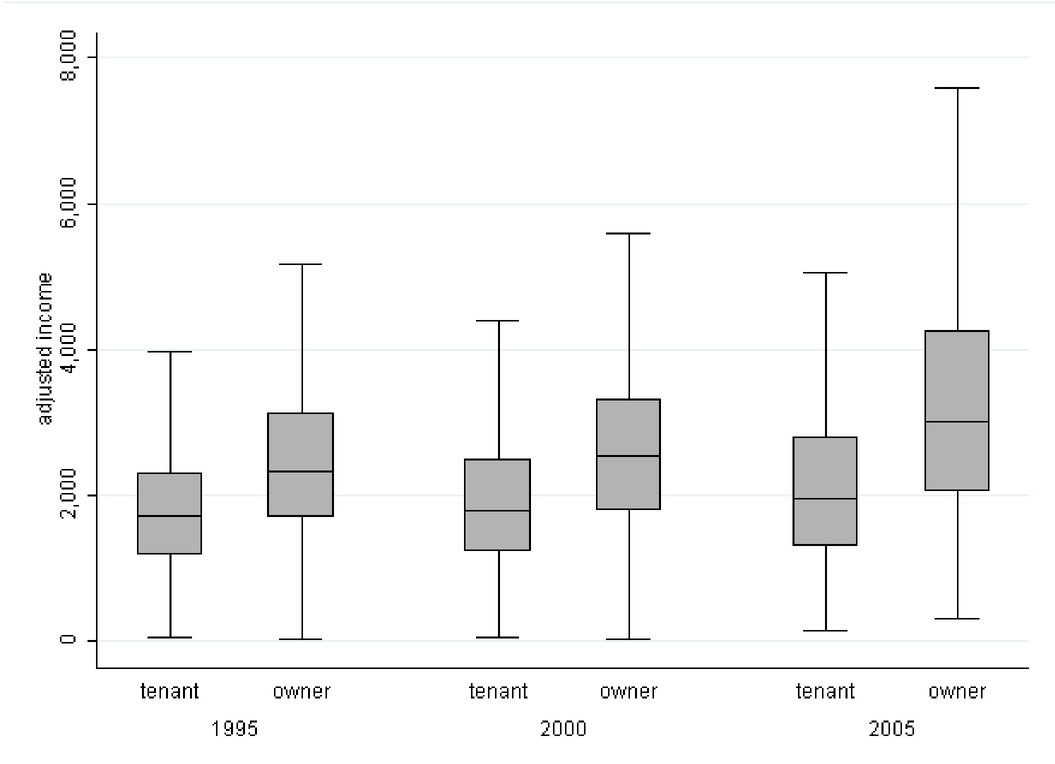


FIGURE 5.5: Boxplots of disposable monthly income in Euros for households with owners or tenants

5.5 Estimation Approach

The estimation objective is to analyze the effects of the German subsidy program on energy efficiency and to test the hypotheses presented in Section 5.3. The subsidy program is meant to give incentives to invest in energy efficiency thus reducing energy consumption. The subsidy program can be effective by increasing the number of investments in energy efficiency (quantity effect) and/or by improving the quality of the investments in terms of energy efficiency (quality effect). In the first model approach, the impact of the subsidy on the probability of dwelling modernizations is analyzed to capture the quantity effect (see Figure 5.6 arrow A). In the second approach, the impact of these dwelling modernizations investments on energy expenditures[70] is investigated (see Figure 5.6 arrow B). A differences-in-differences-in-differences (DDD) approach is applied which allows for an identification of the impact of dwelling modernizations made during the subsidy periods and estimates the effect B. Thus, the second approach measures the

[70]Energy expenditures and energy consumption are used as synonyms because prices are controlled for while estimating the impacts on energy expenditures.

quality effect, i.e. whether dwelling modernizations reduce energy expenditures dependent on the prevailing subsidy program. Moreover, both approaches, A and B control for the ownership status in order to identify potential differences in the dwelling modernization and energy consumption behavior in owner- and tenant-occupied dwellings.

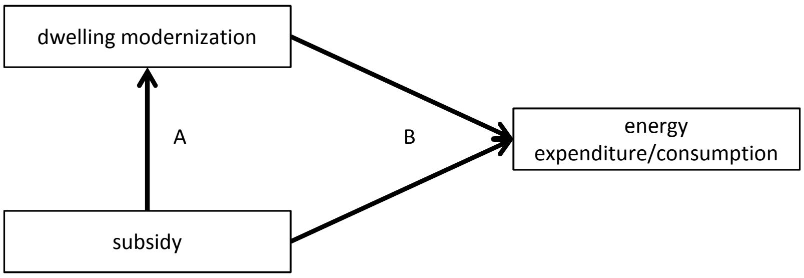


FIGURE 5.6: Estimation strategy

5.5.1 Number of investments in energy efficiency

First, an examination is performed to determine to what extent the number of dwelling modernizations can be explained by household characteristics and subsidies. The model estimates:

$$z_{i,t} = \alpha + \beta h_{i,t} + \gamma s_{r_i,p_t} + \delta_0 d_{0,i,t} + \delta d_{0,i,t} \cdot \gamma s_{r_i,p_t} + \delta_r d_{r_i} + \delta_t d_t + \epsilon_{i,t}, \tag{5.1}$$

where $z_{i,t} \in \{0,1\}$ describes whether a dwelling is modernized, $h_{i,t}$ is a vector of time-variant household and dwelling characteristics, s_{r_i,p_t} is the subsidy ratio in state r_i (with each household i being a part of state $r_i \in R$) in the subsidy program period p_t (for the years $t \geq 1996$, as a part of the program period $p_t \in P$), $d_{0,i,t}$ is a dummy variable indicating the ownership of the dwelling and $\epsilon_{i,t}$ is an error term that is assumed to be independent and identically distributed (i.i.d.). To control for time and regional effects, dummies are included for the different states (d_{r_i}) and for the different years (d_t). Two ordinary least squares models (OLS) with and without state dummies and a probit model are implemented. To avoid an underestimation of standard errors (due to serial correlation), all standard errors are robust and clustered at the household level.[71]

[71]Standard errors based on other clusters such as on a state, year or state and year level have been estimated and the clusters at the household level turned out to be the highest and thus the most conservative.

5.5.2 Heating energy expenditures

The second analysis investigates the impacts of the investments in energy efficiency on heating energy expenditures. The following panel data model is introduced:

$$log(y_{i,t}) = \alpha + \beta h_{i,t} + \gamma_1 log(p_t) + \gamma_2 w_{s_i,t} + \delta d_{i,t}^{DDD} + \delta_r d_{r_i} + \delta_t d_t + \epsilon_{i,t} \tag{5.2}$$

$$\begin{aligned} \text{with } \delta d_{i,t}^{DDD} &= \delta_0 d_{0,i,t} + \delta_1 d_{1,i,t} + \delta_2 d_{2,i,t} + \delta_3 d_{3,i,t} + \delta_4 d_{1,i,t} \cdot d_{2,i,t} + \delta_5 d_{1,i,t} \cdot d_{3,i,t} \\ &+ \delta_6 d_{0,i,t} \cdot d_{1,i,t} + \delta_7 d_{0,i,t} \cdot d_{2,i,t} + \delta_8 d_{0,i,t} \cdot d_{3,i,t} \\ &+ \delta_9 d_{0,i,t} \cdot d_{1,i,t} \cdot d_{2,i,t} + \delta_{10} d_{0,i,t} \cdot d_{1,i,t} \cdot d_{3,i,t}, \end{aligned}$$

where $log(y_{i,t})$ is the logarithm of monthly heating expenditures, $h_{i,t}$ is the matrix of time-variant household characteristics, $log(p_t)$ is the vector of the logarithm of gas prices that vary over time (but not over households), $w_{s_i,t}$ are the heating degree days that vary over states and time, d_{r_i} are state dummies and d_t year dummies. The variable $\epsilon_{i,t}$ is the error term, assumed i.i.d.

The estimation strategy is a differences-in-differences-in-differences (DDD) approach. The presented DDD approach controls for treated groups of households, modernizations and ownership status in order to ensure unconfoundedness so that conditional on these controls treatment assignment is essentially randomized. The matrix $\delta d_{i,t}^{DDD}$ presents the dummy variables and dummy interaction variables of the (DDD) approach. These dummy variables include dummies for dwelling modernizations, the treated household types and the ownership status. Specifically, the dummy variable $d_{0,i,t}$ indicates whether a dwelling is owner-occupied and $d_{1,i,t}$ indicates whether the dwelling has been modernized in previous years. $d_{2,i,t}$ identifies the treated households of the first subsidy period and $d_{3,i,t}$ the treated households of the second subsidy period. The *treated household group 1* indicates those households that modernize during the first subsidy period 1996–2002. The *treated household group 2* are those households that modernize during the second subsidy period 2003–2010. Households that apply for a subsidy may be households that invest more frequently in general or care more than average about their energy consumption and thus may already have lower heating expenditures before the renovation during the subsidy programs (or the contrary). Hence, the dummies $d_{2,i,t}$

and $d_{3,i,t}$ control for general differences in energy expenditures between the treated and non-treated household types.

The interaction terms $d_{1,i,t} \cdot d_{2,i,t}$ and $d_{1,i,t} \cdot d_{3,i,t}$ indicate whether a treated household type has modernized. As the ownership status is additionally included in the last three interaction terms, the first three interaction terms without $d_{0,i,t}$ are included to measure the effects in tenant-occupied dwellings. The landlord-tenant problem may result in a significant difference between heating expenditures of owners and tenants and Figure 5.3 and Figure 5.4 in Section 5.4.2 already gave an indication for this assumption. Therefore, the interaction term $d_{0,i,t} \cdot d_{1,i,t}$ identify modernizations made by owners. The interaction terms $d_{0,i,t} \cdot d_{1,i,t} \cdot d_{2,i,t}$ and $d_{0,i,t} \cdot d_{1,i,t} \cdot d_{3,i,t}$ indicates treated households that have modernized and are owners.

The DDD approach and the inclusion of two treatment periods identify further pre-existing differences in trends and serve to cope with the parallel trend assumption that is assumed to hold for the development of energy expenditures and modernizations between the considered households.

A simplified interpretation of the effects of the DDD approach is presented in Table 5.2:

Table 5.2: Interpretation of dummy variables in the differences-in-differences-in-differences approach

δ_0	$= \overline{y}_{own.} - \overline{y}_{!own.}$
δ_1	$= \overline{y}_{mod.} - \overline{y}_{!mod.}$
$\delta_{2,3}$	$= (\overline{y}_{treat_j} - \overline{y}_{!treat_j})$
$\delta_{4,5}$	$= (\overline{y}_{treat_j,mod.} - \overline{y}_{treat_j,!mod.}) - (\overline{y}_{!treat_j,mod.} - \overline{y}_{!treat_j,!mod.})$
δ_6	$= (\overline{y}_{mod.,own.} - \overline{y}_{mod.,!own.}) - (\overline{y}_{!mod.,own.} - \overline{y}_{!mod.,!own.})$
$\delta_{7,8}$	$= (\overline{y}_{treat_j,own.} - \overline{y}_{treat_j,!own.}) - (\overline{y}_{!treat_j,own.} - \overline{y}_{!treat_j,!own.})$
$\delta_{9,10}$	$= \left[(\overline{y}_{treat_j,mod.,own.} - \overline{y}_{treat_j,mod.,!own.}) - (\overline{y}_{treat_j,!mod.,own.} - \overline{y}_{treat_j,!mod.,!own.})\right]$
	$- \left[(\overline{y}_{!treat_j,mod.,own.} - \overline{y}_{!treat_j,mod.,!own.}) - (\overline{y}_{!treat_j,!mod.,own.} - \overline{y}_{!treat_j,!mod.,!own.})\right]$

For $\delta_2, \delta_4, \delta_7, \delta_9$, the subscript j refers to the first subsidy period 1996–2002. For $\delta_3, \delta_5, \delta_8, \delta_{10}$, the subscript j refers to the second subsidy period 2003–2010. The variable

$\overline{y}$ reflects the average heating energy expenditure of the respective group. The term $own.$ indicates ownership of the dwelling and $!own.$ refers to tenants. The term $mod.$ identifies households that modernized their dwellings and $!mod.$ describes households that did not. The term $treat_j$ indicates the households that modernized in the subsidy program period in general (not only during the subsidy period) and $!treat_j$ are all other households.

Thus, $\delta_{9,10}$ can be interpreted as the triple deviation in the heating expenditures of a) owner and tenants, b) households that modernized c) treated households. The time and regional effects on energy expenditure are additionally controlled for through d_{r_i} and d_t.

In the first step, the model presented in Equation 5.3 is estimated without the DDD approach, i.e. excluding the matrix $\delta d_{i,t}^{DDD}$, and is additionally separately estimated for only owners and only tenants. These reduced models are estimated to analyze the impact of the household and dwelling characteristics on energy consumption and to get an idea of the different energy consumption behavior and price elasticities of owners and tenants.

In the second step, the model in Equation 5.3 is estimated in an ordinary least squares approach (OLS) with and without state dummies, and then in a feasible least squares approach (FGLS) again with and without state dummies. All standard errors are robust and clustered at the household level to avoid an inconsistent estimation of standard errors due to a serial intra-household correlation (see Bertrand et al. (2004)). The FGLS estimation capturing the assumption of serial correlation in the variance covariance matrix, additionally serves to check the robustness of the results.

5.6 Results

5.6.1 Impacts on dwelling modernizations

Previous studies presented in Section 5.2 have shown the importance of accounting for socio-economic and dwelling characteristics in analyzing household investments in energy efficiency. Therefore, the impacts of these characteristics are first described and the effects of the subsidies and the ownership status on renovations are then investigated.

5.6.1.1 Impacts of socio-economic and dwelling characteristics

Table 5.3 presents the determinants of dwelling modernizations based on Equation 5.1. The mean dwelling modernization rate in the dataset for all households between 1992 and 2010 is 5.9% (see Table C.1), which is only slightly impacted by socio-economic and dwelling characteristics. A 1% increase in income increases the probability of dwelling modernization by only 0.01 percent on average over all households. These results indicate that credit barriers may not play a major role.

The categorical variable *household type* is an indicator for the household size and has larger values for more family members. The results mirror that the larger the household, the lower the probability of dwelling modernizations.

The modernization state of buildings from older vintage classes may probably be

TABLE 5.3: Results Estimation A: Probability of dwelling modernizations

dwelling modernizations	OLS (1)	OLS (2)	Probit (3)	AME[1], Probit (3)
owner-occupied	0.0115***	0.0115***	0.0917***	0.0115***
	(0.0023)	(0.0023)	(0.0185)	(0.0025)
log. of adj. income	0.0108***	0.0106***	0.0957***	0.0111***
	(0.0012)	(0.0012)	(0.0109)	(0.0013)
household type	-0.0011***	-0.0012**	-0.0083**	-0.0010**
	(0.0004)	(0.0004)	(0.0035)	(0.0004)
construction period	-0.0075***	-0.0075***	-0.0652***	-0.0075***
	(0.0004)	(0.0004)	(0.0036)	(0.0004)
number of relocations	0.0085***	0.0084***	0.0684***	0.0079***
	(0.0007)	(0.0007)	(0.0048)	(0.0006)
number of rooms (> 6 m^2)	0.0036***	0.0037***	0.0282***	0.0033***
	(0.0005)	(0.0005)	(0.0036)	(0.0004)
need of renovation	0.0034**	-0.0034	0.0291***	0.0034***
	(0.0013)	(0.0013)	(0.0111)	(0.0013)
subsidy ratio	0.0089	-0.0202	-0.0235	-0.0027
	(0.0411)	(0.0314)	(0.3480)	(0.0402)
subsidy ratio, owner	0.0304*	0.0308*	0.3876***	0.0448***
	(0.0166)	(0.0166)	(0.1425)	(0.0165)
Observations	125686	125686	125686	
Clusters	16870	16870	16870	
Overall (Pseudo-) R^2	0.0071	0.0068	0.0159	
Wald-Test (Probit/) F-Test (OLS)	31.03	38.93	1095.16	
Prob. > χ^2 (Probit) / Prob. > F (OLS)	0.000	0.000	0.000	

[1] AME: Average Marginal Effects
Robust standard errors are clustered by households and are reported in parentheses.
All models include a constant and year dummies.
Models (1) and (3) additionally include state dummies.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

lower. The effect of the *construction period* variable shows that this holds true. The effect is significant and reflects a significantly lower probability of younger dwellings being modernized than those from earlier construction periods.

The number of relocations increases the probability of modernizations by 0.79 (model (3)) to 0.85 (model (1)) percentage points, i.e. the more often households relocate, the more probable it is that they will invest in their dwelling. The result seems surprising as one may assume that a household that frequently moves is less likely to invest in their dwelling. However, households in Germany seldomly relocate. 69% of all households in the sample never move and 93% move not more than twice. Thus, the probability of renovations is higher when households move into a new location rather than stay in their current building. There may be various reasons for relocaters to invest, such as further socio-economic characteristics that are not covered in the model (e.g. the type of job).

Dwellings with more rooms and more windows exhibit a higher probability of dwelling modernizations. The probability increases by 0.33 (model (3)) to 0.37 (model (2)) percentage points for each additional room. As window modernizations are a major part of dwelling modernizations, the more rooms that are in a dwelling, the more windows it has, thus increasing the need and probability of modernization. In addition, the worse the condition of the dwelling evaluated by the household (*need of renovation*) the higher the probability of dwelling modernizations.

5.6.1.2 Impacts of subsidies and ownership status

To evaluate Hypothesis 1 and 3 presented in Section 5.3, the impacts of ownership status and subsidies spent are analyzed.

The impacts of the *subsidy ratio* (proportion of subsidies to modernization spendings) on the number of modernizations in tenant-occupied dwellings is not significant in all models. Only a small proportion of dwellings is modernized each year and the modernization rates only change slightly. The probability of renovation of tenant-occupied dwellings (made by landlords) thus seems to be mainly impacted by socio-economic and dwelling characteristics. The number of dwelling modernizations by landlords is not impacted by increasing subsidy levels, which may contradict Hypothesis 1. However, although the number of renovations does not increase through the subsidy, the quality might (Hypothesis 2). The quality impact is investigated in the results of the next section.

The models show the significant impact of ownership status on the probability of dwelling modernizations. The probability of dwelling modernizations increases by about 1.2 percentage points, i.e. almost 20% of the average dwelling modernization rate of 5.9%, when the dwelling is owner-occupied. The resulting effect confirms the results of other studies (Gebhardt, 2012) that there exists an underinvestment in buildings that are not occupied by the owners. Thus, this landlord-tenant problem is prominent in the German building stock and has essential impacts on investments in energy efficiency, supporting Hypothesis 3.

In accounting for the higher renovation probability owners generally have a 1 percentage point increase in the subsidy ratio increases the probability of dwelling modernizations by 0.030 (model (1)) to 0.045 (model (3)) percentage points. Thus, the effect of the subsidy on renovations in owner-occupied dwellings is small. In addition, the effect is only slightly significant in the OLS models. Hence, the results show that the subsidy increased the incentives to renovate only for households of homeowners, which further supports Hypothesis 3.

In summary, it can be concluded that the quantity effect of the subsidy, i.e. the subsidy increases the number of dwelling modernizations, only occurs for homeowners. During times of high subsidies, especially during the second program period, the probability of renovations only increases in owner-occupied dwellings. Landlords did not renovate more buildings with an increasing subsidy. However, if the landlord had decided to invest, the insulation level may have increased. In the next subsection, it is investigated whether this is truly the case.

5.6.2 Impacts on heating energy consumption

After the analysis of the quantity effect of the subsidy on dwelling modernization, this section analyzes the quality effect and attempts to answer the question whether renovations made during subsidy program periods decreased energy consumption. Socioeconomic and dwelling characteristics again play a major role and are controlled for. The first subsection describes their effects. The impacts of the renovations during subsidy periods based on the DDD approach are presented in the second subsection.

5.6.2.1 Impacts of socio-economic and dwelling characteristics

Heating expenditures[72] of households depend on a variety of household and dwelling conditions, as well as energy prices and heating degree days. These variables need to be controlled for in order to identify the impacts of modernizations with respect to the subsidy programs. Therefore, the first three OLS models in Table 5.4 neglect the DDD approach and estimate only the impact of the control variables on heating expenditures. Figure 5.2 shows the large difference in the heating expenditures in owner- and tenant-occupied dwellings. To demonstrate the different heating behaviors, separate models are estimated for a sample of only owners (in model (2)) and only tenants (in model (3)). Model (1) estimates the effects of the control variables for the whole sample. The effects are found to be quite robust in the whole sample over all models ((1), (4) - (7)) and explain between 17.5% (model (1)) and 18.5.% (model (2)) of the variation of total household warm water and heating expenditures. This is in the range of other studies. Rehdanz (2007) explains between 17% and 27% of the variation in heating expenditures and Brounen et al. (2012) explain about 16% of the variance in gas consumption in their basic model.

Heating expenditures increase as the number of heating degree days (HDD) increases, i.e. in colder years, for the whole sample. The impact of the heating degree days is however not significant for the sample of only owners ((model (2)), which may indicate a better insulation of owner-occupied dwellings. Cold days affect the heating expenditures in tenant-occupied dwellings to a larger extent.

The results in Table 5.4 present the price elasticity of expenditure on average over all households (models (1), (4) - (7)) as well as for owners (model (2)) and tenants (model (3)) separately. The price elasticity of energy-demand $\epsilon_{q,p}$ can be derived from the price elasticity of expenditure $\frac{\partial e(p)}{p}\frac{p}{e}$: For a single household, the gas price is exogenous such that the heating expenditures $e(p)$ can be described as $e(p) = pq(p)$, where p is the price

[72]Controlling for the price effect, the terms ‘expenditures’ and ‘consumption’ are used synonymously.

TABLE 5.4: Results Estimation B: Logarithm of heating expenditure per dwelling size

	OLS, All	OLS, Owner	OLS, Tenant	OLS, All		FGLS, All	
log. heat. exp. per m^2	(1)	(2)	(3)	(4)	(5)	(6)	(7)
owner-occupied (d_0)	-0.1801***			-0.1995***	-0.1992***	-0.2229***	-0.2234***
	(0.0083)			(0.0100)	(0.0100)	(0.0104)	(0.0104)
HDD	1.58e-07***	-1.60e-08	2.98e-07***	1.52e-07***	1.43e-07**	1.32e-07***	1.34e-07***
	(5.13e-08)	(6.48e-08)	(7.99e-08)	(5.10e-08)	(6.18e-08)	(4.43e-08)	(4.33e-08)
log. of gas price	0.5706***	0.8255***	0.2537***	0.5661***	0.5673***	0.5804***	0.5803***
	(0.0286)	(0.0396)	(0.0408)	(0.0287)	(0.0287)	(0.0274)	(0.0274)
log. of adj. income	0.0361***	0.0534***	0.0163**	0.0360***	0.0367***	0.0244***	0.0250***
	(0.0065)	(0.0094)	(0.0080)	(0.0065)	(0.0065)	(0.0055)	(0.0055)
household type	0.0069***	0.0002	0.0212***	0.0071***	0.0069***	0.0091***	0.0089***
	(0.0021)	(0.0030)	(0.0027)	(0.0021)	(0.0021)	(0.0017)	(0.0017)
construction period	-0.0409***	-0.0567***	-0.0156***	-0.0416***	-0.0421***	-0.0344***	-0.0348***
	(0.0023)	(0.0032)	(0.0029)	(0.0023)	(0.0023)	(0.0024)	(0.0024)
number of relocations	-0.0353***	-0.0691***	-0.0065**	-0.0352***	-0.0352***	-0.0485***	-0.0485***
	(0.0030)	(0.0056)	(0.0030)	(0.0030)	(0.0030)	(0.0032)	(0.0032)
number of rooms (> 6 m^2)	-0.0666***	-0.0613***	-0.0880***	-0.0666***	-0.0667***	-0.0678***	-0.0679***
	(0.0025)	(0.0030)	(0.0043)	(0.0025)	(0.0025)	(0.0024)	(0.0024)
need of renovation	0.0211***	0.0285***	0.0232***	0.0215***	0.0220***	0.0140***	0.0143***
	(0.0057)	(0.0106)	(0.0063)	(0.0057)	(0.0057)	(0.0043)	(0.0043)

Continuing next page.

modernized (d_1)				0.0357**	0.0364**	0.0445***	0.0450***
				(0.0156)	(0.0155)	(0.0114)	(0.0114)
treated household group 1 (d_2)				-0.0401**	-0.0401**	-0.0347**	-0.0352**
				(0.0166)	(0.0166)	(0.0162)	(0.0162)
treated household group 2 (d_3)				-0.0675***	-0.0697***	-0.0900***	-0.0906***
				(0.0177)	(0.0177)	(0.0150)	(0.0150)
modernized x treated household group 1 ($d_1 \cdot d_2$)				-0.0471**	-0.0482**	-0.0557***	-0.0565***
				(0.0200)	(0.0200)	(0.0151)	(0.0151)
modernized x treated household group 2 ($d_1 \cdot d_3$)				-0.0492***	-0.0493***	-0.0481***	-0.0485***
				(0.0188)	(0.0187)	(0.0146)	(0.0146)
modernized x owner				-0.0881***	-0.0883***	-0.0975***	-0.0981***
				(0.0199)	(0.0198)	(0.0144)	(0.0144)
treated household group 1 x owner ($d_0 \cdot d_2$)				0.0430*	0.0426*	0.0481**	0.0486**
				(0.0232)	(0.0232)	(0.0221)	(0.0221)
treated household group 2 x owner ($d_0 \cdot d_3$)				0.0907***	0.0936***	0.1258***	0.1271***
				(0.0221)	(0.0220)	(0.0197)	(0.0197)
modernized x treated household group 1 x owner ($d_0 \cdot d_1 \cdot d_2$)				0.1271***	0.1283***	0.1362***	0.1373***
				(0.0258)	(0.0258)	(0.0200)	(0.0200)
modernized x treated household group 2 x owner ($d_0 \cdot d_1 \cdot d_3$)				0.1292***	0.1291***	0.1299***	0.1306***
				(0.0221)	(0.0221)	(0.0176)	(0.0176)
Observations	102535	56022	46513	102535	102535	102535	102535
Clusters	15421	8271	8885	15421	15421	15421	15421
Overall (Pseudo-) R^2	0.1749	0.1849	0.1133	0.1773	0.1760	0.1759	0.1748
F-test (OLS)/Wald-test (FGLS)	333.56	208.74	118.81	248.64	324.83	10886.44	10747.69
P>F(OLS)/P>χ^2(FGLS)	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Robust standard errors are clustered by households and are reported in parentheses.
All models include a constant and year dummies for two consecutive years.
Model (1),(3),(5) and (6) additionally include a state dummies.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

and $q(p)$ is the heating energy consumed. Therefore:

$$\frac{\partial e(p)}{\partial p}\frac{p}{e} = \left(q(p) + p\frac{\partial q(p)}{\partial p}\right)\frac{p}{pq(p)} = 1 + \epsilon_{q,p} \tag{5.3}$$

$$\epsilon_{q,p} = \frac{\partial e(p)}{\partial p}\frac{p}{e} - 1 \tag{5.4}$$

$$\text{with} \quad \epsilon_{q,p} = \frac{\partial q(p)}{\partial p}\frac{p}{q(p)} \tag{5.5}$$

The effect of gas prices is significant with an price elasticity of expenditure of 82.55% (model (2)) to 25.37% (model (3)) on average over all households. Thus, for owners, the price elasticity of energy-demand is approximately $\epsilon_{q,p} = \frac{\partial e(p)}{p}\frac{p}{e} - 1 = 0.83 - 1 = -0.17$ and for tenants $\epsilon_{q,p} = 0.25 - 1 = -0.75$. Tenants with higher mean heating expenditures per square meter (see Figure 5.3) react more elastic to increases in energy price compared to owners, who exhibit a very low price elasticity of demand. For tenants, a 10% increase in energy prices results in a 7.5% reduction of energy consumed. According to Khazzoom (1980), a high demand elasticity indicates a larger rebound-effect. Hence, investments in energy efficiency for tenant-occupied dwellings may be less effective in increasing energy-savings. The price elasticity of tenants can be ascribed to the landlord-tenant problem: Since the landlord cannot internalize his investment costs in the rents paid by tenants, the tenant benefits from the energy savings but does not bear the investment costs.
The adjusted income has a significant impact on heating expenditures. A 1% increase in income increases the heating expenditures per m^2 by 0.024% (model (6)) to 0.037% (model (5)) on average for all households. A 1% higher income of owners increases energy expenditures, by 0.053%, compared to tenants who only exhibit an expenditure income elasticity of 0.016. These differences in income elasticities indicate to the landlord-tenant problem. Higher income of tenants does not increase the insulation level and decrease energy consumption to the same extent as the higher income of homeowners does.

Impacts of the household composition (*household type*) are more relevant in explaining heating expenditures than dwelling modernizations. Brounen et al. (2012) have already shown the importance of including the household composition and other socio-economic factors in the explanation of residential gas consumption. The heating expenditures increase as the number of household members increases. However, the impact of the number of household members is not significant for owner-occupied dwellings, which may be traced back to higher insulation standards.

Heating expenditures are significantly lower for dwellings from later rather than from earlier construction periods, especially the effect is stronger when considering owner-occupied dwellings. The *number of relocations* has a negative and significant impact on heating expenditures, as opposed to a positive impact on the probability of dwelling modernizations, as previously discussed. The previous section shows that households which relocate tend to invest more in energy efficiency, thus significantly decreasing heating expenditures. The negative impact is considerably higher for owners than for tenants. Investments made by owners thus appear to be more energy-efficient. Moreover, it may be that households, and especially owners, relocate to more energy-efficient dwellings. The *number of rooms* decreases the heating expenditures per square meter by 6.1% (model (2)) to 8.8% (model (3)). Furthermore, the *need for renovation*, as assigned by the interviewed household members, increases heating expenditures significantly.

In summary, the estimation results have shown that the heating expenditures of owners and tenants differ significantly and that tenants tend to be significantly more price sensitive. The next section analyzes the impacts of ownership status and the impacts of modernizations made during subsidy periods.

5.6.2.2 Impacts of ownership status and modernizations during subsidy periods

In addition to the quantity effect investigated in Section 5.6.1.2, this section examines the quality effect (Hypothesis 2), i.e. the impact on energy consumption of modernizations made by owners and landlords during subsidy periods. The analysis of the impact of the subsidies on the number of dwelling modernizations presented in Section 5.6.1.2 shows that the subsidies only have a significant impact on renovations when made by homeowners. This section attempts to further analyze Hypothesis 3, i.e. whether the landlord-tenant problem causes underinvestment in energy efficiency and reduces the effectiveness of subsidies.

In general, heating expenditures are by 18% (model (1)) to 22.3% (model (7)) significantly lower in owner-occupied dwellings. Homeowners tend to renovate buildings more energy efficiently than landlords do.

In comparison to models (1) to (3), models (4) to (7) additionally include the dummy variables and the interaction of dummy variables in the DDD approach. In general, modernized tenant-occupied (*modernized*) dwellings exhibit significantly higher heating expenditures than other dwellings. Tenant-occupied dwellings seem to be poorly insulated, which, despite being renovated, still cause high energy consumption levels. Putting it differently, it appears that especially poorly insulated tenant-occupied dwellings are modernized and still exhibit high energy consumption levels after the modernization.

The tenants who belong to the *treated household group 1* (whose dwellings are modernized during the first program period) have significantly lower heating expenditures on average compared to other households. Given these conditions, modernizations made within the period 1996–2002 additionally decrease their heating expenditures by 4.7% (model (4)) to 5.7% (model (7)). Tenants who are part of the *treated household group 2* already exhibit lower heating expenditures than other households in general. Their heating expenditures are further reduced by 4.9% by renovation.

Thus, a landlord-tenant problem is present. However, the subsidy programs appear to have a positive impact on investments in energy efficiency made by landlords, despite the landlord-tenant problem. These findings provide a proof for Hypothesis 2 and 3. Moreover, the significant effects of the dummies that control for the household types living in dwellings that were modernized during the sample years, presents the importance of the DDD approach. The DDD approach controls for energy consumption behavior which would have otherwise affected the estimators of the modernizations made during the subsidy periods.

Heating expenditures in modernized owner-occupied dwellings are by 8.8% (model (4)) to 9.8% (model (7)) lower than the heating expenditures in modernized tenant-occupied dwellings. Nontheless, homeowners belonging to the *treated household group 1* generally have by 4.3% (model (4)) to 4.9% (model (7)) higher expenditures and homeowners of the *treated household group 2* have even higher expenditures. These comparably high energy expenditure levels indicate the need of renovation or a lavish energy consumption behavior of treated homeowners.

The isolation of the effects (i.e. $\delta_{9,10}$) of modernizations made by owners during the two subsidy program periods shows an increase for both periods, by 12.7% (model (6)) to 13.7% (model (5)) for the first and by about 13% for the second program period. These positive impacts indicate that the modernizations do not decrease heating expenditures of homeowners of the *treated household group 1* during the subsidy periods. On the contrary, modernization measures made by owners during the subsidy period even lead to higher heating expenditures. These higher heating expenditures may be caused by dwelling modernizations that increased energy consumption such as dwelling extensions and proves that homeowners did not sufficiently invest in energy-efficiency or that they overconsume energy after the investment. These effects control for the generally lower heating expenditures of owners and for the treated household types.

Figure 5.7 sums up the results and presents the differences between the two treated household types in owner- and tenant-occupied dwellings. Figure 5.7 displays the distributions of real heating expenditures for households that did not modernize between 1996 and 2010, for owners and tenants separately. In addition, the distributions of expenditures of households that modernized are shown, before and after the renovation, again separately for owners and tenants. In summary, households comprised of owners exhibit significantly lower heating expenditures than tenant households and invest more in energy efficiency than landlords. By isolating the impact of the already lower heating expenditures of owners, it can be seen that the modernizations made during the subsidy period result in reduced heating expenditures for tenants but not for owners. More than half of the subsidies were paid to owners. Thus, it can be concluded that owners make significant windfall profits when they are willing to renovate and invest in energy efficiency, even without subsidies.

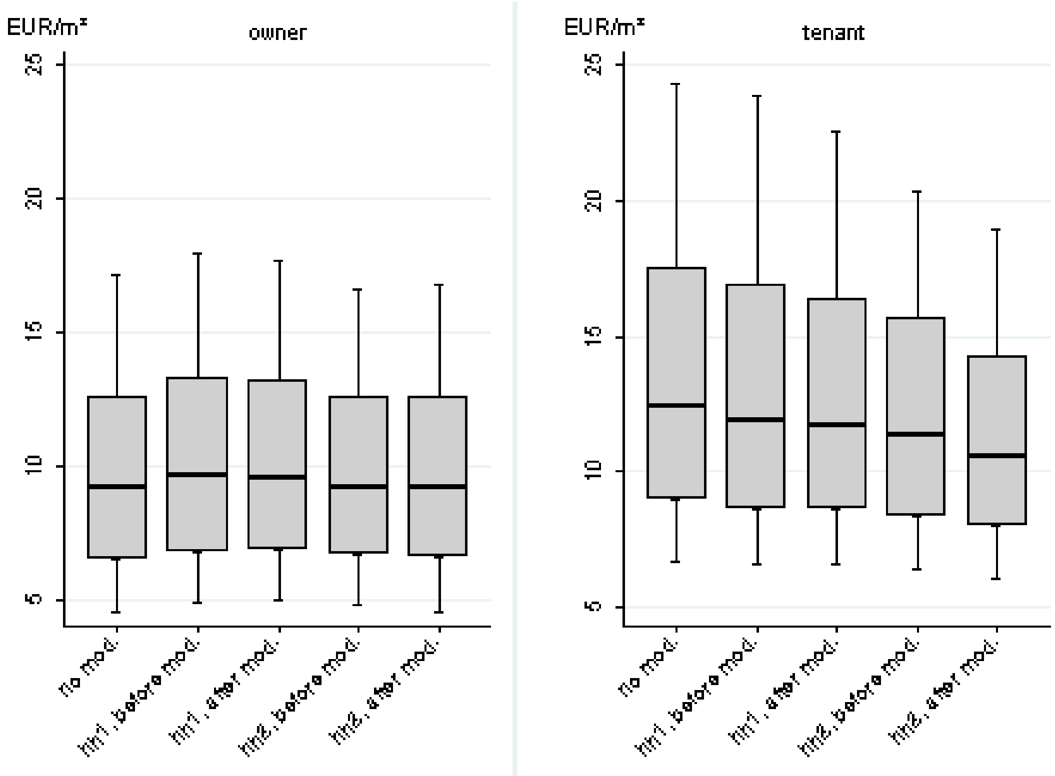


FIGURE 5.7: Treatment effect on real heating expenditures in Euros per m^2
The whiskers of the boxplots indicate the 10% to 90% range.
'no mod.' indicates households that did not modernize their dwelling between 1992–2010.
'hh1' ('hh2') are households that invested in 1996–2002 (2003–2010).
'before' and 'after' indicates the real heat. exp. before and after the modernization.

5.7 Conclusion

Households are heterogeneous concerning their socio-economic characteristics and the state of their dwellings. Hence, the reasons for and the degree of investment inefficiencies are diverse. The theoretical and empirical results show the importance of the heterogeneity of households, as well as the impact of their socio-economic characteristics on investments in energy efficiency and on energy consumption. The effectiveness of policy measures is determined by varying credit constraints and the different valuation of energy savings of households. The results of this paper thus support the results of Brounen et al. (2012) reiterating that socio-economic aspects need to be taken into account in order to develop an optimal policy design. Accounting for the heterogeneity of households is crucial in the design of targeted policies.

The landlord-tenant problem in the German heating market represents a restrictive investment barrier. Investments responsible for decreasing energy consumption mostly occur in owner-occupied dwellings as opposed to tenant-occupied ones. The presented paper provides evidence for this principal-agent problem and the lack of investments in tenant-occupied dwellings. Thus, the energy efficiency gap is broadened by the landlord-tenant problem.

The empirical results show only slight increases in the probability of dwelling modernizations in owner-occupied dwellings throughout the subsidy programs. Therefore, a quantity effect, i.e. when a subsidy leads to more dwelling modernizations, cannot be found for investments made by landlords in tenant-occupied dwellings. However, modernizations made during subsidy periods significantly decrease energy expenditures in tenant-occupied dwellings. Households who own their dwelling generally have significantly lower heating expenditures (by about 20%) than tenants and renovate more often than landlords. The modernizations made by owners during the subsidy program periods did not further decrease their heating expenditures. Homeowners invest in energy efficiency even without subsidies and could realize significant windfall profits through the subsidy payments. Furthermore, a higher income of owners indicates to a lower probability of credit barriers and a higher probability of windfall profits. Thus, the subsidies reflect an indirect redistribution of income to a group that is already economically better off.

The impact of energy prices on heating energy consumption is heterogeneous. Whereas tenants exhibit a high price elasticity, the price elasticity of owners is low. Therefore, the rebound effect in tenant-occupied dwellings may be larger than in owner-occupied ones, which can again be traced back to the landlord-tenant problem. Higher energy consumption of tenants due to insufficient renovations by landlords increase the price sensitivity of tenants and may further counteract the effectiveness of the subsidies.

The investment barrier in tenant-occupied dwellings first needs to be directly eliminated before policy measures can be implemented. Changes in tenancy law and the resolving of information asymmetries between tenants and owners concerning the energy consumption of dwellings may lower the investment barrier. The provision of information and the transparency of the heating energy requirements of dwellings may affect the choice of potential tenants and increase investments by landlords in energy efficiency.

Institutional adaptations (e.g. adaptations of the rental law) to increase incentives for landlords to independently invest may be more effective in achieving energy and greenhouse gas conservation objectives. However, such changes may have other welfare effects. Moreover, demographical changes such as increases in dwelling size and reduction of household members may counteract energy-savings in the future. An analysis of policies accounting for such effects is open for further research.

Appendix A

Supplementary Material to Chapters 2 and 3

A.1 Main equations of the TIGER model

The TIGER model originally developed by Lochner and Bothe (2007) optimizes the European natural gas dispatch given the infrastructure components, i.e. long-distance transmission pipelines, storages and LNG import terminals, minimizing the total costs of gas supply. A detailed model description can be found in EWI (2010b). The **Objective Function**

$$\begin{aligned} C = & \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,n_2} \Big((T_{sc,t,n_1,n_2} + T_{sc,t,n_2,n_1}) \cdot c^{trans}_{t,n_1,n_2}) \Big) \right] \\ & + \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,p} \Big(P_{sc,t,n_1,p} \cdot c^{prod}_{t,n_1,p} \Big) \right] \\ & + \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,s} \big(St_{sc,t,n_1,s} \cdot c^{stor}_{t,n_1,s} \big) \right] \\ & + \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,r} \big(LNGSt_{sc,t,n_1,r} \cdot c^{LNGstor}_{t,n_1,r} \big) \right] \\ & + \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,r} \big(LNGR_{sc,t,n_1,r} \cdot rt_r \big) \right] \\ & + \sum_{sc} \theta_{sc} \sum_{t} \vartheta_t \left[\sum_{t,n_1,z} \big(DD_{sc,t,n_1,z} \cdot dc_{n_1,z} \big) \right] \end{aligned} \tag{A.1}$$

is minimized over the vector $X = (T, P, St, LNGSt, LNGR, DD)$.

Gas supply and demand need to balanced. At each node, gas supply, that could either be storage withdrawal, pipeline supply, LNG import or production, needs to equal gas demand. Thus, the **Node Balance Constraint** yields:

$$\underbrace{\sum_{dr} d_{sc,t,n_1,dr}}_{\text{demand}} = \tag{A.2}$$

$$\underbrace{\sum_{n_2} T_{sc,t,n_2,n_1} + \sum_{pr} P_{sc,t,n_1,pr} + \sum_{r} LNGR_{sc,t,n_1,r} + \sum_{z} DD_{sc,t,n_1,z}}_{\text{inflow at node}}$$

$$- \underbrace{\sum_{n_2} T_{sc,t,n_1,n_2} - \sum_{st} [StIn_{sc,t,n_1,st} - StOut_{sc,t,n_1,st}]}_{\text{outflow at node}}$$

The marginal supply costs estimator at a certain node n_1 at time t is the dual variable associated with the Node Balance Constraint. The dual variable reflects the increase of the Objective Function's optimal value by marginally increasing demand in the Node Balance Constraint. The dual variable is thus interpreted as the shadow price of supply. For a more detailed model description with focus on the determination of marginal supply costs (or nodal prices) see Lochner (2009) and Lochner (2011a).

The following **Technical Constraints** must hold:

Production capacity constraint:

For each y the sum of daily supply volumes from a production region has to be smaller or equal to the annual supply capacity.

$$\sum_{t} \vartheta_t \cdot P_{sc,t,n_1,p} \leq cap^{annualsupply}_{n_1,p} \tag{A.3}$$

Daily production is constrained by daily peak capacity.

$$P_{sc,t,n_1,p} \leq cap^{peaksupply}_{t,n_1,p} \tag{A.4}$$

Pipeline capacity constraint:

Transported gas volumes are restricted by pipeline capacity.

$$T_{sc,t,n_1,n_2} \leq cap^{pipe}_{t,n_1,n_2} \tag{A.5}$$
$$T_{sc,t,n_2,n_1} \leq cap^{pipe}_{t,n_2,n_1}$$

LNG constraint:

Similar to the supply constraints, LNG imports are restricted by daily and annual capacity constraints.

$$LNGR_{sc,t,n_1,r} \leq cap^{peakregas}_{t,n_1,r} \tag{A.6}$$
$$\sum_t \vartheta_t \cdot LNGR_{sc,t,n_1,r} \leq cap^{annualregas}_{y,n_1,r}$$

LNG volumes to be imported are only restricted by LNG import capacity. The LNG costs assumptions (presented in A.3) mirror a long term equilibrium and are therefore higher than pipeline costs. LNG costs cover the costs of volumes on the tanker in front of the terminal.

Storage constraint for t, n_1 and s:

Storage volumes depend on withdrawals and injections of the previous period and are restricted by storage specific working gas volumes.

$$St_{sc,t,n_1,s} = St_{sc,t-1,n_1,s} + StIn_{sc,t,n_1,s} - StOut_{sc,t,n_1,s} \tag{A.7}$$
$$St_{sc,t,n_1,s} \leq wgv_{t,n_1,s}$$

The storage level is determined by withdrawals and injections (minus compressor consumption) and restricted by working gas volume. The gas volumes injected into and withdrawn from the storages $StIn_{t,n_1,s}$ and $StOut_{t,n_1,s}$ are a function of maximum injection and withdrawal rates and the storage level. The maximum injection and withdrawal rates depend on pressure and thus on the current storage level as well as on the storage type. LNG storages operate in the same manner.

List of symbols

Sets and identifiers

$dr \in D$: demand region

$n_1 \in N$: (start) nodes

$n_2 \in N$: (end) nodes

$p \in P$: production region

$r \in R$: LNG regasification terminal index

$s \in S$: storage index

$sc \in SC$: scenario index

$t \in T$: time period (days in this model version)

$z \in Z$: demand groups

Parameters

θ_{sc}: weight of scenario

ϑ_t: weight of modeled period t

$d_{t,n_1,dr}$: demand at node n_1

c^{trans}_{t,n_1,n_2}: transportation costs between nodes n_1 and n_2

$c^{stor}_{t,n_1,s}$: storage costs of storage s

$c^{LNGstor}_{t,n_1,r}$: LNG storage costs at regasification terminal r

$c^{prod}_{t,n_1,pr}$: production costs at node n_1

rt_r: regasification tariff of regasification terminal r

$dc_{n_1,z}$: disruption costs for group z

$cap^{peaksupply}_{t,n_1,p}$: peak supply capacity at node n_1

$cap^{annualsupply}_{y,n_1,p}$: annual supply capacity at node n_1

cap^{pipe}_{t,n_1,n_2}: pipeline capacity from node n_1 to node n_2

cap^{pipe}_{t,n_2,n_1}: pipeline capacity from node n_2 to node n_1

$cap^{peakregas}_{t,n_1,r}$ peak regasification capacity of regasification terminal r

$cap^{annualregas}_{y,n_1,r}$ annual regasification capacity of regasification terminal r

$wgv_{t,n_1,s}$ working gas volume of storage s,

Please note that all cost parameters reflect real values over the time period considered.

Optimization Variables

T_{sc,t,n_1,n_2}: gas volumes transported from n_1 to n_2 T_{sc,t,n_2,n_1}: gas volumes transported from n_2 to n_1

$P_{sc,t,n_1,p}$: production at node n_1

$St_{sc,t,n_1,s}$: gas volumes in storage s

$StIn_{sc,t,n_1,s}$: gas volumes injected into storage s

$StOut_{sc,t,n_1,s}$: gas volumes withdrawn from storage s

$DD_{sc,t,n_1,z}$: demand disruption for demand group z

$LNGR_{sc,t,n_1,r}$: LNG volumes regasified in terminal r

$LNGSt_{sc,t,n_1,r}$: stored LNG volumes at regasification terminal r.

A.2 Model versions applied in Chapters 2 and 3

The model version applied in Chapter 2 is a linear optimization which does not account for different scenarios. Therefore, the identifier sc reflects just one scenario ($sc = 1, sc \in \{1\}$) and the weight of this scenario equals one ($\theta_{sc} = 1$). In addition, only one demand group z ($z \in \{1\}$) to model demand disruptions is considered.

For the analysis in Chapter 3, we include demand stochasticity to account for temperature-related demand fluctuations and the possibility of loss of imports from a country (i.e. Libya and/or Algeria). The model is a stochastic version of the previous linear optimization model minimizing the expected total cost of gas supply in the European gas market. Moreover, we assume two threshold prices $dc_{n_1,z}$ above which demand declines: an interruptible contract price above which industrial consumers reduce their demand, and an infinitely high threshold price above which other consumers are assumed to reduce consumption ($z \in \{1, 2\}$).

A.3 Parameterization and data sources

The TIGER model's input parameters for the simulations of this paper are based on the sources presented in the following table:

TABLE A.1: Data and sources

Input data	Specification of parameters	Sources
supply	export potential of non-European production regions and indigenous production	EWI (2010a)
costs	transportation costs and regasification tariffs	OME (2001)
	storage costs	UNECE (1999)
	production costs and costs of gas supply from a certain production region	EWI (2010a)
demand	annual demand EWI (2010a)	Capros et al. (2008),
	peak day demand	ENTSOG (2009)
infrastructure	all capacity assumptions and working gas volumes	publicly available sources from pipeline, LNG, and storage operators and the European associations' databases (see GIE (2010) and see EWI (2010a,b) for more details)

Assumptions made on storages as discussed above in the context of the storage constraint were developed with storage operators and are discussed in EWI (2010b).

Disruption costs are the most cost-intensive option to keep the node balance. The concrete level of disruption costs does not impact the model results in terms of disrupted volumes as long as these costs are higher than for alternative supply options. Disruption costs vary between countries depending on their demand structure and type of demand (household, industry or power demand), on weather conditions and substitutive energy carriers. Further comprehensive research is necessary to reflect these aspects in precise disruption cost estimations for the European gas market which was out of range within this study. Therefore only the disrupted volumes are evaluated and not the costs of such gas demand reductions.

Appendix B

Supplementary Material to Chapter 4

B.1 Assumptions

B.1.1 Data

The estimation of the discrete choice model is based on data on the distribution of energy carriers chosen by a number of building type categories in 2010, characteristics of these building types and the heating system costs. The number of buildings which have to install a new heating system per model period is derived from the dwelling stock based on exogenous modernization rates. The dwelling stock comprises six different vintage classes, differentiates between single/double and multiple dwellings and three different insulation levels (heat demand levels) per house type vintage class combination. Due to a lack of data for the diffusion of energy carriers per insulation level, we include the average heat demand per dwelling category in our discrete choice estimation. However, we account for the different insulations in our simulation model. Thus, our data comprises twelve different representative dwelling types with different heat demand, heating system costs and distributions of heating systems chosen in 2010. Out of this aggregated data, we generate our data set which represents the number of buildings that changed their heating system in 2010 differentiated by dwelling type with the respective characteristics. We assume that the total annual heating costs $TC_{n,j}$ are a major driver for the representative household n to decide on the investment into a heating system using the energy carrier j.

We define the total annual heating costs as follows:

$$TC_{n,j} = AF \cdot (IC_{n,j} - S_{n,j}) + OC_{n,j} + EC_{n,j} \tag{B.1}$$

where AF is the annuity factor, $IC_{n,j}$ the total investment costs of a heating system of energy carrier j, $OC_{n,j}$ are the annual operating costs and $S_{n,j}$ the subsidy paid by the German government. The current German policy system to support the diffusion of non-fossil heating systems is mainly based on subsidies and does not apply any extra taxes on the 'bad' carbon. $EC_{n,j}$ represent the energy consumption costs which are defined as:

$$EC_{n,j} = p_j \cdot (TD_n / AE_j) \tag{B.2}$$

p_j is the price of the consumed energy carrier, TD_n the total heat demand of dwelling, and AE_j the annual use efficiency of a heating system. (See Tables B.1 and B.2 for the cost and price assumptions.) The energy consumptions costs are determined by the amount of final energy that a house type consumed times the fuel price.[73] The amount of final energy consumed depends on the house type's heat demand, the heating system installed and the corresponding annual use efficiency of the system in 2010. A fixed interest rate of 6% and an assumed household's planning horizon of 15 years determine the annuity factor. For the data sources, see the follwoing tables in the Appendix. An overview of all sources is provided in Table B.1. The costs included in the discrete choice model equal the annual costs per demanded heat energy unit.

Based on the Pigovian carbon tax τ the rate T_j presented in Section 4.3 is derived by the following conversion: $\tau \cdot CF_j = t_j$ and $T_j = t_j \frac{TD_n}{AE_j}$. τ is the carbon tax in Euro per t CO_2-eq. and CF_j converts the Pigovian carbon tax into an energy carrier specific tax rate accounting for the amount of greenhouse gas emissions listed in Table B.3. Biomass is not taxed.

[73] We assume households to not have perfect foresight and that they have bounded rationality. Hence, only the energy costs of the current period are included in their considerations and future energy prices are not accounted for.

Introducing a carbon tax t_j in $Euro/kWh$ for oil, gas and power would lead to the following total annual heating costs TC:

$$TC_{n,j} = AF \cdot IC_{n,j} + OC_{n,j} + (p_j + t_j)\,(TD_n/AE_j) \tag{B.3}$$

and introducing a lump-sum subsidy $S_{n,j}$ on non-fossil fuel heating systems biomass and heat pumps would result in:

$$TC_{n,j} = AF \cdot (IC_{n,j} - S_{n,j}) + OC_{n,j} + p_j \cdot (TD_n/AE_j) \tag{B.4}$$

In the case of a carbon tax being introduced all households of the stock that have a heat pump, a gas or an oil heater are thus affected by such a tax and not only the households that have to make the decision on their heating system, i.e. have to modernize it. However, we assume that the households of the building stock that do not have to change their heating system due to break-down are inelastic to price changes. They neither change their heating system as a result of the tax nor do they change their energy consumption behavior for heating. Thus, their compensating variation is equal to the tax revenue that they generate. In terms of the welfare changes of the introduction of a tax or subsidy only the households who modernize their heating system are relevant.

Table B.1: Data and sources - overview

Input data	Specification of parameters	Sources
dwelling stock	in 2005	Destatis (2008),Destatis (2010b)
	extrapolation until 2010	IWU / BEI (2010)
	new buildings and demolitions	Destatis (2010c),Destatis (2010a)
costs	capital costs	
	except for micro chp	IE Leipzig (2009)
	micro chp	own assumptions
distribution of new heaters installed in 2010	distribution of decentral heating systems	BDH (2010)
	distribution in new buildings	Destatis (2010b)
	distribution in buildings with different construction years	IWU / BEI (2010)
greenhouse gas emissions	emissions of different energy carriers	Öko-Institut (2011)
modernization rates for heating systems and insulation	rates for dwellings with different construction years	IWU / BEI (2010)

Table B.2: Energy prices in Euro/kWh

energy carrier	**year**				
	2010	2015	2020	2025	2030
biomass	0.05	0.05	0.06	0.07	0.07
natural gas	0.06	0.07	0.07	0.08	0.09
heating oil	0.08	0.09	0.10	0.11	0.12
electricity	0.20	0.22	0.23	0.23	0.23

Own assumptions.
In addition, an annual fixed charge of 120 Euros has to be paid for natural gas.

Table B.3: Greenhouse gas emissions of energy carriers

energy carrier	**g CO_2-eq./kWh**
biomass	26
natural gas	242
heating oil	324
electricity	350

Based on Öko-Institut (2011).

Table B.4: Subsidies on heating system investment in Euro

heating system	**single dwelling**	**multi dwelling**
	subsidy I	subsidy I
biomass	2500	2500
heat pump	900	1200
	subsidy II	subsidy II
gas	500	500
biomass	900	1200
heat pump	900	1200

Table B.5: Heat demand in kWh/m^2a per insulation level

dwelling type	**construction period**	**no**	**low**	**average**
single	1900 - 1918	227	197	167
single	1919 - 1948	238	209	175
single	1949 - 1978	222	200	166
single	1979 - 1990	161	152	125
single	1991 - 1995	132	123	111
single	1996 - 2000	116	106	
single	2001 - 2004	99	97	
single	2005 - 2010	92	85	
multi	1900 - 1918	189	163	140
multi	1919 - 1948	194	166	143
multi	1949 - 1978	178	157	138
multi	1979 - 1990	136	125	110
multi	1991 - 1995	121	113	104
multi	1996 - 2000	116	108	
multi	2001 - 2004	105	104	
multi	2005 - 2010	96	90	

Table B.6: Dwelling stock - number of buildings (1000)

dwelling type	construction period	average dwelling area [m^2]	number of buildings (1000)	heating systems							insulation level			
				district heating	gas	electric-city	heating oil	biomass	heat pump	total	no	low	average	total
single	1900 - 1918	135	1988	39	935	144	618	146	106	1988	60	1272	656	1988
single	1919 - 1948	129	1960	45	1062	96	618	78	60	1960	39	1313	608	1960
single	1949 - 1978	141	5522	157	2169	223	2670	169	134	5522	359	4072	1090	5522
single	1979 - 1990	151	1939	43	934	75	763	66	58	1939	738	1073	128	1939
single	1991 - 1995	149	592	18	364	1	185	12	12	592	473	104	15	592
single	1996 - 2000	147	926	43	639	9	196	23	16	926	787	139	0	926
single	2001 - 2004	148	593	30	420	8	85	30	20	593	545	48	0	593
single	2005 - 2010	144	516	24	396	7	47	39	4	516	490	26	0	516
multi	1900 - 1918	430	399	41	269	13	62	8	6	399	8	243	148	399
multi	1919 - 1948	430	353	56	225	11	51	6	4	353	7	236	109	353
multi	1949 - 1978	430	1537	377	709	37	382	17	15	1537	85	1062	390	1537
multi	1979 - 1990	430	402	138	176	11	71	3	4	402	171	193	38	402
multi	1991 - 1995	430	137	18	93	0	24	0	1	137	109	23	5	137
multi	1996 - 2000	430	149	26	101	0	21	0	0	149	131	18	0	149
multi	2001 - 2004	430	60	10	46	0	5	0	0	60	56	4	0	60
multi	2005 - 2010	430	46	6	37	0	3	0	0	46	45	1	0	46

Based on Destatis (2008), Walberg et al. (2011), Destatis (2010b).

TABLE B.7: Capital cost assumptions of heating systems in single dwellings

		capital costs [Euro]					operating costs [Euro/a]	annual use efficiency				
		2010	**2015**	**2020**	**2025**	**2030**	**2010 to 2030**	**2010**	**2015**	**2020**	**2025**	**2030**
energy carrier i	**single dwelling (stock) [142 m^2]**											
gas	gas condensing boiler	6426	6426	6426	6426	6426	117	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	8806	8806	8806	8806	8806	205	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	17017	17017	17017	17017	17017	340	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	13195	13195	13063	12932	12803	50	3.7	3.75	3.80	3.85	3.90
	single dwelling (new) [144 m^2]											
gas	gas condensing boiler	9817.5	9621	9429	9240	9055	147	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	12197.5	11954	11714	11480	11251	235	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	17017	17017	17017	17017	17017	340	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	13195	13195	13063	12932	12803	50	3.7	3.75	3.80	3.85	3.90

Based on IE Leipzig (2009).

TABLE B.8: Capital cost assumptions of heating systems in multiple dwellings

		capital costs [Euro]					operating costs [Euro/a]	annual use efficiency				
		2010	**2015**	**2020**	**2025**	**2030**	**2010 to 2030**	**2010**	**2015**	**2020**	**2025**	**2030**
	multi dwelling (stock) [430 m^2]											
gas	gas condensing boiler	9520	9520	9520	9520	9520	120	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	15232	15232	15232	15232	15232	210	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	24514	24514	24514	24514	24514	400	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	25130	25130	25130	25130	25130	50	3.7	3.75	3.80	3.85	3.90
	multi dwelling (new) [430 m^2]											
gas	gas condensing boiler	15351	15044	14743	14448	14159	120	0.95	0.95	0.95	0.95	0.95
oil	oil condensing boiler	21063	20642	20229	19824	19428	240	0.98	0.98	0.98	0.98	0.98
pellet	pellet heater	24514	24514	24514	24514	24514	400	0.95	0.95	0.95	0.95	0.95
heat pump	air water heat-pump	25130	34165	33823	33485	33150	50	3.7	3.75	3.80	3.85	3.90

Based on IE Leipzig (2009).

Table B.9: Modernization rates

construction period	2010	2015	2020	2025	2030
1900 - 1918	3.3%	3.3%	3.3%	3.3%	3.3%
1919 - 1948	3.3%	3.3%	3.3%	3.3%	3.3%
1949 - 1978	3.3%	3.3%	3.3%	3.3%	3.3%
1979 - 1990	2.3%	2.3%	2.3%	2.3%	2.3%
1991 - 1995	2.3%	2.3%	2.3%	2.3%	2.3%
1996 - 2000	0.0%	2.3%	2.3%	2.3%	2.3%
2001 - 2004	0.0%	0.0%	2.3%	2.3%	2.3%
2005 - 2010	0.0%	0.0%	0.0%	2.3%	2.3%

Based on IWU / BEI (2010).

Table B.10: Distribution of new heaters installed in 2010

dwelling type	gas	oil	biomass	heatpump
single dwelling				
construction period				
until 1918	7.9308%	2.6599%	0.5342%	0.6976%
1919 - 1948	7.7124%	2.5866%	0.5194%	0.6784%
1949 - 1978	21.3081%	7.1464%	1.4351%	1.8744%
1979 - 1990	5.6628%	1.1024%	0.2410%	0.8156%
1991 - 1995	1.7252%	0.3359%	0.0734%	0.2485%
new building (since 2005)	9.9751%	0.6252%	1.4881%	5.7876%
multi dwelling				
construction period				
until 1918	1.6996%	0.5256%	0.1056%	0.0055%
1919 - 1948	1.4807%	0.4579%	0.0920%	0.0048%
1949 - 1978	6.4123%	1.9832%	0.3983%	0.0209%
1979 - 1990	1.3330%	0.2280%	0.0498%	0.0068%
1991 - 1995	0.4531%	0.0775%	0.0169%	0.0023%
new building (since 2005)	1.0790%	0.0418%	0.1242%	0.2372%

Based on BDH (2010),Destatis (2010b),IWU / BEI (2010)

B.2 Discrete choice model - welfare measurement and tests

Figure B.1 presents the structure of newly installed heating systems in Germany in 2010 across different dwelling types and their total annual heating costs in Euro. The groups contain dwellings of the same type with the same year of construction, house type (single/double or multiple and average insulation status/heat demand). The frequency of each group in the sample is indicated by the area of the circles[74]. Analyzing these heating system choices leads to the assumptions that the annual costs of a heating system might have an impact on the households' heating system choices but are not their only driver. In addition, the heating system choice differs systematically across the different dwelling types and the buildings' vintage class.

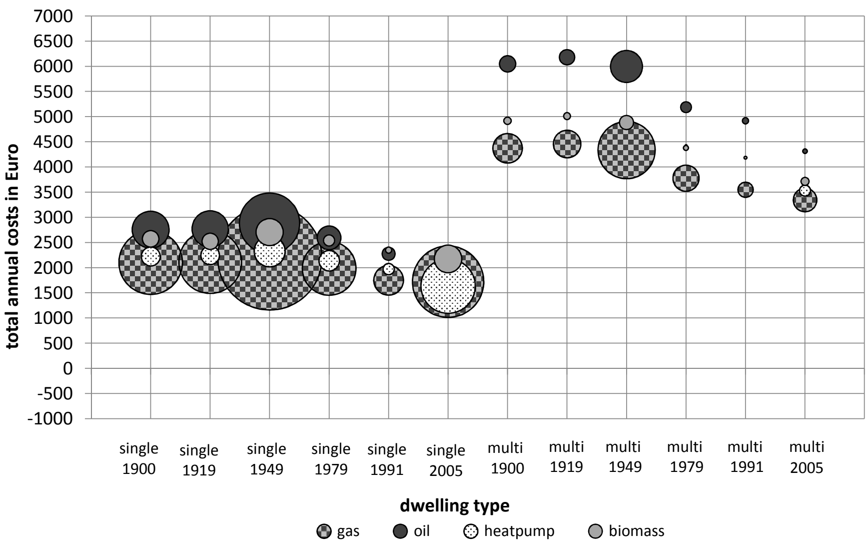


FIGURE B.1: Data: Costs and frequency of energy carriers installed in different dwellings in 2010

Using this data, we estimate a discrete choice model to identify the effects of the annual costs and further building characteristics that have an impact on the heating choice of a household.We thus assume that the probability $P_{n,j}$ that a representative household n adopts a heating system characterized by the energy carrier j is a function of the normalized annual heating system costs $c_{n,j}$ and some building characteristics z_n: $P_{n,j} = f(c_{n,j}, z_n)$. We use the annual heating costs per unit of heat demand in kilowatt hour

[74]Please note that the group with the construction period 1949 – 1978 includes so many buildings because it covers the longest time period. There was no further differentiation of construction periods in the data. In the two vintage classes 1996–2000 and 2001–2004 there were almost no newly installed heating systems in 2010 because of the 15-year lifetime of heating systems on average in Germany.

(kWh) $c_{n,j}$ because we are interested in a normalized impact of costs on the choice of a heating system irrespective of the different dwellings' total heat demand. Considering the total annual costs per unit, we can make them comparable for all buildings. We further assume that all households having the same building characteristics as n behave accordingly.

The normalized costs $c_{n,j}$, i.e. total annual costs divided by the total annual heat demand of the dwelling (the dwelling size times the specific heat demand in kWh/m^2a) are included in the model to estimate an overall cost impact. We additionally define alternative specific, i.e. energy carrier based, variables that could have an impact on the choice of a specific energy carrier based heating system. According to Figure 1, we assume the probability of installing a specific heating system to be different in single and double than in multiple dwellings and in buildings stemming from different vintage classes. Therefore, we include the dummy variable 'single' $z_{1,n}$, with 1 for single and double and 0 for multiple dwellings and the variable 'heat demand' $z_{2,n}$, serving as a proxy for the vintage class[75]. α_j are the alternative-specific constants. β represents the impact of total annual heating cost per kilowatt hour (kWh) $c_{n,j}$. $\gamma_{1,j}, \gamma_{2,j}$ identify the alternative-specific effects of the case-specific variables.

The indirect utility of household n for the chosen heating system j is:

$$V_{n,j} = \alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n} \tag{B.5}$$

with the choice probability being:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} = \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{\sum_i e^{\alpha_i + \beta c_{n,i} + \gamma_{1,i} z_{1,n} + \gamma_{2,i} z_{2,n}}} \tag{B.6}$$

As only the differences of the utilities are of importance for the estimation of the impacts, we define as base alternative 'gas' for which $\alpha_{\text{gas}}, \gamma_{1,\text{gas}}, \gamma_{2,\text{gas}} = 0$.

Table B.11 presents the summary statistics and Table B.12 the results of our discrete choice estimation. The cost impact is significant at a 10%-level and as expected the cost impact is strongly negative. All alternative specific constants are significant at a 1%-level and have a negative impact. Only the biomass constant is not significant. The

[75] By tendency, newer buildings c.p. have a lower heat demand.

negative impact of the alternative-specific constants indicates that the probability to choose either a heat pump, a biomass or oil heater is less probable than choosing a gas-fueled heating system keeping all else equal. This seems realistic because the market share of gas heaters in Germany is above 50% since the last years and households tend to have a preference for well-established systems.

Table B.11: Summary statistics

		Mean	**Std. dev.**	**Min.**	**Max.**
choice					
	biomass	0.0507	0.2194	0	1
	heat pump	0.1042	0.3056	0	1
	gas	0.6681	0.4710	0	1
	oil	0.1770	0.3817	0	1
costs	over all alternatives	0.1336	0.0315	0.0870	0.2155
	biomass	0.1437	0.0362	0.0977	0.2155
	heat pump	0.1222	0.0200	0.0985	0.1624
	gas	0.1172	0.0264	0.0870	0.1711
	oil	0.1514	0.0273	0.1206	0.2072
single		0.8313	0.3745	0	1
heat demand		122.3183	29.5189	70	149.2417

Table B.12: Estimation results

Number of observations = 11052 Wald chi2(7) = 303.59
Number of cases = 2763
Log likelihood = -2471.1913 Prob > chi2 = 0.0000

choice	coef.	std. err.	z	P> |z|
heating system				
costs	-26.7651	15.7391	-1.70	0.089
biomass				
single	1.0193	0.4400	2.32	0.021
heat demand	-0.0167	0.0051	-3.30	0.001
constant	-0.7025	0.7290	-0.96	0.335
gas	(base alternative)			
heat pump				
single	1.9561	0.4129	4.74	0.000
heat demand	-0.0203	0.0037	-5.44	0.000
constant	-1.3075	0.4355	-3.00	0.003
oil				
single	-0.4750	0.1514	-3.14	0.002
heat demand	0.0202	0.0028	7.17	0.000
constant	-2.6533	0.6660	-3.98	0.000

However, our results show that solely the heating system costs are not the only driver of a household's heating system choice. Otherwise every household would have chosen the cost optimal gas based heating system. There might be additional costs a household has to face when deciding on a heating system that cannot easily be observed or quantified. Amongst other these could be switching costs, financing or infrastructure costs. Moreover, there might be further impacts on the heating choice of households in addition to costs that cannot be observed. We are not able to identify the reasons for the household heating choice structure. There might be financing constraints such that a household does not get a credit at all. Behavioral misperceptions might also be a reason. In this case households do not put enough weight on annual heating system costs and therefore have a preference for certain heating systems.

However, some indirect relations such as income effects are mirrored through building characteristics:[76] For instance, one could assume that households with a higher income spend more on insulation and thus live rather in dwellings with lower heat demand or they live rather in single and double than multiple dwellings than households with lower income. The differentiation between single/double and multiple dwellings also serves as a proxy for the tenure status. Moreover, the inclusion of income or a tenure status in the model might not even improve the model because the heating system decision is often made by the builder, which is not necessarily the owner of a building. The precise impact of such non-observable variables cannot be defined in the model but is included indirectly via the building characteristics proxies. We could thus not identify if the effect of $z_{1,n}$ is an income effect or driven by the 'tenure status' or even other causes. This is not of importance for our approach which focuses on cost elasticities to derive a welfare-based greenhouse gas abatement curve.

Including just dwelling characteristics in our model, we only cover systematic differences of heating system installations in our model, which however mainly explain the diffusion of heating systems (see also Braun (2010)). These serve as proxies for the unobservable costs or other impacts that vary across dwelling types. The results in Table B.12 show that the choice probability of non-fossil heating systems biomass and heat pumps is higher in buildings with better insulation and thus lower heat demand,

[76] Based on Eurostat (2007) data, average gross household income in single and double dwellings in 2007 was about 51500 Euros and in multiple dwellings about 36000 Euros. 87% of households living in single dwellings were owners and only 26% in multiple dwellings.

which usually belong to younger vintage classes. The choice probability of these heating systems is also significantly higher for single and double dwellings than for multiple dwellings.

Later works on random utility models of discrete choice or mixed logit models (McFadden and Train (2000), Train (2003)) or the approach presented by Berry et al. (1995) and Berry (1994) and others point out that the approaches presented in McFadden (1976, 1974) neglect product and taste heterogeneity. We assume, that this might be true for products such as cars but is not valid in the case of heating systems installations since the product heat energy is a rather homogeneous good. In addition, especially the approach of Berry et al. (1995) accounts for price endogeneity and price formation on the market level by demand and supply. Our analysis sets its focus on energy consumption neglecting supply and is thus a partial analysis of the residential heat market. Further, we do not deal with price endogeneity as we assume that energy prices are not determined by the residential energy demand: the price of oil and gas is influenced by global supply and demand effects and other sectors such as power generation, transport or industry sectors rather than private households' heat demand. We also assume the price of biomass to be exogenous because the final biomass consumption of the residential sector accounted for 16% of German and only 3% of the European primary biomass production and there is still a significant unused biomass potential (AGEB (2011), Eurostat (2011) and European Commission (2007)). Another often mentioned problem with the presented approach is the Independence of Irrelevant Alternatives (IIA) assumption, which we test for (see the las section of the Appendix).

Computation of the compensating variation

Small and Rosen (1981) introduce a methodology to determine the aggregated compensating variation for discrete choice models and overcome the difficulty of the demand function aggregation and the discontinuity of the demand functions. We apply a generalization of this approach to determine the compensating variation CV_n of the representative household n based on McFadden (1999) associated with a movement of $V_{n,j}$ resulting from introducing a policy.

We have the distribution of the energy carriers j chosen based on the following:

$$P_{n,j} = \frac{e^{V_{n,j}}}{\sum_i e^{V_{n,i}}} \tag{B.7}$$

To compute the consumer surplus based on the utility in the no-policy case and the policy case we get:

$$\int_0^{V_{n,j}^{\text{no policy}}} P_{n,j} dV_{n,j} \tag{B.8}$$

and

$$\int_0^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} \tag{B.9}$$

Thus, for the difference in consumer surpluses of the two scenarios we get:

$$\int_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} P_{n,j} dV_{n,j} = \left[\ln \sum_i \frac{e^{\alpha_j + \beta c_{n,j} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{-\beta} \right]_{V_{n,j}^{\text{no policy}}}^{V_{n,j}^{\text{policy}}} \tag{B.10}$$

To compute the compensating variation of household n CV_n, we need to find the amount of money $\frac{CV_n}{TD_n}$ that compensates the additional 'per heat unit' costs caused by the policy measures to keep the utility at the 'without policy' level. Thus, the following equation based on McFadden (1999) must hold for the compensating variation CV_n of household n for each period y:

$$\ln \sum_j \frac{e^{\alpha_j + \beta (c_{n,j}^{\text{policy}} - \frac{CV_n}{TD_n}) + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{-\beta} = \ln \sum_i \frac{e^{\alpha_i + \beta c_{n,j}^{\text{no policy}} + \gamma_{1,j} z_{1,n} + \gamma_{2,j} z_{2,n}}}{-\beta} \tag{B.11}$$

We have a constant β over all alternatives, so the formula by Small and Rosen (1981) to compute the compensating variation in our logit model can easily be derived:

$$CV_n = \frac{TD_n}{-\beta} \quad \left[ln \sum_j exp(V_{n,j}^{\text{policy}}) - ln \sum_j exp(V_{n,j}^{\text{no policy}}) \right] \tag{B.12}$$

where the difference in brackets just measures the change in utility per heating unit as $c_{n,i}$ are per heating unit costs. TD_n is the total annual heat demand of group n and transfers the utility per kWh/a into the overall all utility of a household with a respective heating demand. The division by β translates the utility into monetary units. This formula by Small and Rosen (1981) depends on certain assumptions: the goods considered are normal goods, the representatives in each group (households with the same dwelling characteristics) are identical with regard to their income, the marginal utility of income β is approximately independent of all costs and other parameters in the model, income effects from changes of the households' characteristics are negligible, i.e. the compensated demand function can adequately be approximated by the Marshallian demand function.

Hausman-McFadden (1984) Test

We conduct tests of Hausman and McFadden (1984) to make sure the Independence of Irrelevant Alternatives (IIA) assumption holds. We therefore reestimate the model presented in Table B.12 by dropping different alternatives i. For instance one could assume that the choice of a heating technology depends rather on fossil versus non-fossil fuels than on the different energy carriers presented. Thus, we first drop the alternative *biomass*, *oil*, and *heatpump* in separate tests, and then both *biomass* and *oil* and both *oil* and *heatpump*. We compare these estimators with those of our basic model.

Under H0 the difference in the coefficients is not systematic. The test statistic is the following:

$$t = (b - \beta)'(\Omega_b - \Omega_\beta)^{-1}(b - \beta) \tag{B.13}$$

$$\text{with } t \sim \chi^2(1)$$

b is the cost coefficient of the reduced estimations dropping alternatives and Ω_b and Ω_β are the respective estimated covariance matrices.

We get:

Table B.13: Hausman-McFadden test of IIA

	b	β	T	Prob(T>t)
cost coeff. drop biomass	-31.97016	-26.76507	0.83	0.3633
cost coeff. drop oil	-26.06515	-26.76507	0.04	0.8399
cost coeff. drop heat pump	-3.358324	-26.76507	0.28	0.5969
cost coeff. drop biomass and oil	-32.64896	-26.76507	0.66	0.4167
cost coeff. drop heat pump and oil	-19.15256	-26.76507	0.03	0.8693

The results show that IIA cannot be rejected.

Appendix C

Supplementary Material to Chapter 5

C.1 Theoretical framework

In recent economic literature, there are different economic reasons why government should intervene in the market and introduce policies on energy efficiency to reduce energy intensities:

- Internalizing externalities such as greenhouse gas emissions
- Reducing the consumption of fossil fuels
- Correcting market failures on the household level (such as credit barriers or inefficiently high personal discount rates caused by market failures for energy savings)

Reasons for following the second objective include supporting sustainability of finite energy resources and keeping energy prices low.[77] The last point is a further issue that may be another barrier for policymakers to overcome while addressing the first two objectives. Inefficiently high personal discount rates for energy savings mean that the evaluation of energy savings from investments by households is inefficient.

The internalization of externalities and the maximization of energy savings in the private housing sector are addressed by national policy by enhancing investments in energy efficiency. Two popular policy measures on energy efficiency are lump-sum subsidies and subsidies on interest rates of investments in energy efficiency. The policies are introduced in a basic theoretical model presented by Allcott and Greenstone (2012)

[77] This paper focuses on the achievement of energy savings through policy interventions. An evaluation whether it is an economically appropriate approach to strive for energy savings or especially fossil fuel savings requires a much larger temporal and geographical scope and will not be addressed.

and Allcott et al. (2011). The socially optimal levels of policy measures are derived accounting for the household investment condition in energy efficiency. It is assumed that an energy efficiency gap exists. Policies can increase welfare because the investments made by households into energy-consuming systems are not economically efficient, i.e. the private net present value of energy savings following the investment is lower than the social net present value.

The consumer (or household) i is willing to make an investment in an energy-efficient good if the following condition holds:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c_i \qquad \text{(C.1)}$$
$$\text{with } c_i = c$$

The household i may make an investment in energy efficiency at cost c_i to achieve energy savings $e_0 - e_1$, where e_0 and e_1 are the energy intensities before and after the investment with $e_0 > e_1$, and p are the private cost of energy. For e_1, the model differentiates between $e_{1,i}$ and $e_{1,s}$. The optimal social energy intensity $e_{1,s}$ is conditional on the socially optimal investment level c with $e_{1,i} \geq e_{1,s}$. The privately chosen energy intensity $e_{1,i}$ reflects either a potential rebound effect, in a case in which the energy efficiency level c has been invested or the result of underinvestment in energy efficiency c_i such that $c_i < c$. Thus, it is assumed that the energy intensity level realized by the investment $e_{1,i}$ may be larger than the social level and lower than the level before the investment ($e_{1,s} \leq e_{1,i} \leq e_0$). For simplification, each household i chooses only one level within this range.

Variable m_i with $0 < m_i$, indicates household specific preferences concerning the energy consumption (or usage of the energy-consuming good) and $m_i = 1$ in case of homogeneous preferences among all households. In the case of $m_i > 1$, household i's energy usage is higher, and in the case of $m_i < 1$, the energy usage is lower than average. The term γ_i reflects the implied discount rate of household i and $\gamma_i \neq 0$ indicates behavioral misperceptions of the implied discount rate.[78] The term $\gamma_i < 1$ indicates an undervaluation of energy savings. Reasons why γ_i may be low or even close to zero include market failures such as a lack of information or principal-agent problems.

[78] Allcott and Greenstone (2012) consider γ instead of γ_i.

Principal-agent problems occur when the investment decision in energy-efficiency is made by other parties than those who are confronted with the energy expenditures (see Jaffe and Stavins (1994)). Another cause may be low energy price elasticities of demand. The variable r is the specific risk-adjusted discount rate. In total, the energy savings (or decrease of energy intensity) $e_0 - e_1$ is discounted by the factor $\frac{\gamma_i m_i}{1+r}$. The opportunity costs of an alternative investment are indicated by ϵ. The model differentiates between two periods: In the first period, the household makes the investment in an energy-consuming system (investment period) and in the second period, the system is applied and energy is consumed (consumption period).

The household's investment condition deviates from a social optimum as the household neglects the externality φ. In addition, the optimal investment level in energy efficiency may not be achieved if the household is confronted with a credit barrier.[79]: In the case of a credit barrier, the willingness to pay of consumer i is $c_i < c$ or it is a more restrictive credit barrier which does not allow a consumer i to get a credit c for the investment in energy efficiency at all. Thus, given a credit barrier, c_i is always assumed to be smaller than the efficient investment level c ($c_i < c$), which causes an underinvestment in energy efficiency as $e_{1,s}$ is conditional on c. There could be different reasons why a household is not willing or able to invest at all. The credit barrier could be caused by a lack of sufficient income, a lack of information or other reasons. A restrictive credit barrier is simplified within the presented theoretical approach by indicating that in this case $\gamma_i \to 0$ such that any policy measure would be ineffective to encourage the household to invest.

The socially optimal energy efficiency level $e_{1,s}$ is below the private energy efficiency level chosen by household i $e_{1,s} \leq e_{1,i}$. A social optimum internalizing the costs of the externality φ and reaching the socially optimal energy efficiency level[80] $e_{1,s}$ would be the following:

$$\frac{m_i(p+\varphi)(e_0 - e_{1,s})}{1+r} - \epsilon \geq c \tag{C.2}$$

[79]The inclusion of the credit barrier is an extension of the model of Allcott and Greenstone (2012) made by the author.

[80]Here, the socially optimal energy efficiency level means an economically efficient usage of energy.

The next sections introduce two different policies that are applied in Germany – lump-sum subsidies and subsidies on interest rates – to this framework. The optimal social tax and subsidy levels are derived. So far, this basic theoretical framework has mainly been presented by Allcott and Greenstone (2012). The introduction of policies in the next sections are further developed by the author.

C.1.1 The energy efficiency gap

An intervention of public policy is only required if an energy efficiency gap exists. The energy efficiency gap may be defined as the difference between the social and the private gain of the investment in energy efficiency:

$$g_e = m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r)) \tag{C.3}$$

The energy efficiency gap g_e reflects the net social gain of the energy efficient investment. The energy efficiency gap g_e is the deviation of the value of the private investment $\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r)$ from the value of the socially optimal investment in energy efficiency $m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r)$. The social gain is achieved through the internalization of the externality and the reduction of energy consumption. To get the net social gain, the value of the energy savings that would have been achieved without any policy intervention is deducted from the social value of energy savings.

C.1.2 Lump-sum subsidies for investments in energy efficiency

Subsidies for energy efficient investments could be introduced to overcome potential credit barriers $c_i < c$.

The household is willing to invest if:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c_i \tag{C.4}$$
$$\text{with } c_i \geq c - s$$

The private benefits of the energy savings must be higher than the expected household's willingness to pay incorporating the subsidy.

For the socially optimal subsidy s_s the following must hold:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - c_i + s_s = \frac{m_i(p+\varphi)(e_0 - e_{1,s})}{1+r} - c \tag{C.5}$$

$$s_s = \frac{m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))}{1+r} \tag{C.6}$$

The optimal subsidy level s_s must thus equal the discounted deviation of the private valuation of energy savings $(\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))$ from the optimal social value of energy savings $m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r)$.

The deviation in the numerator equals the energy efficiency gap g_e in the consumption period. Thus, we get:

$$s_s = \frac{g_e}{1+r} \tag{C.7}$$

Thus, the optimal subsidy s_s equals the discounted energy efficiency gap g_e.

The consumer's undervaluation of energy savings γ_i, the usage of energy m_i as well as the energy savings independently realized by the household $(e_0 - e_{1,i})$ reduce the effectiveness of the subsidy and thus both reduce the optimal subsidy level. The lower the willingness to pay of the household c_i or the higher the credit barrier $c - c_i$ the higher the subsidy needs to be.

A subsidy is able to correct for credit barriers. However, it does not affect the household behavior after the investment and cannot mitigate a rebound effect. In addition, for households that would invest anyways, the subsidy is a windfall.

C.1.3 Subsidies on interest rates of investments in energy efficiency

Subsidies on interest rates aim at decreasing the financing costs of households and address potential credit barriers $c_i < c$.

The household is willing to invest if:

$$\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r-s} - \epsilon \geq c_i \tag{C.8}$$

$$\text{with } c_i \geq c$$

where s is the subsidy, i.e. the percentage of the investment and financing cost ($c(1+r)$) that is subsidized. The private benefits of the energy savings discounted with the reduced interest rate ($r-s$) must be higher than the expected household's willingness to pay. For the socially optimal subsidy s_s, the following must hold for each household i:

$$\frac{\gamma_i m_i p(e_0-e_{1,i})}{1+r-s_s}-c_i=\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r}-c \tag{C.9}$$

$$s_s=\frac{m_i(p+\varphi)(e_0-e_{1,s})-c(1+r)-(\gamma_i m_i p(e_0-e_{1,i})-c_i(1+r))}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r}-(c-c_i)} \tag{C.10}$$

Replacing the numerator by the energy efficiency gap g_e, Equation C.10 can be rewritten as follows:

$$\frac{g_e}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r}-(c-c_i)} \tag{C.11}$$

The optimal subsidy level must equal the level of the energy efficiency gap in the consumption period (numerator) relative to the net social gain of the investment in energy efficiency in the investment period (denominator). Here, the net social gain of the investment in energy efficiency in the investment period is the value of the social energy savings level internalizing the externality $m_i(p+\varphi)(e_0-e_{1,s})$ minus the credit barrier $c-c_i$ (or the additional investment capital needed for the socially optimal investment level).

As for the lump-sum subsidy, the consumer's undervaluation of energy savings γ_i, the usage of energy m_i as well as the energy savings independently realized by the household $(e_0-e_{1,i})$ decrease the effectiveness of the subsidy and thus both reduce the optimal subsidy level. A high willingness to pay of the household c_i also reduces the optimal subsidy level. On the other hand, an increasing credit barrier results in a higher optimal subsidy level s_s.

To summarize, subsidies can be quite effective in reducing credit barriers or inefficiencies of the investment caused by high discount rates (γ_i) for energy savings, but not in reducing overconsumption of energy after the investment (Allcott and Greenstone, 2012, Train, 1985). However, for households that would also invest in energy efficiency without policy intervention, a subsidy is a windfall.

C.1.4 Investment barriers in tenant-occupied dwellings

In the German housing market, landlords are confronted with barriers to internalize the positive externalities of investments made in dwellings because of existing impediments concerning rent prices. On one hand, rent controls restrict the landlords from including investment costs in the current rent price. On the other hand, the independence of heating expenditures from rents and the lack of information on gross warm rent tenants are confronted with, additionally impedes the inclusion of investment costs in rent prices.

Moreover, tenants are not willing to make investments in energy efficiency as they are relationship-specific. A major part of the investment's value is lost when the tenant moves out. This risk of expropriation significantly reduces the tenant's incentive to make the investment himself (see Gebhardt (2012)). In the context of the analysis of investments in energy efficiency, this specific principal-agent is often referred to as the landlord-tenant problem (Jaffe and Stavins, 1994).

The landlord assumes a very high discount rate of energy savings ($1 > \gamma_i > 0$). To illustrate how this may impact the optimal subsidy level, we consider the extreme case in which the landlord may not be able to adapt the rent and benefit from energy savings: $\gamma_i \to 0$. This leads to the maximal energy efficiency gap g_e in tenant-occupied dwellings:

$$\begin{aligned}\lim_{\gamma_i \to 0} g_e &= \lim_{\gamma_i \to 0} \left(m_i(p+\varphi)(e_0 - e_{1,s}) - c(1+r) - (\gamma_i m_i p(e_0 - e_{1,i}) - c_i(1+r))\right) \\ &= m_i(p+\varphi)(e_0 - e_{1,s}) - (c - c_i)(1+r) \qquad \text{(C.12)}\end{aligned}$$

In this case, the energy efficiency gap equals the social value of the sum of the internalization of the externality and the social optimal energy intensity $m_i(p+\varphi)(e_0 - e_{1,s})$ minus the additional amount that is needed to be able to make the energy-efficient investment $(c - c_i)(1+r)$.

The landlord's investment condition $\frac{\gamma_i m_i p(e_0 - e_{1,i})}{1+r} - \epsilon \geq c$ can hardly be fulfilled as $\lim_{\gamma_i \to 0}$ because the tenant would profit mainly from an investment in energy efficiency and the landlord can scarcely internalize this positive externality, which results in an underinvestment problem in energy efficiency and higher energy consumption levels of tenants.

The socially optimal subsidy level to promote the landlord's investment is then:

$$\lim_{\gamma_i \to 0} s_s = \lim_{\gamma_i \to 0} \left(\frac{g_e}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c-c_i)} \right)$$
$$= \left(\frac{m_i(p+\varphi)(e_0-e_{1,s}) - (c-c_i)(1+r)}{\frac{m_i(p+\varphi)(e_0-e_{1,s})}{1+r} - (c-c_i)} \right) = 1+r \qquad \text{(C.13)}$$

As s_s indicates a percentage level, the absolute level of the optimal subsidy would be $c(1+r)$. Hence, in the extreme case ($\lim_{\gamma_i \to 0}$), the subsidy would need to compensate for the total investment and financing costs.

C.1.5 Subsidies, the heterogeneity of households and information assymetries of policy makers

To be able to set the optimal level of a subsidy (either a lump-sum or a subsidy on interest rates), the policy maker has to know the investment household i needs to make to achieve the optimal level of energy savings and abatement of the externality. Thus, he needs to know all the parameters of Equation C.2. In this simplified illustrative model, there is just one socially optimal investment level c and energy intensity level $e_{1,s}$. However, in reality the optimal investment and energy intensities would vary among households. Risk-adjusted discount rates may further depend on houseold i.

Moreover, even the heterogeneity of households captured by the model does not allow policy makers to introduce first-best subsidies. The policy maker would need to have private information on all parameters of Equation C.2 because first-best policies would need to be household-specific without causing additional administration costs. The less heterogeneous the population is and the closer the policy measures are set to the optimal level for a median household, the more efficient is the market outcome. The policy maker is confronted with information assymetry concerning the individual preferences of energy usage m_i, the undervaluation of energy savings γ_i and a potential rebound effect $e_{1,i}$. To determine a second-best subsidy level s_s the policy maker could include the average energy usage $\overline{m} = \sum_{\forall i} m_i$ instead of m_i based on empirical data. Nevertheless, information on a potential rebound effect $e_{1,i}$ is not available to the policy maker. Thus, he will build expectations $E[e_{1,i}]$. If the policy maker underestimates the rebound effect $E[e_{1,i}] < e_{1,i}$, the expected energy efficiency gap will be smaller than the real efficiency gap $E[ge] < ge$. Then the subsidy s chosen by the policy maker is below the optimal subsidy $s < s_s$ and the energy efficiency objectives are not achieved. In case of an overestimation $E[ge] > ge$, the subsidy is set inefficiently high $s > s_s$ which may cause welfare losses and may provide potential windfall profits to households.

Nonetheless, despite the unlikelihood that a policy maker may set the optimal subsidy s_s, the actual subsidy set may still be able to reduce energy consumption and reduce the externality. It may be that households were not able or willing to invest at all and even a suboptimal subsidy may reduce the credit barrier. Thus, even though the level $e_{1,s}$ cannot be achieved, reducing the energy to the level $e_{1,i}$ is already an improvement compared to e_0 as long as the investment and subsidy costs are lower for society than the costs of the externality. A subsidy may therefore increase the number of investments in energy efficiency made by households (Hypothesis 1).

It may also be that a household, who is willing to invest in energy efficiency may be encouraged by the subsidy to choose a higher investment level than the initial one c_i. Such an investment level may be between c_i and c and the resulting energy intensity would be between $e_{1,i}$ and $e_{1,s}$. A subsidy may therefore reduce the energy consumption of a household (Hypothesis 2).

Moreover, if the policy maker has asymmetric information about the landlord-tenant problem and the level of γ_i, he will have difficulties in estimating the energy efficiency gap g_e and in setting an optimal subsidy, which may impact the effectiveness of a subsidy (Hypothesis 3). In addition, if γ_i differs significantly between owners and tenants, the policy maker may need to introduce separate subsidies for investments in owner- and tenant-occupied dwellings.

C.2 Summary statistics

Table C.1: Summary statistics: Estimation A

Variable	Mean	Std. Dev.	Min.	Max.	N
dwelling modernizations	0.059	0.235	0	1	125686
owner-occupied	0.474	0.499	0	1	125686
log. of adj. income	7.685	0.605	0	11.531	125686
household type	2.876	1.704	1	8	125686
construction period	3.404	1.527	1	7	125686
number of relocations	0.594	1.119	0	12	125686
number of rooms (> 6 m^2)	3.942	1.734	1	22	125686
need of renovation	1.319	0.521	1	4	125686
subsidy ratio	0.104	0.078	0	0.29	125686

Table C.2: Summary statistics: Estimation B, owner

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.119	0.603	-5.075	5.051	56022
heating expenditure	1168.296	697.893	1	9999	56022
dwelling size in m^2	125.388	44.664	10	650	56022
owner-occupied	1	0	1	1	56022
HDD	262663.021	39374.617	63908	356910	56022
log. of gas price	4.518	0.251	4.143	4.881	56022
log. of adj. income	7.913	0.567	3.526	11.531	56022
household type	3.194	1.722	1	8	56022
construction period	3.537	1.603	1	7	56022
number of relocations	0.37	0.865	0	9	56022
number of rooms (> 6 m^2)	4.938	1.703	1	20	56022
need of renovation	1.202	0.418	1	4	56022

Table C.3: Summary statistics: Estimation B, tenant

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.366	0.496	-0.693	4.692	46513
heating expenditure	901.33	526.877	36	11160	46513
dwelling size in m^2	78.079	29.204	9	938	46513
owner-occupied	0	0	0	0	46513
HDD	263994.771	36608.335	63908	356910	46513
log. of gas price	4.449	0.258	4.143	4.881	46513
log. of adj. income	7.53	0.54	3.584	10.645	46513
household type	2.722	1.659	1	8	46513
construction period	3.192	1.39	1	7	46513
number of relocations	0.743	1.252	0	12	46513
number of rooms (> 6 m^2)	3.133	1.195	1	22	46513
need of renovation	1.445	0.584	1	4	46513

Table C.4: Summary statistics: Estimation B, all

Variable	Mean	Std. Dev.	Min.	Max.	N
logarithm of heating expenditure per m^2	2.231	0.570	-5.075	5.051	102535
heating expenditure	1047.192	640.079	1	11160	102535
dwelling size in m^2	103.927	45.072	9	938	102535
owner-occupied	0.546	0.498	0	1	102535
HDD	263267.143	38150.194	63908	356910	102535
log. of gas price	4.487	0.256	4.143	4.881	102535
log. of adj. income	7.739	0.587	3.526	11.531	102535
household type	2.98	1.71	1	8	102535
construction period	3.38	1.52	1	7	102535
number of relocations	0.539	1.075	0	12	102535
number of rooms (> 6 m^2)	4.119	1.744	1	22	102535
need of renovation	1.312	0.515	1	4	102535
modernized	0.347	0.476	0	1	102535
treated household group 1	0.186	0.389	0	1	102535
treated household group 2	0.222	0.416	0	1	102535

C.3 Subsidy programs

The high greenhouse gas reduction objectives self-imposed by the German government require effective measures to enhance energy efficiency. Various measures are listed in the National Energy Efficiency Action Plan (NEEAP) of the Federal Republic of Germany (Federal Ministry of Economic Affairs and Technology, 2007) to promote investments in energy efficiency in residential dwellings. The Credit Institute for Reconstruction's (Kreditanstalt für Wiederaufbau (KfW)) CO_2 building redevelopment program and the KfW's living space modernization program as part of the EEAP are major subsidy programs that promote investments in energy efficiency in the residential building stock. The KfW spent more than 38 billion Euros on these two programs in Western Germany between 1996 and 2010, which was mainly financed through government funds. 255 million Euros of the total 38 billion Euros spent were lump-sum payments and the major part of the subsidies have been provided through subsidized credits (subsidies on interest rates). Both programs subsidize investments in energy efficiency but differ in terms of their promotional framework. The CO_2 building redevelopment program had been modified in 2001 and the KfW's living space modernization program had been modified in 2005. The four project variations are summarized in Table C.5.

TABLE C.5: Subsidy programs

		Objective	**Options**	**Instruments**
CO_2 reduction program (CO_2-Minderungsprogramm)	1996–2005:	Reduction in CO_2 emissions	CO_2-saving measures to buildings	Subsidies on interest rates, repayment bonus
Energy efficient reconstruction (Energieeffizient Sanieren/ CO_2-Gebäudesanierungsprogramm)	Since 2001:	Promotion of energy-saving and CO_2-reducing measures to existing buildings	Insulation, install ventilation, Exchange: windows, heating; Conversion of buildings to fulfill KfW energy efficiency standard	Investment grants, repayment bonus, government loans
Residential property modernization program 2003 (Wohnraummodernisierungs-program 2003)	2003–2004:	Promotion of modernization and repair of housing	Modernization and repair of housing, Dismantling of vacant buildings, Improving the housing environment	Subsidies on interest rates, Low-interest loans
Modernization of residential property (Wohnraum Modernisieren)	2005–2011:	Promotion of energy-efficient renovations	Insulation, install ventilation, Exchange: windows, heating	Investment grants, government loans, repayment bonus

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