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Modelling policy instruments in energy system models - the example of renewable electricity generation in Germany

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Modelling policy instruments in energy system models - the example of renewable electricity generation in Germany

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Birgit Fais

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List of Abbreviations

a	year
AA-CAES	advanced adiabatic compressed air energy storage
AEEI	autonomous energy efficiency index
avg.	average
bbl	barrel
BDEW	Bundesverband der Energie- und Wasserwirtschaft, German Association of Energy and Water Industries
BioKraftQuG	Biokraftstoffquotengesetz, German Biofuel Quota Act
BiomasseV	Biomasseverordnung (Verordnung über die Erzeugung von Strom aus Biomasse), German Biomass Ordinance
BKartA	Bundeskartellamt, German Federal Cartel Office
BLUE	Behaviour Lifestyles and Uncertainty Energy model
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung, German Federal Ministry of Transport, Building and Urban Development
BMWi	Bundesministerium für Wirtschaft und Technologie, German Federal Ministry of Economy and Technology
Bn	billion
BNetzA	Bundesnetzagentur, German Federal Network Agency
BSW-Solar	Bundesverband Solarwirtschaft, German Solar Industry Association
CAES	compressed air energy storage
CCS	carbon capture and storage
CDM	Clean Development Mechanism
CERs	Certified Emission Reductions
cf.	confer
CFCs	chlorofluorocarbons
CGE	computable general equilibrium
CHP	combined heat and power
CITL	Community Independent Transaction Log
CO_2	carbon dioxide
ct	€-cent
dena	Deutsche Energie-Agentur, German Energy Agency
e.g.	exempli gratia, for example
EC	European Commission
EEA	European Environment Agency
EEG	Erneuerbare-Energien-Gesetz, German Renewable Energy Sources Act
EEWärmeG	Erneuerbare-Energien-Wärmegesetz, German Renewable Energies Heat Act
EMF	Energy Modeling Forum
EnEV	Energieeinsparverordnung, German Energy Savings Ordinance

EnVKG	Energieverbrauchskennzeichnungsgesetz, German Energy Labelling Law
EnVKV	Energieverbrauchskennzeichnungsverordnung, German Energy Labelling Ordinance
ERUs	Emission Reduction Units
EStG	Einkommensteuergesetz, German Income Tax Act
ESUB	elasticity of substitution
etc.	et cetera
ETP	Energy Technology Perspectives
ETR	environmental tax reform
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EU ETS	European Emissions Trading System
EUA	European Union Allowance
Eurostat	Statistical Office of the European Union
EVPG	Energieverbrauchsrelevante-Produkte-Gesetz, German Law on Energy-Related Products
EWI	Energiewirtschaftliches Institut an der Universität zu Köln, Institute of Energy Economics at the University of Cologne
FIT	feed-in tariff
ff	following
GCAM	Global Change Assessment Model
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
GW	gigawatt
GWh	gigawatt hour
h	hour
i.e.	id est, that is
ICT	information and communications technology
IEA	International Energy Agency
IER	Institut für Energiewirtschaft und Rationelle Energieanwendung, Institute for Energy Economics and the Rational Use of Energy
incl.	including
int.	international
ISE	Fraunhofer-Institut für Solare Energiesysteme, Fraunhofer Institute for Solar Energy Systems
JI	Joint Implementation
KfW	Kreditanstalt für Wiederaufbau, German Reconstruction Credit Institute
km	kilometre
kt	kiloton
kW	kilowatt
kWh	kilowatt hour

KWKG	Kraft-Wärme-Kopplungsgesetz, German Heat-and-Power Cogeneration Act
M	million
m	metre
MAC	marginal abatement cost
MARKAL	Market Allocation Model
max.	maximum
MCFC	molten-carbonate fuel cell
Mt	megaton
MW	megawatt
MWh	megawatt hour
N_2O	nitrous oxide
NAP	National Allocation Plan
NaS	sodium-sulfur (battery)
O&M cost	operating and maintenance cost
OECD	Organisation for Economic Co-operation and Development
ORC	Organic Rankine cycle
p./ pp.	page / pages
p.a.	per annum, per year
PERSEUS	Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading
PFCs	perfluorocarbons
PJ	petajoule
Pkm	passenger-kilometre
Pkw-EnVKV	Pkw-Energieverbrauchskennzeichnungsverordnung, German Energy Labelling Ordinance for passenger cars
PV	photovoltaics
R&D	research and development
ReMIND	Regional Model of Investments and Development
ren.	renewable
RES	reference energy system
RES-E	electricity generation based on renewable energy sources
Res-IRF	Residential module of Imaclim-R France
s	second
SRU	Sachverständigenrat für Umweltfragen, German Advisory Council on the Environment
StromNEV	Stromnetzentgeltverordnung, German Ordinance on Electricity Grid Access Charges
t	ton
TGC	tradable green certificate
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
TIMES PanEU	The pan-European TIMES model

TIMES-D	TIMES-Deutschland, the German TIMES model
TJ	terajoule
tkm	tonne-kilometre
TWh	terawatt hour
UBA	Umweltbundesamt, German Federal Environmental Agency
ÜNB	Übertragungsnetzbetreiber, Transmission System Operator (TSO)
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
VAT	value added tax
VDE	Verband der Elektrotechnik, Elektronik und Informationstechnik, German Association for Electrical, Electronic and Information Technologies
VDI	Verein Deutscher Ingenieure, German Association of Engineers
vs.	versus
WITCH	World Induced Technical Change Hybrid model

List of Formula Symbols

c	commodity index
p	process index
r	region index
t	index for the current time period from 1,..,T
s	time slice index
v	index for the vintage year
R	set of all regions
T	set of all time periods
FOS	set of all fossil electricity generation technologies
$NONREN$	set of all non-renewable electricity generation technologies
REN	set of all renewable electricity generation technologies
S	set of all time slices
V	set of all vintage years
$FUEL$	set of all input fuels
$EMIS$	set of all GHG emission commodities and
ELC	set of all electricity output commodities
$exp_{r,p,c}$	index for export processes *p* of commodity *c* to region *r*
fit_p	index for processes *p* in the feed-in tariff system
$imp_{r,p,c}$	index for import processes *p* of commodity *c* from region *r*
$in_{r,p,c}$	index for process *p* with commodity *c* as input
$out_{r,p,c}$	index for process *p* with commodity *c* as output
$vint_{r,t,p}$	index for vintage periods of processes *p* that have been installed in a previous period *v* but still exist in time period *t*
$ACT_{r,t,p,s}$	activity variable
$act\_cost\_d_{r,t,p,s}$	discounted variable operation cost (without fuel cost)
$actlo_{r,t,p,s}$	dual variable of a lower bound on the activity variable (reduced cost)
$actup_{r,t,p,s}$	dual variable of an upper bound on the activity variable (economic rent)
$cap\_pasti_{r,t,p}$	past capacity
$capact_{r,v,t,p,s}$	dual variable of the capacity-activity constraint
$combal_{r,t,elc,s}$	dual variable of the commodity balance of the output electricity (*elc*)
$combal_{r,t,fuel,s}$	dual variable of the commodity balance of the fuel input (*fuel*)
$cst\_act_{r,t,p}$	specific variable operation cost
$cst\_flo_{r,t,p,c,s}$	specific flow cost
$cst\_fom_{r,t,p}$	specific fixed operation and maintenance cost
$cst\_inv_{r,t,p}$	specific investment cost
$cst\_inv_{r,v,p}$	specific investment cost
d_t	duration of time period *t*
$EXP_{r,t,p,c,s}$	export variable (for export process *p* of commodity *c* to region *r* in time period *t* and time slice *s*)
FOS	set of fossil electricity generation technologies

$\boldsymbol{FLO_{r,t,p,c,s}}$	flow variable
$\boldsymbol{ghg\_bnd_{r,t,emis,s}}$	dual variable of an upper bound on greenhouse gas emissions (*emis*)
$\boldsymbol{IMP_{r,t,p,c,s}}$	import variable (for import process *p* of commodity *c* from region *r* in time period *t* and time slice *s*)
$\boldsymbol{NCAP_{r,t,p}}$	new investment variable (of process *p* in time period *t*)
$\boldsymbol{NCAP_{r,v,p}}$	new investment variable (of process *p* in vintage period *v*)
$\boldsymbol{prc\_ts_{r,p,s}}$	time slices *s* of process *p*
$\boldsymbol{price_{r,t,p,c,s}}$	specific import and export cost (for process *p* and commodity *c* from/to region *r* in time period *t* and time slice *s*)
$\boldsymbol{q_{r,t}}$	dual variable of the quota on renewable electricity generation (equal to the certificate price in the TGC system)
$\boldsymbol{quota_{r,t}}$	quota for the electricity generation from renewable energies
$\boldsymbol{sub\_fom_{r,t,p}}$	specific subsidy on installed capacity and
$\boldsymbol{\beta_t}$	discount rate in time period *t* to the base year
$\varepsilon_{r,t,p,emis,fuel}$	emission factor specifying how much emissions (*emis*) are produced per unit of the input commodity (*fuel*) in process *p* and
$\eta_{r,t,p,s}$	activity-based efficiency of converting the input flow (*fuel*) into the output flow (*elc*)

Abstract

Germany currently faces the challenging transition to a more sustainable energy system while at the same time maintaining high levels of energy security and internationally competitive energy prices. Energy system analyses have for a long time played a crucial role in supporting the political decision-making process by identifying sustainable technology pathways and contrasting the impacts of alternative energy futures. The actual policy measures necessary to reach the political targets are, however, usually not explicitly represented in such models and often only taken into account in an implicit and aggregate manner in the exogenous scenario assumptions.

Given the significance of policy intervention for the future development of energy systems around the world, the target of this thesis is therefore to explore the usefulness of bottom-up, technology-rich energy system models for the evaluation of different types of energy and climate policy instruments, to develop explicit modelling techniques to represent such instruments endogenously and to apply this methodology in the scope of a comparative scenario analysis for the German energy system with the national TIMES-D model.

One of the major advantages of energy system models can be found in their high level of technological detail allowing to assess the impact of technology- or sector-specific measures as well as the effect of major technological breakthroughs. At the same time, increased attention needs to be paid to the representation of economic feedbacks and behavioural aspects when using such models for policy evaluation.

Due to the importance of renewable energies for the decarbonisation of the energy system, the analysis at hand draws upon the example of renewable electricity generation in Germany as a use case and develops flexible modelling approaches for the two most important policy instruments in this sector, i.e. the German feed-in tariff scheme and the European Emission Trading System.

The subsequent scenario analysis focuses on three research questions: (1) the long-term development of the German energy system under the current policy framework, (2) the interactions between these two policy measures and (3) a comparison of alternative support mechanisms for renewable electricity generation. Based on the comprehensive feed-in tariff system, renewable electricity generation rises substantially in Germany until 2030. This expansion constitutes, however, a significant cost burden for electricity consumers. When countries are joined through an emission trading system, national policy tools, like the German feed-in tariff scheme, can have an impact on all participating countries. The additional support for renewable electricity in Germany entails a drop in emission certificate prices while incentivizing no additional emission reduction on European level. The cost of the German feed-in tariff scheme could be reduced considerably by adhering more strongly to the principle of cost efficiency. At the same time, it has to be kept in mind that technology-specific support systems allow to limit the profit margins of renewable generators and thereby the cost burden on electricity consumers.

Kurzfassung

Die Energiewende in Deutschland mit dem Ziel einer nachhaltigen Energieversorgung bei gleichzeitig hoher Versorgungssicherheit und international wettbewerbsfähigen Energiepreisen stellt eine enorme Herausforderung dar. Die Energiesystemanalyse leistet einen wesentlichen Beitrag zur Unterstützung der politischen Entscheidungsfindung, indem sie mögliche Entwicklungspfade für die Energieversorgung identifiziert und kontrastiert. Die tatsächlichen Politikinstrumente, die zur Erreichung der politischen Zielvorgaben notwendigen sind, werden jedoch in der Regel nicht ausdrücklich dargestellt und nur implizit in den exogenen Szenarioannahmen berücksichtigt.

Aufgrund der Bedeutung von Politikmaßnahmen für die zukünftige Entwicklung des Energiesystems, besteht die Zielsetzung dieser Doktorarbeit darin, den möglichen Beitrag von prozessorientierten Energiesystemmodellen für die Bewertung unterschiedlicher Instrumententypen in der Energie- und Klimapolitik zu untersuchen, explizite Modellierungsansätze für solche Instrumente zu entwickeln und diese im Rahmen einer kontrastiven Szenarioanalyse für das deutschen Energiesystem mit dem nationalen TIMES-D Modell anzuwenden.

Einer der wesentlichen Vorteile von Energiesystemmodellen besteht in ihrem hohen technologischen Detaillierungsgrad, der es möglich macht, technologiespezifische Maßnahmen sowie den Einfluss von Technologiesprüngen zu bewerten. Zusätzlichen Anstrengungen sind bei der Darstellung makroökonomischer Zusammenhänge und des Konsumentenverhaltens notwendig, wenn solche Modellansätze zur Politikbewertung herangezogen werden.

Angesichts der wachsenden Bedeutung erneuerbarer Energien fokussiert die vorliegende Analyse den erneuerbaren Stromerzeugungssektor in Deutschland und entwickelt flexible und endogene Modellierungsansätze für die zwei wichtigsten Politikinstrumente in diesem Bereich – die fixe Einspeisevergütung des Erneuerbare-Energien-Gesetzes (EEG) und das Europäische Emissionshandelssystem.

Die darauffolgende Szenarienanalyse behandelt drei Forschungsfragen: (1) die langfristige Entwicklung des deutschen Energiesystems unter den derzeitigen politischen Rahmenbedingungen, (2) die Wechselwirkungen zwischen den zwei genannten Instrumenten und (3) ein Vergleich alternativer Fördermechanismen für erneuerbaren Strom. Auf Grundlage des EEG steigt die erneuerbare Stromerzeugung in Deutschland bis 2030 deutlich an. Die ist jedoch gleichzeitig mit einer signifikanten Kostenbelastung für die Stromverbraucher verbunden. Ein Zusammenschluss über einen supranationalen Emissionshandel kann dazu führen, dass nationale Maßnahmen, wie das EEG, Auswirkungen auf alle Mitgliedsländer haben. Die zusätzliche Förderung für erneuerbaren Strom in Deutschland schlägt sich in keiner zusätzlichen Emissionsminderung auf europäischem Niveau nieder, bewirkt allerdings einen Rückgang der Emissionszertifikatspreise. Die Kosten der deutschen Einspeisevergütung könnten durch eine stärker kosteneffiziente Ausrichtung erheblich gesenkt werden. Gleichzeitig muss beachtet werden, dass durch eine technologiespezifische Förderung die Gewinnspannen der erneuerbaren Erzeuger und damit die Kosumentenbelastung deutlich begrenzt werden können.

1 Introduction

1.1. Motivation and objectives

The decarbonisation of the energy sector constitutes one of the major topics in energy policy worldwide. Accordingly, the German Energy Concept refers to "*securing a reliable, economically viable and environmentally sound energy supply*" as "*one of the great challenges of the 21st century*" (BMWi and BMU 2011, p. 3). The aim is to realize substantial emission abatement efforts while at the same time ensuring competitive energy prices and a high level of energy security. In this context, ambitious emission reduction targets have been implemented both on the European and the national level. With respect to the European Union (EU) the objective of reducing greenhouse gas emission by 20 % unit 2020 compared to 1990 has been established by the Climate and Energy Package (cf. EC 2008a) and in the Energy Roadmap 2050 (cf. EC 2011c) a reduction commitment of 80-95 % below 1990 levels by 2050 has been adopted. Moreover, emission mitigation is backed up by setting additional targets regarding the expansion of renewable energy sources and improvements in energy efficiency.

Against the background of these significant challenges, an increasing political intervention in the energy sector can be observed with various measures being taken both on the supply and the demand side. Apart from that, the types of environmental policy instruments that are employed have changed and broadened considerably. Traditionally, environmental policymaking was strongly focused on so called command-and-control instruments where certain activities are directly prescribed or forbidden by the government. In recent years, however, a gradual shift towards market-based instruments, like emission taxes or tradable permit systems, has taken place. An important example is the European Emissions Trading System (EU ETS), which was introduced in 2005 and is still the largest greenhouse gas emissions trading system in the world. In addition, a number of policy measures have been implemented that are not directly aimed at emission control but are intended to promote certain low-carbon technologies. Here, the strong support for renewable electricity technologies by means of fixed feed-in tariffs or tradable green certificate schemes is particularly noteworthy.

The rising use of energy and climate policy instruments shows that the issue of climate change occupies a prominent place on the political agenda. Yet, criticism is also being voiced that such a policy mix might lead to redundancy and inefficiencies eventually resulting in high abatement costs. These concerns are also reflected in the growing social debate on the impacts of the transition to a more sustainable energy system concentrated mainly on the increasing cost burden on energy consumers.

At the same time, the recent developments in energy and climate policy have triggered a growing research activity in policy evaluation in this area. Quantitative tools are needed to assess the long-term impacts of different policy instruments on the energy system. The benefits of energy modelling as a basis for the policy making process is highlighted by the following quote by the government of the United Kingdom:

"Rigorous analysis and, where appropriate, modelling is in the best interests of both Ministers and senior officials. They lead to better decisions and improved policy outcomes. Without soundly based analysis and modelling, those involved in the formulation of policy and the delivery of services will work in the dark." (Cabinet Office 2000, p. 8)

The development of quantitative energy models gained impetus in the 1970s where in light of the two oil crises the focus was put on energy security and the potential of fuel-saving technologies. Yet since then, due to the altered policy environment, the requirements on energy modelling have undergone major changes and new research priorities have been added. Thus, apart from determining technical potentials for emission reduction, the effects of specific policy measures under real-world conditions need to be explored. For that reason, the existing modelling tools, should be assessed with respect to their suitability for policy evaluation. Furthermore, in energy modelling the impacts of the various types of environmental policy instruments have so far been usually only taken into account in an implicit manner by integrating their effects into the exogenous scenario assumptions. This, however, strongly limits the flexibility and transparency of the model approach. Therefore, modelling strategies for the explicit representation of such instruments in energy models are required.

Against this background, the objectives of this thesis are centred on the following three research questions:

- to assess the usefulness of conventional bottom-up energy system models for policy evaluation;
- to develop explicit modelling approaches for the representation of different types of policy instruments in energy system models using the example of the European Emissions Trading System and the German feed-in tariff (FIT) scheme for renewable electricity and
- to illustrate the benefits of such modelling techniques in the scope of comparative scenario analysis focusing mainly on renewable electricity generation in Germany.

1.2. Methodology and structure

In order to address the abovementioned research questions in a comprehensive manner, this thesis follows a clear structure, divided into an overview on the theory of energy and climate policy instruments and their representation in energy system models, the detailed description of the methodology and the application in a scenario analysis on the German energy system.

Chapter 2 lays the theoretical foundation for the following analysis. After shortly outlining the justification for policy intervention in the energy sector based on neoclassical environmental economics, a classification and brief description of the most important environmental policy instruments is provided. Moreover, a set of evaluation criteria typically used in environmental economics is presented and applied to the various policy measures. In addition to the standard instruments, a special emphasis is put on instruments that promote the innovation and diffusion of environmental technologies, most importantly support schemes for renewable electricity. In view of the already mentioned rise in the implementation of environmental policy tools, a subchapter is dedicated to the rationale and drawbacks of multiple policy instruments to address climate change as well as the resulting policy interactions. Finally, a short overview on the current energy and climate policy in Germany is given, with a more detailed depiction for the EU ETS and the German feed-in tariffs for renewable electricity.

The following Chapter 3 is concentrated on the current state of research regarding environmental policy evaluation with the help of quantitative energy models - starting with a short overview on the development of energy modelling and establishing the basic differentiation between top-down and bottom-up model approaches. Afterwards, the question on the suitability of existing modelling tools for the assessment of policy measures is addressed from a different angle by establishing in a first step the most important criteria of an ideal model for policy evaluation based on the approach by Jaccard et al. (2003). On this basis, the major strengths and weaknesses of typical top-down and bottom-up models are identified and contrasted. As in the following scenario analysis a conventional bottom-up energy system modelling approach will be applied, the two main shortcomings of this type of model, the limited consideration of behavioural factors as well as of macroeconomic feedbacks, are discussed in detail and first solutions are presented.

In Chapter 4 the modelling techniques for the explicit representation of the two most important policy instruments currently influencing renewable electricity generation in Germany - the EU ETS and the FIT system - are developed and described in a detailed manner. For the scenario analysis, the German energy system model TIMES-D is applied for which the basic structure and the major extensions and improvements realized in the scope of this thesis are outlined. After delineating the basic modelling approach, the methodology for the EU ETS puts a special focus on the endogenous integration of supranational emission trading systems into national energy system models. With respect to support systems for renewable electricity generation, a comprehensive modelling strategy is established for the endogenous representation of the German feed-in tariff system in TIMES taking into account the complex tariff structure and various special regulations. In addition, techniques for the modelling of quantity-based support schemes for renewable electricity, i.e. tradable green certificate systems and tendering procedures, are depicted.

Based on these model approaches, a comparative scenario analysis for Germany is conducted in Chapter 5 which allows to highlight how the explicit modelling of policy instruments in an energy system model can be used to explore the long-term impacts of such instruments taking into account all repercussions and interactions within the energy system. After giving an overview on the basic scenario assumptions and scenario characteristics, the analysis concentrates on three issues: (1) the development of the German energy system in the reference case assuming that the considered policy instruments are maintained in their current version; (2)

the interaction between the EU ETS and the German FIT system and (3) a comparison of the current FIT system with alternative support schemes for renewable electricity generation. Results on the development of the electricity sector, the impacts and the cost burden of the respective support system for renewable electricity, the effects on electricity prices and demand, CO_2 emissions as well as energy system costs are presented in detail.

Chapter 6 closes with a short summary on the findings and the future research needs in the area of energy modelling for policy evaluation.

2 Theoretical background on policy instruments

In order to be able to explicitly model policy measures in energy system models, it is essential to have extensive background knowledge on what types of policy instruments exist, what their most important characteristics are and how they can be evaluated and contrasted. Therefore, Chapter 2 gives an overview on the assessment criteria that are usually invoked in neoclassical environmental economics which are then applied to the most important types of conventional environmental policy instruments. A separate chapter is devoted to policy tools that focus on the promotion of specific technologies, as these have gained substantial importance in climate policy during the last years. While environmental economic theory generally looks at different instruments separately and compares their features, in reality usually a policy mix is implemented to deal with environmental problems. That is why Chapter 2 also addresses the implications of using multiple policy instruments and the issue of policy interaction. The chapter closes with a brief description of the current energy and climate policy in Germany.

2.1 Foundation: need for environmental policy instruments[1]

The beginning of modern environmental policy is usually dated to the late sixties and early seventies where it mainly concentrated on air pollutants, water quality and solid waste disposal. At the same time, in the seventies the most important theoretical work in the area of neoclassical environmental economics was established, which is still used today for a theoretical understanding of environmental policy instruments (cf. Rogall 2008, pp. 27ff). The basic idea of environmental economics consists in integrating the environment, represented through environmental commodities like “clean air”, into the economic system. Just like regular commodities, these environmental commodities affect the well-being of society, are perceived as scarce and should therefore be taken into account in the economic resource allocation problem.

The aim is then to determine the most efficient way to allocate the scarce resources to the various production processes and the produced goods to the consumers. In neoclassical theory, the *Pareto Criterion* is used as the main indicator to assess the efficiency or optimality of a given allocation of resources, defining an efficient allocation as the one compared to which no other allocation is feasible that increases the utility of at least one individual without decreases the utility of any other (cf. Breyer 2011, p. 199). In welfare economics it is argued that, under the assumption of competitive markets[2], free markets automatically ensure a Pareto efficient allocation of resources. The market mechanism functions through decentralized economic decisions based on a price system which serves to indicate the scarcity of the

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[1] A previous version of Chapters 2.1-2.5 has been published in Götz et al. (2012a) as part of the ETSAP Project “Integrating policy instruments into the TIMES Model”.

[2] In detail, the first theorem of welfare economics states that under the assumption of complete markets with price-taking behaviour and perfect information, in the absence of externalities and transaction costs and with locally non-satiated preferences every market equilibrium is Pareto efficient (cf. Beyer 2011, p. 211)

different commodities and to equate demand with supply in equilibrium such that marginal utility of consumption equals marginal cost of production. Hence, on competitive markets a misallocation or overexploitation of resources and goods can be ruled out (cf. Endres 2011, pp. 9ff).

The simple allocation mechanism through markets does, however, not work in the case of environmental commodities. According to environmental economic theory, this can be attributed to two main issues: the characterization of environmental commodities as public goods and the existence of external effects. In contrast to private goods, pure public goods can be described by means of the two properties non-excludability and non-rivalry. Using the example of the environmental commodity clean air, this means that nobody can be excluded from benefiting from this commodity and total available supply is not reduced substantially when it is consumed by one individual. Sometimes it is also argued that only so far many environmental commodities are treated as public goods, while in reality the exploitation of their functions is subject to rivalry, e.g. the supply of clean air is diminished when a large group of consumers uses it as a dump for pollutants. Thus, instead of pure public goods, environmental commodities can also be considered as common goods where only the criterion of non-excludability but not of non-rivalry applies (cf. Rogall 2008, p. 62). As a consequence of their characterization as public or common goods, no regular markets for most environmental commodities exist and their consumption entails external effects that are not accounted for in the market system. Externalities can be formally described as follows:

"An externality exists when the consumption or production choice of one person or firm enters the utility or production function of another entity without that entity's permission or compensation." (Kolstad 2011, p. 92)

An example for a negative production externality, as it might arise in any production process involving the emission of greenhouse gases or other pollutants, is shown in Figure 2-1. Externalities lead to a divergence between private and social costs. In this case of an externality on the production side, the producer only takes into account the costs of production he incurs, i.e. the private costs, when setting the price. Consequently, the resulting price p_p is lower than the Pareto optimal one p_s (including all social costs, both private and external ones) and demand (given as marginal utility of consumption) is too high. Hence, in the presence of negative external effects, the market equilibrium is inefficient with an over-usage of environmental commodities. These effects have often been characterized as "market failure", while the fundamental problem consists in a non-existence of markets for environmental commodities (cf. Wiesmeth 2012, p. 66).

On the basis of these "missing markets" for environmental commodities and the consequent overexploitation, political intervention is justified. The aim of environmental policy instruments is therefore to internalize external effects in order to reestablish the optimality of the resource allocation in equilibrium. Closely related to the concept of internalizing all externalities of production and consumption is the polluter-pays-principle in environmental policy, stating that whoever is responsible for the pollution should bear the costs to the extent of either the damage done to society (“strong” principle) or the exceeding of an acceptable level of pollution (“weak” principle) (cf. OECD 2007a).

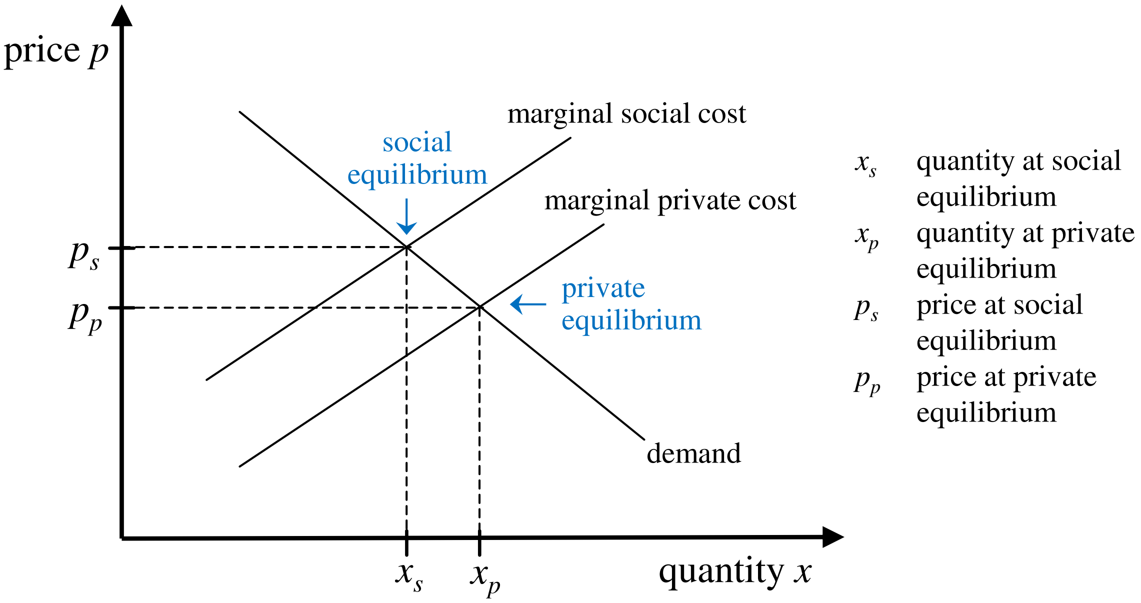

Figure 2-1: Negative production externality (own illustration based on Tietenberg and Lewis 2012, p. 26)

Furthermore, the question on the optimal balance between environmental protection and environmental use needs to be addressed in the framework of environmental policy. When no political measures are taken, high environmental damage costs arise. At the same time, the implementation of environmental protection measures also results in additional costs. According to neoclassical theory, an efficient allocation is obtained when marginal environmental avoidance cost equal marginal environmental damage cost, as illustrated in Figure 2-2.

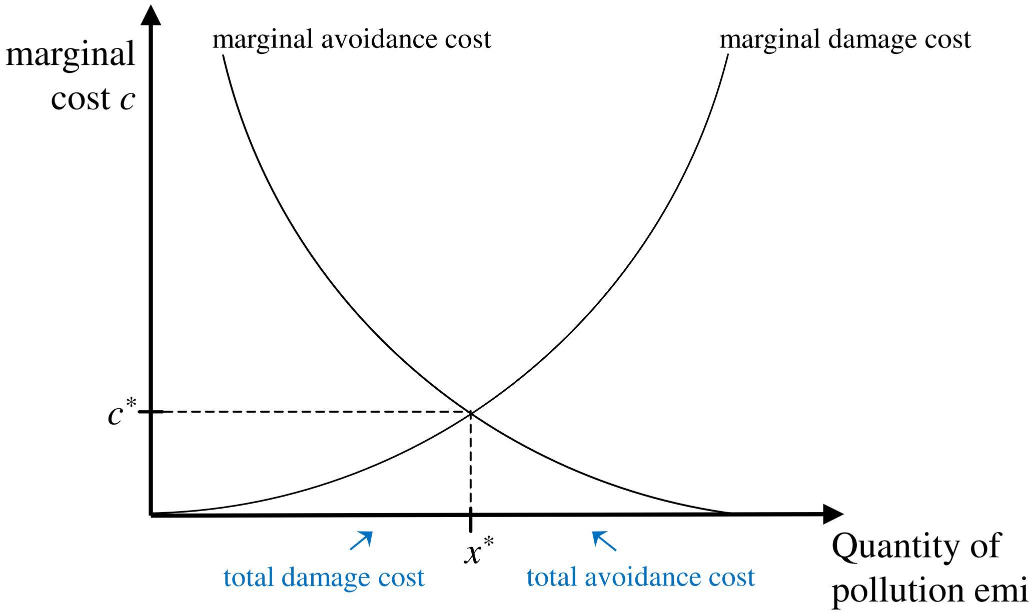

Figure 2-2: Determination of the efficient balance between environmental protection and environmental use (own illustration based on Tietenberg and Lewis 2012, p. 364)

It is obvious that in order to determine this optimal allocation a considerable amount of information is required which is apparently not available in practice (cf. Endres 2011, pp. 22ff). First of all, the utility any environmental commodity has (or the perceived damage which is associated with pollution) depends on each consumer's preferences which are not known to the policy maker, as no markets for environmental commodities where preferences are revealed through the price system exist, and are subject to changes over time. Avoidance costs, on the other hand, depend on the technological state of the art and its future development. Thus, both the marginal avoidance and the marginal damage costs may shift over the course of time affecting also the efficient allocation. An additional problem arises when taking into account future environmental damages which need to be assessed with the help of an appropriate discount rate.

Thus, in reality environmental policy has to deal with information deficits and will therefore not be able to internalize all external effects correctly. Consequently, theoretical solution approaches for the internalization of externalities, like the Pigovian tax and the Coase theorem[3], can only be used as a guideline when designing environmental policy instruments. In practice, the desired environmental quality or standard is generally set exogenously by a team of experts based on scientific, technical, medical and economic criteria, which, however, is not likely to meet exactly the Pareto efficient allocation. Policy instruments will then be constructed with the principal aim of reaching this environmental standard (e.g. a certain emission reduction target) in the most cost efficient manner (cf. Böhringer 1999).

2.2 Evaluation criteria

Having determined the necessity for environmental policy, the crucial question consists in choosing the appropriate policy instruments in order to reach the given target. To facilitate the decision making, a number of evaluation criteria are used, which are outlined in the following.

2.2.1. Ecological precision

Ecological precision, or ecological efficiency, describes the capacity of a policy instrument to fulfil a predefined emission standard or target (in a given region) precisely. Thus, this principle is only focused on attaining a certain goal with the highest possible probability without looking at the cost impact (i.e. economic efficiency). It is particularly crucial in the case of environmental crisis or highly hazardous pollutants. Under this criterion, one can also assess the adjustment time which is needed under a given policy regime to reach the target (cf. Endres 2011, pp. 141ff).

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[3] Arthur Pigou introduced the idea of a tax on activities which entail negative externalities in order to correct the market equilibrium already in the 1920s (cf. Pigou 1962). Ronald Coase stated in his theorem that an efficient allocation in the presence of externalities can be achieved through direct negotiations between the affected parties if property rights are assigned beforehand and no transaction costs occur (cf. Wiesmeth 2012, p.100).

2.2.2. Cost efficiency

In most studies, cost efficiency, sometimes also referred to as cost effectiveness, constitutes the central principle against which environmental policy instruments are measured. It represents the capacity of an instrument to fulfil a predefined emission standard or target at the lowest possible cost (cf. Endres 2011, p. 121). This is achievable by equating the marginal abatement costs across all available abatement channels (increased energy efficiency, fuel substitution, etc.) and all agents (firms and facilities of all production sectors, households, etc.) such that all economic actors are confronted with a common price on their emissions at the margin (cf. Baumol and Oates 1971). In order to apply the criterion, a clear definition of the considered cost factors is needed (cf. Böhringer 1999). The narrow definition of cost efficiency usually only comprises the compliance costs of the targeted agents and sectors. If, however, the goal is to evaluate the economy-wide cost effects of a certain policy regime, additional costs have to be taken into account, mainly administrative costs (i.e. the costs to implement, monitor and enforce a policy) and macroeconomic impacts (i.e. cost effects on sectors outside of the policy regime, especially fiscal interactions with pre-existing instruments) (cf. Goulder and Parry 2008).

2.2.3. Dynamic efficiency

With the concept of cost efficiency, policy instruments are assessed from a static point of view, assuming that abatement options and technologies are given and unchanging. It has, however, often been argued in environmental economics that in the long term, technological change will play the most prominent role in achieving environmental goals. For example, according to Kneese and Schultz (1978) *"over the long haul, perhaps the single most important criterion on which to judge environmental policies is the extent to which they spur new technology towards the efficient conservation of environmental quality"*. Thus, the criterion of dynamic efficiency or dynamic incentive effect is applied to evaluate the capacity of an instrument to induce the development and deployment of new technologies which reduce the cost of emission mitigation (cf. Endres 2011, p. 130). Accordingly, while the static cost efficiency is concentrated on the minimization of abatement costs in the short term, the principle of dynamic efficiency seeks to minimize emission reduction cost over a longer time period. When analysing the dynamic efficiency of an environmental policy instrument, a differentiation is often made between the potential to encourage the adoption of new, yet existing technologies and the potential to incentivize R&D activities for future technologies (cf. Requate 2005).

2.2.4. Additionally: Political feasibility, distributional equity, flexibility

While ecological precision as well as static and dynamic cost efficiency are surely the most important criteria to evaluate environmental policy instruments, additional aspects have gained importance in recent analyses. The political feasibility and social acceptance of environmental instruments can in practice turn out to be crucial for the decision-making process (cf. Feess 2007, p. 50). Here it has to be noted, that political feasibility does not only depend on the attributes of an instrument but is closely related to the specific political setting with varying constraints, institutional structures, traditions, advocacy groups, etc. (cf. Green and Yatchew 2012). Closely related to the issue of feasibility are distributional impacts of different policy measures, especially between polluting enterprises and other economic agents or across household income groups. Moreover, policy flexibility, i.e. the ability of an instrument to adjust to new information in a flexible and quick manner, has to be taken into consideration (cf. Goulder and Parry 2008).

2.3 Types of environmental policy instruments

The growing endeavours to control global greenhouse gas emissions have assigned additional significance to the issue of instrument choice. The following chapter provides an overview over the most important types of policy instruments which are currently in the centre of the scientific and political discussion when it comes to emission mitigation strategies. The aforementioned evaluation criteria will be applied to highlight the advantages and disadvantages of each instrument.

2.3.1. Command-and-control policies

Command-and-control instruments have dominated environmental policy for a long time. They consist of mandatory regulations where the government directly intervenes in the activities of individual firms by prescribing or forbidding certain activities (cf. Rogall 2008, p. 240). A differentiation is made between technology-based standards, where compliance is only achieved by adopting a certain technology or equipment, and performance-based standards, which stipulate uniform emission ceilings on the firm-level leaving the technology choice to the firm (cf. Hackett 2011, p. 223). Examples of currently valid command-and-control instruments comprise the requirement to install catalytic converters and other legislation to reduce atmospheric pollution as well as the international ban on CFCs (chlorofluorocarbons). In many cases, regulations do not directly focus on emissions but specify measures which will eventually lead to an emission reduction, as for example minimum energy efficiency standards for buildings or obligations to cover a certain percentage of energy consumption (e.g. of residential buildings) through renewable energies.

The major advantage of command-and-control instruments consists in their high ecological precision making them particularly beneficial to control highly hazardous pollutants and for cases were the spatial distribution of emission is of significance. Taking a closer look, however, it becomes obvious, that regulations usually only target the emission level of an individual firm, such that total emissions which are subject to economic growth are less easy to control (cf. Endres 2011, p. 141). Moreover, an additional drawback arises when looking at the time needed to reach a certain environmental goal. Command-and-control policies usually specify less ambitious requirements for old plants than for new ones thus giving inadvertently an incentive to use the old, less eco-friendly plants for a longer period of time (cf. Endres 2011, p. 144). In the light of behavioural barriers to investments in energy efficiency, though, additional relevance is attached to regulatory mandates as they enforce the realization of in many cases highly cost efficient measures (e.g. in the building sector) which are otherwise not carried out voluntarily (cf. Hackett 2011, p. 224).

With respect to cost efficiency, a differentiation must be made between technology- and performance-based standards. While with regulations setting a specific emission target an individual firm still has the incentive to search for the most cost efficient manner to reach this target, this is not the case for regulations prescribing the use of a certain technology. When looking at the totality of emitting firms, though, both types of command-and-control instruments exhibit considerable disadvantages, as regulations usually set uniform standards not taking into account the heterogeneity of individual polluters. A cost efficient distribution of the emission reduction burden will, however, only be achieved, when the contribution of each firm is determined depending on their individual abatement cost curve. This would require the regulator to have information on the cost situation of each polluter such that a cost efficient differentiation of command-and-control policies is practically impossible (cf. Endres 2011, pp. 121ff). Furthermore, an additional weakness of mandatory regulations consists in the fact that, contrary to emissions taxes, under a command-and-control policy framework firms are not charged for the remaining pollution ("weak" form of the polluter-pays-principle), leading to a lower output price and a less pronounced decline in the demand for environmentally harmful goods. Thus, in order to reach the overall emission reduction target, the options of fuel substitution and increased energy efficiency would have to be used above the optimal level, while the output-reduction option is neglected further compromising the cost efficiency of the policy outcome (cf. Cansier 1996, p. 206; Goulder and Parry 2008).

A further shortcoming of command-and-control instruments results from their insufficient stimulation of technological progress. Performance-based standards can spur some efforts to find new processes which make it possible to fulfil the emission targets at lower cost. In general, however, mandatory regulations provide no inducement to develop and introduce technologies that entail emission reductions beyond the standards fixed by the government. In order to increase dynamic efficiency, attempts have been made to increase the flexibility by means of gradually tightening the standards according to the current technological state of art. It has been observed, however, that this approach often tends to have either no or even a dampening effect on innovation and to cause lock-ins into certain technologies, because under such a policy regime polluters have an incentive not to unfold any possibilities of technological improvement and political revision processes are often time consuming and lag behind the actual technological progress (cf. Endres 2011, pp. 131ff).

One of the reasons why regulatory mandates have long experienced widespread use is their relatively high acceptance in society (cf. Rogall 2008, p. 243). The fact that polluting firms are only burdened with the cost of pollution going beyond the standard generally facilitates the implementation of such regulations. It has also been argued that (technology-based) regulatory approaches have the advantage of comparatively low monitoring costs, especially when a large number of individual, point-source emissions have to be controlled. Thus, according to Cole and Grossman (1999) if not only compliance but also monitoring costs are taken into account, in some cases, where abatement costs are relatively low and monitoring costs relatively high, the comparative advantage of market-based instruments like emission taxes or tradable permits in terms of cost efficiency might be even offset.

2.3.2. Market-based instruments (1): Emissions taxes

In environmental policy, command-and-control instruments are usually contrasted with so called market-based instruments that try to influence behaviour through market signals instead of setting explicit directives with respect to environmental quality (cf. Stavins 2001). Market-based instruments function either as price-based, i.e. by assigning prices to environmental commodities, most importantly emissions taxes, or as quantity-based, i.e. by assigning property rights and creating markets for environmental commodities, most importantly emission trading systems (cf. OECD 2007a). These types of instruments have gained in importance in environmental policy since the 1990s, their role being highlighted in several official documents like the *Agenda 21* (UNCED 1992), the *Green Paper on market-based instruments for environment and related policy purposes* of the European Commission (EC 2007) or the *OECD Environmental Outlook to 2050* (OECD 2012).

Accordingly, instead of directly limiting environmentally hazardous activities, with emission taxes such activities are made more expensive by putting a charge on the emitted quantity of a pollutant. The approach goes back to the works of Arthur Pigou in the 1920s, but rather than trying to strictly internalize all external effects, the idea today is to reach a certain predetermined environmental standard with the help of imposing a price on pollution. In literature, this is often referred to as the “price-standard approach” introduced by Baumol and Oates (1971) (cf. Endres 2011, p. 109). It has to be noted, however, that the taxes and fees associated with environmental issues which are implemented in practice deviate considerably from the theoretical concept of an emissions tax. As it is often difficult to measure emissions directly, the consumption of input commodities, produced goods or services related to emissions is used as tax base, like for example taxes on gasoline, electricity or motor vehicles (cf. Goulder and Parry 2008). In the European Union, environmental taxes are defined with respect to the tax base which needs to be *“a physical unit (or a proxy of it) of something that has a proven, specific negative impact on the environment”* (Eurostat 2001, p. 9), including all taxes on energy and transport. Moreover, a differentiation can be made regarding the intent of the tax. While fiscal taxes aim at raising revenue, the rational of pure environmental taxes is to influence behavior so as to reduce pollution. Hence, an environmental tax fulfills its objective when revenues are comparatively small (cf. Wiesmeth 2012, p. 185).

The major advantage of using taxes for emission control lies in their high cost efficiency, both on the level of the individual firm and for the totality of polluters. With a price on emissions, a polluting firm will undertake abatement activities as long as their individual marginal abatement costs are below the tax rate using all possible options of emission mitigation. From this it follows that with a uniform emission tax the most cost efficient manner of fulfilling a certain reduction target will also be reached on the aggregate level, because all affected polluters will reduce emissions until their marginal abatement costs equal the tax rate leading to a single emission price on all sources. Thus, in equilibrium marginal abatement costs will be the same for all affected firms, whereas their contribution to emission mitigation will vary (cf. Endres 2011, pp. 122ff). The superiority of emission taxes regarding cost efficiency as compared to mandatory regulations is graphically illustrated in Figure 2-3. For simplicity reasons, only two firms are taken into account which both emit the pollutant *E*. The graphs show the marginal abatement cost curves for each firm (MAC_1 and MAC_2) as well as the (horizontally) aggregated curve adding the reduction potentials at different cost levels for both firms (MAC_{1+2}). It follows that emission mitigation becomes more costly as reduction levels get more ambitious. Moreover, it is assumed that the abatement cost curve of *Polluter 2* is steeper than the one of *Polluter 1* leading to higher marginal (and absolute) abatement costs for the same reduction level. At the outset, with no measures in place, emissions sum up to E^* in total with both firms emitting the same amount (E_1^* and E_2^*). In the case of a undifferentiated command-and control policy both firms are obliged to cut their emissions by half, resulting in emission levels of $E_1^*/2$ and $E_2^*/2$ as well as relatively high marginal abatement costs for *Polluter 2* (MAC_2^*) and lower costs for *Polluter 1* (MAC_1^*). The aggregated abatement costs curve MAC_{1+2} shows the tax rate $\bar{t}$ which would be required if the halving of total emission was to be achieved through a uniform tax rate. In this case, each polluter will abate its individual emissions up to the point where marginal abatement costs equate the tax rate. Consequently, *Polluter 1* lowers its emissions additionally to $\overline{E}_1$ associated with slightly higher marginal abatement costs $\overline{MAC_1}$, while *Polluter 2* decreases its mitigation efforts with the result of a higher emission level $\overline{E}_2$ and the same marginal abatement costs ($\overline{MAC_2}$ = $\overline{MAC_1}$). Due to the fact that the marginal abatement cost curve of *Polluter 2* is steeper than the one of *Polluter 1*, the drop to $\overline{MAC_2}$ is more pronounced as the increase to $\overline{MAC_1}$. Accordingly, absolute abatement costs (given as the area under the marginal abatement cost curve) will be lower under the tax regime than with the mandatory standard, as in Figure 2-3 for *Polluter 1* mitigation costs only rise by area *a*, while mitigation costs for *Polluter 2* diminish by the larger area *b*. Thus it becomes obvious, that the uniform emission tax leads automatically to a cost efficient allocation of emission reduction without the regulator having to know the abatement cost curves of each affected polluter.

An additional remark on cost efficiency has to be made, however, with respect to the design of many environmental taxes currently in existence. A deviation from using emissions as the tax base often entails efficiency losses as not all reduction options may be activated equally.

If, for example, a tax is put on electricity consumption, the only avoidance strategy consists in lowering electricity demand, whereas no incentives for higher efficiency or fuel substitution in electricity generation are generated (cf. Goulder and Parry 2008).

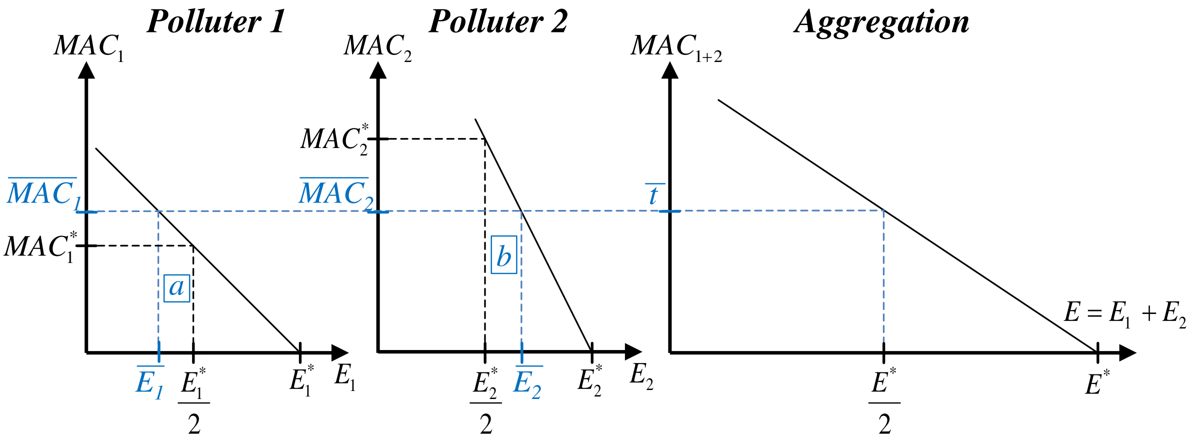

Figure 2-3: Graphical depiction of the cost efficiency of an emission tax compared to a uniform mandatory standard (own illustration based on Endres 2011, p. 125)

Apart from the high cost efficiency, emission taxes stand out by their strong incentive to introduce new technologies which will reduce abatement costs. Whereas command-and-control instruments only create an inducement to reach a certain standard at minimal cost, tax systems generate constant pressure to realize abatement cost savings regardless of the reduction level already reached. The difference between the two policy approaches stems from the fact that with taxes, emitters do not only pay for the avoided but also for the remaining emissions, such that each additional unit of abated emissions brings cost savings in the form of lower tax payments (OECD 2001, pp. 23f). This distinctive incentive structure is further highlighted in Figure 2-4. It shows the marginal abatement cost curve of a firm before ($\overline{MAC}_{old}$) and after ($\overline{MAC}_{new}$) the implementation of a new, emission-saving technology. The emission level $\overline{E}_{old}$ is assumed to be the standard prescribed in the case of a command-and-control approach and at the same time the level which is reached with the help of an emission tax t before the introduction of the new technology. After the innovation, marginal abatement cost drops to $\overline{MAC}_{new}$, such that for both policy instruments, abatement cost savings in the amount of area a are realized. While the emission level remains the same ($\overline{E}_{old}$) with the mandatory standard, in the case of the emission tax, firms have an incentive to lower emissions to $\overline{E}_{new}$ thereby saving tax payments (represented by areas c and d in Figure 2-4). Thus, in total the polluter is able to obtain cost savings that amount to areas c and a (as area d accounts for additional abatement costs) and therefore has a stronger incentive to introduce an innovative technology than in the case of a fixed emission standard where potential savings are limited to area a.

When looking at the ability to reach a given emission target precisely, emissions taxes clearly exhibit disadvantages. It is an intrinsic feature of an environmental tax not to be aimed at the quantity of the commodity in question, but to change behavior through pricing signals.

Hence, in order to set the tax rate such as to arrive at a predetermined target, the regulator would require information on the adjustment behavior of all affected polluters, i.e. would have to know their marginal abatement cost curves. Hence, in reality a certain emission standard could only be reached through a stepwise trial-and-error process until the appropriate tax rate is found. Given the lengthiness of political decision-making and the adverse impacts on planning security such a process would have, this does not seem to be a viable approach. Moving away from the static view, additional difficulties with respect to ecological precision arise, as important economic parameters like economic growth, technological progress or inflation rates, which change over time, influence the polluters' response to the tax system. Moreover, it has to be mentioned that the applicability of emission taxes reaches a limit in the case of non-uniformly mixed pollutants where the regional distribution matters and the risk of local "hot spots" needs to be averted (cf. Cansier 1996, pp. 174ff).

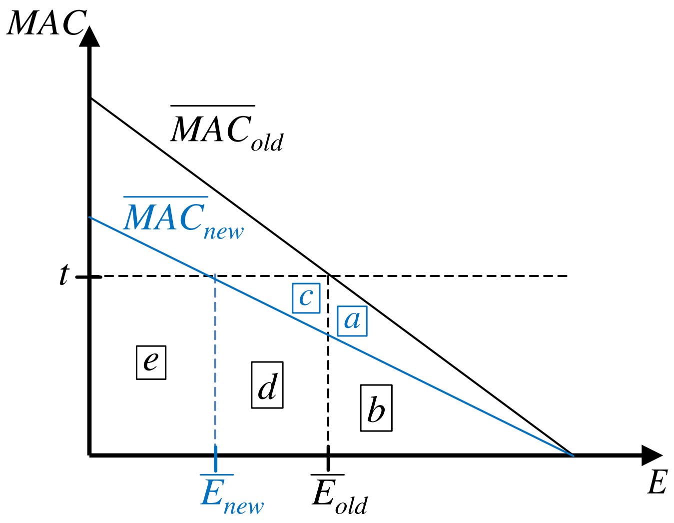

Figure 2-4: Graphical depiction of the dynamic efficiency of an emission tax compared to a uniform mandatory standard (own illustration based on OECD 2001, p. 23)

The size of the administrative costs of environmental taxes depends largely on the tax design, e.g. the complexity of the tax base, the number of specific tax provisions, etc. (cf. OECD 2001, pp. 91ff). One of the main obstacles to the acceptability of effective emission taxes is the additional burden they constitute for the affected economic agents, as, unlike with command-and-control instruments, costs arise not only for the abated emissions but also for the residual ones. With respect to industrial companies, this might raise issues of international competitiveness, whereas in the case of households the income distribution might be impaired. Environmental taxes can have a regressive impact as they often charge goods of basic necessity (especially energy), such that low-income households are more adversely affected (cf. Kosonen and Nicodeme 2009). In this context, additional attention needs to be paid to the question on how the revenues of an environmental taxes are spent, which might lead to an alleviation of the distributional effects. Since the 1990s, the concept of environmental tax reforms (ETR) has taken on greater significance. The idea here is to use the additional environmental tax revenues to lower conventional taxes on production factors, such as labour or capital, i.e. to transfer the tax burden from so called “goods” to “bads” (cf. EEA 2005, pp. 83f). This approach has often been associated with the double dividend hypothesis stating that such a (revenue neutral) tax shift could generate two possible dividends: firstly, welfare gains through the (cost efficient) internalization of environmental externalities (primary welfare gain) and secondly, welfare gains through the reduction of other distortionary taxes (revenue-recycling effect), which could for example, in the case of cutting labour taxes, result in more employment. Theoretical and empirical literature casts, however, doubt on the existence of this double dividend (cf. OECD 2001, pp. 35ff; Böhringer et al. 1997). As Parry and Oates (1998) outline, when analyzing the double dividend hypothesis in a second-best setting with pre-existing factor taxes, a third effect, called the tax-interaction effect, has to be taken into account which works in the opposite direction of the revenue-recycling effect. As environmental taxes will raise the cost of production, after-tax factor return will decrease, intensifying the distortions of the already existing factor taxes. Whether a double dividend can be realized, depends therefore on the magnitude of the revenue-recycling and the tax-interaction effect, with many analytical studies stating that under most conditions the latter tends to outweigh the former (cf. Goulder 1998).

2.3.3. Market-based instruments (2): Tradable allowance systems

Apart from emission taxes, tradable allowance systems for environmental goods represent the most important market-based environmental policy instrument. The approach, originated by Dales (1968), consists of the following steps: (1) the political decision maker (on national or international level) sets a limit on the use of a certain natural resource (e.g. maximum emissions of a pollutant) for a given region and time period; (2) within the specified limit, the overall right to emission is split up into a large number of partial rights permitting the user to emit the proportionate fraction of the total amount; (3) these rights are then transferred to the polluters as tradable emission certificates. Thus, an emissions trading system, also referred to as cap and trade system, is based on the idea of assigning property rights and thus creating artificial markets for environmental commodities (cf. Endres 2011, pp. 110ff). A tradable allowance system is therefore conceptually the mirror image of emission taxes – instead of setting the price of emission and leaving the quantity determination to the market, here the maximum emission level is fixed while the certificate price is market-determined. Consequently, the adjustment behavior of the affected polluters is similar in the sense that abatement activities are undertaken as long as the certificate price on the market exceeds marginal abatement costs, whereas any further emissions are covered through emission allowances purchased on the market (cf. Feess 2007, pp. 123f).

One of the most crucial aspects when implementing an emissions trading system consists in choosing a procedure for the initial allocation of the certificates, with the main differentiation between auctioning and free allocation. The process of auctioning off the certificates is in line with the strong version of the polluter-pays-principle as the participating polluters have to pay both for the avoided and the remaining emissions. In the case of an initial allocation free of charge, difficulties arise regarding the determination of the current emission level of each polluter. Here, the distribution can either be established based on historical emission levels (grandfathering) or on a differentiated reference standard that applies to all installations of a sector (benchmarking) (cf. Möst et al. 2011). Critics have pointed out, however, that grandfathering tends to favour firms with high emission levels, who hitherto have done little for environmental protection, and to discriminate new entrants to the market (cf. Cansier 1996, pp. 193f). Additional issues regarding the design of a cap and trade system include the scope (with respect to the covered pollutants, the regional expansion and the target group), the length of the trading periods as well as the implementation of banking/borrowing (the option to store certificates for a future period or to use certificates of future periods in an earlier one) (cf. Rudolph et al. 2011).

With respect to cost efficiency, the results for emission taxes can be transferred to emission trading as both instruments create the same incentive structure. In the context of a tradable allowance system, the certificate price assumes the role of the tax rate in establishing a uniform price on emission that will ensure a distribution of abatement activities between polluters at minimal cost using all possible mitigation channels. Thus, the graphical representation in Figure 2-3 can also be adopted to illustrate the cost efficiency of emission trading schemes, with the difference that instead of the tax rate here the emission level $E^* / 2$ will be fixed by the regulating authority, resulting in a permit price at level $\bar{t}$ (cf. Endres 2011, pp. 121ff). Furthermore, emission mitigation will be cost efficient with emission trading irrespective of the initial allocation mechanism, as also in the case of free allocation polluters will orient their decision as to whether to abate emissions or buy certificates on the market price. The only prerequisite is the development of well-functioning markets for emission allowances with a large enough number of sellers and buyers (cf. Cansier 1996, p. 195).

Basically, a cap and trade system has the same effect on technological progress as emissions taxes, as polluters can achieve savings in terms of certificate costs with every additional unit of abated emissions realized with the help of an innovative technology. This is also the case with free allocation: even though firms initially did not pay for their permits, these permits could be sold on the market and therefore create opportunity costs representing foregone profits. In the long-run, however, an important difference to emissions taxes is observable. While with a tax system the incentive for innovation remains constant over time given the exogenously fixed tax rate, in an emission trading system the pressure on innovation declines as the certificate price drops with a rising number of firms that have already introduced emission-saving technologies. Hence, it becomes crucial, that the political decision maker takes the anticipated technological progress rates into account when setting the long-term emission caps. Moreover, the regulator has the possibility, to withdraw allowances from the market in the case of a price drop with the additional effect of tightening the emission target (cf. Endres 2011, p. 134). On the whole, while the superiority regarding dynamic efficiency of market-based instruments over command-and-control regimes has clearly been established in theoretical and empirical literature, no clear ranking seems to have emerged in the comparison of emissions taxes and permit trading systems (cf. Jaffe et al. 2002; Requate 2005).

One of the advantages of emission trading systems is their high ecological precision. In such a system, the predetermined emission target will be fulfilled with certainty without the regulator having to know the marginal abatement cost curves of the affected polluters. There is, however, one limitation with respect to non-uniformly mixed pollutants where the regional distribution of emissions needs to be controlled, which is not feasible with a tradable allowance system (cf. Feess 2007, pp. 126f).

Recent studies indicate that permit trading schemes involve comparatively high administrative costs on the government side and high transaction costs for the participating firms, which might reduce the cost efficiency of such instruments. Environmental taxes can usually be relatively easily integrated into the existing tax system and be operated by existing tax authorities, whereas for an emission trading system new structures, institutions, etc. have to be established giving rise to additional administrative costs (cf. Pope and Owen 2009). An analysis by Heindl (2012) shows that especially for smaller emitters the operating costs of an emission trading scheme constitute a high burden. With respect to distributional impacts, it is obvious that allocating the certificates free of charge puts less pressure on the affected polluters. At the same time, one must not forget that under auctioning additional government revenue is generated, which can be used to decrease distortionary taxes or compensate those who have been affected negatively by the cap and trade system (cf. Goulder and Parry 2008). The free allocation mechanism can also be criticized on the grounds of generating high windfall profits, as the affected firms pass on the opportunity costs of the freely allocated permits to the consumer (cf. Sijm et al. 2006). On the other hand, free allocation is sure to increase the acceptability and political feasibility of an emission trading system.

2.3.4. “Soft” policy instruments

With the aim to cover all types of policy tools for environmental goals, so called “soft” policy instruments are introduced here as a third category, in addition to command-and-control and market-based mechanisms. These instruments are based on the cooperation principle and try to induce modifications in the behaviour of economic agents through incentives and the provision of information relying on voluntarism, learning processes and procedural change. Most importantly, information campaigns, voluntary agreements (that are not legally binding), environmental product labelling, public disclosure requirements, best practice dissemination and environmental management systems are counted in this category (cf. Hertin et al. 2004). In order to illustrate the classification of policy instruments, the approach of Bemelmans-Videc et al. (1998) can be utilized distinguishing between *carrots* (i.e. economic instruments which manipulate market incentives), *sticks* (i.e. command-and-control tools that entail a high level of coercion) and *sermons* (i.e. “soft” instruments that imply less constraints and mainly build on persuasion). Environmental subsidies are sometimes placed in the first category – here, however, they are treated as "soft" instruments given their usually limited scope and financial resources (cf. Rogall 2008, p. 244).

"Soft" policy instruments are mostly used to change the attitude of economic agents towards environmental action, provide information on possible emission mitigation options and to overcome barriers to (in many cases) cost efficient investments in energy efficiency. Their main advantage can be found in their high level of acceptability which facilitates their implementation. Moreover, these measures are usually associated with comparatively low administrative costs (cf. Gunningham and Sinclair 2004). On the other hand, one must not forget that the impact of these non-binding measures will hardly be sufficient to accomplish comprehensive environmental goals. Conceptually, they are no longer grounded on the basic ideas of environmental policy, like the polluter-pays-principle and the internalization of environmental externalities. Apart from that, subsidy schemes are often not cost efficient as they are likely to attract free riders. Critics have also expressed concern that a complete reliance on soft, non-binding measures might in the long run encourage a regulatory race to the bottom. Thus, on the whole one can conclude that soft environmentally policy instruments are only useful as complementary measures to precede and accompany more effective tools from the command-and-control or market-based categories (cf. Rogall 2008, pp. 248f).

2.4 Policies promoting environmental technologies

Economists usually argue that any environmental policy intervention should be clearly focused on the market failure it tries to correct. That means, if the purpose of a policy instrument is to internalize the negative externalities from greenhouse gas (GHG) emissions, it should directly aim at reducing these emissions taking into account all possible mitigation options. Yet, in reality, a large variety of policy instruments can be observed that try to foster the innovation and diffusion of certain environmental technologies that will help to abate GHG emission, especially in the area of renewable energies. Therefore, it needs to be analyzed whether there is a rationale for the implementation of specific instruments that encourage environment-related technological change or if it is sufficient and more cost efficient to concentrate on measures that directly target the reduction of GHG emissions, like emission trading systems or carbon taxes.

2.4.1. Rationale for technology policies

Environmental policy and technological change are closely intertwined (cf. Popp 2002). On the one hand, major technological innovations are required if substantial emission reduction targets are to be reached. On the other hand, standard emission abatement policies, like emissions taxes, per se already provide incentives to spur technological innovations. The effect that alterations in relative prices will have themselves on technological progress is referred to as the induced-innovation hypothesis and was first initiated by Sir John Hicks (1932). The question remains, however, whether environmental policies alone are capable of bringing about the socially optimal rate of innovation. If environmental externalities were the only market failure inherent to environmental technologies, no argument to justify any additional, specific measure for technology promotion could be brought forward.

It has, however, often been noted that the two steps of technology development, innovation and diffusion (or adoption), exhibit themselves market failures and external effects. Jaffe et al. (2005) divide these into knowledge externalities, adoption externalities as well as market failures due to imperfect information. Knowledge externalities, associated with the innovation phase, occur when a firm investing in the invention of a new technology is not able to capture all the benefits of this innovation for themselves, as other firm copy or imitate their technology or use the results in their own research. Hence, due to the characterization of new knowledge as a public good, innovators generate a positive external effect for other firms, often referred to as knowledge spill-overs. This results in a private return to innovation considerably lower than the social return. Consequently, R&D activities in the private sector will be less than socially optimal warranting governmental intervention in the form of public sector research, subsidies for private R&D, tax credits, stricter patent rules, etc. With respect to the diffusion phase of a new technology, the existence of additional market failures is less controversial. It has been argued that similar to the innovation phase, early adopters of a technology create positive externalities for later adopters and manufacturers through learning-by-using (on the demand side) and learning-by-doing (on the supply side), thereby giving rise to dynamic increasing returns. If this is the case, government action to stimulate the diffusion of new technologies through subsidies, technology standards, information campaigns, etc. could be justified. Furthermore, imperfections in the capital markets for technology development due to the high uncertainty of returns and the asymmetric distribution of information between developer and investor might lead to bottlenecks in the financing of innovation projects (cf. Jaffe et al. 2005).

It has to be pointed out, however, that all these arguments can only be used as a basis for a general promotion of technology development without concentrating on specific areas, like the environment. Economists have often argued that the government is not very well-suited for “picking winners” and that the market mechanism is more likely to channel funds to the most promising areas (cf. Lundvall and Borrás 2005). Yet, some reasons have been brought forward that could explain the particular focus on environmental technologies. First of all, special attention might be warranted given the public good nature of environmental commodities that renders them an area of government procurement (cf. Jarre et al. 2005). Besides, Goulder and Parry (2008) as well as Matthes (2010) argue that in order to achieve ambitious emission reduction goals extensive technological breakthroughs and the development of backstop technologies will be needed which should be fostered by means of targeted policy tools, especially in the light of the expected dramatic cost reductions due to learning effects. Apart from that, one must not forget the implications of the long timescales both for the formulation of climate change policies and targets and the turnover of energy capital stock such that the uncertainty about future emission prices or tax rates might dampen innovation activities today (cf. Fischer and Newell 2008; Montgomery and Smith 2007). In this context, Jaffe et al. (2005) also argue that in a second-best world where not all environmental externalities from climate change are yet internalized, technology policy might even play a more prominent role as such tools are more easily implemented than emission pricing policies.

On the whole, it seems that against the background of knowledge externalities and imperfect information, policy instruments aimed at supporting environmental R&D activities can be justified, while there is less consensus regarding the need for specific policies promoting the adoption of certain environmental technologies. In reality, though, governmental intervention can be found both in the area of innovation and adoption of environmental technologies. Especially support schemes for the market introduction and diffusion of renewable electricity technologies have gained momentum in recent years and will therefore be discussed in more detail in the next section.

2.4.2. Instruments for the promotion of renewable electricity

Increasing the use of renewable energies is seen as one of the major strategies to combat climate change. This is reflected in the fact that currently all 27 member states of the European Union have some type of support scheme for renewable electricity in place (cf. de Jager et al. 2011, p. 27ff). In addition to the justifications for technology promotion measures outlined in the previous sections, further arguments for supporting renewable electricity generation are brought forward by the proponents of such instruments. First of all, it is argued that renewable energies can contribute to energy security by a diversification of energy supply and a reduction of import dependency (cf. Olz et al. 2007, pp. 23ff). Yet at the same time, relying more heavily on renewable energies in electricity production might also pose risks to energy security due to the intermittency of important renewable sources like wind and solar and the need for scarce raw materials for some renewable energy technologies (cf. Sathaye et al. 2012, pp. 727f). Moreover, it is claimed that fostering renewable electricity technologies will lead to a creation of viable export industries and additional jobs. This argument is, however, very controversial given the fact that energy generation exhibits relatively high capital to labour ratios and in other areas job opportunities might be lost due to high electricity prices such that the net effect might be negligible or even negative (cf. Green and Yatchew 2012). Because of the decentralized generation structure of many renewable energies, the European Commission names rural development as an additional rationale for the promotion of renewable electricity generation (cf. EC 2009a).

A variety of policy instruments has been applied to promote the use of renewable energies in electricity production. As with market-based instruments, a differentiation is made between price-based and quantity-based measures (cf. Menanteau et al. 2003). Fixed feed-in tariffs (FIT) form part of the first category as the price for renewable electricity is set exogenously. Renewable electricity producers are offered guaranteed prices over a fixed period of time usually in combination with a purchase guarantee. They are therefore not responsible to sell their production to the market themselves and their revenues are independent of the development of the electricity price. The tariff level is determined by the regulator usually based on the generation costs of renewable electricity (plus a reasonable rate of return). Thus, the remuneration level can be varied by the type of technology or renewable energy source, the capacity of the installation, project location, etc. The additional costs that distributors incur in this system are usually passed through to power consumers by means of a levy on end-use electricity prices. A variation of this scheme consists in fixed feed-in premiums whose size is also set administratively and which are paid on top of the electricity price. Accordingly, this approach generally does not contain a purchase guarantee. In order to lower the uncertainty in revenues for renewable producers, the premium can be pegged in some manner to the spot market electricity price, for example by introducing caps and floors (cf. Couture and Gagnon 2010). Apart from that, fiscal incentives or investment grants also belong to the price-based measures, but are usually only employed in a complementary way.

One of the most important quantity-based instruments are tradable green certificate (TGC) schemes, where the regulator specifies, based on the political targets, a certain quota of capacity or generation of electricity that needs to be covered by renewable sources. This quota obligation is then complemented by a certificate trading systems. Producers are awarded a green certificate for each unit of renewable generation, which they can sell to the entity responsible for fulfilling the quota (usually electricity distributors). Hence, renewable electricity producers generate revenues on two markets: the conventional electricity market by selling the produced electricity (in competition with all electricity producers) and the market for green certificates (in competition with all renewable producers) (cf. Drillisch 1999, p. 10). This implies that the price for green certificates is determined through a competitive market mechanism. Technology differentiation can be introduced to a quota system with the help of banding, i.e. different renewable technologies receive different multiples of green certificates for each unit of generation (cf. Buckman 2011). In order to avoid non-compliance, sanction measures need to be put in place.

Tendering procedures also form part of the group of quantity-based measures and can be viewed as a synthesis between feed-in tariffs and quota systems (cf. Bechberger et al. 2003, p. 8). Here, a predefined target of renewable capacity or generation is assigned through a bidding process to the bidders with the lowest price. That means that renewable producers are in direct competition with each other. The regulator possesses a number of parameters when defining the specific design of a tendering procedure. First of all, different types of auctions and price-finding mechanisms can be applied (e.g. uniform-price vs. pay-as-bid auction). The price established in the auctioning process can either be paid as a fixed tariff or a premium on top of the electricity price. Similarly, the regulator can assign the responsibility to market the electricity generated either to the producer (in case of a premium) or the grid operator (in case of a fixed tariff). Like all other support mechanisms, tenders can be defined as technology-neutral or -specific (with separate auctions for each renewable source). With respect to the financing of the additional costs of the instrument, either a surcharge on electricity prices or the use of general tax funds would be possible. Real-world experiences have shown that it is crucial to implement penalties for non-compliance, as otherwise the acquired contract may only be seen as an option to invest in the respective installations (cf. Frontier Economics 2012, p. 82ff).

Table 2-1 presents an overview on the basic characteristics of the four major support mechanisms for renewable electricity described above. A variety of studies has looked at the advantages and disadvantages of the different support schemes based on model analyses as well as the experience in European countries and the Unites States (cf., amongst others, Ragwitz et al. 2007; IEA 2008; Sawin 2004; Menanteau et al. 2003; Green and Yatchew 2012; Butler and Neuhoff 2005; Schmalensee 2011). It becomes apparent that a variety of dimensions needs to be taken into account when evaluating policy instruments for the promotion of renewable electricity which will be outlined in the following.

Table 2-1: Characteristics of major support schemes for renewable electricity (own illustration based on Frontier Economics 2012, p. 54)

	Feed-in tariffs	**Feed-in premiums**	**Tradable green certificates**	**Tendering procedures**
Control variable	Price of renewable electricity		Quantity of renewable electricity	
Type of remuneration	Fixed tariffs	Fixed premiums + electricity price	TGC price + electricity price	Auction price (+ electricity price)
Determination method for remuneration	Administrative		Through market mechanisms	
Revenues	Predictable	Uncertain		Dependent on design
Technology differentiation	Possible in principle; optional			
Marketing responsibility (producers)	No	Yes	Yes	Dependent on design

Cost efficiency

As the share of electricity generation covered by a support scheme rises, the issue of a cost efficient promotion becomes more important. Cost efficiency can be generally accomplished by a technology-neutral design ensuring that always the cheapest generation options are chosen first (cf. Frontier Economics 2012, p. 17f). Thus, a technology-neutral system fosters the diffusion of those renewable technologies which are closest to market competitiveness. In theory, all types of support schemes, both price- or quantity-based, could be established as technology-neutral. In reality, however, FIT systems have usually been set up with technology-specific tariffs. To reduce the cost burden and the free-rider effects under a technology-specific FIT scheme, regular adjustments of the tariffs as well as automatic tariff degression mechanisms can be applied. With respect to dynamic efficiency, all support systems are supposed to have strong incentives on innovation, either because of competition (TGC and tendering schemes) or the possibility to increase the profit margin (FIT).

Distributional impacts

While cost efficiency is one of the major criteria to evaluate renewable support systems, attention also needs to be paid to the resulting public costs, i.e. the transfer costs for consumers or taxpayers. Even though a system features high cost efficiency through a minimization of generation costs, the burden on consumers might still be high if the renewable generation sector is able to generate high profits. Hence, it is argued that in addition to maximizing cost efficiency, support schemes should be formulated in such a way that producer rents are limited (cf. Resch and Ragwitz 2010). Uniform remuneration tends to lead to an over-subsidization of less costly technologies resulting in high profit margins for producers, while stepped tariffs that reflect disparities in generation costs of renewables can limit the producer surplus and the additional costs for consumers. Figure 2-5 offers a stylized illustration of this distinction. Hence, whether the support expenditure resulting from a technology-neutral system are actually lower than those arising under a technology-specific one, depends on the size of two effects: the reduction of transfer costs due to higher cost efficiency versus the higher windfall gains for low-cost technologies.

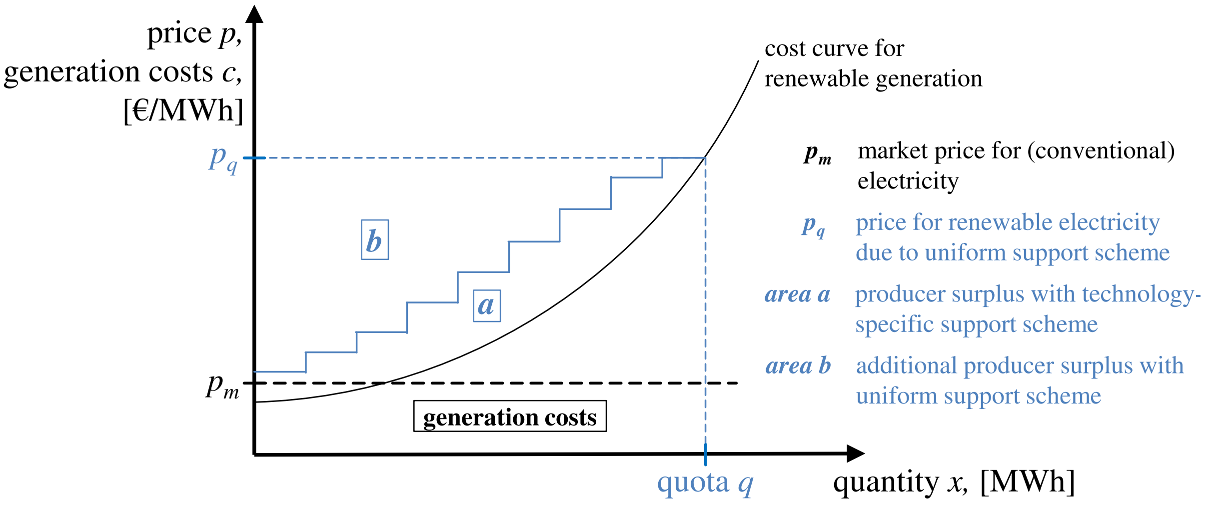

Figure 2-5: Comparison of producer surplus with uniform and technology-specific support schemes for renewable electricity generation (own illustration based on Ragwitz et al. 2007, p. 101)

Technology promotion

One of the main justifications for the introduction of a specific policy instrument for the promotion of renewable electricity is to foster the market introduction and adaption of innovative technologies in whose development considerable learning effects and associated cost reductions are expected. When the aim is to realize these learning effects, a broad technology portfolio should be addressed. Thus, technology-specific schemes allow for a higher technology diversification at the expense of a cost efficient realization of renewable electricity targets.

Yet, given the expectation of considerable learning effects, it has been argued that in the long-run it might be more cost efficient to foster at once the market penetration of different types of renewable technologies in order to realize those cost reduction potentials (cf. Ragwitz et al. 2007). It has to be kept in mind, however, that in future such learning effects will be realized on a global scale on which the design of the support scheme in Germany will have little impact. In the past, it has also been highlighted that assuming a pioneering role in the promotion of a large variety of renewable energy technologies entails the additional benefit of creating viable and innovative export industries. Yet, when looking for example at the strong development of China's renewable energy equipment industry in recent years, this argument becomes highly questionable (cf. Frondel et al. 2009).

Marketing responsibility and competition

The currently prevailing instrument of fixed feed-in tariffs excludes renewable generation from all market forces. Expecting that the renewable share in electricity production will rise significantly, the issue of market integration gains greater importance. Here, putting the responsibility to sell the generated electricity directly to the market on the renewable producers, like it would be the case with fixed premium systems and TGC schemes, ensures that both investment and operation decisions react to market signals. Introducing renewable producers to markets forces involves a number of benefits. First of all, receiving price signals from the market would induce producer to adjust their feed-in according to demand. Yet, it has to be pointed out that this option is only significant for a small portion of renewable generation which is not supply-dependent and exhibits relevant variable costs, i.e. mainly biomass[4]. For fluctuating sources like wind or solar power as well as for sources with negligible variable costs like run-off river hydropower and geothermal energy reacting to market signals would only be relevant in times of negative electricity prices (cf. Frontier Economics 2012, p. 58). Integrating renewable generation into competitive markets can also open the possibility for renewable producers to provide system services. Here, even for intermittent sources the provision of negative balancing energy can be profitable (cf. Consentec and R2B Energy Consulting 2010, p. 42f). Apart from that, if producers are responsible for marketing their generation, stronger incentives to increase forecasting quality as well as to comply with forecasts in the case of fluctuant sources can be expected. In addition, it is important to note that stronger market integration does not only influence operational decisions but can also help to align investment decisions more strongly to the actual need for power plant capacity. Quantity-based quota schemes exhibit the additional advantage of creating dynamic competition between renewable investments at different points in time which would not be the case with previously fixed premiums (cf. Frontier Economics 2012, p. 74).

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[4] Here, an additional constraint for a demand-responsive supply for heat-led CHP plants needs to be taken into account (cf. Frontier Economics 2012, p.58).

Target achievement

Support mechanisms for renewable electricity are set up in order to fulfil a certain predefined political target. High ecological precision is, however, only guaranteed under quantity-based instruments avoiding both a target shortfall and a cost explosion in case of over-fulfilment. If the targets under a quota system or a tendering procedure are fixed for a comparatively long time horizon, quantity-based mechanisms can also be more easily coordinated or combined with other policy instruments, in particular emission trading schemes. For price-based measures, the risk of missing the target can be reduced by fixing the tariffs/premiums as a function of the growth rate in the previous period, i.e. if the expansion of renewable electricity generation has been higher than expected, tariffs/premiums are lowered faster. It has to be noted that for feed-in premiums the uncertainty regarding target achievement is even higher given the fact that the premium is paid on top of the uncertain market price for electricity. That is why in some legislations cap and floor values have been added such that the premium reacts to changing market conditions (cf. Couture and Gagnon 2010).

Transaction costs

Under any support mechanism for renewable electricity, transaction costs need to be taken into account both for the regulator and the renewable investor. With price-based schemes, the regulator faces the necessity to establish and periodically revise the tariffs in a way that both an over-subsidization and an incentive level too low to reach the target are prevented. TGC schemes, on the other hand, require high upfront costs to create functioning markets for green certificates. On the investors' side, advantages in terms of transaction costs can be observed for FIT systems, while all schemes that require renewable producers to market their electricity generation themselves imply higher transaction costs which might prevent smaller investors from participating. However, the creation of new marketing structures based on intermediaries, e.g. through existing energy traders, might effectively reduce this cost component and facilitate the participation of small businesses (cf. Bieberbach et al. 2012). These new marketing channels can also be of benefit in the case of tendering procedures where small investors are likely to face prohibitively high transaction costs when competing on their own.

Distribution of risk

It is often argued that one of the major advantages of FIT systems consists in the planning security provided to renewable producers as tariffs remain fixed over a long-time period and therefore provide predictable revenue streams. It has been pointed out that this security is of special importance in the case of investments in renewables since they represent both emerging and capital-intensive technologies and projects are often carried out by small investors (cf. Couture and Gagnon 2010). Certificate prices in TGC schemes as well as revenues under feed-in premium systems, on the other hand, depend on the market such that their future development is uncertain. To account for this higher risk, it has been suggested to consider higher hurdle rates for investments in renewables under support systems where future revenues are uncertain (cf. Redpoint Energy 2010). As a consequence, in order to attract the same amount of renewable electricity generation, the remuneration offered under such schemes would need to be higher than under mechanisms with reliable returns (cf. Kopp et al. 2012).

Yet, when evaluating support instruments from a macroeconomic perspective, one must not forget that also under a system with fixed tariffs the risk does not disappear from the system but is merely transferred to the consumers who face uncertain future support expenditures. Here, the problem of potentially high windfall profits for renewable producers in the case of feed-in premiums needs to be highlighted: if electricity prices rise unexpectedly, investments in renewable generation will increase with fixed premiums leading to a combination of high electricity prices and high support expenditures. In contrast, under a TGC scheme renewable investors as well as electricity consumers have an “implicit hedge” as electricity prices and certificate prices can be expected to react in an opposite way to each other (cf. Frontier Economics, p. 72). Apart from that, it has been observed that falling technology costs have very different effects on the transfer costs under price and quantity-based instruments. With a FIT scheme, if investment cost for renewable technologies decrease faster as was expected when setting the tariffs, investments increase leading to higher support expenditures. In contrast, under a quota system consumers will benefit from declining technology costs as certificate prices will decrease. One difficulty that might arise, however, with a TGC scheme is establishing a stable and reliable long-term political framework where the renewable targets need to be fixed for at least 20 years ahead (cf. Frontier Economics 2012, p. 74).

Additional effects on the electricity system

A strong expansion of electricity generation based on renewable energies has substantial impacts on the electricity system. Due to the intermittency of the most important sources, the need for backup capacity and operating reserves increases in order to avoid system failure. It has already been mentioned that efforts to better integrate renewable energies into the electricity market can help to alleviate this problem. Yet, when evaluating support mechanisms for renewable electricity generation, additional side effects on the electricity system should be taken into account as their magnitude and form might differ between instruments. For example, the size and temporal distribution of the merit-order effect of renewable electricity generation can depend on what types of renewable technologies are installed (cf. Sensfuß et al. 2008). The same holds true for the demand for storage capacity and grid expansion caused by large shares of renewables in electricity generation. In many cases, the regional concentration as well as the decentralization of renewable generation makes substantial extensions of the existing grid infrastructure, both in the transmission and distribution network, necessary. Consequently, a combination of general support instruments for renewable generation and regional control mechanisms might be considered (cf. BMVBS 2011).

When looking at the different criteria that should be kept in mind when evaluating instruments for the promotion of renewable electricity, it becomes apparent that considerable target conflicts may occur (cf. Figure 2-6). Most notably are the conflicts between cost efficiency and the promotion of a broad technology portfolio as well as between cost efficiency and the distributional impacts on consumers. Both these issues depend largely on the question whether support schemes are designed as technology-neutral or technology-specific.

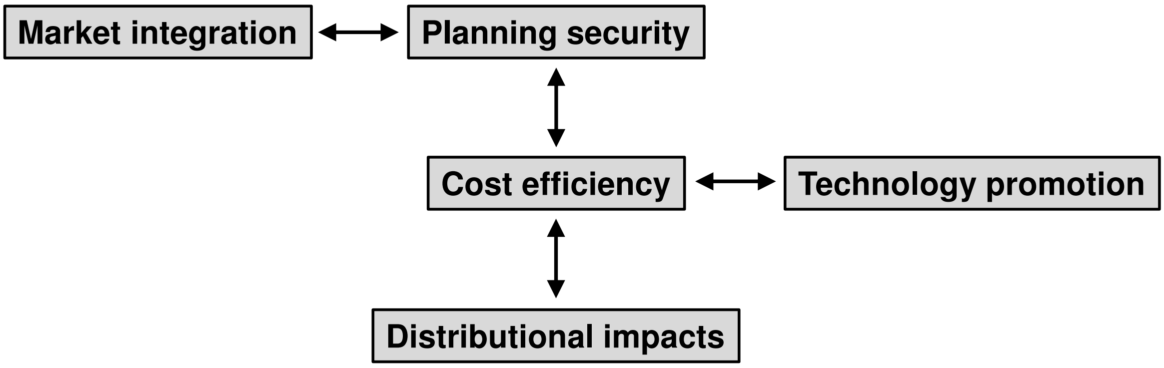


Figure 2-6: Potential target conflicts in the promotion of renewable electricity (own illustration based on Frontier Economics 2012, p.11)

Altogether, it can be observed that support instruments for renewable electricity have gained increasing significance in recent years, with a clear focus on FIT systems in Europe (cf. the overview given in Figure 2-7) and a stronger emphasis on TGC schemes in several U.S. states (cf. Schmalensee 2011). In some cases, different mechanisms are also used in combination. In Italy and the United Kingdom, for example, feed-in tariffs for less mature technologies have been added to a general quota system. Tendering schemes are often applied as a complementary instrument for large-scale project (mainly for offshore wind). In some countries (e.g. Spain) producers have the option to choose between fixed tariffs or premiums (cf. de Jager et al. 2011, pp. 27ff).

An additional alternative for the promotion of renewable energies in electricity generation has been recently introduced to the debate, namely the introduction of capacity markets for renewable sources (cf. Kopp et al. 2012). So far, the idea of complementing energy-only electricity markets with capacity markets has mainly been discussed for conventional generation given concerns that liberalized electricity markets might not provide the appropriate incentives to invest in new capacity thus failing to ensure resource adequacy. This issue is aggravated by rising shares of renewable in electricity production as they increase price volatility, reduce the general price level through the merit-order effect and lead to lower degrees of capacity utilization of conventional power plants (cf. Cramton and Ockenfels 2012). The basic mechanism of a capacity market starts with the regulator determining a fixed amount of capacity required in order to warrant security of supply. This capacity is then assigned through a competitive market mechanism (e.g. auctions or bilateral contracting) such that the providers with the lowest price are awarded the contract. Hence, the fact that through capacity markets electricity generators receive an additional cash flow makes this concept also interesting as a mechanism to foster the expansion of renewable electricity generation. It offers the same benefits as the tendering procedure outlined above ensuring that always the most cost efficient technologies are chosen to fulfil the target. However, a number of unresolved questions regarding the use of capacity markets for renewable electricity still remain such that an application in the near future is rather unlikely (cf. Kopp et al. 2012). At the same time, it gets increasingly obvious that the current electricity market design is not suitable for the case of dominant shares of renewable sources and reform strategies are needed to integrate renewable and conventional generation (cf. Matthes 2013).

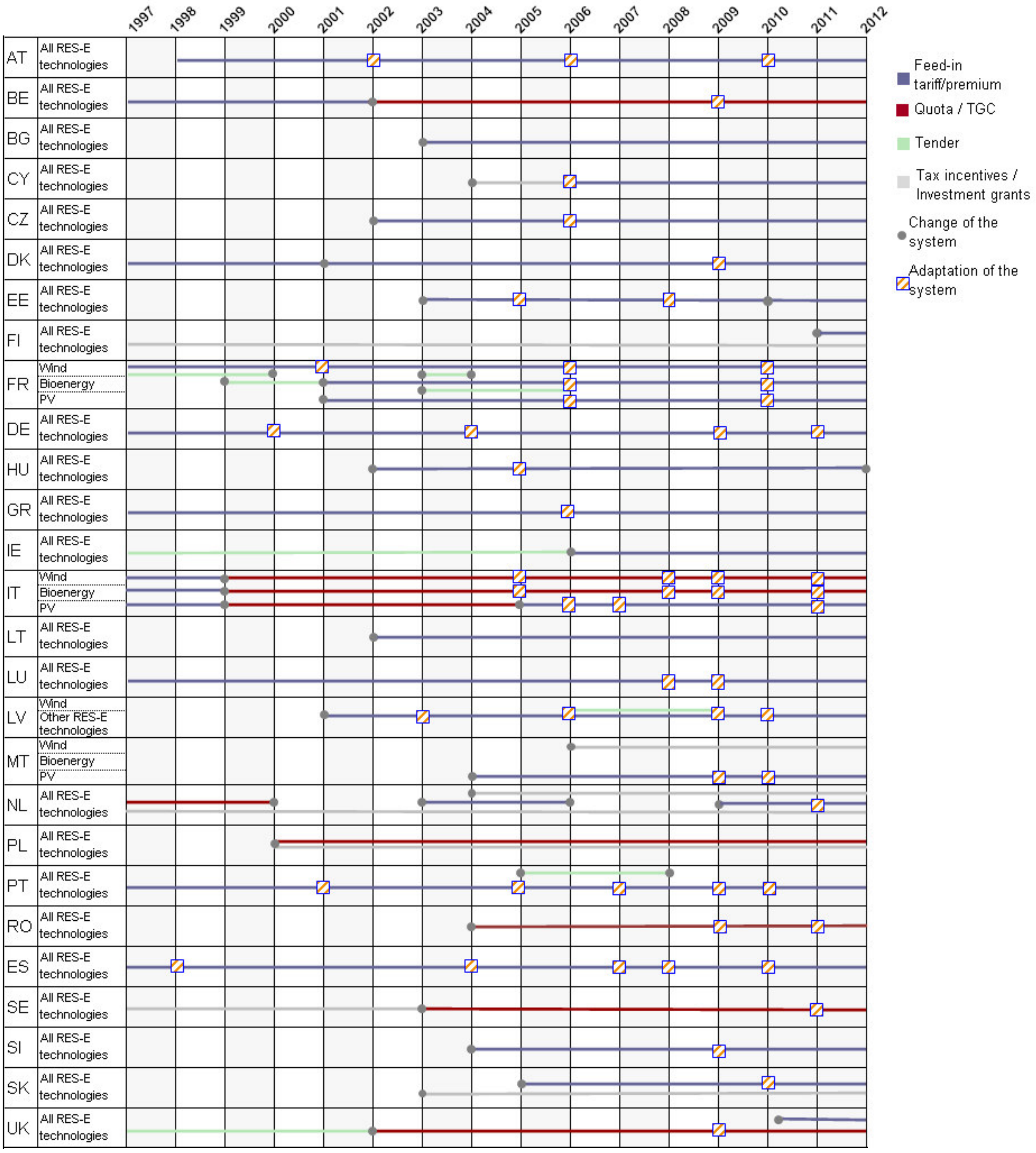


Figure 2-7: Overview on the support instruments for renewable electricity in the EU-27 (Source: EC 2013)

In general it can be noted that many of the support instruments described above have been highly successful in stimulating renewable electricity generation. At the same time, the question remains whether a clear justification for the specific promotion of the adoption of renewable technologies based on environmental externalities from climate change or market failures adherent to technological innovation and diffusion can be found.

2.5 The use of multiple policy instruments and policy interaction

Economics literature on environmental policy usually sees different policy instruments as alternatives and therefore concentrates on comparing the features of different types of instruments. In political reality, however, in most cases several policy instruments are implemented to address an environmental externality, like for example climate change, and it is generally stated that such a policy mix is more suitable to achieve environmental targets (cf. for example OECD 2007b; Giljum et al. 2006). According to the Tinbergen rule, the number of policy instruments should match the number of political targets such that each target is covered by a specific measure while at the same time limiting interaction which could arise from an excessive number of instruments (cf. Tinbergen 1952; Knudson 2008). Hence, it needs to be clarified under which circumstances the use of multiple instruments might be justified.

Analyses on the rationale of using a policy mix for environmental externalities are usually set in a second-best world. This means that there exists some kind of constraint in the general equilibrium system making it impossible that one of the conditions of Pareto optimality is reached leading to a situation where the attainment of the other Pareto conditions might no longer be welfare improving (cf. Lipsey and Lancaster 1956). Bennear and Stavins (2007) name the two most important incidences where this might be the case in the context of environmental policy: political constraints and market failures. When evaluating environmental policy instruments, pre-existing political distortions stemming, for example, from the tax system have to be taken into account. This can lead to the result that in combination with the tax system already in place, implementing a revenue-raising instrument, like a pollution tax or an auctioned permit system, has the benefit of providing the possibility to cut other distortionary taxes. The fact that multiple market failures can warrant the use of multiple policy instruments has already been shown for policy tools fostering technological innovation and diffusion.

Moreover, analyses have highlighted that other types of market failures play a role when designing environmental policies. First of all, barriers to more energy-efficient investment due to asymmetric information and behavioural issues can be overcome by additional measures like information campaigns, labelling systems or subsidies for energy audits (cf. Lehmann 2008). Secondly, market failures related to split incentives, most importantly the landlord/tenant dilemma, might need to be addressed by specific instruments promoting, for example, energy-saving measures in rented buildings or heating contracting (cf. OECD 2007b, p. 26). When taking transaction costs into consideration, the first-best solution might no longer be optimal as it causes high administrative and monitoring costs. This is especially the case with non-uniformly mixed pollutants, where a combination of a tradable permits scheme with localized emission standards might be advantageous, or with situations where emissions are difficult to monitor thus making enforcement more challenging. Here, a combination of a tax and a subsidy (e.g. a deposit-refund system) might represent the second-best optimal solution (cf. Lehmann 2008). Furthermore, several recent studies have pointed out the benefits of implementing so called hybrid instruments, where a price-based and a quantity-based market-oriented tool are combined in order to reduce the uncertainty, either regarding the emission level or the price of emission, that arises if one of the instruments is implemented alone (cf. Jacoby and Ellerman 2004; Hepburn 2006; Murray et al. 2009; Philibert 2009; Fankhauser et al. 2011). For example, by complementing an emission trading scheme with an emission tax that can be chosen in the case of high marginal abatement costs, a safety valve in the form of a cap on the certificate price is created.

Hence, it can be demonstrated that under certain conditions the use of multiple policy instruments to address environmental issues can be justified. From this, however, it cannot be concluded that the combinations of policy instruments that are currently in place actually constitute socially optimal mixes. Moreover, attention must be paid to the interactions between different policy instruments in order to create a coordinated and consistent policy mix (cf. Bennear and Stavins 2007).

An extensive study on the nature of policy interactions in climate policy has been conducted within the scope of the INTERACT project (cf. Sorrell et al. 2003). Here, a basic definition of policy interaction is provided as follows:

"Policy interaction exists when the operation of one policy affects the operation or outcomes of another." (Sorrell et al. 2003, p. 27)

In order to evaluate the interaction between policy instruments in a specific case, a theoretical background on the different types of interactions and their potential effects is needed. Policy interactions can be defined along different lines (cf. Oikonomou and Jepma 2008):

- *Internal vs. external*: Two policy instruments can either operate in the same policy area (e.g. two environmental policy instruments), or in different ones (e.g. an environmental policy instrument and a fiscal policy instrument).
- *Horizontal vs. vertical*: Horizontal interactions refer to two instruments that are implemented at the same level of governance (e.g. the EU level), while vertical interactions occur in the case of instruments on different levels of governance (e.g. one instrument on the EU level, one on the national level of a member state).
- *Direct vs. indirect*: An interaction is classified as direct if one specific target group is directly affected by both policy instruments in question. With indirect interactions, on the other hand, at least one of the policy instruments influences the target group only indirectly (e.g. the group is not directly targeted by the policy instrument but impacted by the adjustments that are made by a directly affected target group).

According to Sorrell and Sijm (2003), the analysis of policy interactions in climate policy involves several steps. First of all, it is helpful to define the *scope* of each instrument in order to identify possible overlaps (both in terms of directly and indirectly affected target groups). This is followed by an examination of the *objectives* of each policy tool. In climate policy, all instruments should generally have the same target, i.e. the mitigation of GHG emissions – assessed along the lines of ecological precision, cost efficiency, dynamic efficiency and the other evaluation criteria outlined in Chapter 2.2. When taking a closer look, however, it becomes apparent that environmental instruments often follow additional objectives besides emission reduction such as technology promotion, reduction of import dependency or even broader economic policy goals. This further complicates the evaluation of policy interactions. In the next step, the *operation* of the instruments, e.g. their joint effects on the different target groups, is determined. With respect to a given policy target, the combination of two instruments can have different implications ranging from conflicting over neutral to reinforcing. In this context, Gunningham and Sinclair (2004) speak of "*inherently complementary combinations*" (where the effectiveness and the efficiency of the instruments is increased when used in combination with each other), "*inherently counterproductive combinations*" (where the effectiveness and the efficiency is clearly deteriorated through the interaction), and "*combinations where the outcome will be context-specific*". Other areas that need to be considered in the process of evaluating policy interactions comprise the analysis of the *implementation* of the policy instruments, looking at the potentials for coordination and rationalization of the administrative necessities, and the *timetable* of each instrument.

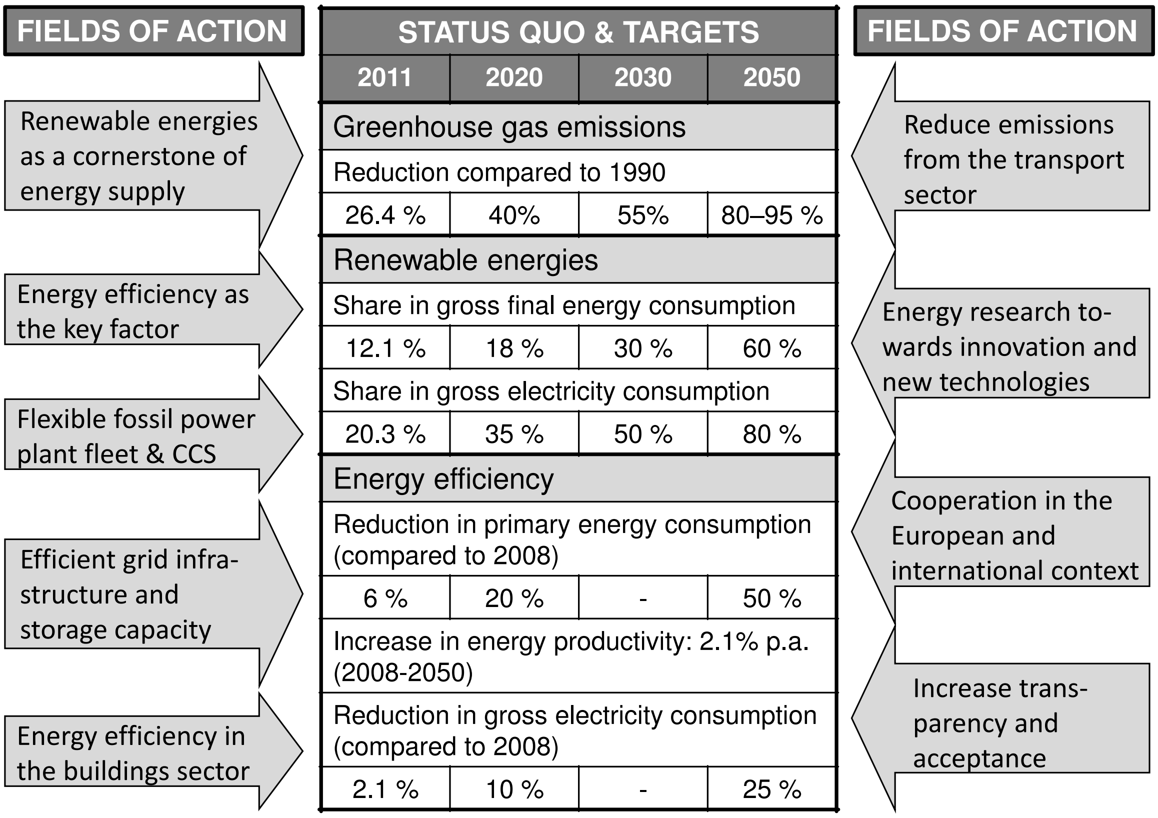
2.6 The German energy and climate policy

The following chapter will provide a short overview on the cornerstones of the current energy and climate policy in Germany, focusing in particular on the two policy instruments that will be explicitly modelled in the following scenario analysis – the feed-in tariff system for renewable electricity and the EU Emissions Trading System.

2.6.1. Overview: The Energy Concept and current policy measures

The current energy and climate policy agenda in Germany is mainly based on a comprehensive Energy Concept which was published in September of 2010. It offers a long-term strategy with the purpose to secure "*a reliable, economically viable and environmentally sound energy supply*" (BMWi and BMU 2011, p. 3). Thus, in accordance with the three target dimensions which dominate energy policy today (cf. European Council 2007, p. 10f) the goal is to (1) achieve substantial advances in terms of environmental protection (dimension sustainability), (2) at the same time maintain affordable and competitive energy prices (dimension competitiveness) and (3) ensure reliability of energy supply (dimension security of supply).

To meet these challenges, various quantitative targets and nine fields of action have been formulated in the energy concept (cf. Figure 2-8). The primary goal consists in reducing greenhouse gas emissions by 40 % until 2020 and by 80 to 95 % until 2050 compared to 1990. In order to do so, specific target values for the contribution of renewable energy sources to gross final energy consumption (18 % in 2020; 60 % in 2050) and gross electricity consumption (35 % in 2020; 80 % in 2050) as well as for the reduction of primary energy consumption (-20% until 2020 and -50% until 2050) have been laid down. The fields of action that have been established to attain these objectives comprise, apart from support mechanisms and regulations for renewable energies and energy efficiency, mainly measures to make conventional power plants more flexible, test the prospects of carbon capture and storage (CCS), strengthen the electricity network and storage systems, promote alternative drive concepts in the transport sector as well as increase transparency and social acceptance for the transition process. Moreover, the transformation of the Germany energy system is to be accompanied by a comprehensive federal energy research programme. The objectives and strategic guidelines of the Energy Concept are based on a number of quantitative scenario calculations contrasting the long-term development of the German energy system in a business-as-usual and several target scenarios (cf. EWI et al. 2010).



STATUS QUO & TARGETS			
2011	2020	2030	2050
Greenhouse gas emissions			
Reduction compared to 1990			
26.4 %	40%	55%	80–95 %
Renewable energies			
Share in gross final energy consumption			
12.1 %	18 %	30 %	60 %
Share in gross electricity consumption			
20.3 %	35 %	50 %	80 %
Energy efficiency			
Reduction in primary energy consumption (compared to 2008)			
6 %	20 %	-	50 %
Increase in energy productivity: 2.1% p.a. (2008-2050)			
Reduction in gross electricity consumption (compared to 2008)			
2.1 %	10 %	-	25 %

Figure 2-8: The German Energy Concept: targets and fields of action (own illustration based on BMWi and BMU 2011 and BMWi and BMU 2012, p. 16)

Originally, nuclear power was regarded as a bridging technology in the Energy Concept helping to meet emission reduction targets at reasonable cost in the mid-term before the transition to an energy system mainly based on renewable energies is completed. That is why, on the basis of the Energy Concept it was decided in October 2010 to reverse the nuclear phase-out until 2022, originally stipulated in 2000, in favour of an average lifetime extension of all German nuclear power plants of 12 years. However, the nuclear disaster in Fukushima in March 2011 gave rise to an abrupt change in the government's nuclear policy resulting in an immediate shutdown of eight nuclear power stations and a gradual phase out of the remaining nine plants until 2022 (cf. Bundesgesetzblatt 2012c). Nevertheless, the government adhered to the original targets of the Energy Concept which are now to be reached by reinforcing the efforts with respect to energy efficiency and the expansion of renewable energies (cf. BMU 2011d). In order to ensure target achievement, the monitoring process was strengthened which consists of an annual monitoring report and a triannual progress report. The first monitoring report was published in December 2012 (cf. BMWi and BMU 2012).

Given the growing challenges in energy policy, especially with respect to climate protection, the number of instruments that have been introduced in the course of the last decade has risen substantially. Table 2-2 provides an overview over the most important energy and climate policy instruments that are currently implemented in Germany. Next to comprehensive measures that encompass the entire energy system, like the energy and electricity taxes or the Energy Research Programme, most instruments are targeted on a certain sector. In general a combination of command-and-control policies and market-based instruments is observable. For example, in the buildings sector the Energy Savings Ordinance (Energieeinsparverordnung, EnEV) and the Renewable Energies Heat Act (Erneuerbare-Energien-Wärmegesetz, EEWärmeG) stipulate mandatory requirements regarding energy efficiency standards or the share of renewable energies in heat supply. At the same time, subsidy programmes in the form of investments grants, low-interest loans etc. are available for measures that go beyond the obligatory standards. Yet, even though the large variety of instruments ensures that all aspects of the transformation to a more sustainable energy supply are covered, it also raises concerns in terms of considerable overlaps, interactions and inefficiencies in the German energy and climate policy. Apart from that, in some cases additional measures are implemented on the regional level of the federal states of Germany.

Moreover, it has to be kept in mind that the German energy and climate policy is more and more embedded in the European context. This becomes most visible in case of the EU Emssions Trading System, but also concerns strategic target decisions like the EU Climate and Energy Package from 2008 (cf. EC 2008a) and associated directives like, for example, the Renewable Energy Directive (cf. EC 2009a), the Energy Performance of Buildings Directive (cf. EC 2010c) or the Energy Efficiency Directive (cf. EC 2012c). In the following, the two policy instruments which form the centre of attention in the scenario analysis in Chapter 5, the European Emissions Trading System and the German feed-in tariff scheme for renewable electricity, will be presented in more detail.

Table 2-2: Overview on current energy and climate policy measures in Germany

Name	Type	Description	In force since	Source
Cross-sector				
Energy and Electricity Tax	Quantity tax	Excise tax on the consumption of fossil fuels and electricity, with special tax relief rules for the manufacturing industry	1999 (Electricity), 2006 (Energy, superseding the Mineral Oil Tax)	Bundesgesetzblatt (2012e), Bundesgesetzblatt (2012j)
Energy and Climate Fund	General funding	With the revenues from the nuclear fuel tax and the auctioning of certificates from the EU ETS a special fund has been created to finance various support programmes related to climate change, energy efficiency and renewable energies	2010	Bundesgesetzblatt (2011g)
6th Energy Research Programme	Research and development	Federal research funds with a budget of about 3.5 Bn € for the period from 2011 to 2014 financing both basic and applied research projects focusing on energy efficiency, nuclear safety, renewable energies (including storage and grid technologies), electromobility & hydrogen technology, etc.	First comprehensive energy research programme in 1974, current from 2011 to 2014	BMWi (2011)
Energy efficiency initiative (and other campaigns)	Information and education	Information campaign of the German Energy Agency (dena) on the efficient use of electricity targeting households, industry, the tertiary sector and public institutions	2002	cf. the homepage of the initiative http://www.stromeffizienz.de
Energy conversion				
EU Emissions Trading System (EU ETS)	Tradable allowance system	Downstream emission trading scheme on the European level covering 31 countries and putting a cap on emissions from energy-using installations in power generation and energy-intensive industry sectors as well as aviation	Phase 1: 2005-2007 Phase 2: 2008-2012 Phase 3: 2013-2020	EC (2009b)
Renewable Energy Sources Act (EEG)	Feed-in tariffs / premium	Priority purchase and guaranted feed-in tariffs for eletricity generation from renewable sources, since 2012 alternative premium scheme available	2000, amended in 2004, 2009 and 2012	Bundesgesetzblatt (2012l)
Grid expansion planning	Regulation	Legislative measures intended to facilicate and accelerate the expansion of the electricity grid including an obligatory annual grid expansion plan and the Grid Expansion Acceleration Act to speed up the planning and approval procedure	2011	Bundesgesetzblatt (2013a), Bundesgesetzblatt (2012m)
CHP law (KWKG)	Feed-in premium, investment grant	Feed-in premiums for electricity generation in new and modernised CHP plants, investment grants for the extension of heating networks and thermal storage systems	2002, amended in 2009 and 2012	Bundesgesetzblatt (2012f)
KfW funding programmes	Low-interest loan	Various schemes with low-interest loans for power (and heat) generation units based on renewable energies, special programmes for offshore wind and geothermal energy	Various start times	cf. hompage of the KfW Bankengruppe www.kfw.de
Nuclear phase out	Regulation	Electricity generation from nuclear energy is phased out until the end of 2022	Final phase out decided in 2011	Bundesgesetzblatt (2012c)
Nuclear Fuel tax	Quantity tax	Tax on nuclear fuel which is imposed when a reactor is fitted with a fuel element (tax rate of 145 € per gram of nuclear fuel)	2011	Bundesgesetzblatt (2010)
Aid to the coal industry	Subsidy	Subsidies for the hard coal mining industry in Germany, amounting to more than 1.5 Bn € in 2010; will be phased out gradually until 2018	Subsidization began in 1958	Bundesgesetzblatt (2011c)
CCS Law	Regulation	Legal basis for the permanent storage of CO_2 in Germany regulating the exploration, testing and demonstration of the CO_2 storage technology	2012	Bundesgesetzblatt (2012a)
Industry				
EU Emissions Trading System (EU ETS)	Tradable allowance system	The EU ETS covers several energy-intensive industry sectors	see above	EC (2009b)
KfW funding programmes	Low-interest loan, investment grant	Various subsidy schemes offering low-interest loans and investment grants for energy consulting services as well as environmental and efficiency measures, etc.	2008	cf. hompage of the KfW Bankengruppe www.kfw.de
Energy management systems	Regulation	Companies that benefit from reduced energy and eletricity tax rates are obliged to introduce a certified energy or environmental management system	2013	Bundesgesetzblatt (2012e), Bundesgesetzblatt (2012j)

Name	Type	Description	In force since	Source
Buildings sector				
Energy Savings Ordinance (EnEV)	Regulation	Energy efficiency standards for new residential and non-residential buildings and buildings undergoing major renovations, requirements for the presentation of Energy Performance Certificates	2002, superseding the Thermal Insulation and the Heating System Ordinance, amended in 2004, 2007 and 2009	Bundesgesetzblatt (2012k)
KfW funding programmes	Low-interest loan, investment grant	Various subsidy schemes offering low-interest loans and investment grants for energy-efficiency measures that go beyond the mandatory regulations	First energy efficiency programme in 1996	cf. hompage of the KfW Bankengruppe www.kfw.de
Renewable Energies Heat Act (EEWärmeG)	Regulation	Obligation for new residential and non-residential buildings (and existing public buildings undergoing major renovations) to cover part of their heat supply with renewable energies	2009, amended in 2011	Bundesgesetzblatt (2011d)
Market incentive programme	Investment grant, low-interest loan	Investment grants, redemption grants as well as low-interest loans for renewable heating systems in existing residential and non-residential buildings	2000	BMU (2012e)
Energy-using products				
Energy-related products law (EVPG)	Regulation	National implementation of the EU Ecodesign Directive setting a framework for fixing mandatory ecological requirements for energy-related products (as part of the Top-Runner strategy)	2008, amended in 2011	EC (2009e), Bundesgesetzblatt (2011e)
Energy labelling (EnVKG, EnVKV)	Regulation	Obligatory labelling schemes for energy-using and energy-related products providing information on energy efficiency	1997, last amended in 2012	Bundesgesetzblatt (2012d), Bundesgesetzblatt (2012b)
Energy efficient procurement	Regulation	Guidelines for a better consideration of energy-efficiency aspects in public procurement	2008	Bundesanzeiger (2008)
Transport				
Motor vehicle tax	Quantity tax	Annual tax on all vehicles used on public roads based on engine size, fuel type, European pollutant class and since 2009 CO_2 emissions; electric vehicles are currently exempt from the tax for a period of 10 years	Vehicle tax since 1927, environmental component since 1985 (based on pollutant class)	Bundesgesetzblatt (2012g)
CO_2 standards for new passenger cars	Regulation	EU regulation setting binding emission standards for new cars: fleet average of 130 g CO_2/km for 2012 (phased in until 2015) and 95 g CO_2/km for 2020	2009	EC (2009f)
Biofuels Quota Act (BioKraftQuG)	Regulation	Obligation to cover a certain share of total fuel consumption through biofuels; target of 7 % net reduction of GHG emissions from fuel consumption through the use of biofuels for 2020	2007	Bundesgesetzblatt (2012h)
Truck toll	Quantity tax	Toll charges for all heavy goods vehicles with a gross vehicle weight of 12 t and above based on the distance travelled on motorways and the emission class of the truck	2005	Bundesgesetzblatt (2011a)
EU Emissions Trading System (EU ETS)	Tradable allowance system	CO_2 emissions from all flights arriving or departing from one of the ETS member states are included since 2012	2012	EC (2011b)
KfW funding programmes	Investment grant	Subsidy scheme for the purchase of eco-friendly (emission class EURO IV) utility vehicles (gross vehicle weight ≥12 t)	2007	cf. hompage of the KfW Bankengruppe www.kfw.de
Energy labelling for passenger cars (Pkw-EnVKV)	Regulation	Obligatory labelling scheme for car manufacturers and retailers providing information on fuel consumption and CO_2 emissions	2004	Bundesgesetzblatt (2012i)

2.6.2. The EU Emissions Trading System (EU ETS)

In Europe, emission trading gained greater attention as a viable market-based tool to reach mitigation targets with its mentioning in the Kyoto Protocol (cf. Ellerman and Buchner 2007). After attempts to introduce an EU-wide carbon tax had failed in the 1990s, a Green Paper on greenhouse gas (GHG) emissions trading within the European Union was published in 2000 with the intention to initiate the process of developing an adequate trading scheme on the EU level (cf. EC 2000). In October 2003, the EU ETS directive (cf. EC 2003) was adopted establishing the years 2005 to 2007 as the pilot trading period. Thus, the EU ETS was the first transnational and is currently the largest GHG emissions trading system in the world. At the moment, it covers about 11,000 energy conversion and energy-intensive industrial installations in 31 countries which are responsible for almost 50 % of the CO_2 emissions in these participating states. In the following, the most important features of the EU ETS, which are essential for developing a realistic modelling approach, are outlined.

Basic design and targets

The EU ETS has been set up as a typical cap and trade system, where a limit on the absolute amount of emissions in a given period of time is fixed and a market for emission allowances is created. In the case of the EU ETS, the tradable unit has been defined as European Union Allowance (EUA) representing 1 ton of CO_2 emitted. Each emitter included in the scheme has to surrender the amount of allowances necessary to cover the total emissions of his installation in each year within the first four month of the following year.

For the first two trading periods relatively short timeframes were chosen, the first one (2005-2007) functioning as a trial period and the second one (2008-2012) coinciding with the commitment period for the emission reduction targets specified under the Kyoto Protocol. In these periods, the actual cap on emissions and the allocation of allowances were determined in a highly decentralized manner: each country had to develop a National Allocation Plan (NAP) resulting in individual caps for each member state such that the total ETS cap was unknown beforehand. Apart from being relatively complex, this approach gave rise to substantial differences in allocation rules and to concerns about fairness since each member state had incentives to favour its own industry (cf. Heindl and Löschel 2012).

As a consequence, in the third trading period (2013-2020) the National Allocation Plans have been replaced by a single EU-wide cap along with harmonized allocation rules. In line with the overall GHG reduction target of 20 % until 2020 compared to 1990 (cf. the EU Climate and Energy Package, EC 2008a), a mitigation goal of 21 % compared to 2005 has been fixed for the ETS sectors in the third phase. In order to reach this target by 2020, the cap is reduced each year in a linear fashion by a factor of 1.74 %. It is planned that this annual reduction factor will also be applied in subsequent trading periods (cf. EC 2008b). For the sectors not covered by the EU ETS, an EU-wide mitigation target of 10 % until 2020 compared to 2005 has been laid down in combination with specific national targets assuming that with this division between ETS and Non-ETS sectors overall reduction costs will be minimized. In the EU Climate and Energy Package from 2008 a proposal has been made to raise the general GHG mitigation target for 2020 from 20 % to 30 % if an international agreement is concluded in which other developed countries commit themselves to comparable emission reductions. This would result in an adjustment of the ETS target for 2020 to 34 % and of the Non-ETS target to 16 % (cf. EC 2010a). Figure 2-9 illustrates the development of the EU ETS cap for both potential targets in phase 3. It is assumed that after 2020 in both cases the linear reduction factor of 1.74 % is used leading to a decrease in ETS emissions until 2050 of 71 % compared to 2005 for the 21 %-target and of 84 % for the 34 %-target.

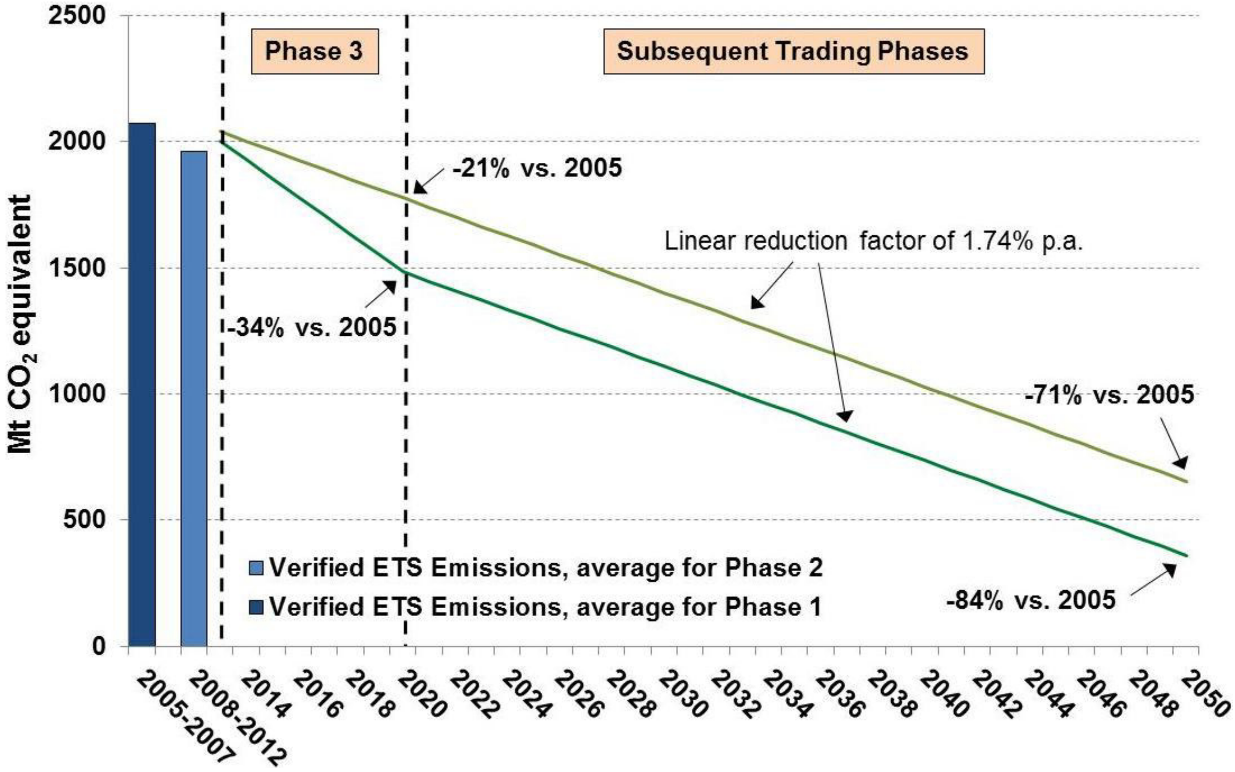


Figure 2-9: Development of the EU ETS cap until 2050 (own illustration based on EEA 2012a and EEA 2012b)

Scope

From economic theory it follows that the benefits of an emissions trading system in terms of cost efficiency will be the larger, the greater the scope of the system in terms of included regions, sectors and greenhouse gases. In reality, however, significant restrictions may arise when defining the extent of the trading system.

As far as the regional coverage is concerned, the then 25 EU member countries took part in the scheme when it was launched in 2005 with Romania and Bulgaria joining simultaneously with their accession to the EU in 2007. After the inclusion of the non-EU members Norway, Iceland and Liechtenstein in 2008 and Croatia in 2013, the EU ETS currently covers 31 countries accounting for about 11 % of global CO_2 emissions (cf. UNFCCC 2012 and BMWi 2012).

With respect to the target group, a downstream system was chosen meaning that emissions are directly controlled at their source and that emitters are responsible for submitting the required ETS certificates. From this it follows that only large installations could be included in order to limit the administrative cost burden (cf. Klepper 2011). From 2013 onwards, the following sectors take part in the EU ETS (cf. EC 2009b) accounting for almost half of the overall CO_2 emissions in the ETS member countries:

- Combustion installations with a total rated thermal input exceeding 20 MW
- Mineral oil refineries and coke ovens
- Production or processing of ferrous metals including metal ore, pig iron and steel
- Mineral industry including the production of cement clinker, lime, glass, ceramic products, mineral wool insulation material using glass, rock or slag and gypsum products
- Production of pulp, paper and cardboard (with a production capacity exceeding 20 tonnes per day)
- Since 1 January 2012: aviation, all flights arriving or departing from an airport in one of the ETS member states
- From 1 January 2013: Production of aluminium and other non-ferrous metals (with a total rated thermal input exceeding 20 MW)
- From 1 January 2013: Chemical industry, including the production of nitric acid, adipic acid, glyoxal and glyoxylic acid, ammonia, bulk organic chemicals by cracking, reforming, partial or full oxidation, hydrogen and synthesis gas as well as soda ash and sodium bicarbonate
- From 1 January 2013: Carbon capture and storage from ETS installations

While in the first and second trading period only CO_2 emissions were covered (with the option to opt-in other greenhouse gases in phase 2), perfluorocarbons (PFCs) from the production of primary aluminium and nitrous oxide (N_2O) from the production of nitric acid, adipic acid, glyoxal and glyoxylic acid (cf. EC 2009b) are added to the scheme from 2013 onwards.

Allocation mechanisms

Mainly for reasons of political acceptability, free allocation of permits was chosen as the basic principle in the first two trading periods. Member countries had the possibility to auction up to 5 % of all allowances in the first and up to 10 % in the second phase, but, especially in the first period, this option was hardly made use of (cf. Klepper 2011). In the EU ETS directive from 2003, no strict regulations were prescribed with respect to the method of defining the amount of allowances allocated to each installation, but for existing emitters allocation was generally based on historical emission levels (concept of grandfathering) or the projection of growth rates of business-as-usual emissions (cf. Sijm 2012, p. 44). In order to ensure equity between existing and new installations, each member state was required to set aside a reserve of free permits for new entrants, which on average amounted to 3 % of total permits in the first trading period with substantial differences in the size of the reserve and the allocation rules across countries (cf. Parker 2010).

Strong criticism has been voiced with respect to the large windfall profits that electricity generators were able to make by passing on the opportunity costs of the freely allocated permits to consumers (cf. Ellerman and Buchner 2007). Against this background, allocation rules will change considerably with the beginning of the third trading period. With the elimination of the National Allocation Plans, allocation rules are harmonized for the whole system and a stronger emphasis is put on auctioning. It is expected that in 2013 about half of the allowances will be auctioned and this share will rise gradually until 2020 (cf. EC 2010b). For those sectors where all or part of the allowances are allocated for free a product benchmark approach is applied which is generally based on the average greenhouse gas performance of the 10 % best installations in the EU in that product group (cf. Heindl and Löschel 2012). Table 2-3 gives an overview over the allocation procedures for the different sectors under the EU ETS from the third trading period onwards. For new installations or the extension of existing installations, a new entrants' reserve of 5 % of the total amount of allowances has been set aside for the third trading period (cf. EC 2009b).

Table 2-3: Harmonized allocation mechanisms in the EU ETS from 2013 onwards

Sector	Allocation rule
Electricity generation	Full auctioning[1]
Industry & heat generation	Free allocation of 80 % of allowances in 2013 reduced linearly to 30 % in 2020 Allocation is based on benchmarking: - **Product benchmark:** allocation dependent on the production of products (in: t CO_2/t product); if not applicable - **Heat benchmark:** allocation dependent on the amount of measurable heat consumed (in: t CO_2/TJ of heat consumed); if not applicable - **Fuel benchmark:** allocation dependent on the amount of fuel consumed (in: t CO_2/TJ of fuel used); if not applicable - **Process emissions approach:** allocation is 97 % of historical emissions **Exemption:** Sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage receive 100 % of their allowances for free (allocation based on benchmarking)[2].
Aviation	Free allocation of 82 % of allowances Based on benchmarks calculated as the airline's share in the total amount of passengers and cargo transported in 2010 (measured in terms of tonne kilometres)

Sources: EC 2008c; EC 2009b; EC 2011a; EC 2011b

[1] Option for transitional free allocation of up to 70 % in 2013 decreasing to zero until 2020 under certain conditions for economically weaker member countries (cf. EC 2009b)

[2] For eligibility criteria cf. EC (2009b); the selected sectors are listed in EC (2009c)

Increased flexibility: banking/borrowing and CDM/JI

In order to increase intertemporal flexibility and smooth compliance costs over time, banking, i.e. the option to store unused allowances for future periods, is allowed in the EU ETS within trading periods. While transferring allowances from phase 1 to phase 2 was practically not conceded (cf. EC 2006), unlimited inter-period banking is permitted from phase 2 onwards. With respect to borrowing, i.e. the option to borrow allowances from future periods to use them in the current one, the regulations in the EU ETS are more restrictive. Within one period, borrowing is possible from one year to another, as installations receive their allowances for each year (end of February) before they have to hand in the required allowances for the previous year (end of April). Inter-period borrowing is officially not allowed – the only option would come at a very high interest rate by paying the penalty (see below) and surrendering the missing permits at a later date (cf. Chevallier 2012; Ellerman and Buchner 2007).

With the aim of expanding the available compliance options and potentially reducing compliance costs, access to the project-based mechanisms CDM (Clean Development Mechanism) (since 2005) and JI (Joint Implementation) (since 2008) defined under the Kyoto Protocol has been granted through the Linking Directive (cf. EC 2004). It allows emitters to use credits gained from CDM or JI projects[5], i.e. for emission reductions outside of the European Union, to fulfil their obligations under the EU ETS. In the first trading period, the decision on the maximum amount of "external" credits allowed per installation was left to the member states. The only requirement was to comply with the principle of supplementarity, stipulated in the Marrakesh Accords (cf. UNFCCC 2001), according to which the use of CDM and JI has to be supplemental (usually defined as up to 50 %) to domestic action in Annex I countries. After stricter regulations were applied in the second period (cf. De Sépibus 2008), for the phase from 2013 to 2020 the EU ETS legislation is specified such that the use of CDM/JI credits cannot exceed 50 % of the ETS emission reductions below the 2005 levels (cf. EC 2009b).

Monitoring and enforcement

With the implementation of the EU ETS, a new administrative infrastructure had to be developed, including the creation of a national regulatory authority in each member state. These institutions are responsible for establishing and managing allowance registries that track all allowance transfers and emissions by installation and report to the Community registry (the Community Independent Transaction Log, CITL). With the beginning of the third trading period the national registries are replaced by the Union registry. Apart from that, the monitoring and verification of the operators' emission reports is performed by the national authorities subject to harmonized Community guidelines (cf. EC 2012a and EC 2012b).

To ensure compliance, a penalty of 100 € (40 € in the first trading period) for each tonne of CO_2 equivalent not covered by an allowance has been put in place. Even after paying the fine, the missing allowances have to be surrendered in the following year (cf. EEA 2005).

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[5] Credits from land use, land-use change and forestry projects as well as from nuclear facilities are excluded (cf. EC 2004).

Experiences so far

The introduction of the EU ETS entailed the creation of a completely new commodity market in the European Union, whose performance can be evaluated by the development of the price for emission allowances (EUAs) and the trading volumes.

At the beginning of the first trading period, EUA prices rose steadily with peaks at over 30 €/EUA and exhibited high levels of volatility (cf. Figure 2-10). A significant price drop occurred after the verified emissions data for 2005 was published in April of 2006 and it became obvious that a considerable overallocation of allowances had taken place. Until the end of phase 1, the EUA price fell to zero as allowances could not be "banked", i.e. carried over to the next trading period. Against the background of substantial cutbacks in the allocation of emission permits from 2008 onwards, prices recovered and only started to drop with the onset of the international financial and economic crisis at the end of 2008. Since the middle of 2009, a relatively stable price level (in nominal terms) of around 15 €/EUA can be observed (cf. Wråke et al. 2012). The maturing of the market for emission allowances is also reflected in the significant increase in the transaction volumes from 362 million allowances in 2005 to about 5.2 billion in 2010 (cf. EC 2008d; Point Carbon 2011). The use of CDM and JI credits is still comparatively limited with surrendered CERs ("Certified Emission Reductions" from CDM projects) amounting to less than 6 % and surrendered ERUs ("Emission Reduction Units" from JI projects) to about 1 % of total surrendered allowances in the EU ETS from 2008-2011 (cf. EEA 2012b).

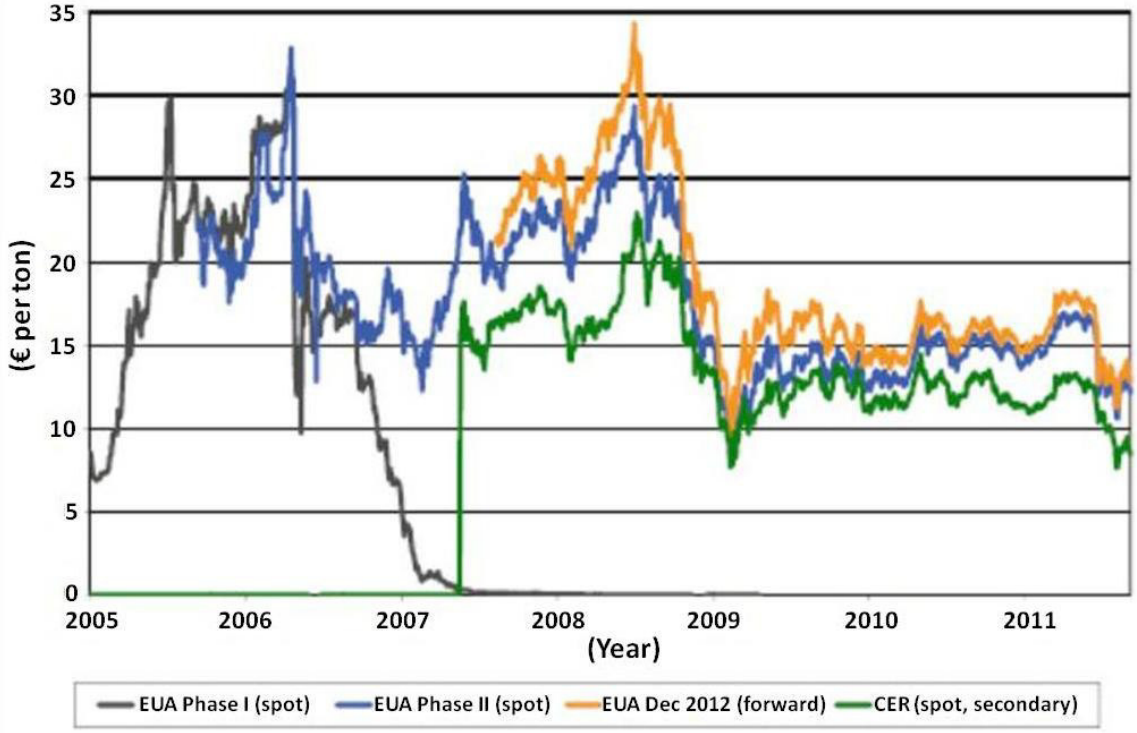

Figure 2-10: Prices of emission allowances (EUAs) in the EU ETS (Source: Wråke et al. 2012)

2.6.3. The German feed-in tariff system

In Germany, a feed-in tariff scheme for renewable electricity, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG), was introduced in the year 2000 with the aim to shift electricity generation on to a more sustainable pathway, to reduce the demand for fossil fuels as well as to foster renewable technologies. Basically, this system comprises three structural elements: (1) grid operators are obliged to connect any renewable generation unit to the grid and, if necessary, to strengthen and expand the existing grid system; (2) renewable electricity is to be granted priority purchase, transmission and distribution and (3) grid operators pay previously fixed tariffs to the renewable electricity producers.

The basic tariff system

The feed-in tariffs are set by the policymaker with regard to the development stage and the cost situation of the different renewable generation technologies. Thus, tariffs vary according to the source of renewable energy (hydro, wind, solar, biomass and geothermal energy), the capacity of the installation and, in the case of wind, the location of the project[6] (cf. Table 2-4). For each installation, they are paid over a period of twenty years. In order to incentivise constant efforts to increase cost effectiveness, tariffs for newly installed plants are subject to an annual degression at a certain percentage. Major amendments to the FIT law have been conducted in 2004, 2009 and 2012 and were based on a scientific monitoring process. Their main objective consisted in adjusting the tariffs to the current competitive situation of the different renewable generation technologies and in avoiding situations of excess subsidisation. Most importantly, substantial cuts were executed in the case of solar photovoltaics with tariffs falling by more than half between 2009 and April of 2012. Moreover, in 2010 a quantity control mechanism has been introduced for PV installations linking the annual degression rate of tariffs to the amount of capacity installed in each year (also referred to as “flexible ceiling”).

The FIT surcharge

The additional costs that transmission system operators incur due to the difference between FIT tariffs and wholesale electricity prices can be passed on to electricity consumers. A special equalisation scheme is laid down in the FIT law levelling the electricity generation and the costs under the FIT system between the four transmission grid operators in Germany. On this basis, the FIT surcharge, i.e. the additional levy on end-use electricity prices, is then calculated as (cf. Bode and Groscurth 2006):

$$\textit{FIT surcharge} = (\textit{Ø-FIT tariff} - \textit{Ø-wholesale electricity price}) * \textit{FIT quota} \qquad (2\text{-}1)$$

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[6] For onshore wind farms, higher initial tariffs are paid for a longer period of time if the installation yield is lower than a previously defined reference yield (due to a location with less favorable wind conditions). For offshore wind farms, the same applies for plants that are further located from the shore or in greater water depths.

Table 2-4: Tariffs of the German FIT system for 2012 (cf. Bundesgesetzblatt 2012l)

	Tariffs (ct/kWh)	Bonus (ct/kWh)		Annual degression rate
Hydropower (including modernisation (≤ 5 MW) and extension of existing power plants)				
≤ 500 kW	12.7	-		1%
≤ 2 MW	8.3			
≤ 5 MW	6.3			
≤ 10 MW	5.5			
≤ 20 MW	5.3			
≤ 50 MW	4.2			
> 50 MW	3.4			
Landfill, sewage and mine gas				
≤ 500 kW$_{el}$	6.84 - 8.6	*Gas processing bonus* (upgrade to natural gas quality; ≤ 500 kW$_{el}$): 1 - 3 ct/kWh depending on rated output		1.5%
≤ 1 MW$_{el}$	5.89 - 6.84			
≤ 5 MW$_{el}$	4.93 - 5.89			
> 5 MW$_{el}$	3.98 (only mine gas)			
Biomass[a]				
		Substance tariff class I[b]	Substance tariff class II[b]	2% (only on basic tariffs and gas processing bonus)
≤ 150 kW$_{el}$	14.3	6	8	
≤ 500 kW$_{el}$	12.3		8 / 6[d]	
≤ 750 kW$_{el}$	11	5[c]		
≤ 5 MW$_{el}$		4[c]		
≤ 20 MW$_{el}$	6	-	-	
		Gas processing bonus (see above)		
Geothermal energy				
Independent of capacity	25	*Bonus for using petrothermal technology*: 5 ct/kWh		5%, starting in 2018
Wind power				
Onshore				
Initial tariff[e]	8.93	*System services bonus*[f] (until 2015): 0.48 ct/kWh; *Repowering bonus*[g]: 0.5 ct/kWh		1.5%
Basic tariff	4.87			
Offshore				
Initial tariff[h]	15	-		7%, starting in 2018
Basic tariff	3.5			
Photovoltaics[i]				
Rooftop installations				
≤ 10 kW	19.5	-		Flexible degression depending on market volume, ranging between -6% (if installed capacity in the previous year < 1000 MW) and 29% (if installed capacity in the previous year > 7500 MW)
≤ 40 kW[j]	18.5			
≤ 1 MW[j]	16.5			
≤ 10 MW	13.5			
Free-standing installations				
≤ 10 MW	13.5			

[a] Special tariffs are available for small manure installations (≤ 75 kW$_{el}$; 25 ct/kWh) and biowaste fermentation plants (16 ct/kWh if ≤ 500 kW$_{el}$; 14 ct/kWh if ≤ 20 MW$_{el}$).

[b] Additional remuneration for substances listed in the Biomass Ordinance (BiomasseV) (cf. BMU 2011a)

[c] For plants with a capacity between 500 kW$_{el}$ and 5 MW$_{el}$ only 2.5 ct/kWh for electricity from bark or forest waste wood

[d] For plants with a capacity between 500 kW$_{el}$ and 5 MW$_{el}$ only 6 ct/kWh for electricity from manure

[e] The higher initial tariff is paid for the first five years. This period is extended by two months for each 0.75% by which the installation yield falls short of 150% of a previously defined reference yield.

[f] Bonus for wind power plants that fulfill the requirements of the System Services Ordinance (cf. Bundesgesetzblatt 2011f)

[g] Bonus for the replacement of existing wind power plants (installed before 2002) on the same or an adjacent site

[h] The higher initial tariff is paid for the first 12 years. This period is extended by 0.5 months for each full nautical mile beyond 12 nautical miles that the installation is located from the shore and by 1.7 months for each full metre of water depth over 20 metres. Alternatively, operators of plants installed before 2018 can also opt for the "acceleration model", receiving a higher initial tariff of 19 ct/kWh for 8 years (plus the same extension based on the distance to shore and water depth as in the normal model).

[i] Here, the tariffs according to the additional amendment on photovoltaics that have been decided in June 2012 and apply retroactively as of 1 April 2012 are reported (cf. BMU 2012a).

[j] For rooftop installations with a capacity between 10 kW and 1 MW a market integration model has been introduced: for these installations, only 90% of the electricity generated can be remunerated through the FIT system, while the rest must be used for own consumption or sold to the market.

Thus, the FIT surcharge in one year is obtained as the difference between the average FIT tariff (*Ø-FIT tariff*, across all renewable energy sources) and the average annual electricity price on the wholesale market (*Ø-wholesale electricity price*) multiplied by the *FIT quota*, i.e. the percentage share of electricity remunerated through the FIT system in total final electricity consumption.

Special provisions in form of a reduced FIT surcharge have been implemented for manufacturing enterprises and rail operators with comparatively high electricity consumption in order to prevent endangering their international or intermodal competitiveness. According to the amended FIT law, the following requirements need to be fulfilled in the case of manufacturing enterprises: (1) an electricity consumption of more than 1 GWh per annum, (2) a ratio of electricity costs to gross value added of more than 14 % and (3) a certified energy audit assessing energy consumption and the potentials for energy savings has been carried out. These companies then only pay the full FIT surcharge for the first GWh of consumption, 10 % of the regular charge for the consumption between 1 and 10 GWh, 1 % between 10 and 100 GWh and 0.05 ct/kWh for the share of electricity exceeding 100 GWh. Enterprises whose electricity demand is above 100 GWh and whose ratio of electricity costs to gross value added is more than 20 % only pay a FIT surcharge of 0.05 ct/kWh for their entire electricity consumption. The reduced surcharge of 0.05 ct/kWh also applies in the case of rail operators with an electricity demand of at least 10 GWh for the amount of electricity exceeding 10 % of the annual consumption. Apart from the rail operators, this regulation benefits mainly parts of the chemical, the paper, the iron and steel as well as the non-ferrous metal industry in Germany (cf. BMU 2011b).

Market integration mechanisms

Under the basic feed-in tariff system in Germany, renewable producers are freed from the responsibility to sell their generation to electricity markets such that they have no incentive whatsoever to react to market signals. In recent years, first steps have been undertaken to increase the market orientation of the system. With the amendment in 2009, the so-called “green electricity privilege” was implemented in order to foster the direct selling of low-cost renewable generation. Under this scheme, electricity suppliers are exempted from paying the FIT surcharge to grid operators if at least 50 % of their sales consist of renewable electricity eligible for FIT tariffs. Given the increase in the FIT surcharge, especially in 2011, the provision became highly attractive leading to substantial windfall profits and rising costs for the non-privileged consumers that have to pay the full FIT surcharge (cf. Traber et al. 2011). Consequently, in 2012 the conditions to enter the green electricity privilege have been tightened considerably. Now, it is additionally required that at least 20 % of the 50 % electricity generation from installations covered by the FIT system originate from fluctuating sources (i.e. wind and solar energy). Apart from that, the exemption from the FIT surcharge has been limited to 2 ct/kWh. As a consequence, the relevance of the green electricity privilege as decreased significantly in 2012 (cf. Hummel 2012).

At the same time, an alternative direct marketing scheme was introduced in 2012 with the aim to increase the market experience of renewable producers and to set incentives to make generation more demand-responsive. With the conventional system based on fixed tariffs remaining in place, renewable electricity producers can now choose alternatively a market premium, which they receive when selling the generated electricity directly to the market. This market premium is calculated as the difference between the fixed tariff for the respective installation and the average monthly market value of the respective generation[7] plus a so-called management premium. This extra premium is granted to cover the additional cost of directly selling the electricity to the market and was set at 1.2 ct/kWh (falling to 0.7 ct/kWh until 2015) for wind and solar energy and at 0.3 ct/kWh (falling to 0.225 ct/kWh until 2015) for all other sources. Finally, it has to be noted that producers can switch freely between the basic tariff system, the green electricity privilege and the market premium on a monthly basis.

Experiences so far

The German FIT system has been highly successful in promoting the expansion of renewable electricity in Germany (cf. Figure 2-11).

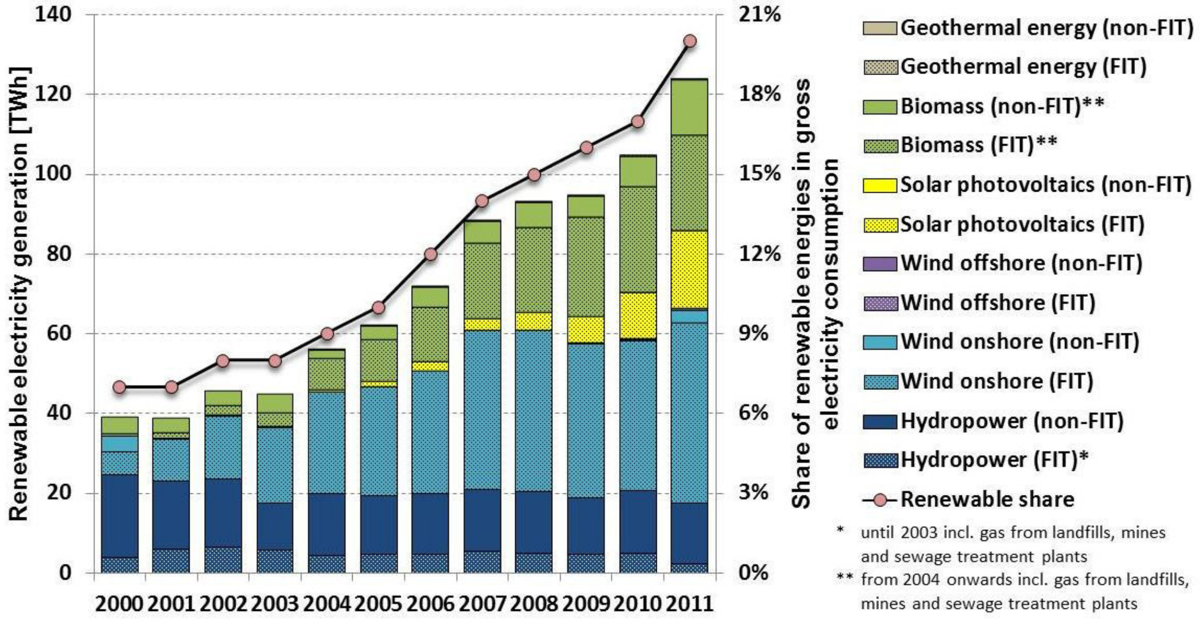

Figure 2-11: Development of electricity generation from renewable sources in Germany (sources: BMU 2012b and BMU 2012c)

The generation from renewable sources has increased from 40 TWh in 2000 to almost 124 TWh in 2011, of which about three quarters are remunerated through the FIT system. This corresponds to a share of renewable energies in gross electricity consumption of 20.5 %

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[7] In the case of wind and solar power, the average monthly market value is calculated as the ratio between the average value of hour contracts on the sport market multiplied by the quantity of electricity actually generated from the source in that hour and the total quantity of electricity generated from the source in this month, whereas for all other sources the market value is the actual monthly average of hour contracts on the spot market (cf. Bundesgesetzblatt 2012l, Annex 4).

in 2011 compared to 6.8 % in 2000. Accordingly, the target set in 2004 for 2010 (share of 12.5 %) has already been exceeded in 2007, while in 2011 the target value originally stipulated for 2020 has already been fulfilled. With almost 40 % in 2011, onshore wind farms dominate renewable generation, followed by biomass with about 30 %. Given the technology-specific design of the FIT scheme, the installation of less mature and more costly technologies has also been encouraged, reflected in the dynamic growth of solar photovoltaics whose contribution has risen to nearly 20 TWh in 2011.

Figure 2-12 provides additional insights on the role of renewable energies in electricity generation. Due to the lower capacity factors especially of fluctuating renewable sources, an expansion of renewable electricity generation is associated with a disproportionally large increase in installed capacity. Consequently, renewable energies already accounted for about 38 % (66 GW) of total gross electricity generation capacity installed in Germany in 2011. Most notably, solar photovoltaics, whose share in gross electricity generation amounted to 3 %, were responsible for approximately 14 % of installed capacity in 2011. It has to be noted, however, that because of their supply characteristics only a small part of the installed capacity of intermittent sources like wind and solar photovoltaics can contribute to guaranteed capacity.

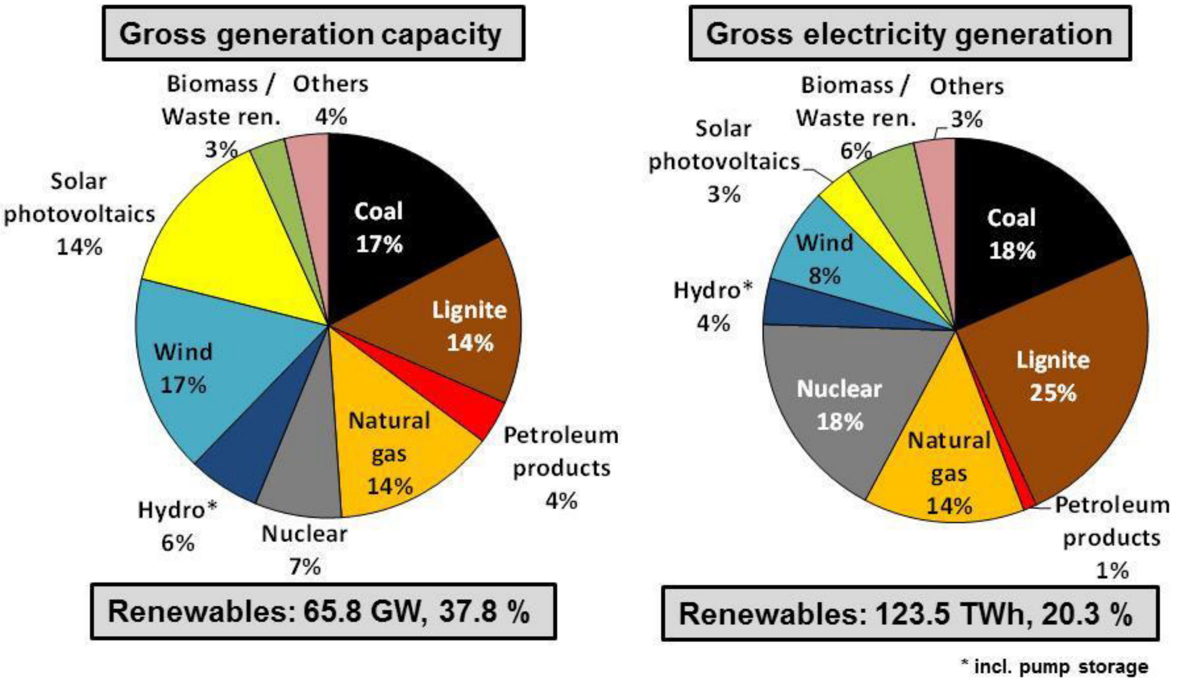

Figure 2-12: Gross generation capacities and gross electricity generation in Germany in 2011 (sources: BMWi 2012 and BMU 2012b)

The strong expansion of renewable electricity generation in Germany came at the cost of rapidly rising support expenditures. The differential costs of the FIT system, i.e. the FIT payments minus the market value of the FIT electricity generation, have increased more than ten times since 2001, reaching more than 12 billion € in 2011 (cf. Figure 2-13). Moreover, the distribution of the differential costs across renewable sources has changed substantially over the years. While in the beginning onshore wind energy dominated the support expenditures, this share has dropped continually. In contrast, in the case of solar photovoltaics the high tariff level and the dynamic growth in recent years have led to a considerable rise in differential costs. Hence, given the wide spread in tariffs, significant differences can be observed with respect to the contribution of the various renewable energy sources and the costs they entail for the system: while the share of solar photovoltaics in total generation from FIT installations amounted to 21 % in 2011, more than half of the entire FIT differential costs went to solar photovoltaics. In comparison, onshore wind farms only accounted for about 16 % of FIT differential costs in 2011 even though producing almost half of the electricity in the FIT system.

The increasing support expenditures of the FIT system are reflected in a strong surge in the FIT surcharge from 0.25 ct/kWh in 2001 to 3.53 ct/kWh in 2011. Apart from the rising quantity of electricity covered by the system and the growing importance of technologies receiving comparatively high tariffs this increase can be ascribed to the special regulations for privileged consumers. The amount of final electricity consumption for which only the reduced surcharge of 0.05 ct/kWh had to be paid has risen from 37 TWh in 2004, when the rule has been introduced, to 85 TWh in 2011 (cf. BMU 2012c). Correspondingly, the remaining electricity consumption which is used as a basis to calculate the regular FIT surcharge has shrunken.

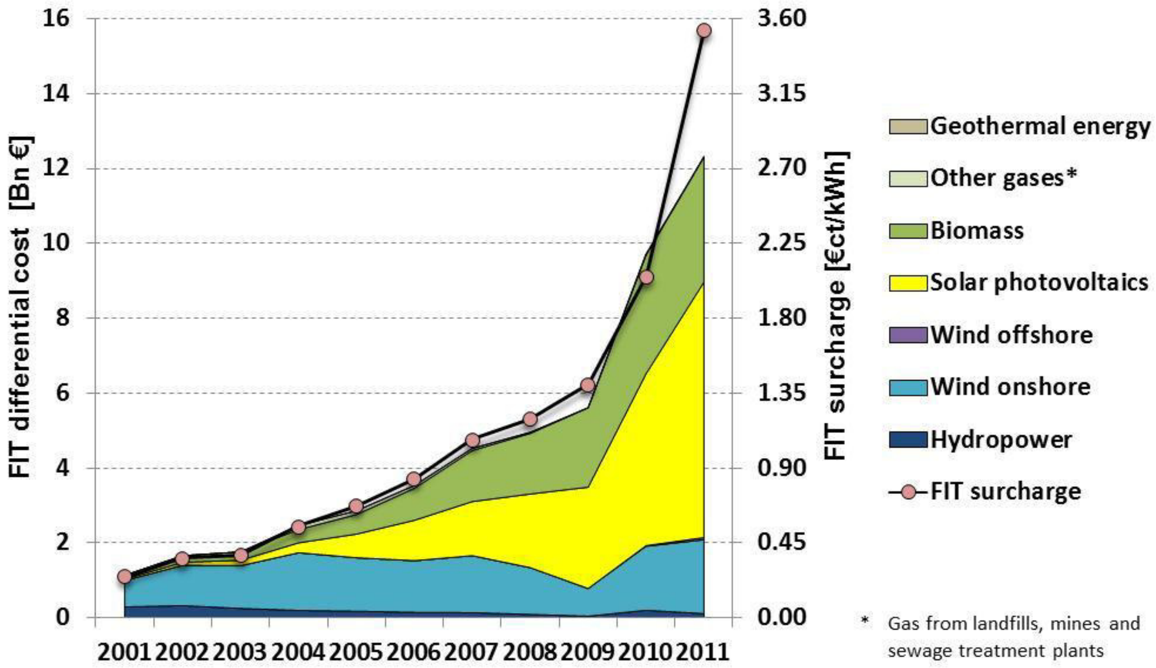

Figure 2-13: Development of the FIT differential cost and the FIT surcharge in Germany (source: BMU 2012c)

Looking at the average tariffs which all installations using the same renewable energy source have received in a certain year, the considerable gap between the remuneration level of solar photovoltaics and the other energy sources is highlighted once more (cf. Figure 2-14). In

2011, average tariffs ranged between 7.4 ct/kWh (gas from landfills, mines and sewage treatment plants) and 40.2 ct/kWh (solar photovoltaics). The development of the tariff level for each renewable source over time is of additional interest. By fixing annual degression rates, the idea of the FIT system was to gradually lower tariffs in order to account for the expected cost reductions for renewable technologies due to learning effects. Figure 2-14 shows, however, that a significant reduction has only taken place in the case of solar photovoltaics, while the average tariff level (in nominal terms) for hydropower, wind energy and other gases has remained relatively constant. Here, it has to be taken into account that in recent years some installations with low remuneration have dropped out of the FIT system in favour of the green electricity privilege scheme. Even more striking is the fact that the average tariff for biomass has doubled from 9.5 ct/kWh in 2001 to 19.1 ct/kWh in 2011. This is due to the introduction of a number of additional bonuses for the use of energy crops in the scope of the tariff revisions in 2004 and 2009.

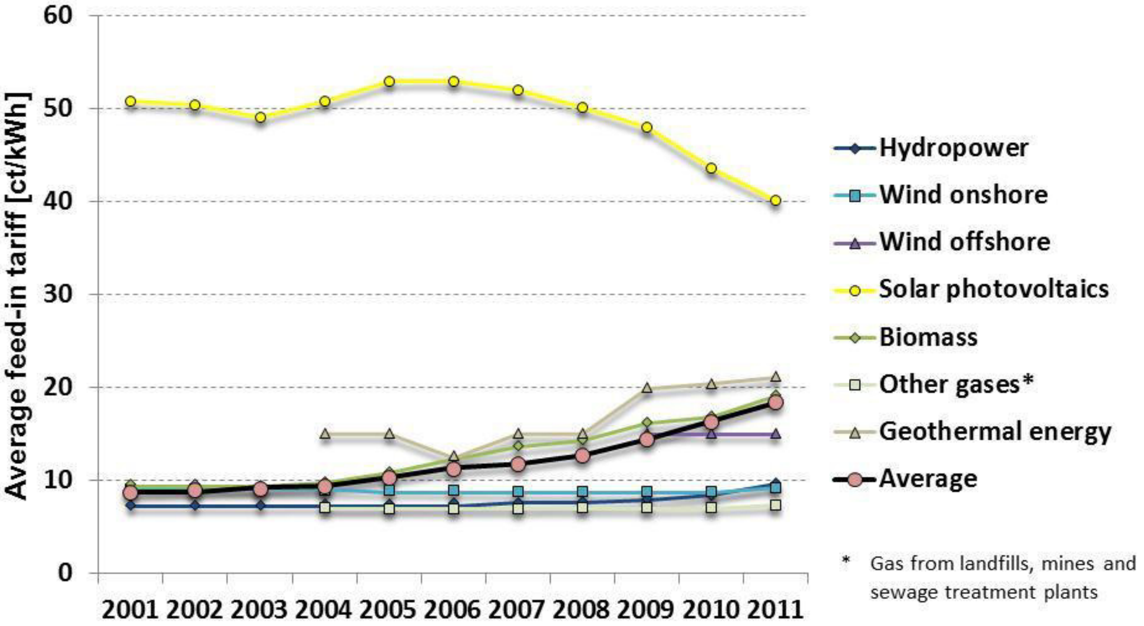

Figure 2-14: Development of the average feed-in tariffs by energy source in Germany (source: BMU 2012c)

When discussing the costs of the German FIT scheme, it has to be considered that even if the system was abolished today it would still create additional costs in the future as FIT payments are guaranteed over a period of 20 years. Until the end of 2012, cumulated FIT payments amounted to about 99 billion €$_{2010}$ of which wind energy was responsible for 36 % and solar photovoltaics for almost a third (cf. Table 2-5). Taking into account the remuneration period of 20 years, cumulated FIT payments of 304 billion €$_{2010}$ and cumulated differential costs of 186 billion €$_{2010}$ have to be incurred for all generation units installed until the end of 2012. In the long term, solar PV installations dominate with a share of 47 % in cumulated payments and of almost 62 % in cumulated differential costs.

On the whole, the German FIT system has caused a strong expansion of renewable electricity generation. It offers renewable producers a high level of planning security and has promoted a diverse technology portfolio. Yet, against the background of the rising importance of renewable energies in electricity generation, growing criticism regarding the present design of the FIT scheme has been voiced in recent years. First of all, shortcomings can be observed with respect to cost efficiency given the technology differentiation of the tariffs, which favours investments in more costly technologies, and the insufficient adjustments of the tariff level to decreasing investment costs in the case of some renewable sources. Secondly, being a price-based instrument, the basic FIT system does not contain a quantity control mechanism such that the risk of missing or over-fulfilling the political target arises. In fact, recent studies show that based on the current FIT system the goal of a renewable share of 35 % in gross electricity consumption in 2020 will be clearly exceeded (cf. BMU 2012d; Götz et al. 2012b) - associated with an additional cost burden on consumers.

Table 2-5: Cumulated FIT payments and differential cost for all generation units installed until the end of 2012 (own calculations based on BMU 2012c, BDEW 2013)

	Wind energy	**Solar photovoltaics**	**Total**
Cumulated FIT payments 2000-2012 [Bn €$_{2010}$]	35.7	30.8	**98.7**
Cumulated FIT differential cost 2000-2012 [Bn €$_{2010}$]	17.1	27.0	**64.1**
Cumulated FIT payments 2000-2032 [Bn €$_{2010}$]	69.5	144.3	**304.4**
Cumulated FIT differential cost 2000-2032 [Bn €$_{2010}$]*	20.9	115.0	**186.2**

* The calculations are based on the market value of FIT electricity generation obtained from the scenario calculations for the reference case (cf. Chapter 5.3).

Furthermore, one of the major drawbacks identified in the current FIT system is its exclusion of renewable generation from all market signals. Preliminary evaluations for 2012 reveal that the newly introduced market premium has strongly encouraged the direct marketing of renewable electricity. Gawel and Purkus (2012) estimate that in June 2012 almost 70 % of wind power has been covered by the premium system, followed by 27 % of generation based on biomass. At the same time, the system is being frequently criticized for its low efficiency and the considerable extra costs that have been caused mainly by the high management premiums granted in addition to the actual market premium. For 2012, it is expected that the additional expenditures amount to 400-500 million € associated with an increase in the FIT surcharge of 0.1 ct/kWh (cf. Hummel 2012; Nick-Leptin 2012). This cost increment could be justified if the new scheme generated at least comparable benefits in terms of market and system integration of renewable energies. Given the strong participation of fluctuating wind energy generation where no incentives to strengthen demand response exist, this is, however, doubtful (cf. Nestle 2011). In order to limit windfall profits, suggestions have already been made to reduce the management premiums, especially for non-regulatable generation (cf. Rostankowski et al. 2012). In addition, it has to be noted that even if the system is effective in introducing renewable producers to directly sell their generation to the market, they are still not exposed to the actual price risks of the electricity market.

Concern has also been expressed regarding the regional disparities in the revenues from FIT payments between the federal states in Germany. Mainly due to the high concentration of solar photovoltaics, Bavaria was able to generate a surplus of 1.2 billion € in 2012 (calculated as the difference between tariff payments for renewable installations in Bavaria and FIT surcharge payments from Bavarian electricity consumers) - compared to a loss of 1.8 billion € in North Rhine-Westphalia (cf. BDEW 2013). Apart from that, strong regional disparities in the electricity generation from renewable energies gives rise to the question whether the FIT system should be complemented by regional control mechanisms in order to avoid grid bottlenecks and to limit the need for grid expansion. On the other hand, in a long-term perspective, the advantages, especially in terms of cost efficiency, of harmonizing the various national schemes for the promotion of renewable electricity generation on a European level should be taken into consideration (cf. EC 2011c).

3 Current state of research: Energy models for policy evaluation

With the background on the different types of policy instruments and the most common evaluation criteria, the following chapter looks at the different modelling approaches that can be applied to analyse the long-term impacts of different environmental policy instruments on the energy system and the economy as a whole. In addition, the ideal requirements for a quantitative modelling framework for policy evaluation are explored and contrasted with the attributes of existing energy models. On this basis, the last two subchapters concentrate on the two main areas for improvement of bottom-up energy system models when used for policy evaluation: the behavioural dimension and the integration of macroeconomic feedbacks.

3.1 Overview on energy modelling[8]

Major progress in scientific modelling approaches is usually fuelled by changing demands from policy makers. Accordingly, even though the origins of energy modelling go back to the 1960s, the most important quantitative energy model tools used for the long-term evaluation of possible future energy paths were developed in the 1970s. In this decade, the two oil crises gave rise to an increased focus on energy policy concerns and corresponding efforts for the development of energy system models (cf. Hoffman and Jorgenson 1977). This development is also reflected in the creation of the Energy Modeling Forum (EMF) in 1976 with the aim to *"improve the use and usefulness of energy models in the study of important energy issues"* (Sweeney and Weyant 1979, p.1).

Energy system models provide a consistent tool for decision making and planning for complex problems in energy policy or for energy utilities. The aim, therefore, does not consist in predicting the exact future development of the energy system, but to analyse possible trends in energy supply and demand, from which so called "robust steps" can be identified, i.e. decisions and actions that turn out to be necessary and appropriate even when taking a wide uncertainty range of the most significant influencing factors into account (cf. Voß 1982). For that reason, energy modellers usually look at various scenarios in order to evaluate different potential energy futures. Scenarios can be described as *"plausible, challenging and relevant stories about how the future might unfold"* (Raskin et al. 2005), based on a consistent set of assumptions on the most important determinants in the energy system.

In order to assess energy models according to their applicability for policy evaluation it is helpful to look at the different types of modelling approaches that exist today. From the beginning, a differentiation has been made between two broad categories: top-down and bottom-up models. Top-down models look at the energy system "from above", i.e. from a macroeconomic perspective. This entails a high level of aggregation, while at the same time a full equilibrium framework is applied taking into account all repercussions of the energy system on the rest of the economy. Today, the field of top-down energy modelling is dominated by

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[8] A previous version of Chapters 3.1-3.5 has been published in Götz et al. (2012a) as part of the ETSAP Project "Integrating policy instruments into the TIMES Model".

computable general equilibrium (CGE) models, while input-output and macroeconometric models are other important examples (cf. Möst and Fichtner 2008). In these models, the relationships between the different sectors of the economy are represented with the help of aggregate supply and demand functions. Hence, the technical production conditions in the energy sector are modelled on the basis of production functions describing the substitution possibilities between the production factor energy and the other input factors (usually capital and labour). The most important model parameters, which are usually estimated based on historical data, are therefore the elasticities of substitution (ESUB), determining the substitutability between two inputs, and the autonomous energy efficiency index (AEEI), denoting the rate of price-independent progress in energy productivity. From this it also follows that no individual technologies can be represented in top-down models (cf. Jaccard 2009).

While top-down models are rooted in economic principles, bottom-up energy system modelling approaches have been mainly developed in engineering. These models depict the energy system “from below”, i.e. the entire energy system from primary energy supply to energy services demand in the different end-use sectors, including all conversion steps, is described in a process-oriented manner. Thus, a large variety of technologies, both on the energy supply and demand side, are functionally modelled with their economic, technological and ecological parameters. In the model, the energy system is then represented as a network of processes (technologies) and commodities (energy carriers, materials, etc.), the so called reference energy system (RES). This makes it possible to base the substitution between different energy carriers and input factors on an explicit choice between different technologies. Given the high level of technological detail, energy system models are partial equilibrium models. The analysis focuses on the energy system, while macroeconomic repercussions are not taken into account in the traditional approach. A differentiation can be made between models where the demand for energy services and useful energy is exogenously given and fixed and those which assume own-price elasticities for the different demand categories (actual partial equilibrium approach). With respect to the mathematical formulation, two main approaches can be distinguished. Simulation models describe the development of the energy system based on exogenously defined scenario assumptions, while optimization models calculate the optimal configuration of the energy system given the objective function and a set of constraints that contain the technical limitations, demand assumptions, political objectives (e.g. emission reduction targets), etc. In most cases, the objective function comprises total energy system costs such that the optimization problem consists in either minimizing net total cost (with exogenously given demands) or maximizing net total surplus of suppliers and consumers (with own-price elastic demands) (cf. Remme 2006, pp. 79ff).

3.2 Ideal attributes of energy models for policy evaluation

The policy environment in which energy models are applied today has changed significantly since the 1970s. With the issue of climate change, energy policy has acquired a new focus. Hence, given the necessity of introducing new policy instruments, the role of energy modelling in designing and evaluating such instruments has increased considerably. Simultaneously, research priorities have undergone a substantial shift. In the 1970s and 1980s the main concern of energy policy was clearly energy security, such that the principal aim of energy system modelling was to assess the potentials of different technologies to derive cost effective energy savings with financial costs being the main driver in these models. Today, in contrast, in addition to identifying technological pathways to arrive at certain climate goals, analyses concentrate also on the question of what could be achieved with different types of policy instruments taking into account the conditions under which such instruments would operate, e.g. behavioural and political constraints (cf. Worrell et al. 2004).

Against the background of this growing research need, the question arises what could be the contribution of energy system models in this process of evaluating policy instruments. Having the basic differentiation between bottom-up and top-down models in mind, one can also look at the question from another perspective examining what features an energy model would ideally need to possess to be appropriate for policy evaluation. Here, the approach initiated by Jaccard et al. (2003) provides a valuable starting point. It identifies three criteria that an ideal model would require to be useful for the assessment of different types of policy instruments: Technological explicitness, microeconomic realism and macroeconomic completeness (cf. Figure 3-1).

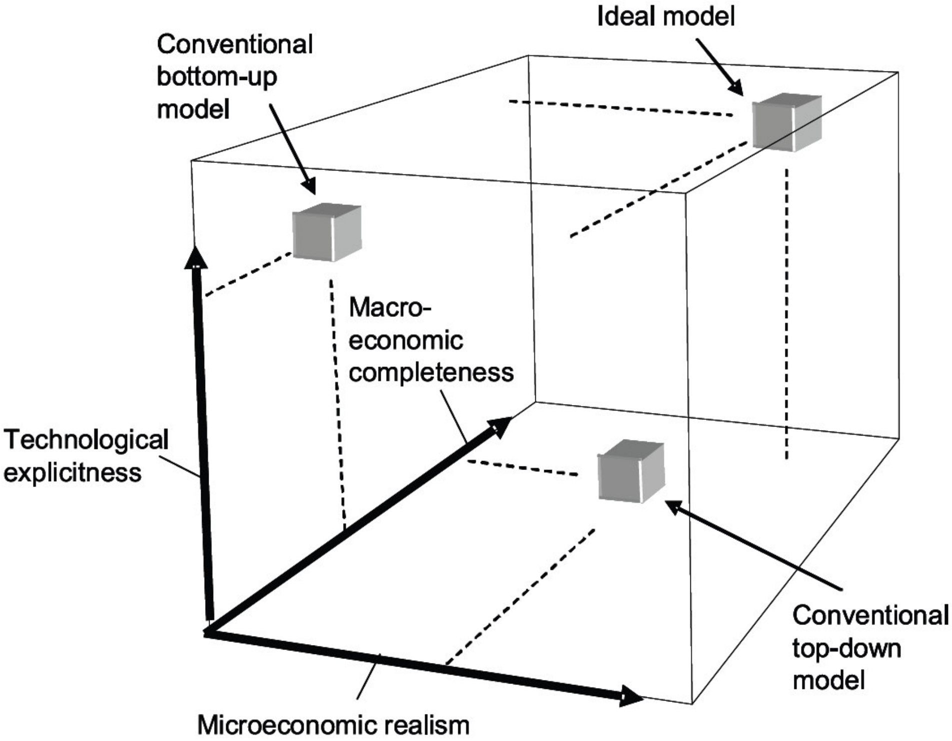

Figure 3-1: Dimensions of an ideal energy model for policy evaluation (Hourcade et al. 2006)

In this context, technological explicitness refers to the fact that energy models for policy evaluation should include information on a large variety of technologies as represented by their technical and economic characteristics. This is particularly important as many climate policy approaches tend to focus on a limited set of technologies, whose consequences for industrial production or household consumption is manageable and therefore enjoy greater political acceptability. The impact of such policy measures can only be evaluated when these technologies are described in an explicit way in the model. Moreover, a successful fulfilment of ambitious emission reduction goals depends greatly on the future breakthrough of different low-emission technologies, for which potentials, cost assumptions (including cost reductions through learning effects) and possible technological improvements also need to be incorporated in the model.

The second dimension, microeconomic realism, comprises all factors that influence the decision-making behaviour of firms and households. When choosing between different technologies that provide the same energy service, financial costs play of course the dominant role. Yet other aspects, like intangible cost terms representing differences in quality or other non-economic factors, perceived risk associated with the investment in new technologies or heterogeneous preferences, can also affect technology choice. Thus, not taking account of these factors in the model might result in over- or underestimating the impact of environmental policy instruments, especially in the household sector.

Finally, it has to be kept in mind when evaluating instruments of energy and climate policy that the energy system does not operate as a separate entity but is part of the economic system as a whole. Therefore, the third dimension highlights the necessity of integrating macroeconomic feedbacks into the model, since environmental policy instruments can have an effect on the structure of the economy and total output. It is useful to mention, however, that the importance of this aspect depends on the scope of the analysed instrument in terms of regional, sectoral and technological coverage, as the macroeconomic implications of a technology-specific measure clearly concentrated on one specific sector can be assumed to be rather limited.

It has to be noted that using energy system models for policy evaluation entails a change in perspective. Usually, such models assume the perspective of a social planner simultaneously minimizing total discounted costs (or maximizing welfare) of the entire system (cf. Keppo and Strubegger 2010). Accordingly, these analyses do not take into account any state influence on the market prices in terms of taxes or subsidies as these only constitute a redistribution of resources among different economic agents. Furthermore, a social discount rate is used reflecting the opportunity cost of capital for the economy as a whole. When, however, the aim consists in assessing the impact of environmental policy instruments, the perspective of the energy systems analysis needs to be modified, because the policy effects depend strongly on the individual decision-making of different economic agents facing market prices including all forms of state influence and applying private discount rates in their investment choices. Hence, the viewpoint can no longer be that of a social planner but the individual perspective of households, firms, etc. needs to be taken into consideration (cf. Ostertag et al. 2000, pp. 35ff). The change in the research focus also has an impact on the way scenarios are constructed: while most studies that estimate technical potentials utilize goal-oriented scenarios, i.e. scenarios that incorporate exogenously fixed target values, for example for emission reduction or the minimal use of renewable energies, analyses that look at the effect of a given policy instrument refrain from setting specific targets a priori and rather examine what the policy tool can contribute to a certain policy objective.

3.3 Strengths and weaknesses of energy system models in policy evaluation

At this point it has to be highlighted that the goal cannot consist in finding or creating the ideal modelling tool that will answer all questions related to policy evaluation. Each tool is developed for a specific purpose and will therefore have its strengths and weaknesses. Such being the case, it is more useful to look at the existing modelling approaches and assess them against the criteria established in the previous section.

The main advantage of bottom-up engineering models can be easily identified in their high level of technological detail. Hence, it is the only approach that can be applied to evaluate the effect of technology-specific measures and, even more importantly, to incorporate the impact of new technologies, for which no historical data is yet available (cf. Hoffman and Jorgenson 1977). Bottom-up energy system models also provide the possibility to model technology competition and to integrate the long-term trends in technology costs depending on their installed capacity with the help of learning curves. In estimating future developments, less reliance is put on historical data, whose main purpose usually is only to calibrate the model to the base year. In this way, it is feasible to model technological breakthroughs and other discontinuities, which can be surely expected in the face of ambitious emission mitigation targets (cf. Swan and Ugursal 2009).

At the same time, engineering energy models exhibit some drawbacks regarding the other two attributes of an "ideal" model outlined in the previous section. Bottom-up energy system models have often been criticized for ignoring critical aspects of the decision-making behaviour of different economic agents, especially private households. As Webler and Tuler (2010, p. 2690), put it: "*Getting the engineering right is not always enough*", there are other dimensions that influence decision-making. Engineering models usually rely on financial costs as the key decision variable for technology choice assuming that technologies that provide the same energy service can be regarded as perfect substitutes (cf. Jaccard 2009). This gives rise to a number of issues concerning consumer behaviour. First of all, limiting the analysis to pure financial costs implies that other significant cost elements, like transaction costs or intangible costs related to non-economic factors, are overlooked. Apart from that, bottom-up models generally have the underlying assumption of unbounded rationality, thereby disregarding important market imperfections (cf. Mundaca et al. 2010). This has often been reflected in the use of a social discount rate in the assessment of investment decisions of households and firms. Finally, the concept of the representative consumer adopted in energy system models ignores the influence that diverging preferences and market heterogeneity can have on technology diffusion.

An additional point of criticism that has been voiced with respect to the traditional approach of bottom-up energy system models is their lack of taking repercussions on the rest of the economy into account. This holds especially true for models that use fixed demands for energy services or useful energy. In doing so, the flexibility of the energy system to respond to changes in prices or policy measures is clearly underestimated, possibly leading to an overestimation of the costs of emission abatement measures (cf. Worrell et al. 2004). Furthermore, it has to be kept in mind that important aspects of policy evaluation, especially the impact of environmental policy instruments on the structure and level of economic output, employment, income distribution, etc., cannot be carried out with the help of engineering models. Some other drawbacks of bottom-up energy system models that have been mentioned in a number of studies include the large data requirements, often at a level of detail not easily available, and the fact that in policy evaluation additional cost parameters, like administrative or programme costs, have in some cases not been considered (cf. Swan and Ugursal 2009).

When looking at top-down energy modelling tools, it can be observed that areas where bottom-up models exhibit weaknesses are usually those where top-down models have their greatest strengths. An intrinsic characteristic of the top-down approach consists in its inclusion of all macroeconomic feedbacks. Moreover, as all decisive model parameters are generally estimated from time-series data, behavioural aspects are also, at least roughly, taken into account (cf. Swan and Ugursal 2009). At the same time, however, this strong dependence on historical data also constitutes a major drawback of these models in policy evaluation. It is doubtful that, especially for crucial parameters like the elasticities of substitution and the autonomous energy efficiency index, the historical development correctly reflects future trends given the substantially different political challenges, energy price levels and technological options (cf. Bataille et al. 2006). Thus, there is a risk that models tend to only project current trends into the future and thereby reinforce the status quo (cf. Laitner et al. 2003). Most climate policy instruments rely heavily on the realization of significant technological breakthroughs, which cannot be modelled if technological change is treated exogenously. In general, the most critical weakness of top-down models is their high level of aggregation making it impossible to evaluate technology-specific policy instruments. On the other hand, this is also why data requirements for top-down approaches are much more limited than for bottom-up tools (cf. Swan and Ugursal 2009).

In the past, both modelling approaches have been applied to evaluate policy scenarios with different emission reduction levels. Considerable differences can be observed when looking at the estimated carbon abatement costs, with cost results from bottom-up models usually being substantially lower than those from top-down approaches. Several reasons can be brought forward for this trend (cf. Schäfer 2012). Firstly, by disregarding behavioural factors, like barriers to energy-efficient investment, and using social discount rates, engineering models tend to indicate large potentials for emission mitigation at low costs. Secondly, important economic factors, like rebound effects, that dampen the expected energy savings from improvements in energy efficiency, are not taken into account. Finally, the assumption of perfect foresight underlying most bottom-up energy system models makes sure that the most cost optimal transition path is found in the long-term. Factors that lead to an overestimation of abatement costs in top-down models comprise the low level of technological flexibility and the dependence on parameters that are estimated from historical data.

Given the limitations and strengths of both model approaches, efforts have been undertaken, especially with the growing focus of energy policy on greenhouse gas abatement, to combine them and create so-called “hybrid” models (cf. Hourcade et al. 2006) (cf. Figure 3-2). Here, the strategy is either to increase the technological detail in existing top-down approaches (cf. for example the models WITCH (Bosetti et al. 2009), ReMIND (Schmid et al. 2012) and IMACLIM-R (Sassi et al. 2010)) or to include macroeconomic feedbacks and behavioural parameters in bottom-up tools (cf. for example the models CIMS (Jaccard et al. 2003), GCAM (Calvin 2011) and MARKAL-MACRO (Loulou et al. 2004)). In the following, the two main weak points of traditional bottom-up energy system models when applied for policy evaluation, concerning the behavioural and macroeconomic dimension, will be described in more detail with the major aim to illustrate approaches that have been developed so far to address these issues.

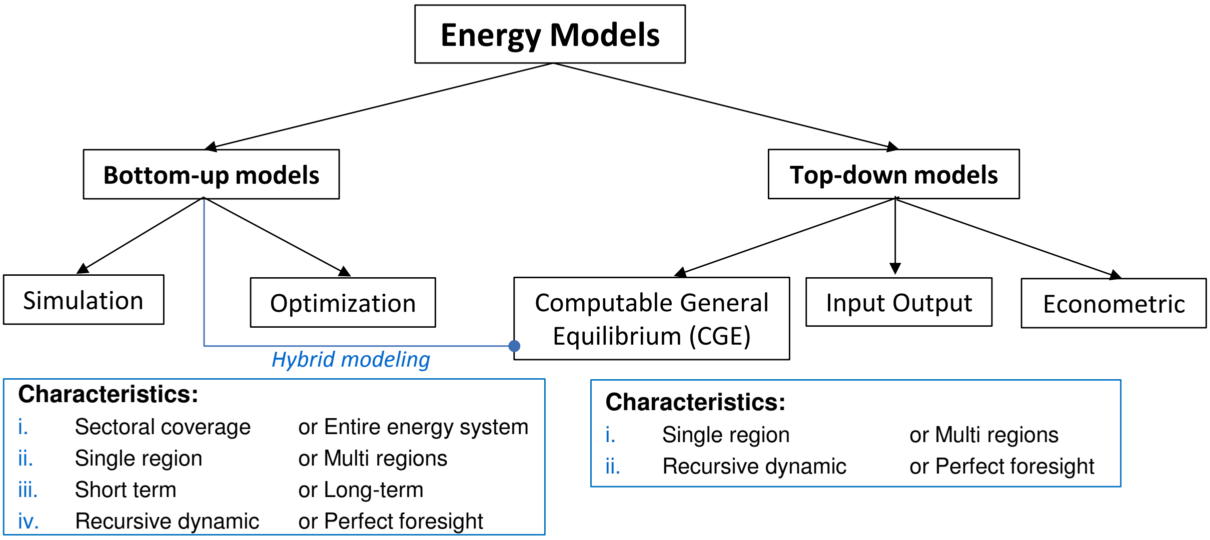

Figure 3-2: Classification of energy models

3.4 Main challenges (1): Consumer behaviour

In the previous sections it has already been established that investment decisions by households or firms do not only depend on financial costs but on a number of additional drivers. Hence, for a realistic assessment of the impact of policy instruments, these factors need to be taken into account in energy system models. Before looking at different modelling strategies, it is, however, crucial to have some background information on the issue of decision-making behaviour.

3.4.1. The debate on the energy paradox

The discussion on the varying representation of consumer behaviour in energy modelling evolved mainly around the debate on the energy paradox in the 1980s and 90s (cf. Hourcade et al. 2006). This phenomenon, also referred to as the energy-efficiency gap, describes the fact that there seems to exist a substantial gap between the actual investment in more energy-efficient technologies and the level perceived as socially optimal (cf. Jaffe and Stavins 1994). In economic terms, the decision for or against an energy efficient device should be based on a net present value calculation weighing the higher up-front investment costs against the long-term (discounted) savings in operating costs. It has been observed, however, that in reality investments which prove to be cost efficient based on their net present value are often not realized. Accordingly, bottom-up energy system models identify significant potentials for cost efficient investments in energy efficiency, while in the economic perspective of top-down models the existence of an energy-efficiency gap cannot be acknowledged based on the assumption of rational behaviour and perfect markets (cf. Hourcade et al. 2006).

It is essential to understand the reasons behind the energy paradox in order to be able to evaluate the effectiveness of different types of policy instruments in reducing the energy-efficiency gap and to arrive at a realistic modelling approach. Here, it needs to be pointed out that increasing energy efficiency cannot be considered as a goal in itself, but only as a means to achieve a more efficient resource allocation, i.e. higher economic efficiency. Jaffe and Stavins (1994) summarize all factors that may explain the low investment activity in energy efficiency under the term *market barriers*. A differentiation is then made between *market failures* and *non-market failures*.

Market failures describe all incidents in which the market mechanism does not lead to the optimal allocation of resources. Thus, a government intervention might be justified, if it leads to an improvement in overall welfare. With respect to investments in energy efficiency, a main source for market failures is often identified in the limited availability of information (cf. Howarth and Sanstad 1995). Information is generally viewed as a public good resulting in an underprovision through private markets. Thus, consumers might not possess all the necessary information about possible future energy savings in order to make an appropriate investment choice. Additional market failures that can be ascribed to information problems consist in the positive knowledge externalities that early adopters create through learning-by-using for potential other adopters. For this, they receive, however, no compensation thereby lowering the incentive to adopt new technologies (cf. Gillingham et al. 2009). Especially in the building sector another type of market failure can be observed in terms of the split-incentive problem, where the party that decides on and pays for an investment (e.g. the builder or landlord) is not the one who profits from the reduced energy costs (e.g. the purchaser or tenant) (cf. Murtishaw and Sathaye 2006). In some studies, liquidity constraints are also named as a cause of less than optimal investments in energy efficiency (cf. Blumstein et al. 1980). There exists, though, less empirical prove for this incident and if it is the case, it is no problem specific to investments in energy efficiency.

Yet, it is not certain that the energy-efficiency gap can be explained entirely on the basis of market failures. Jaffe and Stavins (1994) highlight another set of factors that cannot be attributed to a malfunction of the market mechanism. These non-market failures mainly comprise costs factors that consumers incur when investing in energy efficient devices, but are not included in simple net present value calculations. Hence, their behaviour is still rational and the optimal investment choice is made. First of all, transaction costs fall into this category which are often higher for new technologies where less user experience has been gained so far. Closely related to that is the higher perceived risk that consumers might attach to a new technology (cf. Groves 2009). Apart from that, one must not forget that investments in energy efficient products usually have long payback periods such that uncertainties regarding future energy prices and the market trends for new technologies need to be taken into account in the investment decision (cf. Sorrell 2004). Furthermore, consumers might perceive a new, more energy efficient technology not as a perfect substitute to an old one due to differences in quality (as for example fluorescent compared to incandescent lighting). In this context, market heterogeneity also plays a crucial role. For example, the potential energy savings will have more weight in the investment decision of a consumer who will use the product very frequently compared to another consumer who rarely makes use of it (cf. Jaffe et al. 1999). Here, a number of non-economic factors also come into play, like differences in comfort, design, etc. (cf. Mundaca et al. 2010).

The theory on market and non-market failures is still based on the assumption of rational behaviour. Studies from the behavioural economics literature have, however, observed that this assumption cannot always be applied to consumer choices and have therefore introduced the concept of bounded rationality or other heuristic decision-making methods (cf. McFadden 1999). This implies that consumers do not always possess the ability and resources to process all the information required to arrive at the optimal solution (cf. Shogren and Taylor 2008). That is why Gillingham et al. (2009) have introduced *behavioural failures* as a third category to explain the energy-efficiency gap. Here, social and cultural norms as well as the influence of family and acquaintances (cf. Dawnay and Shah 2011) also can have a decisive impact on investment choices. It might be justified to implemented specific policy instruments, like educational or information programmes, to address these behavioural failures given that this leads to an increase in welfare.

Jaffe et al. (1999) have shown that the different concepts of the energy-efficiency gap can result in alternative notions on the optimal level of energy efficiency. In Figure 3-3 different levels of economic efficiency are contrasted with different levels of energy efficiency. As has already been stated, the ultimate aim consists in maximising economic efficiency. Starting from the zero point which represents the reference case where no policy instruments are in place, there exists the possibility for specific policy interventions dealing with market (and behavioural) failures. As a result, both economic and energy efficiency are increased, creating a “win-win” or “no regrets” situation. This is referred to as the *Economists’ Narrow Optimum*. In contrast, bottom-up engineering models tend to arrive at a different optimum when simply minimizing investment and operating costs, the *Technologists’ Optimum*. Here, a higher level of energy efficiency is reached at the expense of the overall welfare level, as both market and non-market failures are eliminated. Jaffe et al. (1999) then consider an additional optimum, the *True Social Optimum*, where all other market failures, most importantly environmental externalities, are removed up to the point where benefits (in terms of economic efficiency) exceed the costs.

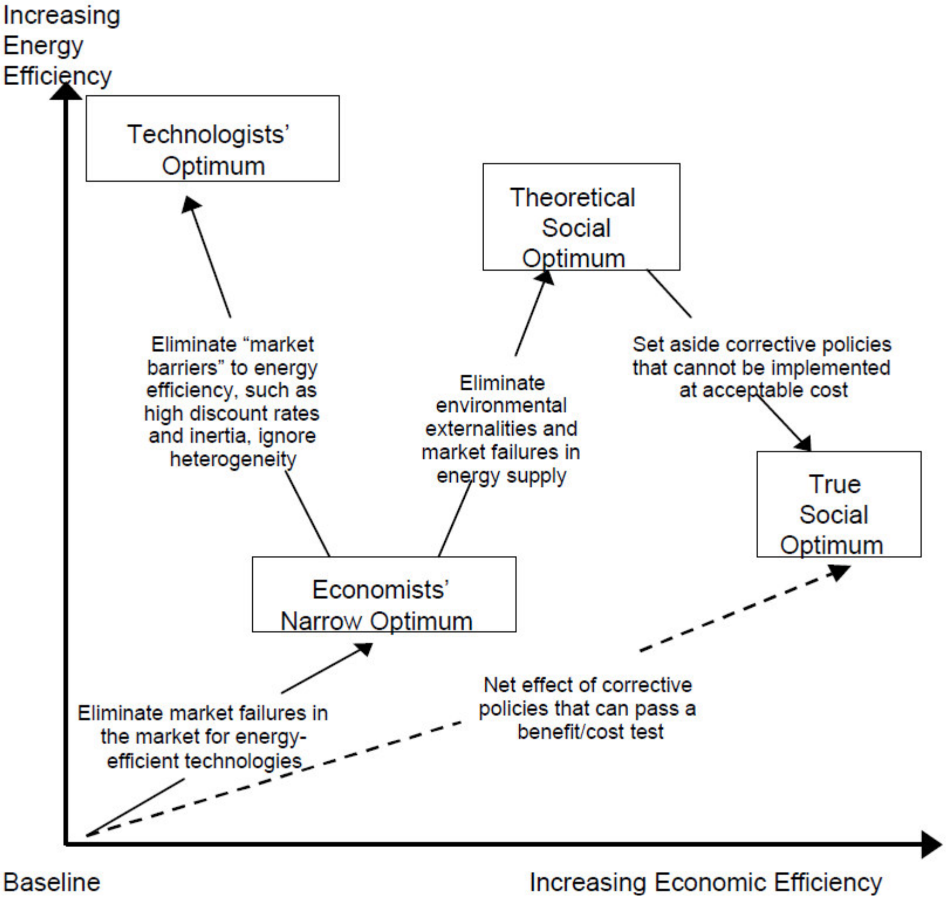

Figure 3-3: Alternative concepts on the optimal level of energy efficiency (Jaffe et al. 1999)

To conclude, it can be observed that by ignoring market barriers to energy efficient investments, bottom-up energy system models tend to overestimate the potentials for cost efficient energy savings. When modelling these barriers, the differentiation between market and non-market failures needs to be kept in mind.

3.4.2. Modelling approaches to incorporate consumer behaviour

As it can be understood from the previous section, the large variety of factors influencing consumer behaviour makes it all the more difficult to arrive at a realistic representation of decision making in energy system models. What is more, after integrating parameters on consumer behaviour, an understanding needs to be developed on how policy instruments might influence these parameters.

A basic approach to model investment barriers in energy system models has consisted for a long time in using high implicit discount rates (cf. Mundaca et al. 2010). These can be described as the subjective rates that can be empirically observed in the investment decisions of private households or other economic agents. This has the advantage that extensive empirical research has been conducted on these discount rates, starting with Hausman (1979), Gately (1980) and Ruderman et al. (1987) who arrive at high estimates of in some cases over 100 % for implicit discount rates of energy-efficient equipment in households. Accordingly, in many energy system models sector-specific discount rates are applied, with higher rates for private households and private transport and lower ones for energy conversion and industry (cf. for example E3M-Lab (2011) for the PRIMES model and IEA (2005) for the ETP model). Discount rates can also be differentiated between technologies to reflect social acceptance. It becomes more problematic, however, when the aim shifts from describing the actual status quo to modelling the impact of policy interventions as many of these instruments target exactly those market failures that the high discount rate are supposed to reflect. Some analyses have taken the approach to mimic the impact of policy measures by lowering the discount rates (cf. Mundaca 2008; Božić 2007). Yet, it has to be noted that there exists no good empirical foundation on the effect of policy instruments on implicit discount rates such that this approach appears rather intransparent and dependent on expert judgement. Moreover, it involves the risk of mixing up the two components that are behind the market barriers (market and non-market failures) or even of ignoring the non-market failures by reducing the discount rates to the level of social discount rates (cf. Mundaca et al. 2010).

A more sophisticated method to include consumer behaviour in energy system modelling has been developed in the hybrid model CIMS (cf. Jaccard 2009). CIMS is a bottom-up technology-rich simulation model of the energy system that also includes macroeconomic feedbacks. To account for behavioural aspects, the calculation of the market shares of competing technologies is not only based on financial costs, but extended by the following parameters. A weighted average time preference rate is used for discounting which is the same for all technologies providing the same energy service, but can vary between different energy uses. Apart from that, a cost term is added to capital and operational costs that reflects all intangible costs and benefits of a certain technology. This might be, for example, the perceived drawbacks of using public transport instead of one's own car to fulfil the demand for personal transport. Finally, an additional parameter is incorporated to capture market heterogeneity, which prevents that the technology with the lowest life-cycle cost covers the entire market.

Murphy and Jaccard (2011) have illustrated the impact that integrating consumer behaviour into the framework of an energy systems analysis can have on the results, especially regarding greenhouse gas abatement costs. They have contrasted the marginal abatement cost curve for the US calculated (1) by McKinsey (2007) based on a conventional bottom-up approach and (2) with the CIMS model using, as far as possible, the same scenario assumptions. It shows that generally marginal abatement costs are higher when consumer behaviour is taken into consideration. Furthermore, in the calculations with CIMS, the contribution of energy efficiency to the entire reduction potential is less pronounced compared to the other options of greenhouse gas abatement.

As Jaccard (2009) highlights himself, the value of such a more complex modelling technique depends greatly on a good empirical foundation. In CIMS, discrete choice models based on stated preference surveys are mainly used to estimate the three behavioural parameters. Other modelling teams have taken up and further developed the approach from the CIMS model, as for example the Res-IRF model focusing on the residential sector in France (cf. Giraudet et al. 2011) and the BLUE model depicting the energy system of London (cf. Strachan and Warren 2011). In general, it has to be noted that this method has greatly increased the transparency of representing decision-making behaviour in energy system models. However, substantial uncertainties with respect to the estimation of the behavioural parameters persist. And just as it was the case with using implicit discount rates, it gets even more complicated when trying to evaluate the impact of different policy instruments on these parameters.

Another approach to deal with the sociological dimension of investments in energy efficient equipment has been introduced through the SOCIO-MARKAL model (cf. Nguene et al. 2011). Within the scope of the conventional bottom-up energy system optimization model MARKAL, the effect of awareness campaigns is modelled by introducing “virtual technologies”. These include the cost of the awareness campaign, which, if used, directly has an effect on the investment decision (e.g. using more efficient light bulbs instead of the conventional ones). This technique has the advantage of being easily integrable into an existing linear optimization model. Yet, comprehensive sociological surveys need to be conducted in order to get realistic values for all the required parameters.

3.5 Main challenges (2): Economic flexibility

Energy system models are constructed by definition as partial equilibrium models such that repercussions on the rest of the economy are not taken into account. Consequently, the impact evaluation of environmental policy instruments is also restricted to the energy system when using this modelling technique. To measure economy-wide effects, for example on the gross domestic product (GDP), employment and trade, alternative approaches, like CGE models, can be applied. In the following, some problematic issues that arise from using a partial equilibrium approach for policy evaluation and possible ways of increasing the economic flexibility of bottom-up energy system models are highlighted.

3.5.1. Problems arising from the partial equilibrium approach

First of all, by fixing the demand for energy services or useful energy, as it is the case in many conventional bottom-up energy system models, the flexibility of the energy system in reacting to rising energy prices or emission reduction targets is considerably restricted (cf.

Worrell et al. 2004), because one important abatement option is disregarded: while the abatement options of increased energy efficiency, fuel substitution as well as, in most cases, of carbon capture and storage are taken into consideration in such models the possibility of reducing demand for energy services is neglected.

Secondly, it has to be kept in mind that changes in energy prices or greenhouse gas reduction targets can also have an impact on the structure of the economy, as for example the production in energy-intensive industry branches, like iron and steel, needs to be diminished (cf. Bataille et al. 2006). These adjustments cannot be estimated with the help of partial equilibrium models, yet they can have a significant effect on the energy demand. Closely related to this issue is the aspect of carbon leakage, i.e. the shift of (energy/emission-intensive) production from countries with stringent mitigation objectives to countries with no or weak target values (cf. Barker et al. 2007). This mechanism can only be evaluated with the help of supranational/global CGE models.

Finally, an intense debate has developed in recent years regarding the integration of rebound effects in energy system models. The results from bottom-up approaches tend to indicate large energy saving potentials from improvements in energy efficiency. However, the assessment changes when taking into account the energy cost savings that follow from the higher level of energy efficiency. Then it is likely that energy efficiency improvements fall short in delivering the expected energy saving potential, since the associated cost savings may actually encourage greater demand for energy services.

A differentiation can be made between different types of rebound effects (cf. Figure 3-4). A *direct rebound effect* arises when the demand for the energy service where the efficiency improvement was realized is increased due to the decrease in energy costs (cf. Berkhout et al. 2000). For example, a consumer who has bought a more fuel-saving car might choose to drive more given the lower fuel costs. According to microeconomic theory, this effect can be divided into a substitution and income (for households) or output (for producers) effect. The substitution effect defines how the now cheaper energy service substitutes for the consumption of other goods and services (or input factors) at a constant level of utility/output. The income (or output) effect describes the movement to a higher level of utility (or output) through an increase in consumption of all goods and services (or inputs) (cf. Sorrell 2007). The *indirect rebound effect* also comprises several components. First of all, the energy that is used to produce the equipment that is needed to improve energy efficiency has to be taken into account (denoted as embodied energy). Apart from that, the cost savings associated to one energy service can also be used to raise the consumption of other goods and services that require energy as well. Lower heating costs might, for example, allow for an additional holiday trip. In addition, the possibility of more economy-wide effects stemming from a higher level of productivity and lower energy prices need to be considered.

All these effects can significantly influence the effectiveness of policy instruments promoting energy efficiency. According to the Khazzoom-Brookes postulate, it might even occur that improvements in energy efficiency entail an increase rather than a decline in energy consumption (cf. Saunders 1992). Even though this hypothesis has not been verified empirically, taking rebound effects into consideration still can have strong implications on the results of energy systems analyses.

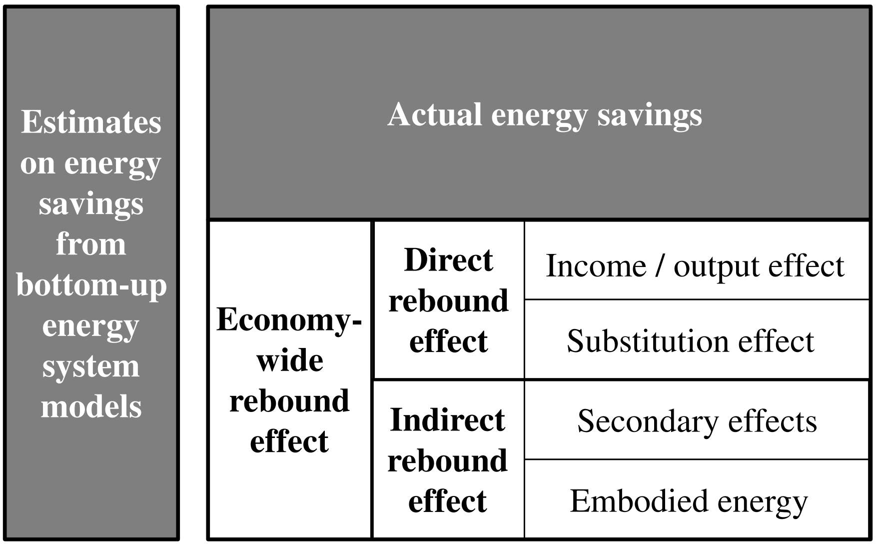

Figure 3-4: Classification of rebound effects from energy efficiency improvements and impacts on energy savings (own illustration based on Sorrell 2007, p. 4)

3.5.2. Increasing economic flexibility in bottom-up energy system models

In general, it can be stated that approaches for the inclusion of macroeconomic feedbacks in bottom-up energy system models have been much more widely explored than the integration of behavioural parameters.

A first attempt to enhance the economic flexibility of energy system models can consist in introducing price-elastic demands (cf. Loulou et al. 2005). By assigning own-price elasticities to the different categories of demand for energy services and useful energy, the different economic agents can react more flexibly to changes in energy prices or more stringent emission mitigation targets. This also implies a modification in the optimization approach: instead of minimizing net total energy system cost, as it is the case with fixed demands, now the net total surplus of producers and consumers is maximized. In addition, price elastic demands have been used to study the direct rebound effect in the framework of an engineering energy model (cf. Wang 2011).

In the hybrid model CIMS, a macroeconomic module is added where the different demand categories are modified according to the changes in energy prices (cf. Bataille et al. 2006). For the residential and commercial sector, elasticities of substitution to adjust home energy consumption versus other goods, consumption versus savings and goods versus leisure are applied. The demand for personal transportation depends on its own-price elasticity, while the demand for freight transportation is connected to the value added of the industrial sector. The industrial output is adjusted with the help of Armington elasticities of substitution, describing the degree of substitutability between domestic and foreign goods.

On the whole, it has to be pointed out, however, that to account for all macroeconomic feedbacks in an energy systems analysis some sort of coupling of the bottom-up model with a top-down CGE model is required. Combining the two approaches is challenging due to the fact that they are based on different mathematical programming approaches – linear programming versus mixed complementarity programming. According to Böhringer and Rutherford (2005), three different coupling strategies can be distinguished. Firstly, attempts have been made to "soft-link" existing large-scale bottom-up and top-down models (cf. for example Hoffman and Jorgenson 1977; Hogan and Weyant 1982; Schäfer and Jacoby 2006). In this case, the different models are still run separately but important model drivers are exchanged between the two models in an iterative process. For example, the top-down model delivers data on GDP, industrial output, etc. to the bottom-up model, whereas data on energy prices, the rate of technological progress, etc. is taken from the bottom-up model and implemented in the top-down approach. This method is relatively easy to handle, but, as Böhringer and Rutherford (2005) point out, issues of inconsistency might arise due to different theoretical assumptions.

Secondly, some modellers have followed the approach of "hard-linking" an existing bottom-up with a reduced form representation of a top-down model. A notable example is the link of the energy system model MARKAL with the single sector general equilibrium model MACRO into a single, self-contained model (cf. Loulou et al. 2004). While this strategy ensures a high level of consistency, the representation of the economic system remains relatively superficial.

The third approach makes use of the possibility to specify market equilibrium models as mixed complementarity problems to create entirely integrated models containing both the detailed representation of technologies and all macroeconomic feedbacks (cf. Böhringer 1998; Böhringer and Rutherford 2005). The strong appeal of this methodology lies in its overall consistency and flexibility, but at the same time issues of dimensionality and algebraic complexity clearly reduce its practicability.

4 Modelling policy instruments for renewable electricity generation in TIMES-D

The aim of the following chapter is to present in a comprehensive manner the possibility of and the challenges in explicitly modelling policy instruments in the scope of a national energy system model using the example of different support systems for renewable electricity generation, most importantly the German feed-in tariff system, and the EU Emissions Trading System (EU ETS). As a basis, the most important features and recent improvements of the model that will be applied afterwards in the scenario analysis, TIMES-D, are outlined. Subsequently, the modelling approaches for both types of instruments are described in detail.

4.1 The German energy system model TIMES-D

For the quantitative analyses the energy system model TIMES-D is employed. TIMES-D is based on the model generator TIMES, which has been developed in the scope of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). It is a multi-periodic bottom-up energy system model that follows a partial equilibrium approach for representing, optimising and analysing energy systems on local, regional, national or global scales. TIMES employs linear optimization techniques that depict the energy system as a network of processes (e.g. different types of power plants, heating systems, transport technologies, etc.) and commodities (e.g. energy carriers, emissions, materials, etc.). It usually minimizes (under perfect foresight) the total energy system costs required to meet the exogenously set sectoral energy demands subject to additional constraints, as, for example, a cap on total GHG emissions. This detailed, process-oriented model allows for the evaluation of technical adjustment processes within the energy system in the case of changes in the exogenously set model assumptions, e.g. in the political framework or the energy prices. For further information on the TIMES model generator see Loulou et al. (2005).

The application used for the analysis at hand, the TIMES-D model, represents the whole energy system of Germany taking into account exchange processes with neighbouring countries (with the help of cost potential curves). Demand sectors considered are the industry, service/commercial (including agriculture), residential and transport sector, which are further disaggregated. The German model contains more than 380 end-use technologies encompassing several vintage classes and represented by techno-economic parameters such as the utilisation factor, energy efficiency, lifetime, capital costs, operating and maintenance costs, etc. The supply side of the model covers energy conversion processes, like petroleum refining, coal processing, heat and electricity generation, etc. It includes over 120 conversion technologies for central electricity and district heat generation based on fossil (coal, lignite, oil, gas), nuclear and renewable (hydro, wind, solar, biomass, geothermal) resources. The technological and economic data for supply side technologies comprises the availability factor, capacity factor, efficiency, technical lifetime, specific capital costs, etc. Moreover, assumptions are laid down concerning energy prices, resource availability, the potentials of renewable energy sources, etc. In addition to the energy flows, energy and process related emissions of greenhouse gases as well as other air pollutants are accounted for in the model. TIMES-D has a high temporal disaggregation level with 32 time slices (4 on the seasonal, 2 on the weekly and 4 on the daily level). A more detailed description of the basic structure of the TIMES-D model can be found in Remme (2006).

In the scope of this thesis, several model extensions and improvements have been carried out.

First of all, in order to ensure that the sectoral coverage of the EU ETS is depicted in a realistic manner, the industry sector in TIMES-D has been regenerated on the basis of the structure used in the European TIMES model TIMES PanEU (cf. Kuder and Blesl 2010). The industrial sector is now differentiated into 14 sub-sectors with a distinction between energy-intensive (iron/steel, aluminium, copper, ammonia, chlorine, cement, lime, hollow glass, flat glass and pulp/paper) and non-intensive branches (other non-ferrous metals, other chemicals, other non-metallic minerals and other industries). In the case of the energy-intensive sectors, the reference energy system is represented in a process-oriented manner and the demand commodities are specified as physical goods (e.g. tons of steel). In contrast, for the non-energy intensive branches a standard modelling structure is applied based on five main types of energy use (steam, process heat, machine drive, electro-chemical and other uses). Here, demand is divided into different demand categories for energy services (e.g. cooling or space heating).

Another focus in the model revision was put on the (renewable) electricity generation sector. Both for conventional and for renewable power and heat generation plants an extensive update of technology and cost parameters has been conducted, mainly on the basis of IER et al. (2010), Wissel et al. (2010) and Blesl et al. (2012). With the aim to allow for a realistic representation of the complex tariff structure of the German FIT system, additional renewable generation technologies have been added to the model, e.g. ORC (Organic Rankine cycle) CHP (combined heat and power) plants for geothermal energy, repowering plants for onshore wind energy, modernization processes for hydropower plants, small-scale biomass cogeneration units and biogas fuel cells. In this context, the technical potentials for electricity generation from renewable sources as well as the maximum annual expansion rates for renewable electricity generation have also been revised and updated. Furthermore, the availabilities for electricity generation from fluctuating renewable sources have been modified based on the load profiles of recent years.

In light of the expected substantial increase in electricity generation from renewable energies and especially from intermittent sources, repercussions on the entire electricity system need to be taken into account in the modelling approach. That is why the representation and model parameters for electricity storage processes have been revised and additional storage technologies have been implemented in the model (advanced adiabatic compressed air energy storage (AA-CAES) and different battery storage systems). A strong expansion of renewable electricity generation will also have effects on the electricity grid making considerable investments necessary in order to transport electricity from often remote generation sites (e.g. coastal regions) to the centres of consumption and to integrate the rising share of fluctuating generation. Accordingly, the model structure representing the grid infrastructure in TIMES-D has been updated and specific costs for reinforcing and expanding the electricity grid - both for the transmission and the distribution grid - have been introduced into the model. These expansion costs are bound to the amount of installed capacity for onshore and offshore (only for the transmission grid) wind energy as well as solar photovoltaics. In the case of geothermal energy, competitiveness strongly depends on the possibility of a combined generation of electricity and heat. At the same time, this limits the generation potential as an adequate heat demand needs to be available at a reasonable distance. To account for this issue in the model, specific district heat potentials from geothermal energy and associated grid expansion cost have been added.

Changes in the scenario assumptions, e.g. regarding emission reduction targets or the expansion of renewable electricity, usually entail repercussions on the prices for energy services and are therefore also likely to induce adjustments in energy demand. Taking these interactions into consideration is essential when analysing the effect of different policy instruments on the energy system. For that reason, the mathematical formulation of the TIMES-D model, which so far has been run with fixed demands that were exogenously given, has been modified to include elastic demands. Price elasticities represent a measure for the responsiveness of demand to variations in price (cf. Läge 2002, p. 59). In the elastic-demand mode of TIMES, own-price elasticities are defined for each energy service demand category, while cross-price elasticities are assumed to be zero. The modelling approach then consists of two steps. Firstly, the reference case, for which demand levels have been previously specified, is calculated with fixed demands in order to identify one point on each demand function. Secondly, all alternative scenarios are run with elastic demands such that all alterations in demand for energy services are then determined within the model on the basis of the selected elasticities. It has to be kept in mind that by introducing the elastic demand feature, the economic rationale behind the optimization algorithm changes as the aim no longer consists in minimizing the cost of covering the previously fixed demand for different energy service categories but to establish an equilibrium where the total economic surplus (as the sum of producer and consumer surplus) is maximized (cf. Loulou et al. 2005). In that way, it is possible to take one of the major feedback channels of the economy on the energy system into account.

For the explicit representation of the different policy instruments examined in the scope of this analysis, distinct modelling approaches were developed which will be presented in detail in the following chapters.

4.2 The representation of emission trading schemes in a national TIMES model[9]

To incorporate emission reduction targets or CO_2 prices into a scenario analysis has long been common practice in energy system modelling. Challenges may occur, however, when trying to depict the actual features of a specific trading scheme as realistically as possible. Here it becomes obvious that the design of real-world tradable permit systems can deviate substantially from the idealised and abstract representation in theoretical literature, especially in terms of regional and sectoral coverage or the mechanism for the allocation of emission certificates. After briefly illustrating the relatively simple basic approach for modelling emissions trading schemes in energy system models like TIMES, special attention is paid in the following chapter to the problematic issue arising in many energy system analyses that the modelled region does not cover the entire trading region of a given emissions trading system such that not all abatement and trading options are represented in the model. Moreover, Chapter 4.2 addresses some additional critical issues that can be observed in the real-world design of emissions trading systems, namely the limited sectoral scope, particularities in the allocation mechanisms for emission certificates in the EU ETS, the possibility to bank and borrow emission certificates and the possible link with other emission trading mechanisms.

4.2.1. Modelling emissions trading systems in TIMES: basic approach

Emissions trading systems represent quantity-based mechanisms such that the basic approach for their integration into an energy system model is comparatively straightforward.

The cap on greenhouse gas emissions can be modelled by putting an upper bound on the flow of emissions of those sectors participating in the trading scheme with the help of a user-defined constraint (based on the parameter *UC_FLO*). The dual variable of this bound equals the marginal costs of the last (most expensive) unit of emission abated to fulfil the constraint. It can be therefore interpreted as the certificate price that would arise in the emissions trading system under the modelled conditions[10]. At the same time, the dual variable of the emission constraint reflects the impact of the emissions trading system on the objective function (cf. Remme et al. 2009).

The second fundamental feature of a cap and trade system, the trading mechanism, is already implicitly included in an optimization model like TIMES. The linear optimization approach ensures that the most cost efficient way of fulfilling the cap is realized – as it would be the case when emission allowances can be traded between emitters. Hence, sectors (or regions) that exhibit lower abatement costs and therefore deliver a disproportionately large contribution to the necessary emission reductions in the model can be understood as the emitters who,

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[9] A previous version of this chapter has been published in Götz et al. (2012c) as part of the ETSAP Project “Integrating policy instruments into the TIMES Model”.

[10] Alternatively, the shadow price of a GHG constraint can also be considered as the tax rate on emissions that would be required to achieve the given reduction target. With respect to the allocation mechanism, an ideal-typical mechanism where the same incentive effect for each ton of CO_2 abated is created irrespective of the mitigation measure is established with this modelling approach, which in reality could be achieved with the help of auctioning (cf. Chapter 5.2).

under an emissions trading system, sell certificates to those installations with higher abatement costs that contribute less to emission mitigation (cf. Remme 2006).

In order to exemplify the impact of introducing a tradable allowance scheme into an energy system model, a look is taken at the electricity generation costs of a fossil power plant which are represented by the dual equation of the activity variable of the respective generation process (assuming that the activity is defined as the electricity output) (cf. Remme 2006, pp. 136f):

$$act\_cost\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,fuel,s} + capact_{r,v,t,p,s} - \boxed{\frac{\varepsilon_{r,t,p,emis,fuel}}{\eta_{r,t,p,s}} \cdot ghg\_bnd_{r,t,emis,s}} \qquad (4\text{-}1)$$

$$\geq \; combal_{r,t,elc,s}$$

$$\forall r \in R, \forall t \in T, \forall p \in FOS, \forall s \in S, \forall v \in V, \forall fuel \in FUEL, \forall emis \in EMIS, \forall elc \in ELC$$

With:

p	process index,
r	region index,
t	index for the current time period from 1,..,T,
s	time slice index,
v	index for the vintage year,
$act\_cost\_d_{r,t,p,s}$	discounted variable operation cost (without fuel cost),
$capact_{r,v,t,p,s}$	dual variable of the capacity-activity constraint,
$combal_{r,t,elc,s}$	dual variable of the commodity balance of the output electricity (*elc*),
$combal_{r,t,fuel,s}$	dual variable of the commodity balance of the fuel input (*fuel*),
$ghg\_bnd_{r,t,emis,s}$	dual variable of an upper bound on greenhouse gas emissions (*emis*),
$\varepsilon_{r,t,p,emis,fuel}$	emission factor specifying how much emissions (*emis*) are produced per unit of the input commodity (*fuel*) in process *p*,
$\eta_{r,t,p,s}$	activity-based efficiency of converting the input flow (*fuel*) into the output flow (*elc*),
R	set of all regions,
T	set of all time periods,
FOS	set of all fossil electricity generation technologies,
S	set of all time slices,
V	set of all vintage years,
FUEL	set of all input fuels,
EMIS	set of all GHG emission commodities and
ELC	set of all electricity output commodities.

With the emissions trading system in place, electricity generation costs for fossil power plants are extended by an additional cost component representing the cost of purchasing allowances for the emission output of the respective installation (highlighted in equation 4-1). This cost term is calculated as the shadow price of the GHG emission constraint multiplied by the ratio of the emission factor for the respective fuel and greenhouse gas and the efficiency of the power plant. Thus, the emissions trading system will have an impact on the electricity price determined in the model (assuming that a generation process based on fossil fuels is the price-setting technology) and the competitiveness of fossil power plants. For other sectors that might be covered by the tradable allowance system the effect can be determined in the same way, as, for example, in the industry sector the production costs in manufacturing processes using fossil fuels will also rise with the additional costs for emission certificates.

4.2.2. Supranational emissions trading schemes in national energy system models

Problem definition

One of the main benefits of emission trading as a climate policy instrument, namely its ability to ensure that emission targets are fulfilled in a cost efficient manner, can be the better exploited the more emitters are covered by the trading scheme. Thus, in political reality one of the objectives is to create tradable allowances systems with a large regional scope, as it is the case with the EU ETS which currently comprises 31 countries.

In energy system modelling, this often gives rise to the problem that the model does not represent the entire trading region. Even though European energy system models, like the TIMES PanEU model (cf. Blesl et al. 2009), have been developed, national models are still in use as they exhibit a number of advantages. Due to their smaller size in terms of regional coverage, they often feature a higher level of sectoral as well as technological detail and/or a higher time resolution. Especially for the explicit representation of policy instruments, where the methodological approach can become comparatively complex, a flexible modelling tool with manageable computation times is of great relevance. For the case study at hand, the aim consists in modelling the EU ETS in a flexible way in the national energy system model for Germany TIMES-D (cf. Remme 2006; Götz et al. 2012b).

In the past, energy systems analyses have dealt with the problem of the model region not coinciding with the trading region in mainly two different manners. One possibility is to set a fixed emission reduction path for the respective country (cf. for example EWI et al. 2010). This allows to calculate a CO_2 price within the model, which would, however, only apply to the considered country. At the same time, the trading system with the foreign ETS participants is completely neglected presuming the national emission mitigation as invariant to changes in the scenario assumptions. Alternatively, fixed certificate prices can be integrated into the model (cf. for example BMU 2010a; UBA 2009). This would ensure that the emission reduction in the ETS sectors of the respective country is determined endogenously. However, the influence of changing national framework conditions on the allowance price is not taken into account. This effect might be negligible for small member states, but it can be assumed that countries like Germany, being currently responsible for almost a quarter of the ETS CO_2 emissions, can impact the certificate price significantly when, for example, changes in the national policy on nuclear energy or renewable electricity are implemented.

To overcome these shortcomings, a modelling approach has been developed that makes it possible to determine both the emission reduction in the national (here German) ETS sector and the ETS certificate price endogenously within the model.

The modelling approach

The basic idea of this model approach, as illustrated in Figure 4-1, is to depict both the emission reduction options for Germany and the rest of the EU ETS system in TIMES-D. In order to do so, an additional process is introduced into the model which contains the emissions of all ETS sectors outside of Germany which would arise if no tradable allowance system was in place and therefore no reduction measures would be undertaken. This procedure makes it possible to put a cap on total EU ETS emissions instead of on Germany alone. While the emission mitigation in the German ETS sector is still based on the explicit modelling of technologies within the reference energy system, the reduction options in the rest of the countries participating in the EU ETS need to be added to the model.

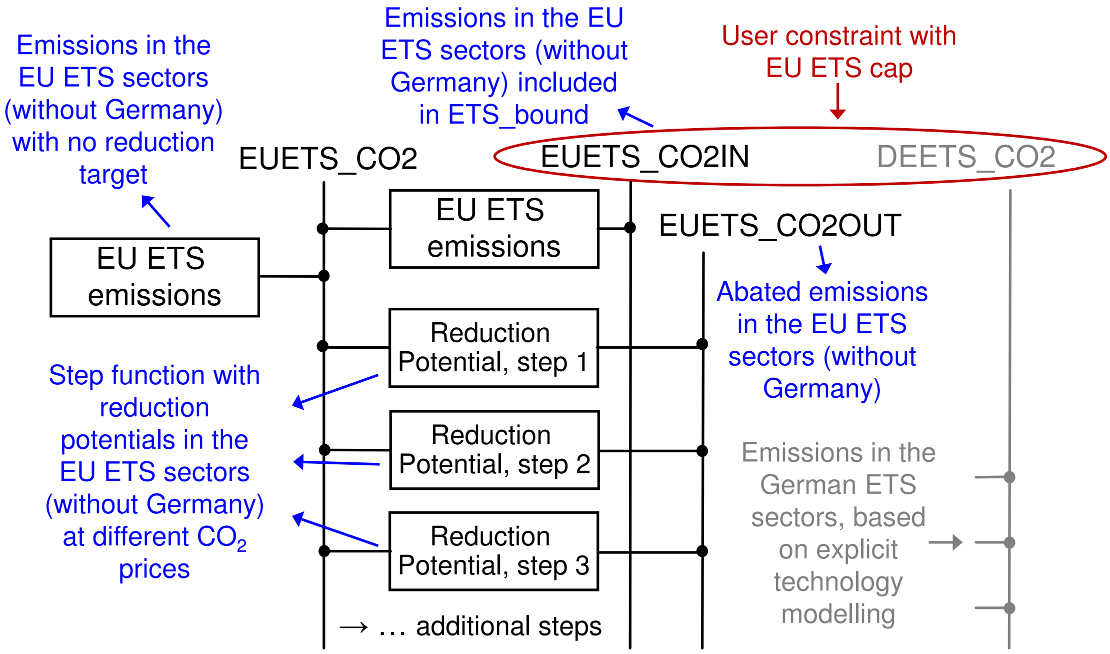

Figure 4-1: Modelling approach to represent the EU ETS in the German TIMES-D model

This is done with the help of a CO_2 abatement cost curve, modelled as a step function containing the CO_2 reduction potentials in the ETS sectors outside of Germany at different certificate price levels. In the model, each step is represented by a separate process comprising the maximum abatement potential (modelled with the parameter *ACT_BND*) and the marginal abatement costs for the corresponding step (modelled with the parameter *FLO_COST*). An additional process needs to be implemented which contains those ETS emissions from outside of Germany which are not avoided through one of the mitigation processes. The user constraint representing the EU ETS cap will then be put on the German ETS emissions and those from the rest of the ETS which are not abated. Hence, in the model the decision is to either reduce the ETS emissions outside of Germany and pay the associated abatement costs laid down in the cost curve or to increase mitigation efforts in Germany where all technologies are modelled with their cost parameters. Through the optimization approach, marginal abatement costs for Germany and the rest of the ETS sectors are approximated and a uniform certificate price for the whole system will be determined as the shadow price of the upper bound on total ETS emissions.

It becomes obvious that to realize this modelling approach comprehensive data on the emission reduction potentials at different certificate price levels in the ETS sectors outside of Germany are required. This information can be either obtained by an extensive literature research, by conducting a quantitative model analysis at European scale or by aggregating the results from several national model analyses. For the case at hand, a version of the Pan-European TIMES model, TIMES PanEU, which has been created in the scope of the NEEDS project (cf. Blesl et al. 2009) and is constantly further developed at the IER Stuttgart (cf. for example Blesl et al. 2010; Blesl et al. 2011), is applied. TIMES PanEU comprises 30 regions (EU-27 plus Switzerland, Norway and Iceland) with a less detailed time resolution (12 time slices) and less sectoral detail than TIMES-D. For the current study, instead of fixing an upper bound on CO_2 emissions in the ETS sectors, several model runs with different ETS certificate price levels (discounted to the base year) are executed in the Pan-European model.

In the first model run, an allowance price of zero is assumed in order to determine the amount of ETS emissions which would arise if no emissions trading system was in place. In the following model runs, the certificate price is raised gradually. Here, a time-integrated approach is chosen, i.e. the abatement potentials for each modelling year are calculated in one model run. The difference in emission abatement between one model run and the next represents the reduction efforts that would occur at the corresponding allowance price level. For example, deducting the emission quantity resulting from the model run with a certificate price of 10 €/t CO_2 from the one with a price of 20 €/t CO_2 would yield the reduction potential for the step in the abatement cost curve between 10 and 20 €/t CO_2. Hence, with the help of these model runs in the European TIMES model, the mitigation potential for each of the reduction processes that are implemented in the TIMES-D model can be ascertained. The emission abatement in Germany can be simply subtracted from the European potential, as with fixed certificate prices the mitigation efforts in one country are independent of the other countries.

In the present case, an abatement cost curve with 12 steps corresponding to CO_2 prices between 10 and 150 $€_{2000}$/t CO_2 in 2030 has been constructed based on the model runs. As an example, the resulting curve for 2020 is shown in Figure 4-2. In TIMES-D, each of the steps is then translated into one of the reduction processes. It has to be pointed out, however, that the thus calculated reduction potentials on the European scale only apply for the given framework conditions. If it is assumed that major policy changes, for example regarding the promotion of renewable energies, occur in the EU as a whole or in a number of member countries, the abatement cost curve would have to be determined anew.

Furthermore, the interaction between the reduction targets in the EU ETS and the cross-border exchange of electricity has to be kept in mind. If the participating electricity generators in one country do not possess comparatively cost efficient abatement options, their strategy might be to increase electricity imports from neighbouring countries at the expense of their own production given that this is less expensive than purchasing the required emission allowances and generating the electricity themselves (cf. Enzensberger et al. 2002). In order to take this effect into account in the model approach, data on electricity imports to and exports from Germany at different certificate price levels and the corresponding electricity prices on the European level are also taken from the scenario runs with the TIMES PanEU model and are bound to the different steps in the abatement cost curve. That means that the amount of electricity imported to or exported from Germany is associated to the burden sharing in emission mitigation between Germany and the rest of the EU ETS.

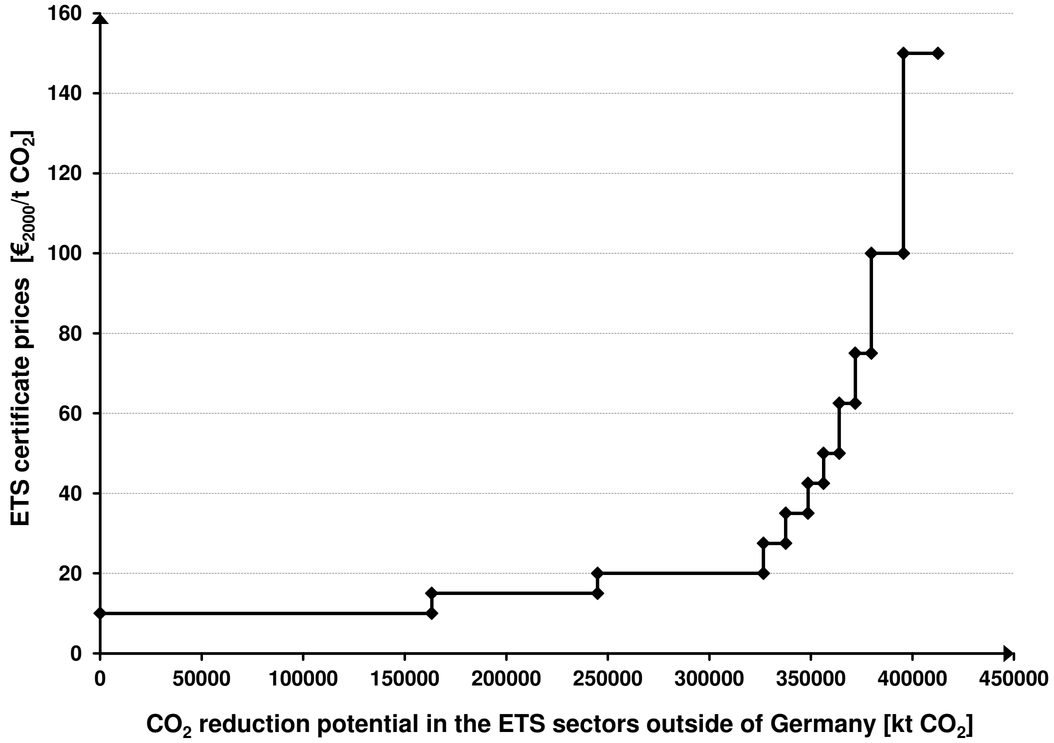

Figure 4-2: Exemplary abatement cost curve for the ETS sectors outside of Germany for 2020 generated with the TIMES PanEU model

4.2.3. Modelling of further features of emissions trading systems

Sectoral scope

Mainly due to administrative reasons, the EU ETS was set up with a limited sectoral coverage concentrated on large combustion installations and energy-intensive industries limiting its ability to induce the most cost efficient manner in reaching the overall reduction target. This feature complicates the realistic representation of the EU ETS in an energy system model and at the same time gives rise to a number of interesting research questions.

With the aim to reproduce the actual sectoral scope of the EU ETS as close as possible in the model, a high level of technological and sectoral detail is needed. As outlined above, the

TIMES-D model differentiates between energy-intensive (subdivided into iron and steel, aluminium, copper, ammonia, chlorine, cement, lime, glass as well as pulp and paper) and non-intensive branches (other nonferrous metals, other non-metallic minerals, other chemicals and other industries). Consequently, from 2013 onwards the bound on ETS emissions in the model is put on all industries except the category “other industries”. In energy conversion, all installations with a total rated thermal input exceeding 20 MW are covered which leads to the exclusion of a number of smaller, decentralized CHP and electricity only plants. When comparing the statistical emission values with the model results it turns out that the sectoral delimitation made in the model meets the current overall ETS emission levels fairly well.

Under the present design of the EU ETS as a downstream trading system, where the actual emitters of greenhouse gases are targeted, an extension to additional sectors would raise considerable challenges. In sectors like transport or private households a large number of small emitters would have to be included entailing prohibitively high transaction costs for those participants and an extreme increase in monitoring costs. At the same time, enhancing the sectoral coverage offers the advantage of increasing the cost efficiency and liquidity of the system and also of reducing the risk of price volatility (cf. Sorrell 2010). The objective of integrating all sectors into an emissions trading system could be achieved with the help of an upstream scheme, where the suppliers (or importers) of fossil fuels are responsible for holding the emission certificates and meeting the predefined cap. The resulting certificate costs are directly passed on to fossil fuel prices such that in the whole economy a uniform price signal for emission mitigation emerges (cf. Philibert and Reinaud 2004). Such an upstream system is easily implemented in an energy system model by putting an upper bound on total CO_2 or GHG emissions. This approach can then be applied to conduct a comparative analysis contrasting the effects of the EU ETS and a comprehensive upstream trading system in terms of the sectoral contributions to emission reduction, certificate prices, energy system costs etc.

Apart from that, when looking at an emissions trading system with limited sectoral coverage one must not forget that the EU ETS is part of an overall strategy on emission mitigation assigning reduction targets to both the ETS and the Non-ETS sector with the aim to equalize marginal abatement costs between the two sectors. Under the “Effort Sharing Decision” (cf. EC 2009d), national binding targets for the emitters not included in the emissions trading system have been established. Energy system models provide an appropriate framework to analyse the question whether the target division between ETS and Non-ETS sectors actually turns out to be efficient in the long run. An equalization of marginal abatement costs might especially be inhibited when additional (national) climate policy instruments are introduced whose impact on emission abatement has not been accounted for when setting the targets.

This problem is graphically highlighted in Figure 4-3. Here, both the marginal abatement costs for the ETS sector (MAC_{ETS}, left y-axis) and the Non-ETS sector ($MAC_{Non\text{-}ETS}$, right y-axis) are depicted. Without a reduction target in place, the emission levels amount to E_{ETS}^{*} (to be read from left to right) in the ETS sector and $E^{*}_{Non-ETS}$ (to be read from right to left) in the Non-ETS sector. It is assumed that in the beginning, before any additional policy instruments are introduced, a cost efficient distribution of the overall mitigation target is achieved such that when fulfilling the emission caps ($\overline{E}_{ETS}$ and $\overline{E}_{Non-ETS}$) each sector reaches the same marginal abatement costs ($\overline{MAC}_{ETS}$ and $\overline{MAC}_{Non-ETS}$ in intersection A). When, however, an additional policy instrument is implemented that reduces emissions in the ETS sector, the marginal abatement cost curve and the initial emission level in the ETS sector ($\tilde{E}_{ETS}$) shift to the left. An example for such a policy measure would be a national support system for renewable electricity that displaces electricity generation from fossil fuels and therefore causes an emission reduction in the ETS sector. In the illustration at hand, this reduction is given by the difference between the emission levels E^{*}_{ETS} and $\tilde{E}_{ETS}$. Consequently, if the emission budget for the ETS sector is not changed, the marginal abatement costs that are necessary to comply with the original ETS emission budget drop to $\widetilde{MAC}_{ETS}$, while in the Non-ETS sector marginal abatement costs remain the same. In order to realize a cost efficient division of reduction targets with the national policy instrument in place, the emission budgets would have to be adjusted to point B where the original marginal abatement cost curve of the Non-ETS sector and the new one of the ETS sector intersect leading to lower (and equal) abatement costs in both sectors (assuming that the overall emission cap is not altered). It has to be noted that the cutback in the ETS emission budget is smaller than the emission reduction associated with the additional policy instrument (cf. Walz 2005). Moreover, it has to be kept in mind that additional policy measures are generally associated with additional transaction costs such that the cost efficiency of reaching the overall reduction target is further affected when more than one instrument is implemented.

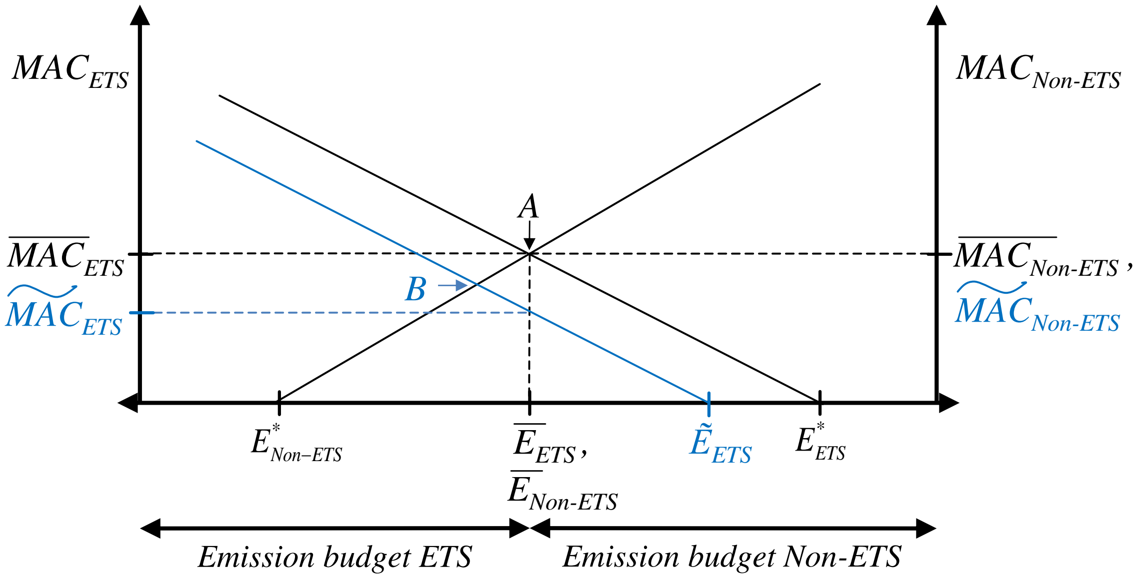

Figure 4-3: Graphical depiction of the effect of an additional policy instrument reducing emissions in the ETS sector on the cost efficient division of targets between the ETS and the Non-ETS sector (own illustration based on Walz 2005)

In an energy system analysis, the target division between the ETS and Non-ETS sector can be examined by setting a separate emission cap in both sectors. When analysing the cost efficiency of the initial distribution, attention needs to be paid to the fact that a number of national instruments have been introduced to ensure compliance with the Non-ETS targets, like efficiency standards in the building sector, biofuel quotas in transport etc. The impact of these measures should not be taken into account when determining the marginal abatement costs in the Non-ETS sector in the model, as this would already lead to a reduction in the shadow price of the constraint on Non-ETS emissions.

Allocation mechanisms

In Chapter 2.2.3, it has already been outlined that from a static perspective the mechanism with which emission certificates are initially distributed in a tradable allowance scheme, i.e. auctioning or free allocation, have no influence on the market outcome, as in both cases the most cost efficient abatement options will be realized. When integrating an emissions trading system into an energy system model with the approach described above, an ideal-typical allocation mechanism is assumed under which the same incentive effect for each ton of CO_2 abated arises irrespective of the actual mitigation measure.

In reality such an incentive structure can be induced by auctioning[11] all certificates, while the free allocation regulations that have been applied in the EU ETS clearly deviate from this ideal-typical distribution. One of the provisions that might lead to a distortion in abatement efforts that has been highlighted specifically in literature is the use of fuel-specific benchmarks for the free allocation of certificates to new installations that most countries have applied in the first and second period. This free distribution can be understood as a reduction in investment costs that favours the installation of new power or industrial plants (cf. Fichtner et al. 2007). Some attempts have been made to consider this effect in energy system models by adding a power plant specific investment subsidy (amounting to the value of the freely allocated certificates) to new processes (cf. Blesl 2007; Golling and Lindenberger 2008; Fichtner et al. 2007; Schwarz 2005). It becomes apparent that under auctioning fewer power plants based on fossil fuels are installed such that the expansion of low-emission technologies is facilitated and certificate prices are slightly lower. While in general such deviations from the idealistic design of policy instruments in the implementation practice should be kept in mind, the distortions stemming from the allocation mechanisms will get less significant in the EU ETS in the future as auctioning gains in importance and are therefore not further regarded in this analysis.

Banking and borrowing

The option to bank emission certificates for future use or to borrow certificates from later periods allows for greater intertemporal flexibility in the EU ETS. Typically, in energy system models one time period, represented by one model year, comprises several years. As

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[11] It is assumed that for the auctioning of emission certificates, a clearing-price auction is applied such that all units are sold for the same price.

emission reduction targets are only fixed for each time period and not each actual year, flexibility in the compliance time within one period is taken into account in the model. The intertemporal flexibility can be additionally increased in the model by using a cumulative constraint on GHG emissions leading to the same reduction over the entire time horizon but without setting mitigation targets for each model period (cf. Läge et al. 1999).

Inclusion of CDM/JI credits

The possibility to use credits from CDM or JI projects for compliance under the EU ETS widens the range of potentially cost efficient abatement options. With respect to the modelling process, the inclusion of CDM/JI credits can be understood as an extension of the regional coverage to areas which are (usually) not covered by the model. Hence, the model approach that has been developed for the representation of supranational emissions trading schemes in national energy system models (cf. Chapter 4.2.2) can be transferred in order to integrate the potentials for CDM/JI projects in a regional or national energy systems analysis. This requires the creation of an abatement cost curve containing the reduction potentials of CDM/JI projects at different prices levels for all model years (cf. Enzensberger et al. 2002). Apart from that, a restriction needs to be implemented in the model to account for the limitation on the use of CDM/JI credits for the overall emission reduction under the EU ETS.

4.3 Modelling different support systems for renewable electricity in TIMES[12]

In the following chapter, a methodological approach on how to represent different types of support systems for renewable electricity in the energy system model TIMES will be described. Energy system models provide an appropriate quantitative framework for the evaluation of the long-term implications of support schemes for renewable electricity taking into account all interactions and repercussions within the energy system. Yet, so far the effects of such support schemes have in most cases only been taken into account in an indirect way by exogenously setting minimum volumes for the electricity produced from the different types of renewable energies through user constraints (cf. UBA (2009) and IER et al. (2010)). This, however, clearly reduces the flexibility of the model, as generally no changes in the electricity generation from renewable sources will occur when the scenario assumptions are altered. Moreover, the interaction with other types of policy instruments, e.g. the European Emissions Trading Scheme, cannot be evaluated. Apart from that, the impacts of the support instruments on retail electricity prices, as the additional costs are passed down to final consumers, are neglected when exogenously fixing the minimum generation from renewable energy.

Some first attempts have been made in recent years to incorporate renewable electricity generation in the optimisation approach and to explicitly represent specific support instruments (cf. the Green-X model (Ragwitz et al. 2007), PERSEUS-RES-E model (Möst and Fichtner 2010), and the simulation model in Frontier Economics (2012)). With the exception of the

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[12] A previous version of this chapter has been published in Götz et al. (2012d) as part of the ETSAP Project "Integrating policy instruments into the TIMES Model".

PERSEUS-RES-E model, these approaches have the disadvantage that renewable electricity generation is analysed in an isolated manner, i.e. electricity prices are set exogenously such that no interactions with conventional power generation are considered and the effects on the demand side are neglected. Apart from that, the support systems for renewable electricity are generally modelled in a very simplified and abstract manner without keeping in mind the often complex structure of the real-world application of such instruments.

Therefore, using the example of the German FIT system as a starting point, the aim of the analysis at hand is to develop model approaches with which instruments for the promotion of renewable electricity generation can be explicitly integrated into an energy system model such that all features influencing the competitiveness of renewable technologies are accounted for in a realistic and detailed manner and the effects both on the generation side and the demand side are determined endogenously.

4.3.1. Feed-in tariffs in TIMES

In the case of FIT systems, the modelling approach is split up into two parts: firstly, it will be shown how the payment side (i.e. the tariffs) can be introduced into the model and secondly, the representation of the demand side (i.e. the FIT surcharge) will be outlined.

The payment side (1): The tariffs

It is often highlighted that FIT systems cannot be characterized as subsidies in the strict sense, due to the fact that they do not involve any payments from government units (cf. OECD 2007a). From the point of view of the renewable plant operator, however, the tariffs can be understood as a subsidy, as they constitute a compensation for the renewable electricity generation above the market price. Hence, in the modelling approach the TIMES parameters which are already available to represent subsidies are used. In TIMES, subsidies are treated as payments from outside the system and therefore enter the objective function with a negative sign. In the case of feed-in tariffs, which can be interpreted as subsidies on the amount of electricity generated, the parameter *FLO_SUB*, describing a subsidy on a process flow, would be most appropriate.

At this point, however, attention needs to be called to a number of special features that the German FIT system exhibits and that have to be accounted for in the modelling approach:

- The tariffs are paid over a limited period of time (usually 20 years). As the technical lifetime of some renewable generation technologies exceeds this time span, the limitation of the payment period has to be explicitly specified within the model framework.
- According to the legal stipulations, the tariffs remain constant in nominal terms during the payment period resulting in a gradual decline in real terms. In the model, real monetary values are applied such that the reduction of tariffs due to inflation has to be considered when fixing the tariffs in the model.

- While the tariff level for a particular plant stays nominally constant throughout the payment period, each year tariffs are reduced for newly installed plants according to the degression rates in the FIT law. Thus, tariffs for new plants depend on their vintage year.

These characteristics are not specific to the German system, but are applied in most FIT systems throughout the European Union (cf. Ragwitz et al. 2012). The impact of the feed-in tariffs on the competitiveness of renewable generation technologies depends substantially on these features such that taking them into consideration in the model is essential for a realistic representation of the FIT system.

In order to integrate the annual degression of tariffs, the characteristics of the processes describing the different renewable electricity technologies need to be defined as dependent on their vintage year. In the default settings of TIMES, all process parameters are tied to the current model year, but by assigning the set *PRC_VINT* to a specific process all its parameters, including the tariffs, can be vintaged. It has to be mentioned, however, that using the vintaging option clearly increases the model size.

The representation of the other two important features, the limitation of the payment period and the tariff reductions caused by inflation, can be accomplished with the help of a *SHAPE* curve. This TIMES parameter establishes user-defined multiplication factors which are applied to age-dependent process parameters. Hence, for a specific renewable electricity plant built in a certain year the tariff would be paid in full height in the first year after construction (i.e. multiplication factor = 1). In the second year, tariffs (in real terms) are reduced by the annual inflation rate (i.e. multiplication factor = 1/1.023 with an annual inflation rate of 2.3 %). Thereby, inflation can be accounted for in each year of the payment period. The assumption on the future inflation rate can have significant implications on the development of the feed-in tariffs. This is highlighted in Figure 4-4 showing the *SHAPE* curve for different inflation rates. It becomes apparent that when assuming an average inflation rate of 2.3 %, after 20 years in real terms the tariffs only amount to about 65 % of the initial value stipulated in the FIT law. Consequently, tariffs do not only decrease on a year to year basis for newly installed plants because of degression, but tariffs also decline considerably for one specific plant due to inflation.

Apart from that, the *SHAPE* curve is also applied to include the limitation of the payment period into the model. If the lifetime of a plant exceeds 20 years, the *SHAPE* parameter is set to zero from the 21st year onwards. Furthermore, shaping of process parameters also makes it possible to model other changes in the tariff structure of one specific installation. For onshore and offshore wind energy, a differentiation is made between a high initial tariff, which is paid over a specific number of years, and a lower basic tariff for the rest of the payment period. In other cases, a certain bonus is only provided for a limited number of years. This drop in remuneration can be reflected in the *SHAPE* curve by using the ratio of the basic tariff (or the tariff without bonus) to the initial tariff (or the tariff with bonus) as multiplication factor.

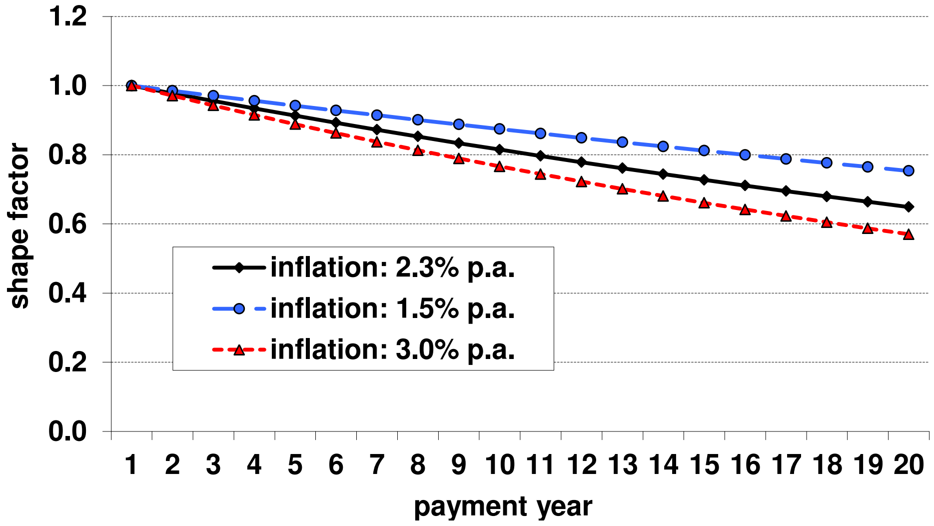

Figure 4-4: Development of the feed-in tariffs in real terms for one specific installation as a function of the inflation rate

Yet, introducing the TIMES parameter *SHAPE* also complicates the modelling process further. At the time that this methodology was developed, the *SHAPE* parameter could not be used in combination with the parameter *FLO_SUB*. To assign a *SHAPE* curve to *FLO_SUB*, the parameter *FLO_SUBX* would be necessary which would have to be established in the TIMES model code. Therefore, an alternative approach is created based on the parameter *NCAP_FSUB*. This parameter specifies a subsidy on the installed capacity of a process and can be used in combination with *NCAP_FSUBX*, whose parameter value is a discrete number indicating which *SHAPE* curve should be applied to the tariffs defined in *NCAP_FSUB*. This requires converting the assessment basis of the feed-in tariffs from the amount of electricity generated (ct/kWh) to the installed capacity (ct/kW) based on the availability factors laid down in the input data. Moreover, to avoid additional capacity being installed (to receive the subsidies) without being used for electricity production, the availability is laid down as fixed (instead of using an upper bound). At the same time, using fixed availability factors seems to reproduce the situation in reality quite well, as with the fixed tariffs the electricity supply from renewables is usually not oriented on the market situation but on the availability of renewable sources.

So on the whole, with the help of the parameter *NCAP_FSUB* in combination with *PRC_VINT* and *SHAPE* a modelling technique can be developed to integrate feed-in tariffs explicitly into the framework of the energy system model TIMES. To illustrate how the tariffs affect energy system costs, a simple representation of the objective function, including the subsidies on the installed capacity of renewable technologies highlighted in equation 4-2, is given in the following:

$$\min \sum_{t=1}^{T} \beta_t \cdot \left[\begin{array}{l} \sum_{p} \sum_{s \in prc\_ts_{r,p,s}} cst\_act_{r,t,p} \cdot d_t \cdot ACT_{r.t,p,s} \\ + \sum_{p} \left(cst\_fom_{r,t,p} \cdot d_t \cdot \left(cap\_pasti_{r,t,p} + \sum_{v \in vint_{r,t,p}} NCAP_{r,v,p} + NCAP_{r,t,p} \right) \right) \\ - \boxed{\sum_{p \in fit_p} \left(sub\_fom_{r,t,p} \cdot d_t \cdot NCAP_{r,t,p} \right)} \\ + \sum_{p} \left(\sum_{v \in vint_{r,t,p}} cst\_inv_{r,v,p} \cdot NCAP_{r,v,p} + cst\_inv_{r,t,p} \cdot NCAP_{r,t,p} \right) \\ + \sum_{(r,p,c) \in imp_{r,p,c}} \sum_{s \in prc\_ts_{r,p,s}} price_{r,t,p,c,s} \cdot d_t \cdot IMP_{r,t,p,c,s} \\ - \sum_{(r,p,c) \in exp_{r,p,c}} \sum_{s \in prc\_ts_{r,p,s}} price_{r,t,p,c,s} \cdot d_t \cdot EXP_{r,t,p,c,s} \\ + \sum_{p \in out_{r,p,c} \cup p \in in_{r,p,c}} \sum_{s \in prc\_ts_{r,p,s}} cst\_flo_{r,t,p,c,s} \cdot d_t \cdot FLO_{r,t,p,c,s} \end{array} \right] \begin{array}{l} \longrightarrow \text{Variable operation costs} \\ \longrightarrow \text{Fixed operation costs} \\ \longrightarrow \textbf{Subsidies on capacity} \\ \longrightarrow \text{Investment costs} \\ \longrightarrow \text{Import costs} \\ \longrightarrow \text{Export revenues} \\ \longrightarrow \text{Flow costs} \end{array} \qquad (4\text{-}2)$$

With:

c	commodity index,
$exp_{r,p,c}$	index for export processes *p* of commodity *c* to region *r*,
fit_p	index for processes *p* in the feed-in tariff system,
$imp_{r,p,c}$	index for import processes *p* of commodity *c* from region *r*,
$in_{r,p,c}$	index for process *p* with commodity *c* as input,
$out_{r,p,c}$	index for process *p* with commodity *c* as output,
$vint_{r,t,p}$	index for vintage periods of processes *p* that have been installed in a previous period *v* but still exist in time period *t*,
$ACT_{r,t,p,s}$	activity variable,
$cap\_pasti_{r,t,p}$	past capacity,
$cst\_act_{r,t,p}$	specific variable operation cost,
$cst\_flo_{r,t,p,c,s}$	specific flow cost,
$cst\_fom_{r,t,p}$	specific fixed operation and maintenance cost,
$cst\_inv_{r,t,p}$	specific investment cost,
$cst\_inv_{r,v,p}$	specific investment cost,
d_t	duration of time period *t*,
$EXP_{r,t,p,c,s}$	export variable (for export process *p* of commodity *c* to region *r* in time period *t* and time slice *s*),
$FLO_{r,t,p,c,s}$	flow variable,
$IMP_{r,t,p,c,s}$	import variable (for import process *p* of commodity *c* from region *r* in time period *t* and time slice *s*),
$NCAP_{r,t,p}$	new investment variable (of process *p* in time period *t*),
$NCAP_{r,v,p}$	new investment variable (of process *p* in vintage period *v*),
$prc\_ts_{r,p,s}$	time slices *s* of process *p*,
$price_{r,t,p,c,s}$	specific import and export cost (for process *p* and commodity *c* from/to region *r* in time period *t* and time slice *s*),
$sub\_fom_{r,t,p}$	specific subsidy on installed capacity and
β_t	discount rate in time period *t* to the base year.

Hence, energy system costs are reduced when adding the subsidies for renewable electricity. Further insights on how the modelling approach functions can be gained by looking at a simplified version of the dual equation of the activity variable of a renewable electricity generation process (assuming that the activity is defined as the electricity output) (cf. Remme 2006, pp. 136f):

$$act\_cost\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,fuel,s} + \boxed{capact_{r,v,t,p,s}} - actup_{r,t,p,s} \geq combal_{r,t,elc,s} \tag{4-3}$$

$$\forall r \in R, \forall t \in T, \forall p \in REN, \forall s \in S, \forall v \in V, \forall fuel \in FUEL, \forall elc \in ELC$$

With:

$\boldsymbol{actup_{r,t,p,s}}$	dual variable of an upper bound on the activity variable (economic rent) and
REN	set of renewable electricity generation technologies.

The dual equation of the activity of an electricity generation process contains all cost components which need to be covered by the electricity price. The electricity price (right-hand side of equation (4-3)) is calculated as the dual variable (i.e. the shadow price) of the commodity balance of electricity output. Thus, when the left-hand side of equation (4-3) is larger than the electricity price, the technology is not competitive and the activity of the process will be zero. For an activity level above zero, the left-hand and right-hand side of equation (4-3) need to be equal, meaning that the electricity price covers all cost components of the activity of the process. For example, if generation costs (represented by the first three terms in equation (4-3)) of a renewable technology are lower than the electricity price, this technology will be applied up to its full potential for the respective model period. In this example, the potential is limited by an upper bound on the activity of the process. Hence, the shadow price of this constraint (negative value) represents the economic rent associated with electricity generation with this technology.

When modelling the FIT system with *NCAP_FSUB*, the fixed operation and maintenance costs of the respective installations are lowered, rendering them more competitive when compared to conventional generation technologies. In equation (4-3) this is reflected in a decrease in the capacity related cost which are included in the highlighted variable $capact_{r,v,t,p,s}$, representing the dual variable of the capacity-activity constraint, i.e. in the case of a power plant the part of the electricity price that is needed to cover fixed operation and investments costs (cf. Remme et al. 2009). Consequently, it is decided endogenously through the optimization mechanism which processes for electricity production will be invested in.

However, the modelling approach with *NCAP_FSUB* also has its limitations. The conversion of tariffs from *FLO_SUB* to *NCAP_FSUB* is based on the condition that there is a fixed ratio between electricity generated and installed capacity. This is the case for electricity-only plants and combined heat and power plants for which the ratio between heat and power generation is fixed. The conversion is not possible, though, for CHP installations with a flexible power to heat ratio, as for example extraction-condensing CHP plants based on biomass. Consequently, for this type of CHP technology it is unavoidable to put the subsidy directly on electricity generation with the help of *FLO_SUB*. Yet, this makes it impossible to integrate the annual degression of tariffs, the tariff reduction due to inflation and the limitation of the payment period with the help of the parameters *PRC_VINT* and *SHAPE*. In order to still guarantee a realistic representation of the FIT system, it is therefore necessary to introduce for each renewable CHP technology with flexible power to heat ratio one process for each model period that can only be installed in the respective model period. This process then receives the average tariff for each model period for the following 20 years, taking into account the annual degression and inflation rates. It is apparent that this technique entails the implementation of a large number of additional processes, such that its application is limited to CHP plants with a flexible heat to power ratio. As an overview, the modelling approaches for different types of electricity generation technologies are outlined in Figure 4-5 to Figure 4-7.

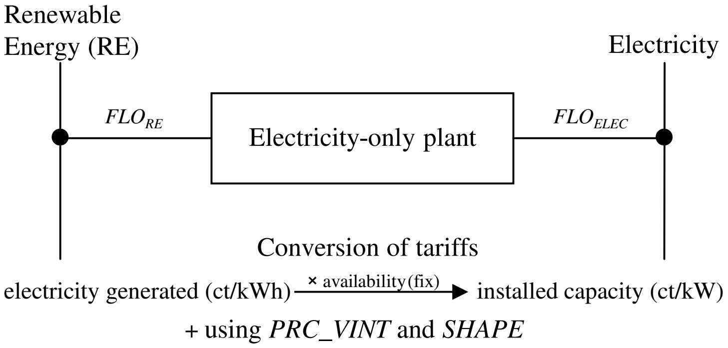

Figure 4-5: Modelling approach to integrate feed-in tariffs in TIMES in the case of an electricity-only plant

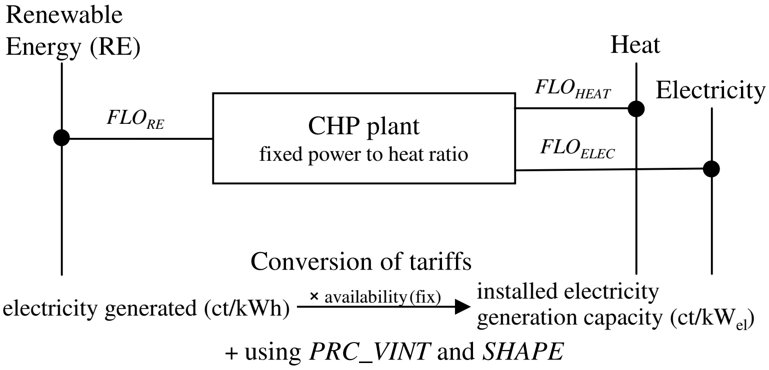

Figure 4-6: Modelling approach to integrate feed-in tariffs in TIMES in the case of a CHP plant with fixed power to heat ratio

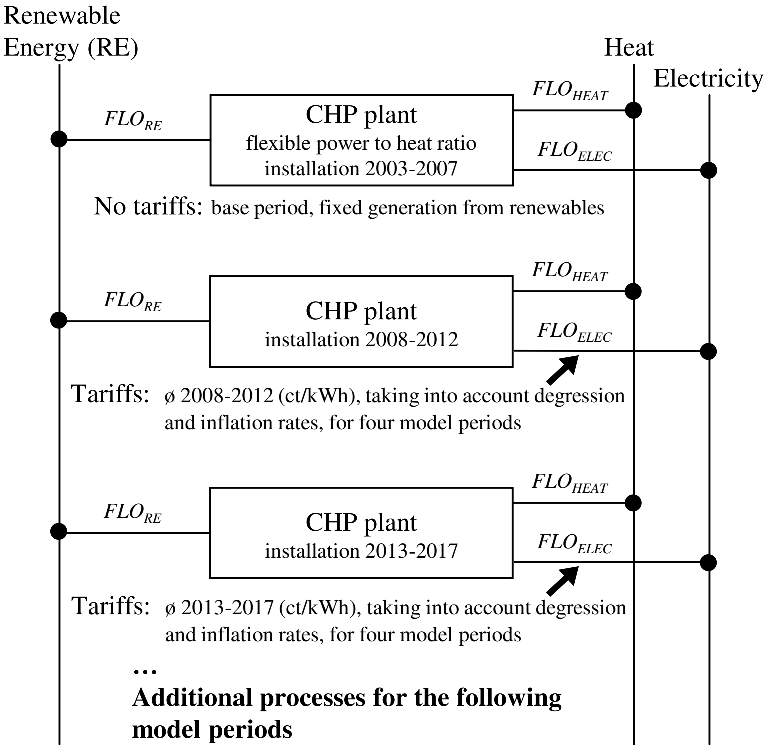

Figure 4-7: Modelling approach to integrate feed-in tariffs in TIMES in the case of a CHP plant with flexible power to heat ratio

The payment side (2): Special provisions in the German FIT system

Apart from the regular tariffs for new installations, FIT systems usually contain a number of special provisions that need to be taken into account in the modelling approach. In the case of the German FIT law, this concerns the modernization of existing hydropower plants, the repowering of onshore wind farms and the flexible degression scheme for solar photovoltaics. Moreover, when trying to evaluate the impacts of feed-in tariffs on the energy system, other factors that might influence the expansion of renewable electricity generation should be taken into consideration. In the analysis at hand, the focus is laid on tax incentives for solar PV rooftop installations.

Modernization of hydropower plants

Hydropower has been utilized for electricity production in Germany for several decades and the potential has already been exploited almost entirely. Furthermore, stringent ecological requirements have to be met when installing new hydropower plants (Kaltschmitt et al. 2006). Therefore, more attention is put on the modernization and reactivation of existing power plants and since 2004, the German FIT scheme contains special tariffs for modernized hydropower installations. According to the amended FIT law from 2012, existing hydropower plants are entitled to tariff payments (at the same level as new installations) if the installed or potential capacity is raised or if technical facilities to reduce output by remote means are implemented. In the case of an installed capacity of up to 5 MW, total electricity generation is remunerated, while for installations with more than 5 MW tariffs are only paid for the share of electricity that can be attributed to the increase in capacity. The costs of modernization are set at 1000 €/kW (cf. Kaltschmitt et al. 2006; Staiß et al. 2007) and it is assumed that the modernization entails an increment in installed capacity of 5 % (cf. BMU 2011c).

When integrating this special tariff rule into the model, it has to be kept in mind that operators of existing hydropower plants have two options: either to keep operating in the same manner - thereby avoiding additional costs but also forfeiting tariff payments - or to carry out modernization activities and enter the FIT system. In TIMES, the modernization option is introduced with the help of an additional process subsequent to the original process representing the existing hydropower plant (cf. Figure 4-8).

This process contains the cost of modernization as well as the feed-in tariffs (using *NCAP_FSUB*). As the modernization process is bound to the existing power plant through its output, the increase in installed capacity is modelled with the help of the parameter *FLO_FUNC*, usually used to specify the efficiency of a process. In general, for hydropower plants *FLO_FUNC* (describing the relation between hydropower input and electricity output) is fixed to 1. When setting *FLO_FUNC* to 1.05 in the case of the modernization process and defining the activity through the process output, the capacity (and activity) of the process is automatically raised by 5 %. The availability factor (parameter *NCAP_AF*) and the technical lifetime (parameter *NCAP_TLIFE*) for the modernization process are taken from the existing hydropower plant.

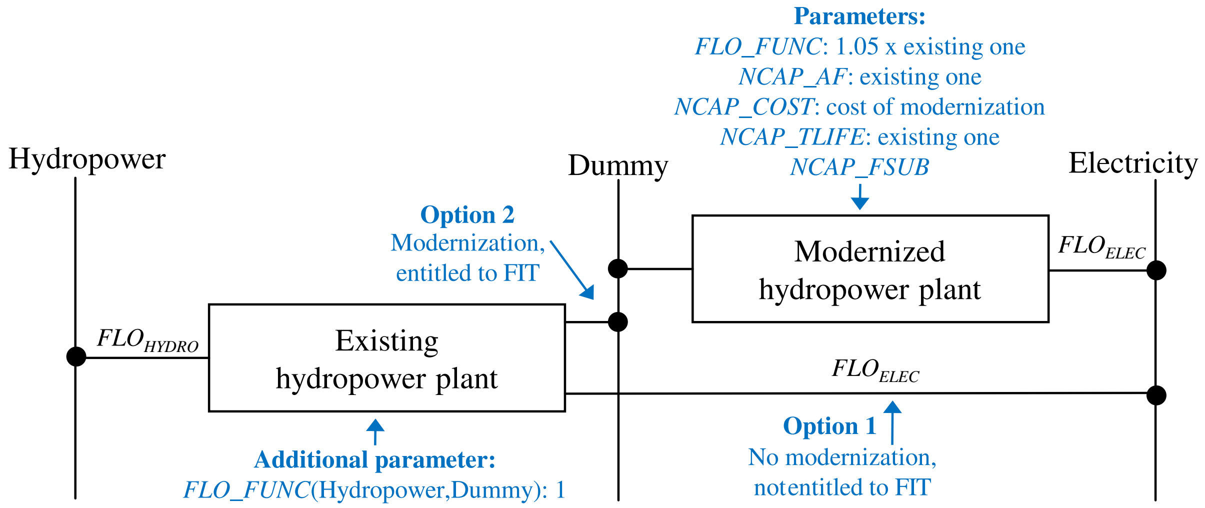

Figure 4-8: Modelling approach for modernized hydropower plants in TIMES

Repowering of onshore wind farms

Besides the regulations for the modernization of hydropower plants, the German FIT law contains another special provision related to existing installations of a renewable generation technology: the repowering bonus for onshore wind power plants. Hence, a similar procedure is chosen to incorporate this tariff option into the model.

Repowering describes the replacement of older and smaller wind turbines with new and more powerful ones. Especially in areas with favorable wind conditions near the coast the potential for electricity generation from onshore wind has already been exhausted to a great extent, such that the repowering option will play a crucial role in further increasing the wind power capacity in Germany. Apart from that, the impact on the landscape is reduced, as a smaller number of wind turbines is needed for the same amount of electricity generation, and improvements in terms of grid integration are expected (cf. BMU 2007a).

Therefore, in the German FIT law from 2012 a bonus of 0.5 ct/kWh in addition to the higher initial tariff for onshore wind power is provided for repowering installations if they satisfy the following conditions: (1) the replaced turbines were commissioned before 2002 and (2) the installed capacity of the repowering plants is at least twice the capacity of the replaced ones. In the model, the relatively conservative assumption is chosen that repowering leads to a doubling of installed capacity (in accordance with BMU (2007) and Rehfeldt and Gerdes (2005)). With respect to the investment costs of repowering plants, it has to be taken into account that these plants can make use of the already existing infrastructure of the replaced installations. Thus, it is assumed that in the case of repowering, the infrastructure related costs (site development, foundations, grid connection, etc.) only amount to 20 % of the investment costs of the actual wind turbine, as compared to 30 % for wind power plants in previously undeveloped locations (cf. Rehfeldt and Gerdes 2005).

As it was the case for the modernization of hydropower plants, the modelling procedure for the representation of repowering is based on the different courses of action the operator of the existing onshore wind power plant can choose. His first option would be to operate the existing plant until the end of its lifetime without replacing it. Alternatively, he could replace it before the end of its lifetime with a more powerful, new turbine. Here, the residual value of the existing installation plus the expected revenues (minus operating costs) for the remaining lifetime need to be taken into consideration. If the plant was installed after 1999, this includes FIT payments. A third option consists in a replacement at the end of the lifetime of the existing turbine. It has to be noted that while the modernization of hydropower plants constituted an alteration to an existing plant which keeps operating, repowering implies the definite replacement of an existing installation. This renders the modelling approach more complex. The different steps that are necessary to integrate repowering of onshore wind power plants into the model are illustrated in Figure 4-9.

First of all, a process representing the repowering plant needs to be added comprising the investment and operating costs as well as the feed-in tariffs (including the repowering bonus). This process is coupled with the existing wind power plant through a dummy commodity ("Dummy 1"). The doubling of installed capacity is again defined via the parameter *FLO_FUNC*. Other specifications, like the availability factor and the amount of capacity contributing to the peak (parameter *NCAP_PKCNT*), are adopted from the existing plant and the lifetime is fixed to 20 years (as is the case with all wind turbines in the model). Hence, with this configuration the replacement of the existing turbine during its lifetime can be modelled. It has to be pointed out that in the model the process for the existing plant will still be used giving rise to fixed operating and maintenance costs such that on the repowering process (which has double capacity) only half of the specific operating cost is put to keep the total amount correct. However, with only "Dummy 1" as input the repowering plant would no longer function once the existing plant reaches the end of its lifetime. Therefore, an additional process ("Dummy for capacity") is introduced which provides the input commodity ("Dummy 3") for the repowering plant after the existing one has been put out of operation. This process has wind power as an input so it can operate independently of the existing plant. Most importantly, the capacity of this process is bound to the decommissioned capacity of the existing wind turbine. This is achieved with the help of the parameters *NCAP_OCOM* and *NCAP_ICOM*. By assigning *NCAP_OCOM* to the existing wind turbine process, it specifies the amount of a commodity (here "Dummy 2") which is released during the decommissioning of the process. This commodity is then required to install capacity of the process "Dummy for capacity" to which *NCAP_ICOM* is allocated. In this way, the capacity of the dummy process (and also of the repowering plant) is limited by the capacity of the existing plants that go out of operation. Thus, also the third option - replacement at the end of lifetime – can be accounted for in the modelling approach.

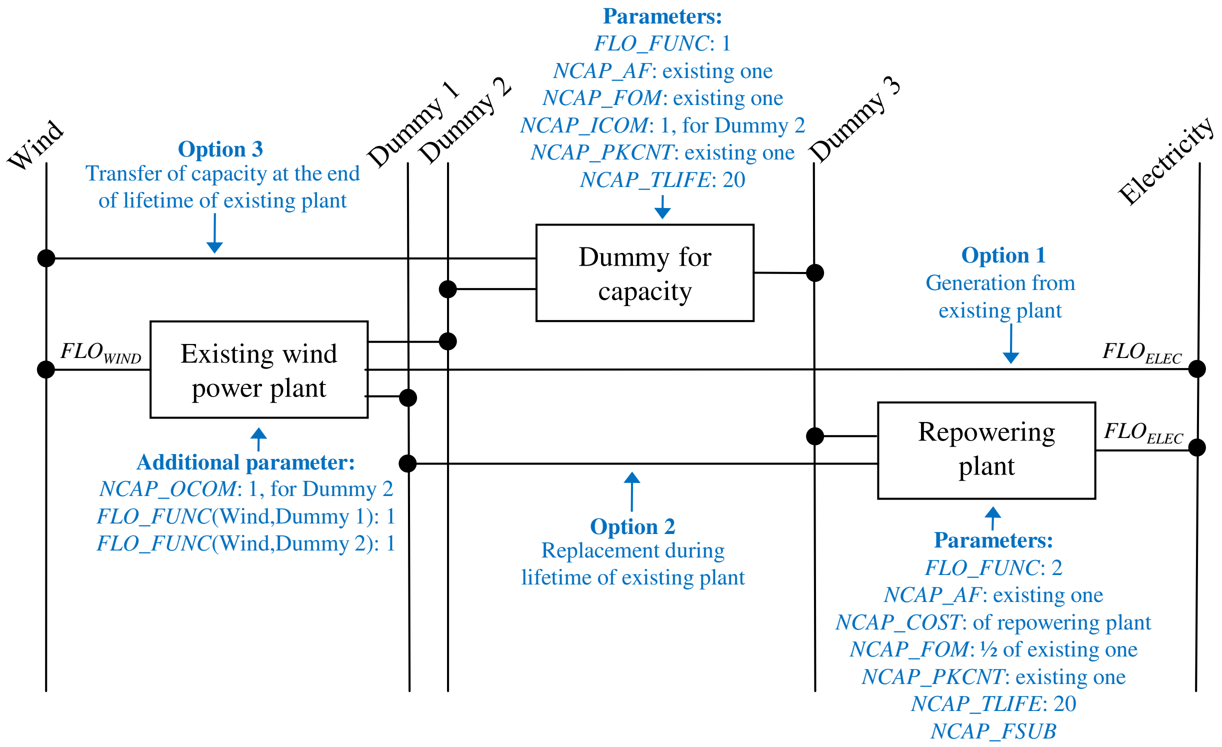

Figure 4-9: Modelling approach for the repowering of existing onshore wind farms in TIMES

Flexible degression for solar photovoltaics

Photovoltaic systems have experienced a period of very dynamic growth in recent years in Germany with an increase in installed capacity from 76 MW_p in 2000 to 24.8 GW_p in 2011 (cf. BMU 2012b). This was fuelled by relatively high feed-in tariffs and a significant drop in investment costs for PV modules (cf. BSW-Solar 2012). Consequently, in addition to a number of substantial tariff cuts, the German government has introduced in 2010 a flexible degression scheme for solar photovoltaics where the annual decline in tariffs depends on the actual market growth. In the current version of the FIT law (including the additional amendment from June 2012), an extension of the solar PV capacity between 2500 and 3500 MW_p per annum has been established as the target value which is associated with a monthly degression rate of 1 % (resulting in 11.4 % p.a.). If the actual annual investments fall below or exceed this "extension corridor", the degression rate is adjusted accordingly resulting in potential rates between -6.2 % and 28.9 % per year (cf. Table 4-1). Furthermore, it has been decided that the total amount of solar PV capacity that will be remunerated through the FIT system is limited to 52 GW_p.

Table 4-1: Flexible degression rates for solar photovoltaics according to the German FIT law from 2012 (own illustration based on BMU 2012a)

Annual extension	Monthly degression	Annual degression
> 7500 MW_p	2.8 %	28.9 %
> 6500 MW_p	2.5 %	26.2 %
> 5500 MW_p	2.2 %	23.4 %
> 4500 MW_p	1.8 %	19.6 %
> 3500 MW_p	1.4 %	15.6 %
Extension corridor: 2500 – 3500 MW	**1 %**	**11.4 %**
< 2500 MW_p	0.75 %	8.6 %
< 2000 MW_p	0.5 %	5.8 %
< 1500 MW_p	0 %	0 %
< 1000 MW_p	-0.5 %	-6.2 %

This flexible tariff scheme can be taken into account in the model by implementing one process for each of the degression steps. These processes all represent the same type of photovoltaic system (i.e. have the same economic and technical features), but they receive different tariffs depending on the degression rate. With the help of user constraints, the increase in installed capacity per model period is then restricted to the corresponding maximum value for the respective degression step. In addition, one more PV process is added which is not included in the FIT system. In this way, an additional user constraint can be put on the other PV processes participating in the tariff system (10 per type of solar PV system) in order to limit the total amount of capacity that is entitled to funding to 52 GW_p. This modelling approach exhibits one slight drawback. While in reality there is only one tariff level for all photovoltaic installations, in the model in each time period the capacity limits for each process would be exhausted consecutively according to their degression rate. This issue can, however, be rectified within the iterative process of several successive model runs, which will be necessary anyway for the calculation of the FIT surcharge (cf. Chapter 4.3.1). In the first model run, the different degression steps will be taken into account resulting in investments in new PV installations at different degression levels (provided that photovoltaic systems are competitive in the FIT system). In the second model run, the highest degression level that is reached in each model period will be applied to all solar PV processes.

Tax incentives for solar PV rooftop installations

While it is certain that the substantial growth rates for solar photovoltaics can be mainly attributed to the high tariff level, other factors that might have influenced investments should be taken into consideration. In this context, the case of solar PV systems is of particular interest as the typical investor differs clearly when compared with the other renewable energy sources. It can be observed that photovoltaic rooftop systems in Germany are usually installed by private households, farmers or small businesses. These investors benefit from a number of incentives which are generally not available to large-scale investors.

First of all, for the financing of photovoltaic installations, soft loans, currently with interest rates between 1 % and 6 %, are available through the government-owned bank *Kreditanstalt für Wiederaufbau* (cf. KfW 2012). In the model, this is captured by applying a lower discount rate of 5 % to PV rooftop systems, as compared to 7 % for all other renewable electricity generation technologies.

Moreover, the German Income Tax Act (EStG, cf. Bundesgesetzblatt 2013b) contains a number of special rules concerning the depreciation of photovoltaic installations. Generally, solar PV systems are written off on a straight-line basis over a period of 20 years. Private tax payers and small businesses (with operating assets of up to 235000 €) then have the option to use an investment deduction (cf. § 7g (1) EStG) allowing them to depreciate off the balance sheet a maximum of 40 % of the planned acquisition costs. In addition, on the residual value a special depreciation of in total 20 % in the year of the installation and the following four years can be applied (cf. § 7g (5) EStG). Hence, on the whole it is possible to depreciate up to 55 % of the investment costs of a photovoltaic system in the year it is installed.

In order to be able to incorporate these special depreciation rules in the modelling approach, the effect such tax incentives might have on the investment decision needs to be analysed. The benefit of an accelerated depreciation can be found in the tax deferral effect, as taxable income in the first year(s) is reduced at the price of a higher taxable income in future years. Due to the time value of money, this results in a positive interest effect (cf. Ostertag et al. 2000). For the case at hand, this can be illustrated by calculating and comparing the net present value of future tax savings for the following two cases: (1) the solar PV installation (assumed value of 50000 €) is depreciated on a straight-line basis only; (2) in addition to the straight-line basis depreciation, the investment deduction of 40 % and the special depreciation of 20 % are applied in the first year (to the same solar PV installation). In the first case, the net present value of the annual depreciation amounts adds up to 32700 €, as compared to

42200 € in the second case (calculated with a discount rate of 5 %). Assuming an average income tax rate of 25 %, the respective net present values of future tax savings then amount to 8200 € and 10600 €. Thus, in the present example, making use of special depreciation options can increase the net present value of tax savings by 2400 €, i.e. almost 5 % of the assumed installation price of 50000 €. This percentage share increases slightly in the case of a cheaper installation price, and vice versa.

Integrating such fiscal incentives into an energy system model is fairly difficult as repercussions on the income situation of households and other economic agents, which might influence their investment decisions, cannot be taken into consideration. In the methodological approach at hand, the effect is approximated by assuming a reduction in investment costs for solar PV rooftop installations by 5 %.

The demand side: The FIT surcharge

Given the fact that renewable electricity generation technologies are generally not yet competitive when compared to conventional technologies, feed-in tariffs need to be significantly higher than current wholesale electricity prices entailing additional costs in electricity generation and changes in electricity prices. A differentiation needs to be made between the impact of FIT systems on wholesale and on retail electricity prices.

As far as wholesale electricity prices are concerned, it has been observed that promoting renewable electricity can have a dampening effect on the price level – referred to as the merit-order effect (cf. Sensfuß et al. 2008). This mechanism is illustrated in Figure 4-10.

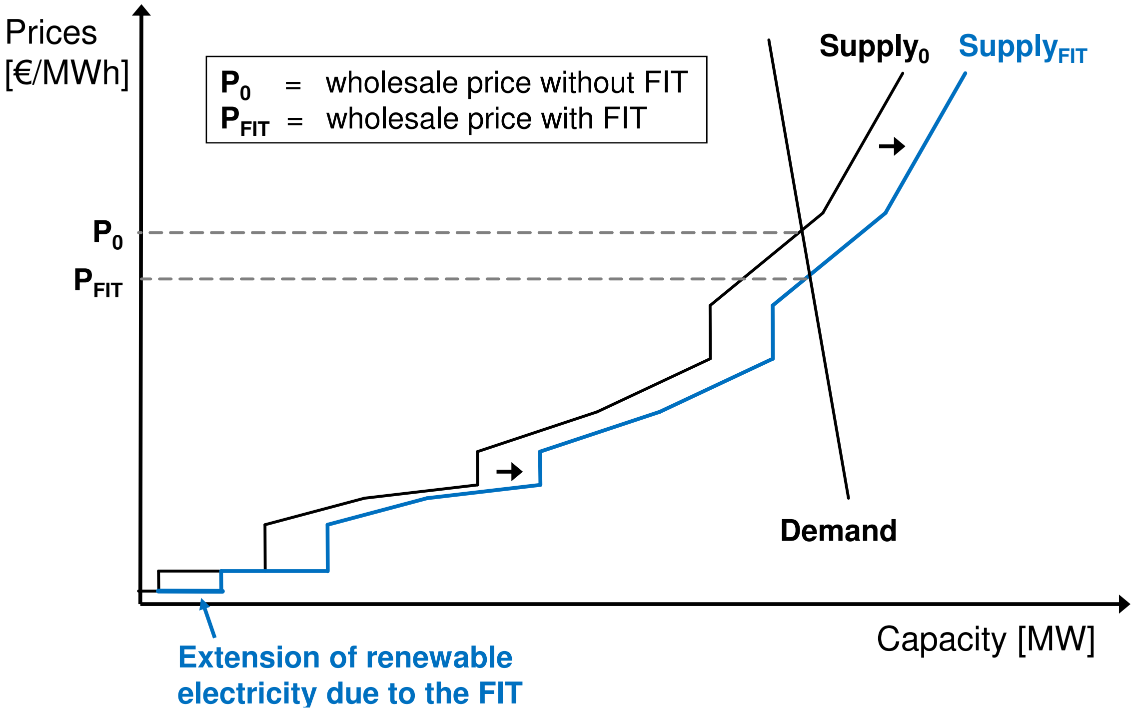

Figure 4-10: Illustration of the merit-order effect of renewable electricity generation (own illustration based on Teske and Schmidt 2008)

The wholesale electricity price is determined as the intersection between the electricity demand and supply curve (also called merit-order curve). This means that the price is set by the (variable) generation costs of the marginal unit which is needed to cover demand. With increased support for renewable electricity, which exhibits low variable generation costs, the most costly part of the conventional generation is driven out of the market. This entails a movement of the merit-order curve to the right and a reduction in wholesale electricity prices.

A clearly different picture arises for retail electricity prices. They can be expected to increase after the introduction of an FIT system, as grid operators are allowed to pass on the additional costs of the system to electricity consumer via the FIT surcharge. Rising electricity prices are likely to lead to adjustment reactions in the end-use sectors – either in the form of a decline in demand for electricity services, the purchase of more efficient appliances or the substitution with alternative energy carriers (e.g. less electricity for heating, changes in manufacturing processes). These effects need to be taken into account in the modelling approach by incorporating the FIT surcharge into the model. When using the parameters *NCAP_FSUB* and *FLO_SUB* to model the feed-in tariffs, the source of funding lies outside of the system boundaries of the model. Hence, energy system costs are even reduced in comparison to a scenario without FIT scheme in place.

The FIT surcharge can be calculated according to equation (2-1) as the difference between the average FIT tariff and the average wholesale electricity price multiplied by the share of FIT electricity in total electricity consumption. Once this term is established, it can be assigned to final electricity consumption in the model with the help of the parameter *FLO_COST*. However, at this stage of the modelling approach, a number of problems arise. First of all, it is apparent that the various components of the FIT surcharge depend themselves on the model results. The aggregate sum of tariff payments can be directly determined within the model by adding an additional output commodity to all FIT processes whose output equals the total amount of FIT payments made for this process (modelled with the parameters *FLO_FUNC*, *FLO_FUNCX* and the same *SHAPE* curves that have been used for the tariffs). There is, though, no linear relationship between the total sum of tariff payments and electricity consumption that would allow to directly link them within the model. Furthermore, it has to be kept in mind that the optimization approach of energy system models always conducts a simultaneous cost minimization over the entire system. Consequently, if tariff payments and the FIT surcharge are directly coupled in the model, they offset each other and the expansion of renewable electricity generation based on the FIT system ceases completely.

That is why an alternative approach to integrate the FIT surcharge into the model is chosen. This comprises a number of consecutive model runs (cf. Figure 4-11). In the first model run, only the payment side, i.e. the tariffs, are introduced into the model and the development of electricity generation based on renewables is determined endogenously. From the results of this model run, the FIT surcharge can be calculated and incorporated in the model. Here, the difference in FIT surcharge between “normal” and “privileged” (electricity-intensive manufacturing enterprises and rail operators) end-users is also accounted for. Thus, in the second model run, both the effects on the payment side and the demand side are represented making it possible to evaluate the impacts of the FIT surcharge on electricity prices and consumption.

In addition, in this model run electricity generation from renewables is fixated, as changes on the demand side should have no effect on renewable electricity generation when receiving fixed tariffs. An added advantage of using subsequent model runs consists in the possibility of implementing additional cost terms in the model that should not influence the extension of renewable electricity. For example, the costs for grid expansion, which will be necessary as more and more decentralised renewable technologies enter the market, should be included in the model. At the same time, these costs should not affect the development of renewable electricity generation, since in reality they do not play any role in the investment decision of renewable plant operators. Therefore, grid expansion costs are only added to the model after the generation from renewable sources is fixated.

Now it has to be taken into consideration that introducing the FIT surcharge in the second model run clearly modifies the model results in terms of electricity consumption as well as electricity generation. Hence, the components of the FIT surcharge themselves will change. As a consequence, an iterative process of several model runs is required in order to adjust the FIT payments and the FIT surcharge to one another. The iteration is ended when the surcharge (in ct/kWh) no longer changes in its second decimal place from one model run to the other.

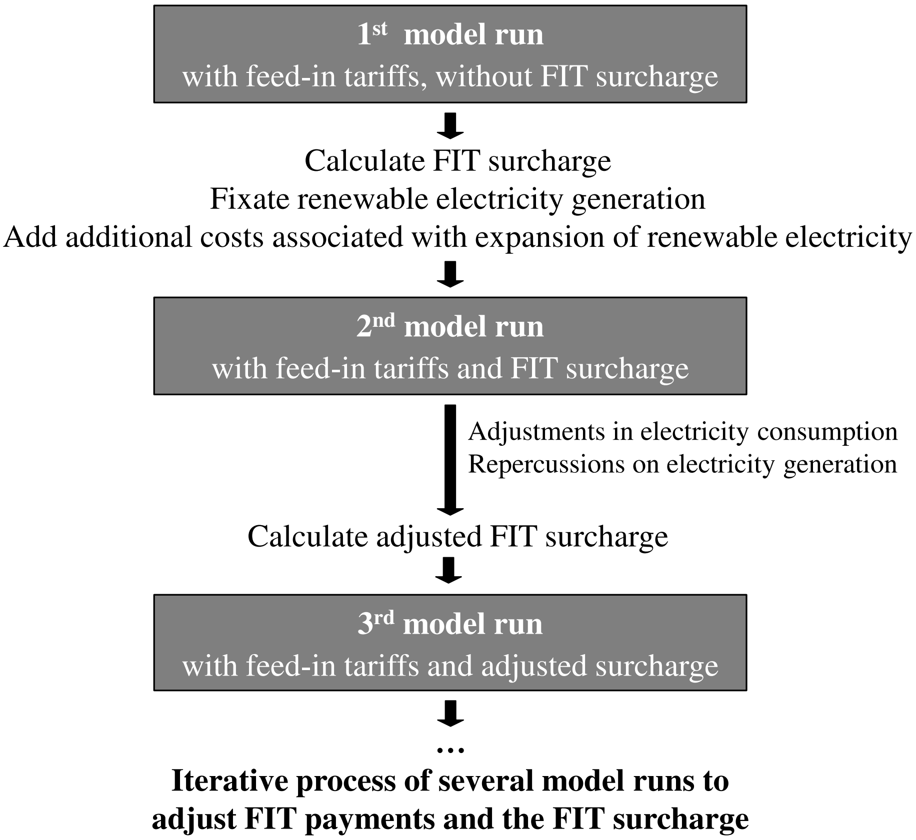

Figure 4-11: Modelling approach to integrate the FIT surcharge in TIMES

In addition, it has to be pointed out that after calculating the FIT surcharge from the model, some additional factors are accounted for before reporting the actual development of the surcharge. First of all, the option of direct marketing is considered which is expected to reduce the FIT surcharge in the long-term. Instead of choosing the feed-in tariffs, plant operators may also sell the generated electricity directly to the market with the possibility of entering and exiting the FIT scheme on a monthly basis. When computing the FIT surcharge, it is assumed that the direct marketing option is chosen if wholesale electricity prices exceed the tariff level for a specific plant (calculated on the seasonal level). Apart from that, in the model the FIT system is only implemented from 2008 onwards, whereas when the actual FIT surcharge is calculated the payments for plants that have been installed between the years 2000 and 2007 need to be incorporated. Here, an extrapolation of the statistical values based on ÜNB (2009) has been carried out.

4.3.2. Modelling of quantity-based support schemes in TIMES

Tradable green certificate schemes

In the discussion on the optimal way of promoting renewable energy sources in electricity generation, feed-in tariff systems are usually contrasted with tradable green certificate schemes (TGC). Here, electricity utilities or grid operators are obliged to cover a certain quota of electricity generation or capacity with renewable energies. In addition, a market for green certificates, representing a certain amount of renewable electricity generation or capacity, is implemented where renewable producers can sell certificates to the obligated electricity suppliers. Thus, while FIT systems establish the price for renewable electricity, TGC schemes address the quantity of renewable generation.

That is why modelling such quota-based schemes in energy system models is much more straightforward than it was the case with fixed feed-in tariffs. Target values for relative shares of renewable energies in electricity generation can be easily integrated in the model with the help of user-defined constraints (making use of the parameter *UC_FLO* in the case of a quota on electricity generation). As it would be the case in the trading system for green certificates, in the optimization process the cheapest generation options to fulfil the quota are chosen. The shadow price of such a user constraint is equivalent to the difference between the generation costs of the technologies covered by the quota and the wholesale electricity price and can therefore be interpreted as the certificate price in the trading system. The effect of the TGC system on electricity generation cost can be illustrated by looking at the dual equation of the activity variable of both a renewable (cf. equation (4-4)) and a conventional (cf. equation (4-5)) generation process. It becomes apparent that generation costs of conventional plants (outside of the quota) increase by the costs that arise from the purchase of green certificates (highlighted cost term equal to the certificate price multiplied by the quota), while generation costs of renewable plants decrease through the selling of certificates (highlighted cost term equal to the certificate price multiplied by the factor 1-quota).

$$act\_cost\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,fuel,s} + capact_{r,v,t,p,s} - actup_{r,t,p,s} - \boxed{q_{r,t} \cdot \left(1 - quota_{r,t}\right)} \tag{4-4}$$

$$\geq \; combal_{r,t,elc,s} \quad \forall r \in R, \forall t \in T, \forall p \in REN, \forall s \in S, \forall v \in V, \forall fuel \in FUEL, \forall elc \in ELC$$

$$act\_cost\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,fuel,s} + capact_{r,v,t,p,s} - actup_{r,t,p,s} + \boxed{q_{r,t} \cdot quota_{r,t}} \tag{4-5}$$

$$\geq \; combal_{r,t,elc,s} \quad \forall r \in R, \forall t \in T, \forall p \in NONREN, \forall s \in S, \forall v \in V, \forall fuel \in FUEL, \forall elc \in ELC$$

With:

$\boldsymbol{q_{r,t}}$	dual variable of the quota on renewable electricity generation (equal to the certificate price in the TGC system),
$\boldsymbol{quota_{r,t}}$	quota for the electricity generation from renewable energies and
NONREN	set of non-renewable electricity generation technologies.

In this context, an important difference between using relative and absolute bounds to model the expansion of renewable electricity needs to be highlighted. When generation from renewable energies is forced into the model by specifying absolute minimum quantities, the dual variable of such a constraint enters the dual equation of the activity variable of the renewable generation process (cf. the highlighted term in equation (4-6)) to reduce the left-hand side such that it is fulfilled with equality (cf. Remme et al. 2009). This shadow price can be interpreted as the subsidy that would be needed to make the respective technology competitive. Consequently, electricity prices do not reflect the additional cost burden of the renewable support system in this case, as the higher costs of renewable technologies are accounted for by the shadow price of the constraint. Energy system costs would still rise due to the higher generation cost in renewable plants, but it is assumed that the required subsidies are funded from outside the energy system and therefore do not raise the electricity price. In contrast, when fixing a relative quota for the renewable share in electricity generation, the additional costs are directly reflected in an increase in the electricity price (cf. Remme 2006, pp. 131ff). Hence, by using relative bounds to model a TGC system, the effect on electricity prices is directly included in the model.

$$act\_cost\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,fuel,s} + capact_{r,v,t,p,s} - actup_{r,t,p,s} - \boxed{actlo_{r,t,p,s}} \tag{4-6}$$

$$\geq \; combal_{r,t,elc,s} \quad \forall r \in R, \forall t \in T, \forall p \in REN, \forall s \in S, \forall v \in V, \forall fuel \in FUEL, \forall elc \in ELC$$

With:

$\boldsymbol{actlo_{r,t,p,s}}$	dual variable of a lower bound on the activity variable (reduced cost).

Different types of quota systems can be evaluated with this modelling approach. Here, the most important differentiation can be made between technology-unspecific systems, where a uniform certificate price for all types of renewable energies is established, and technology-specific systems, where for each renewable energy carrier a separate quota is defined resulting in reduced trading possibilities and distinct certificate prices.

Tendering procedures

Another important promotional instrument for renewable electricity are tendering procedures, assigning previously specified quantities of renewable capacity to producers through a bidding process. The generators with the lowest prices then receive long-term contracts to supply electricity at the established bidding price. Such systems have been applied in some European countries, like for example France, Ireland, Denmark and the United Kingdom, for large-scale projects mainly in the area of wind energy. Usually, tendering schemes are technology- or even project-specific.

When modelling tendering procedures it needs to be taken into consideration that the determination of the quantity of renewable capacity that is to be allotted through the bidding process is based entirely on a political decision. Hence, the minimum quantities for the respective model periods can be specified exogenously and put in the model by way of user constraints. Furthermore, differentiations in the modelling approach arise when specifying the source of financing for the difference between the bidding price and the wholesale electricity price. Generally, two options can be distinguished: the extra costs are either covered by a levy on end-use electricity prices or through general government funds.

In the first case, the use of relative bounds on the capacity of renewable generation processes would be convenient to model the tendering scheme. In this way, the effect on end-use electricity prices would be directly captured in the model. Just as it was the case with TGC schemes, the shadow price of the relative constraint can be interpreted as the difference between the bidding price determined in the tendering procedure and the wholesale electricity price. Thus, the generation costs of the renewable technologies covered by the tender decrease by this price difference multiplied with (1-quota) (cf. equation (4-4)), while the generation costs of generation processes outside of the quota increase by the difference between the bidding and the wholesale electricity price multiplied by the quota (cf. equation (4-5)).

If the funding for the tendering schemes is provided through general government funds, i.e. from outside the energy system, the modelling approach can be based on absolute lower bounds on the different types of renewable capacity. The shadow price of such a constraint reflects the subsidy that would be needed to induce an additional unit of investment in the respective technology. Here, generation costs of processes not included in the tender are not affected by the tendering scheme and therefore the additional costs of the support system are not funded through end-use electricity prices.

5 Scenario analysis[13]

The following scenario analysis is used to highlight how the explicit modelling of policy instruments in the scope of an energy system model can help to analyse and understand the various effects such instruments can have on both the energy supply and demand side. After outlining the most important scenario assumptions, the focus is put on three areas: (1) the development of the German energy system under the current policy framework; (2) the interaction between the German feed-in tariff scheme for renewable electricity and the EU Emissions Trading System and (3) the comparison of the German FIT system with alternative support schemes for renewable electricity.

5.1 Scenario assumptions

For the scenario analysis, a comprehensive set of input assumptions that influence future energy demand and technology choice needs to be established. These assumptions are based on a large variety of sources, while special attention is paid to the consistency of the data.

5.1.1. Socio-economic assumptions

The basic demographic and economic data used in the following scenario analyses is mainly adopted from the study *Energieprognose 2009* (cf. IER et al. 2010) (cf. Table 5-1). From 2010 to 2030, the gross domestic product (GDP) of Germany is assumed to grow at an average annual rate of 1.3 %, with a downward trend over time. In the same period, Germany's population is expected to decrease by about 2 million inhabitants to 79.7 million in 2030 resulting in an increase in GDP per capita of almost 34 % compared to 2010. Due to the trend towards smaller household sizes, the number of households as well as the total dwelling area in Germany still rises until 2030. When aviation is not taken into consideration, the passenger transport volume only exhibits a further increase until 2020 and then drops again roughly to the level of 2010 as a result of the decline in population. With the expected on-going rise in air travel, however, total passenger transport volume still grows slightly until 2030. The freight transport volume, on the other hand, which is mainly bound to the development of GDP, is assumed to rise substantially by nearly 42 % in the period from 2010 to 2030.

Table 5-1: Key socio-economic parameters for the scenario analysis (based on IER et al. 2010)

		2010	2015	2020	2025	2030	*Change (2010-2030)*	*Avg. change p.a. (2010-2030)*
GDP	Bn €$_{2010}$	2498	2794	2949	3095	3250	*30.1%*	*1.3%*
Population	M	81.8	81.8	81.4	80.6	79.7	*-2.6%*	*-0.1%*
GDP per capita	€$_{2010}$/cap.	30549	34151	36242	38389	40792	*33.5%*	*1.5%*
Households	M	40.3	41.0	41.5	41.8	42.0	*4.1%*	*0.2%*
Dwelling area	M m^2	3504	3654	3788	3913	4015	*14.6%*	*0.7%*
Passenger transport volume	Bn pkm	1128	1136	1154	1163	1166	*3.4%*	*0.2%*
Freight transport volume	Bn tkm	622	670	737	806	880	*41.5%*	*1.8%*

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[13] A previous version of this chapter has been published in Götz et al. (2013) as part of the ETSAP Project "Integrating policy instruments into the TIMES Model".

The choice of the discount rate, which is used to make monetary flows from different points in time comparable, has a vital impact on the decision-making and optimization calculus in the model. Discounting reflects the opportunity costs of capital and indicates the weight that is ascribed to future costs and benefits. Hence, high discount rates tend to impair the competitiveness of less mature and capital-intensive technologies that require high upfront cost and whose benefits (in terms of energy savings) are only realized over a long period of time (cf. Böhringer 1999).

In the analysis at hand, sector-specific, subjective (or implicit) discount rates are applied in order to account for the individual decision-making behaviour of different agents in the energy system and to represent their reactions to changes in the political framework conditions in a realistic manner (cf. Table 5-2). Thus, sectors with high hidden costs related to the investment in new equipment - private households, the tertiary sector and agriculture as well as motorized individual transport - are assigned a relatively high real discount rate of 13.7 %. In contrast, for utilities and the industrial sector (including freight transport) the discount rates are guided by the average cost of capital and the profitability expectations in the respective sector resulting in rates of 9.3 % and 7.8 %. An exception is made in the case of renewable electricity generation with a real discount rate of 7 %, as it has been observed that in this sector, profitability expectations – especially for smaller generation units – tend to be lower (Doll et al. 2008). As mentioned above, an even lower discount rate of 5 % is applied for photovoltaic roof systems, where special loan programs with reduced interest rates are available. In the case of geothermal generation plants, a higher rate of 10 % is laid down to reflect the high exploration risks.

Table 5-2: Sector-specific real annual discount rates (based on IEA 2005 and E3M-Lab 2006)

Sector	
Energy conversion	9.3%
PV rooftop installations	*5.0%*
Geothermal electricity generation	*10.0%*
Other renewable electricity generation	*7.0%*
Industry	7.8%
Tertiary sector + Agriculture	13.7%
Residential sector	13.7%
Transport	
Motorized individual transport	*13.7%*
Public transport	*6.0%*
Freight Transport	*7.8%*

In order to take into account adjustments in energy demand due to changes in energy prices, the elastic demand feature is activated in TIMES-D. The values for the long-term own-price elasticities (differentiated by sector and demand category) are taken from the 2010 version of the ETSAP-TIAM model (cf. ETSAP 2011, values for Western Europe). It has to be pointed out that for 2015, due to the closeness in time and the associated reduced ability to react to changes, slightly lower values have been specified (cf. Table A-1 in the Annex).

5.1.2. Energy prices

Regarding the price projections for fossil fuels, the assumptions that have been laid down for the *New Policies Scenario* in the *World Energy Outlook 2012* (cf. IEA 2012) have been chosen (cf. Table 5-3). Thus, the world market price for crude oil rises continuously from 77 US$$_{2010}$/bbl in 2010 to 121 US$$_{2010}$/bbl (190 US$/bbl[14]) in 2030, corresponding to an increment of 56 % in real terms and of 146 % in nominal terms. Based on the global market prices stated in the *World Energy Outlook 2012*, cross-border prices for Germany are calculated, resulting in a price increase of 49 % for crude oil and of 57 % for natural gas between 2010 and 2030. The rise is expected to be less pronounced in the case of hard coal (13 %). For lignite, which plays a crucial role in electricity generation in Germany, the average full costs of lignite extraction in Germany are applied and assumed to be constant over the modelling period.

Table 5-3: Price assumptions for fossil fuels (based on the *New Policies Scenario* from IEA 2012 and BMWi 2012)

		2010	2015	2020	2025	2030
Crude oil price (IEA)	US$$_{2010}$/bbl	77	113	117	119	121
	US$/bbl	77	127	147	168	190
Cross-border prices						
Crude oil	€$_{2010}$/GJ	10.7	14.9	15.4	15.7	15.9
Natural gas	€$_{2010}$/GJ	5.7	8.1	8.5	8.8	9.0
Coal	€$_{2010}$/GJ	2.9	3.1	3.2	3.3	3.3
Lignite	€$_{2010}$/GJ	0.99	0.99	0.99	0.99	0.99

5.1.3. Technology and cost parameters

Since renewable electricity generation plays an essential role in the following scenario analysis, a large variety of generation technologies based on renewable sources are included in the model. The projections regarding their technical and economic development are presented in detail in Tables A-2 to A-9 in the Annex, while Table 5-4 below summarizes the key investment cost assumptions for a selection of renewable electricity technologies. The realization of further learning effects can be assumed to be dependent on the rate of expansion of renewable electricity generation on a global scale, such that in the analysis at hand all learning rates have been fixed exogenously, i.e. independent from the development in Germany.

While no cost degressions are expected in the case of hydropower plants, further substantial learning effects are laid down for solar photovoltaics and onshore wind power plants. Significant investment cost reductions would also be needed to stimulate the development of offshore wind energy in Germany. Here, the learning rates are chosen rather conservatively

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[14] Nominal values are based on the assumption of an annual inflation rate of 2.3 % p.a. from 2013 onwards.

when compared with other recent studies (cf. for example EWI et al. 2010, BMU 2010b). Electricity generation from different types of biomass is usually based on mature technologies so as to allow only relatively moderate learning effects in the future. The prospects for geothermal power plants in Germany can be considered to be the most uncertain. For the present analysis, only very low cost reductions from 2020 onwards are assumed.

Table 5-4: Investment cost assumptions for renewable electricity generation technologies (selection based on Tables A-2 to A-9 in the Annex)

Investment costs, €$_{2007}$/kW	2015	2020	2030
Hydropower, new plant (20 MW)	5800	5800	5800
Hydropower, new plant (3 MW)	4140	4140	4140
Hydropower, modernisation	1500	1500	1500
Photovoltaics, rooftop system	1800	1550	1450
Photovoltaics, freestanding system	1640	1415	1245
Wind power, onshore (incl. grid connection)	1320	1260	1190
Wind power, offshore (distance to shore 80 km, water depth 35 m, incl. grid connection & foundation)	3243	2743	2493
Solid biomass, CHP (6 MW)	3150	2900	2850
Wood gasification, CHP (2 MW)	4150	3650	3400
Biogas, block heating and power station (0.5 MW)	800	750	750
Geothermal energy, OCR CHP (4.5 MW, hydrothermal, drilling depth 3500 m)	7080	7080	6000

Electricity storage technologies are modelled in TIMES-D to provide system services and to accommodate increasing amounts of fluctuating electricity generation. Concerning the use of storage capacities, a rule is applied specifying that at all times a maximum of 20 % of the electricity supplied to the grid may directly originate from fluctuating sources without the necessity of intermediate storage (cf. Remme 2006). The technological and economic parameters for all storage technologies can be found in Table A-10 in the Annex. Cost degressions due to learning effects are only assumed in the case of battery storage systems and hydrogen converters.

The costs for reinforcing and expanding the electricity grid that arise as a result of the growing shares of spatially distributed fluctuating renewable generation are integrated into the model in a simplified manner. Based on a number of recent analyses (cf. BDEW 2011, dena 2005, dena 2010a and EC 2011c), specific grid expansion costs (both for the transmission and the distribution grid) per unit of additional installed capacity of solar photovoltaics and wind energy are calculated. It has to be noted that offshore wind plants are only taken into account in the case of the transmission grid. In the model, the capacity for the processes representing the expansion of the transmission and distribution grid is then bound with the help of user constraints to the capacity of the fluctuating generation. The values for the reinforcement and expansion cost are given in Table A-11 and A-12 in the Annex.

Additional assumptions have also been integrated into the model regarding the district heat potential from geothermal energy and the associated grid expansion cost (cf. Table A-13 in the Annex).

5.1.4. Potentials for renewable electricity generation

When analysing the long-term expansion of renewable electricity generation in Germany, limitations given through technical potentials need to be respected. An overview on the technical electricity generation potentials from different renewable sources laid down in TIMES-D is presented in Table 5-5. For wind energy and solar photovoltaics the generation potentials are determined on the basis of the potentially available land-areas using average space requirements per wind turbine or solar PV installation and availability factors. It needs to be pointed out that the resource-specific potentials cannot be added up as in some cases competition for the same land-areas needs to be taken into account. Moreover, it has to be kept in mind that Table 5-5 provides technical potentials which contain no information whatsoever on the economic feasibility of the different generation options.

Table 5-5: Technical potentials for electricity generation from renewable sources

	Available area [km^2]	**Generation potential [TWh/a]**
Hydropower (run of river and dam storage)	-	24,7[a] (+ 2 TWh through modernisation)
Wind energy		
Onshore		
According to wind velocity classes		
1. 4-5 m/s	22100[b]	332[c]
2. 5-6 m/s	3500[b]	77[c]
3. > 6 m/s	500[b]	15[c]
Total	**26100**	**423**
Offshore		
According to location		
1. Distance to shore 40 km, water depth 25 m	425[d]	18[e]
2. Distance to shore 80 km, water depth 35 m	1440[d]	65[e]
3. Distance to shore 120 km, water depth 40 m	680[d]	32[e]
4. Distance to shore 30 km, water depth 30 m	340[d]	14[e]
Total	**2885**	**129**
Solar PV		
Roof area	838[a]	113[f]
Facade area	200[a]	23[f]
Free-field	4100[a]	554[f]
Total	**5138**	**690**
Geothermal energy	-	321[a]

[a] cf. Kaltschmitt et al. (2006), p. 389

[b] cf. Remme (2006), p. 63

[c] Based on a space requirement of 100 km^2/GW and an availability of 1500 h/a (class 1), 2200 h/a (class 2) and 2900 h/a (class 3)

[d] Based on IER et al. (2010), class 1-3: North Sea, class 4: Baltic Sea

[e] Based on a space requirement of 84.7 km^2/GW and an availability of 3600 h/a (class 1), 3800 h/a (class 2), 4000 h/a (class 3) and 3500 h/a (class 4)

[f] Based on a system efficiency of 13.5 % and an average irradiation of 1000 kWh$_{AC}$/(m^2*a) for rooftop and freestanding installations and 850 kWh$_{AC}$/(m^2*a) for facade installations

In the case of biomass, cost potential curves for the provision of different types of solid biomass (wood, straw and energy crops) are modelled in TIMES-D based on the analysis in Remme (2006) (cf. Figure A-1 in the Annex). These curves cover the entire biomass generation potential within Germany, i.e. only part of this potential is eventually available for electricity generation since alternative utilization options - for heat production and in the transport sector - are taken into consideration in the energy system model.

In order to provide a realistic picture of the development of electricity generation from renewable energies in Germany, in addition to the technical potentials, upper limits for the annual expansion rates of renewable generation from different sources need to be included in the model assumptions. The ceilings stated in Table 5-6 have been derived from the historical development and a comparison of recent studies on the expansion of renewable electricity generation in Germany (most importantly BMU 2012d and ÜNB 2012a).

Table 5-6: Ceilings on the annual expansion of renewable electricity generation (based on IER et al. 2010, BMU 2012d, ÜNB 2012a)

TWh	2015	2020	2025	2030
Hydropower (run of river and storage)	24.5	25.6	26.7	26.7
Wind onshore	62.5	85.0	95.0	110.0
Wind offshore	16.0	49.5	63.8	105.2
Solar photovoltaics	50	60	65	70
Biomass	55	60	64	72
Geothermal energy	1.5	5	8	12
Total	**209.5**	**285.1**	**322.5**	**395.9**

5.2 Scenario characteristics

With the aim to explore how the explicit modelling of different policy instruments can benefit the investigation of the future development of the German energy system, a comprehensive scenario tableau has been developed (cf. Table 5-7). On this basis, three main focal points for the scenario analysis can be identified:

- The reference case: What will the development of the German energy system look like under the current political framework conditions?
- Interaction between the German FIT system and the EU ETS: How do the German feed-in tariff system and the EU Emissions Trading System influence each other?
- Comparison of different support schemes for renewable electricity: What adjustments might be beneficial in the current German FIT system? How does the present support scheme perform in comparison to alternative ones?

Thus, in the reference case (REF) the currently implemented policy measures are integrated into the model: the FIT system for renewable electricity in its version from 2012 and the EU ETS with a reduction target of 21 % for 2020 compared to 2005 (and a linear reduction of 1.74 % p.a. until 2030). The results of this scenario will be presented in detail showing how these two instruments influence the electricity generation sector, electricity consumption as well as CO_2 emissions and what costs are involved.

In a second step, the various interactions between a national support system for renewable electricity generation and a supranational emissions trading scheme will be analysed with the help of the flexible modelling of both policy measures. To do so, a number of scenarios has been set up that contain either none of the two instruments (No_Ins), only the FIT system (FIT_Only), only the EU ETS (ETS21 and ETS34) or both measures (REF and ETS34+FIT). With respect to emissions trading, an additional differentiation is made between the current specification and a stricter regime with a reduction target of 34 % until 2020 compared to 2005. This structure makes it possible to evaluate in a quantitative way how the national FIT system affects emission reduction and certificate prices in the trading system and, on the other hand, how the EU ETS might support the expansion of renewable electricity in Germany.

Table 5-7: Scenario overview

Scenario	Support scheme for renewable electricity	Reduction target in the ETS sector
The reference case		
REF	Current German FIT system (2012 version)	Reduction of 21 % until 2020 compared to 2005; 1.74 % p.a. afterwards
Scenarios on the interaction between the German FIT system and the EU ETS		
ETS21	-	Reduction of 21 % until 2020 compared to 2005; 1.74 % p.a. afterwards
ETS34+FIT	Current German FIT system (2012 version)	Reduction of 34 % until 2020 compared to 2005; 1.74 % p.a. afterwards
ETS34	-	
FIT_Only	Current German FIT system (2012 version)	-
No_Ins	-	-
Scenarios on the comparison of different support schemes for renewable electricity		
Sensitivities on adjustments within the current FIT system		Reduction of 21 % until 2020 compared to 2005; 1.74 % p.a. afterwards
FIT2012_NoPV	Sensitivity on REF ceasing the promotion of solar photovoltaics through the FIT system	
FIT2012_NoES	Sensitivity on REF without the special equalisation scheme for electricity-intensive enterprises and rail operators in the FIT system	
Alternative support schemes		
FIT_Neut	Technology-neutral feed-in tariff system reaching the same absolute amount of renewable electricity generation as in the reference case	
QU_Neut	Technology-neutral quota system reaching the targets for the renewable share in gross electricity consumption of the German Energy Concept	
QU_Spec	Technology-specific quota system reaching the same shares for each renewable source in gross electricity consumption as in Qu_Neut	
QU_Spec_hh	Sensitivity on Qu_Spec with higher hurdle rates for investments in renewable generation technologies	

Finally, the modelling approach is applied to contrast the current German FIT system with alternative support schemes for renewable electricity. In this context, firstly a look is taken at some adjustments which could be easily implemented within the scope of the current FIT system: (1) a sensitivity in which the promotion of solar photovoltaics through feed-in tariffs is stopped (FIT2012_NoPV) and (2) a sensitivity in which the special equalisation scheme for electricity-intensive enterprises and rail operators (that pay a reduced surcharge) is abolished (FIT2012_NoES). Secondly, the following support schemes that might be used to replace the present FIT scheme are explored: (1) a technology-neutral FIT system with which the same total amount of renewable electricity generation is achieved as in the reference case (FIT_Neut); (2) a technology-neutral tradable green certificate scheme where the quotas for renewable electricity are set such that the targets of the German Energy Concept are reached (QU_Neut) and (3) a technology-specific tradable green certificate scheme where for each renewable source a separate quota is specified in such way that the same (cost efficient) generation structure as in scenario QU_Neut is realized (QU_Spec). For the last scenario an additional sensitivity is analysed in which the higher uncertainty for renewable electricity generators under a quantity-based support system is reflected in higher hurdle rates for investments in renewable technologies (QU_Spec_hh). Regarding the EU ETS, in all these scenarios the basic target of 21 % for 2020 applies.

In addition to the explicit modelling of the support system for renewable electricity and the EU ETS, the effects of other current regulations of the German and European energy and climate policy are included in the scenario analyses. The use of nuclear energy for electricity generation is phased out in Germany until 2022. In the buildings sector, the impacts of the Energy Savings Ordinance and the Renewable Energies Heat Act are taken into account, while in the transport sector the Biofuels Quota Act is considered. Technologies with carbon capture and storage (CCS) are assumed to be commercially available from 2020 onwards.

5.3 The reference case: development of the German energy system with the FIT scheme and the current ETS target

The reference case (scenario REF) explores the long-term development of the German energy system under the assumption that the current political framework is kept unchanged. Moreover, the two most important climate policy measures affecting the German power sector are taken into account explicitly: the feed-in tariff system for renewable electricity in its version from 2012 and the EU ETS with the reduction target of 21 % until 2020 compared to 2005.

5.3.1. Electricity generation

Under these assumptions, renewable electricity generation in Germany rises substantially throughout the whole projected period (cf. Figure 5-1). In 2020, renewable energies contribute with 261 TWh or almost 46 % to gross electricity consumption, in 2030 with 315 TWh or 54 %. Thus, compared to 2010 renewable electricity generation triples until 2030. The enormous growth until 2015 of 88 % and of 150 % until 2020 compared to 2010 is in line with other recent scenario results (cf. ÜNB 2012a and BMU 2012d). Accordingly, the target value for the renewable share in gross electricity consumption from the Energy Concept for 2020 of 35 % is exceeded by more than 10 percentage points. Afterwards, the expansion slows down considerably with a growth rate of 24 % for the period from 2020 to 2030. Yet, the target for 2030 of 50 % is still slightly surpassed by 4 percentage points. The share of fluctuating sources in total renewable generation rises from 54 % in 2012 to 72 % in 2030 and to 39 % in total gross electricity consumption.

Despite the considerable increase in renewable electricity, the share of fossil fuels in net electricity supply in Germany only decreases much more slowly from 56 % in 2010 to 42 % in 2020 and 38 % in 2030 due to the simultaneous phasing out of nuclear energy until 2022. While the generation from hard coal and lignite drops significantly from 241 TWh in 2010 to 109 TWh in 2030, the contribution from natural gas rises by 44 % in this period such that gas-fired power plants provide 118 TWh electricity in 2030. Under the ETS reduction target of 21 % in the reference case, CCS will not become a competitive abatement option until 2030. With respect to net electricity imports, no clear picture arises under the chosen scenario assumptions. While in 2015 and 2030 about 8 TWh are exported, imports of 11 TWh and of 30 TWh can be observed in 2020 and 2025. On the whole, net electricity supply varies only slightly in the considered time period and lies with 582 TWh in 2030 only 12 TWh above the level from 2010.

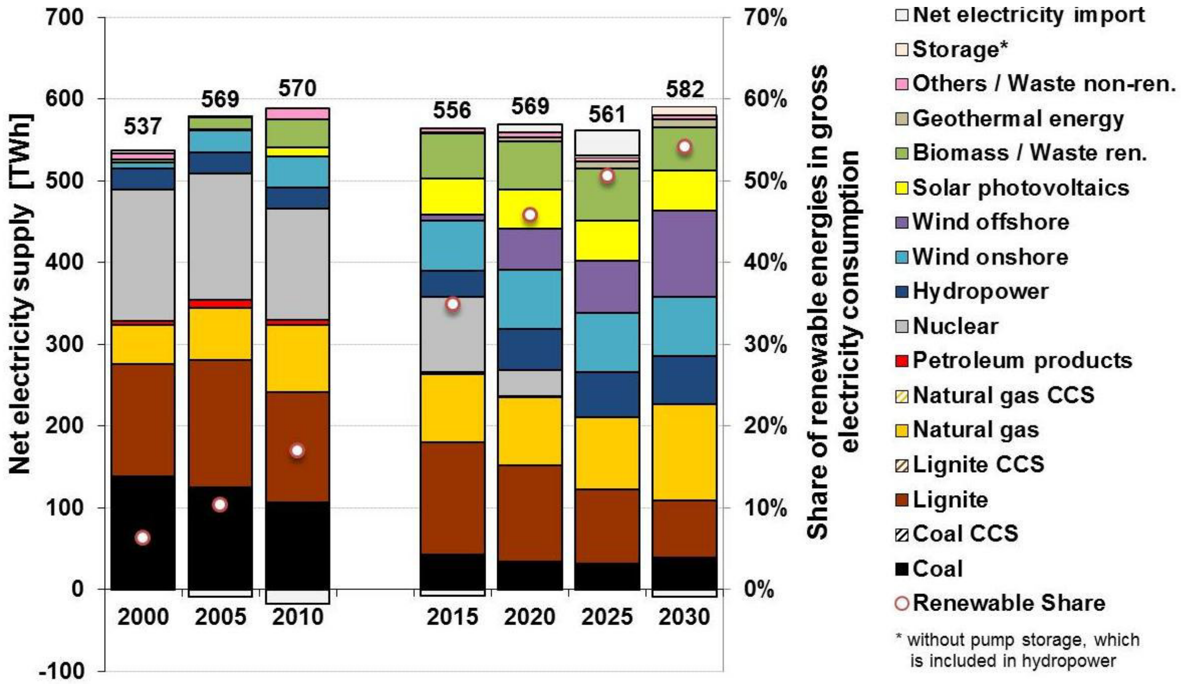

Figure 5-1: Net electricity supply in the reference case (scenario REF)

Table 5-8 presents the development of renewable electricity generation in Germany in greater detail. Hydropower has been utilized for electricity production in Germany for several decades and the potential has already been exploited almost entirely. Apart from that, stringent ecological requirements have to be met when installing new hydropower plants (cf. Kaltschmitt et al. 2006). Hence, only a slight increase in hydro-electricity generation to 27 TWh (without pump storage) is realized until 2030 through investments in new small-scale power plants as well as the modernization and extension of existing plants.

Wind power plays a dominant role in the expansion of electricity production from renewable sources in Germany. In 2020, wind energy accounts for almost half of total renewable generation in the reference case, rising to 56 % in 2030 (30 % of total electricity generation). In order to further enhance the onshore generation capacities, the repowering of older wind farms is of particular importance. In 2020, already 27 % of the onshore wind electricity generation come from repowered wind turbines. In the case of offshore wind energy, a decisive breakthrough is only achieved after 2015. Based on a dynamic growth period between 2015 and 2030, generation from offshore wind farms surpasses the contribution from onshore wind energy for the first time in 2030 with 105 TWh.

Table 5-8: Renewable electricity generation in the reference case

TWh	2000	2010	2012	2015	2020	2025	2030
Hydropower*	25	21	21	24	26	27	27
Wind	8	38	46	69	123	136	177
of which							
onshore	*8*	*38*	*45*	*62*	*73*	*72*	*72*
offshore	*0*	*0*	*1*	*7*	*49*	*64*	*105*
Solar photovoltaics	0	12	28	44	49	49	49
Gases**	1	2	2	2	1	1	1
Biomass	3	32	39	53	58	64	52
of which							
Solid biomass	-	*16*	*17*	*26*	*25*	*31*	*27*
Liquid biomass	-	*2*	*1*	*2*	*2*	*2*	*0*
Biogas	-	*13*	*21*	*25*	*30*	*31*	*25*
Geothermal energy	0	0	0	1	5	8	10
Total	**37**	**103**	**136**	**194**	**261**	**284**	**315**
Renewable share in gross electricity consumption	**6.3%**	**17.0%**	**22.9%**	**34.9%**	**45.8%**	**50.5%**	**54.2%**

*excl. pump storage; **gas from landfills and sewage treatment plants

The feed-in tariffs for solar photovoltaics have been reduced substantially in recent years and degression rates have been aligned more strongly to the actual market growth. Nevertheless, a significant expansion of electricity generation from solar radiation is still expected in the reference case until 2015. These findings coincide with other recent projections (cf. for example ÜNB 2012a). With a rise from 28 TWh in 2012 to 44 TWh in 2015 the target range of an annual extension of 2500 to 3500 MW_p is clearly exceeded resulting in elevated degression rates of 23 % p.a. After that, the overall ceiling on the solar PV capacity that is remunerated through the FIT system of 52 GW_p is quickly reached such that after 2020 generation from solar radiation is not further extended.

The tariff structure for biomass installations has been clearly simplified with the last revision of the FIT system in 2012. The tariff level now mainly depends on the capacity size and the type of biomass that is used. Since electricity generation from biofuels is no longer supported, it remains at the low generation level of 2010 before dropping to zero in 2030. In the case of biogas and solid biomass, substantial growth of factor 1 and 0.75 in relation to 2012 is realized until 2025 based on the increased use in smaller CHP plants. Afterwards, due to the competing utilization options in heat generation and transport, electricity generation from bioenergy declines again slightly. On the whole, biomass accounts for 17 % of renewable electricity generation in 2030, compared to 29 % in 2012.

The exploitation of geothermal energy for electricity generation is still at a very early stage in Germany and projections on the future development are highly uncertain. Moreover, it has to be pointed out that the conditions for geothermal electricity generation in Germany are comparatively unfavourable, given the relatively low temperature level of thermal water at potentially feasible depths. The model results indicate that until 2030, electricity generation from geothermal energy rises gradually to 10 TWh in 2030. Thus, the contribution of geothermal energy to total renewable electricity generation remains limited with 3 % in 2030. Furthermore, it turns out that based on the current feed-in tariffs, the utilization of geothermal energy is only competitive if applied for the combined generation of heat and power. This clearly restricts the generation potential to locations where an adequate heat demand is available at a reasonable distance.

For the reference case, it has also been analysed whether the FIT system for renewable electricity has an impact on electricity generation in CHP plants. Apart from the implicit support through feed-in tariffs for biomass and geothermal CHP plants, combined heat and power generation is promoted in Germany by a specific feed-in premium scheme for new and modernized CHP plants (KWKG, cf. Bundesgesetzblatt 2012f). Moreover, in 2007, the target of doubling the CHP share in total electricity production to about 25 % until 2020 has been specified (cf. BMU 2007b). Looking at the scenario results, it becomes apparent that electricity generation from combined heat and power does indeed rise considerably until 2020 reaching a share of almost 23 % in total generation and thus almost satisfying the governmental target (cf. Figure 5-2). Afterwards, only a slight additional increase until 2030 can be achieved. The growth of heat production in CHP installations is less pronounced given the higher power to heat ratio of the newly installed plants (especially in the case of natural gas). A stronger expansion of combined heat and electricity generation in Germany is clearly restricted by the limited demand for district heating. Even though the relative share of district heat in the heat market rises, the decreasing energy demand for space heating puts a ceiling on the absolute amount of CHP generation.

While the contribution of hard coal and lignite to CHP electricity generation drops to almost zero until 2030, substantial increases can be observed in the production from natural gas rising from 48 TWh in 2010 to 78 TWh in 2030. An even stronger growth occurs, however, in the case of biomass - clearly induced by the feed-in tariffs for biomass CHP plants. With a threefold increase between 2010 and 2025, biomass covers almost 29 % of total CHP electricity generation in 2030. The majority of this generation originates from small-scale biogas installations. Despite the strong absolute growth, the share of geothermal energy in CHP electricity generation amounts to only 8 % in 2030.

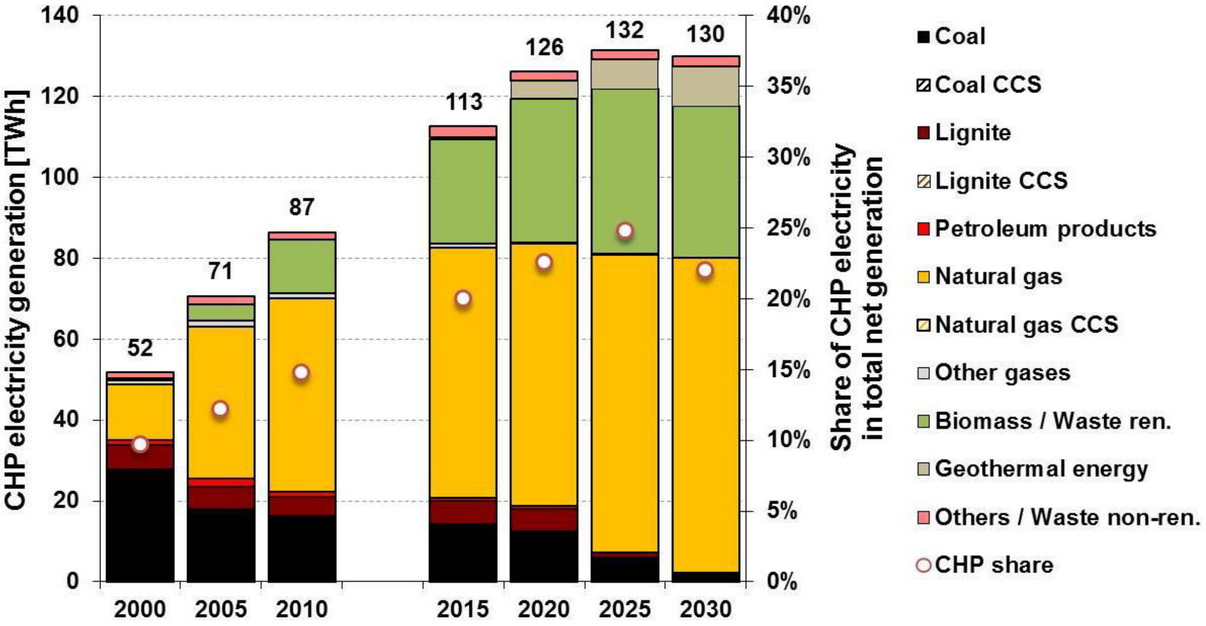

Figure 5-2: CHP electricity generation in the reference case

The growing importance of renewable electricity causes a considerable rise in total installed capacity for electricity generation from 166 GW in 2010 to 204 GW in 2020 (cf. Figure 5-3). Afterwards, installed capacity remains relatively constant until 2030. Generation capacity from renewable sources more than doubles between 2010 and 2020 to 122 GW, with an additional increase to 134 GW in 2030. Both in 2020 and 2030, fluctuating sources account for about 85 % of this amount. In the case of onshore wind, additional capacities of 17 GW are installed between 2013 and 2032, while for offshore wind farms installed capacity rises to 28 GW until 2030. Hence, the goal of the German government of 25 GW is surpassed. In total, wind energy is responsible for 25 % of installed capacity in 2020 and 30 % in 2030. The increase in installed capacity of solar PV amounts to nearly 19 GW in the period from 2013 to 2017. Consequently, with an additional installation of 5 GW in the following modelling period, the overall ceiling on solar photovoltaics supported through the FIT system of 52 GW is reached around 2020. Afterwards, no further expansion can be observed such that both in 2020 and 2030 solar energy accounts for 25 % of total installed capacity. The electricity generation capacity from biomass (including sewage and landfill gas) is raised only slightly from 7.6 GW in 2012 to 10.6 GW in 2030.

Installed capacity based on fossil fuels is expanded by 3 GW until 2015 to 83 GW, followed by a continuous decline until 2030 to 64 GW or 31 % of total electricity generation capacity. In the case of coal and lignite, no new plants are constructed after 2017 such that their share in total installed capacity declines from 29 % in 2010 to 20 % in 2020 and 12 % in 2030. On the other hand, additional flexible gas-fired power plants are required to cover peak load periods and as back-up capacity for the rising fluctuating generation. Between 2013 and 2032, altogether a capacity of 33 GW based on natural gas is installed and the share of natural gas in total capacity rise to 19 % in 2030.

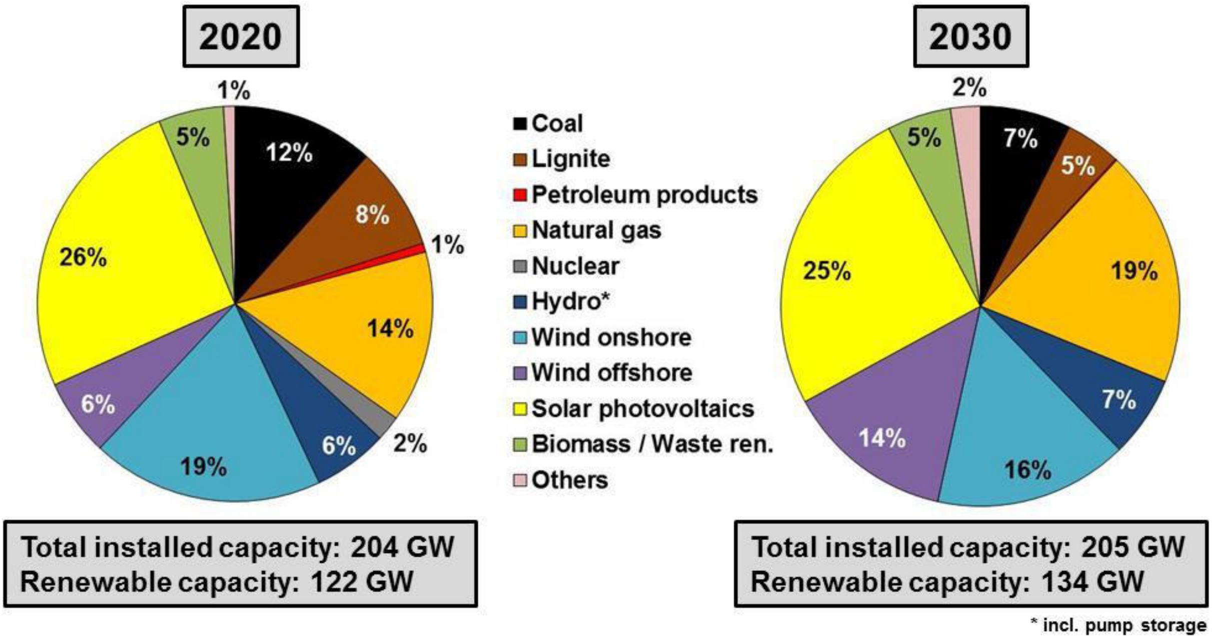

Figure 5-3: Total installed capacity for electricity generation in the reference case

The combination of the relatively constant electricity generation and the growing installed capacity leads to declining utilization rates of the different power plants (cf. Table 5-9). The average capacity factor for fossil-fuelled installations falls already between 2010 and 2015 from about 4300 (50 %) to 3200 (37 %) hours per year and stays around this level until 2030. As far as lignite is concerned, relatively stable full load hours are realized since these plants are used to supply base load and capacities are continuously decreased over the projected period. In contrast, strong impacts occur in the case of coal-fired power plants, whose capacity factor drops by more than 60 % until 2020. As older capacities are being shut down, utilization rates increase again slightly until 2030. In the model results, natural gas power stations are less affected by the expansion of renewable electricity generation resulting in a comparatively moderate decline in the capacity factor. In part, this can be explained by the high share of CHP plants in natural-gas based generation. Moreover, gas-fired power plants can react more flexibly to fluctuating supply and changes in electricity demand.

With respect to installations based on renewable energies, fixed availability factors have been implemented in the model for most sources highlighting the fact that with fixed feed-in tariffs, there are no incentives to adjust (i.e. reduce) supply at any time. In the case of wind energy, the growing significance of offshore generation is reflected in rising full load hours. The reduction observed for hydropower plants can be mainly attributed to the increasing share of pumped storage plants. Lately, growing concerns have been voiced regarding the profitability of fossil fuel plants in view of the declining capacity factors and the necessity of a capacity market, complementing the current energy-only market, is discussed. In an energy system model, this effect is avoided as endogenous electricity prices (given as shadow prices of electricity generation) cover both operating and investment costs. Thus, alternative modelling approaches are necessary to further analyse this issue.

Table 5-9: Annual full load hours in the reference case

h/a	2000	2005	2010	2015	2020	2025	2030
Coal	4430	4560	3880	1518	1454	1661	1957
Lignite	6805	7016	6433	6440	6821	6687	6760
Petroleum products	782	2118	1427	1134	672	159	94
Natural gas	2206	3444	3652	2680	2899	3107	3009
Nuclear	7187	7621	6535	7451	7587	-	-
Hydro	3267	2616	2619	1964	2051	2102	1982
Wind energy	1560	1481	1390	2019	2373	2770	2938
Solar photovoltaics	842	624	668	937	936	936	936
Biomass / Waste ren.	4069	3939	5136	5612	5391	5361	4981
Geothermal energy	-	1000	3693	6108	6285	6390	6602
Others	3110	2630	2446	4943	7191	5759	7176
Average	**4605**	**4551**	**3694**	**2783**	**2615**	**2624**	**2642**

When examining the expansion of renewable electricity generation in Germany, additional impacts and costs need to be taken into account. Integrating the rising share of fluctuating sources into the electricity system will require the extension of storage capacity. When comparing recent studies that analyse the future storage capacity needs for different renewable shares in Germany, it becomes apparent that results are highly uncertain and vary across a wide range (cf. for example BMU 2012d, Kuhn 2011, SRU 2011, UBA 2010 and VDE 2012). As mentioned above, a rule is laid down in the model according to which intermediate storage is necessary when more than 20 % of the electricity supplied to the grid originates from fluctuating sources (cf. Remme 2006). Moreover, curtailment of renewable generation is not possible as the capacity factors of these plants are fixed. This results in an increase in electricity storage capacity of 4 GW (66 %) between 2010 and 2030. Currently, pump storage power plants still constitute the most cost efficient storage option in Germany. However, their potential is limited such that the total installed capacity only increases by 1.3 GW to 7.4 GW in 2030 (cf. Table 5-10). The additional storage demand is covered by Advanced Adiabatic Compressed Air Energy Storage plants (AA-CAES). Even though diabatic CAES systems have lower investment cost, advantages in terms of efficiency and the fact that the additional gas firing is obsolete make AA-CAES installations the preferable option. As battery storages do not become competitive in the model until 2030, total storage capacity in Germany is divided between pump storage (73 %) and compressed air storage (27 %) in 2030. The increase in electricity generation from storage systems is much more pronounced than the capacity expansion. In 2020, already 24 TWh electricity are produced in storages, rising to 43 TWh in 2030. On the whole, it has to be pointed out that the future storage needs in Germany are assessed rather conservatively in this analysis when compared with other studies.

Table 5-10: Development of electricity storage in Germany in the reference case

	2010	2015	2020	2025	2030
Capacity (GW)					
Pump storage	6.1	6.6	6.6	6.6	7.4
Compressed air storage	0	0.3	0.4	2.0	2.7
Battery storage	0	0.0	0.0	0.0	0.0
Total	**6.1**	**6.9**	**7.0**	**8.5**	**10.1**
Generation (TWh)					
Pump storage	6.4	6.7	23.9	28.9	32.3
Compressed air storage	0	0.0	0.1	3.0	10.8
Battery storage	0	0.0	0.0	0.0	0.0
Total	**6.4**	**6.7**	**24.0**	**31.9**	**43.0**

Apart from the additional need for storage capacity, the significant increase in renewable electricity generation will necessitate considerable investments in the grid infrastructure. This concerns both the transmission grid, most importantly to transport wind-generated electricity from the North to the consumption centres in the South and West of Germany, and the distribution grid, in order to integrate decentralised generation plants. In the model, the costs for reinforcing and expanding the electricity grid are accounted for in a simplified manner by means of specific grid expansion costs per unit of additional installed capacity of solar photovoltaics and wind energy. In this context, it has to be highlighted that the grid expansion costs are only introduced into the model in the second model run of the iterative process, i.e. once the development of renewable electricity has been fixated (cf. Chapter 4.3.1). That means that as in reality, where renewable plants operators generally decide on investments without taking the associated grid impacts into account, this additional cost factor does not influence the results on renewable electricity generation. They do, however, have an impact on electricity prices and energy system costs. On this basis, cumulated investment costs of 27.4 billion $€_{2010}$ result for the transmission grid and of 29.2 billion $€_{2010}$ for the distribution grid over the period from 2013 to 2030. In an annualised from, this would correspond on average to 0.98 billion $€_{2010}$ and 1.04 billion $€_{2010}$ per year.

5.3.2. The FIT system

After analysing the development of the German electricity system in the reference case, a closer look is now taken at the characteristics of the FIT system for renewable electricity. First of all, it has to be noted that not the entire generation based on renewable sources is remunerated with feed-in tariffs. For one thing, there is a small amount of installations that have never been included in the FIT system. This applies to the greater part of hydropower, where plants were already installed from the 1970s onwards, and large biomass power stations, for which no tariffs are available. Apart from that, instead of choosing the feed-in tariffs, renewable plant operators may also sell the generated electricity directly to the market with the possibility of leaving and entering the FIT scheme on a monthly basis. In the scenario calculations, the assumption is made that the direct marketing option is adopted once the wholesale electricity price exceeds the current tariff level of a specific plant[15]. Special marketing provisions implemented under the FIT system, like the "green electricity privilege" and the market premium scheme are not taken into account in the model. The "green electricity privilege" has clearly lost in importance since 2012. The current design of the market premium system, on the other hand, yields the same results as the fixed tariffs since the market premium varies as a function of the wholesale electricity price. It is assumed that the additional management premium will be gradually abolished in the next few years.

From the model results for the reference case it becomes obvious that the direct marketing option only becomes relevant after 2020 due to the gradual decrease in the FIT remuneration level and slightly rising wholesale electricity prices (cf. Figure 5-4). Before that, the share of renewable electricity generation covered by the FIT system even rises from 74 % in 2011 to 86 % in 2015 and 83 % in 2020 due to the strong expansion of renewable electricity generation based on the feed-in tariffs. The rising amount of hydropower in the tariff system can be attributed to the modernization of existing plants. In 2025, the share of the FIT scheme in total renewable generation drops to less than 70 % as a large part of onshore wind energy drops out of the system. This can be explained by the specific tariff structure for onshore wind plants which is explicitly represented in the modelling approach: after relatively high initial tariffs, the basic tariff level which is paid after 5 years (or more, depending on the reference revenue model[16]) is less than 5 ct/kWh such that directly selling the electricity to the market becomes more attractive.

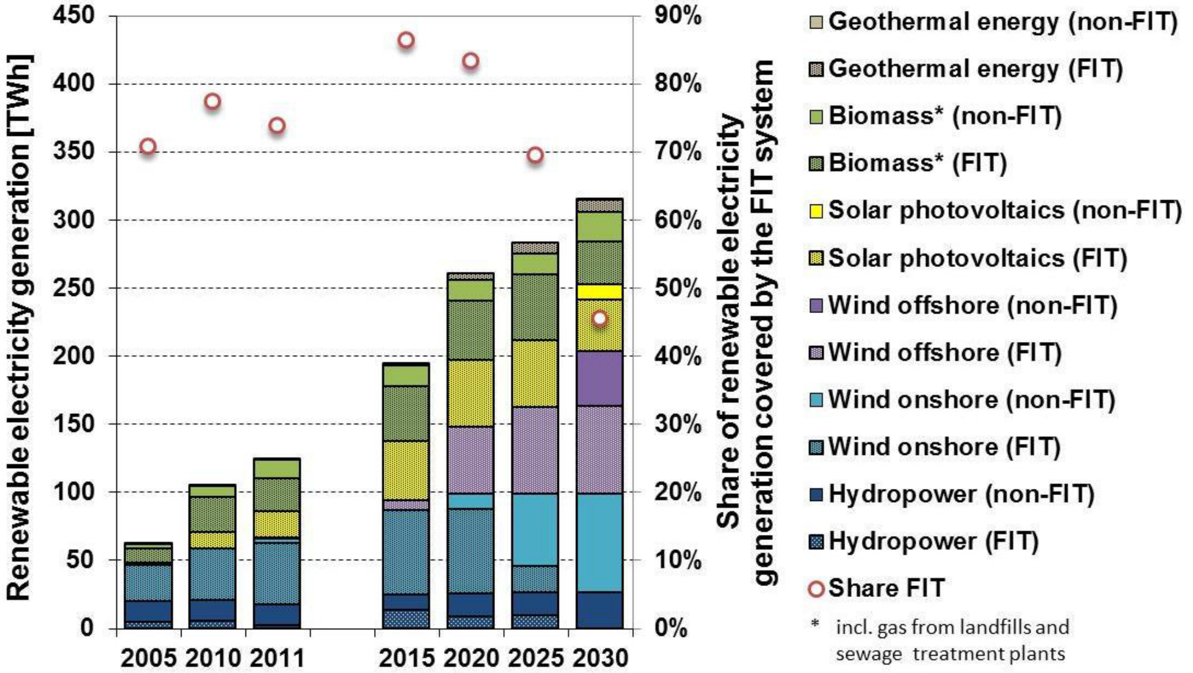

Figure 5-4: Electricity generation in the FIT system in the reference case

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[15] In the model, the comparison of the wholesale electricity price and the feed-in tariff is carried out on the seasonal level.

[16] The reference revenue model, which varies the remuneration level for onshore wind plants as a function of the profitability of their location, is taken into account in the model by representing three types of locations for onshore wind farms, which differ in terms of their wind conditions.

In 2030, less than half of the renewable electricity generation is remunerated through the FIT scheme with the entire generation based on hydropower and onshore wind energy leaving the system. In the case of offshore wind the high degression rates and a similar tariff structure as for onshore wind also result in a decreasing dependence on the FIT system, while solar photovoltaics, small-scale biomass installations and geothermal energy remain mostly in the system.

As a consequence of the substantial growth of electricity production from renewable energies, total feed-in tariff payments rise by 47 % in real terms between 2011 and 2015 to 24 billion €$_{2010}$ followed by an additional increase to almost 29 billion €$_{2010}$ in 2020 (cf. Figure 5-5). Afterwards, due to the annual degression of tariffs and the growing share of renewable electricity directly sold to the market, FIT payments decline to 8.4 billion €$_{2010}$ in 2030. Apart from that, the weight of the different renewable sources in total payments changes considerably over the projected period. In 2020, offshore wind energy, whose share was negligible until 2011, is already responsible for almost a quarter of total FIT payments. At the same time, the relative share of onshore wind declines significantly from 25 % to 18 %, even though absolute payments rise by more than 30 % (in real terms). In 2011, electricity generation from solar energy caused almost half of the entire FIT payments, while in 2020 this share drops to 30 % due to the strong reductions in the tariff level and the slowdown in investments in solar PV after 2015.

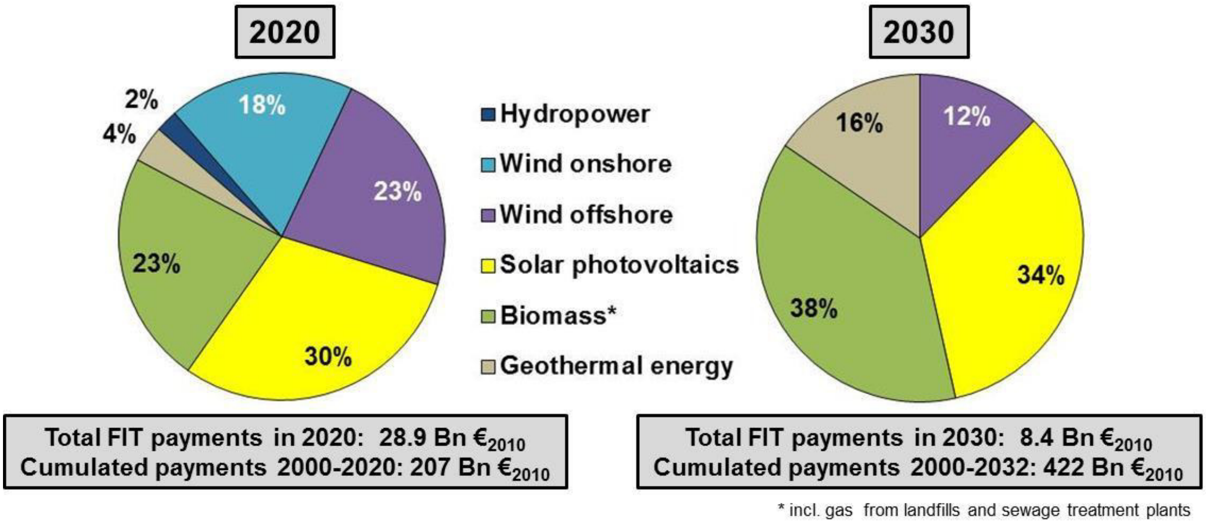

Figure 5-5: Payments in the FIT system in the reference case

After 2020, tariff payments decrease in absolute terms for all renewable sources except geothermal energy where a doubling of generation between 2020 and 2030 (albeit at a very low level) gives rise to a slight increase in payments to 1.3 billion €$_{2010}$. This corresponds to a share in total FIT payments of 16 % in 2030. With 38 %, biomass induces the largest part of tariff payments in 2030, while due to the strong significance of the direct marketing option, the share of wind offshore falls substantially and no payments arise for hydropower and wind onshore. Taking into account past programme years, the FIT system generates cumulated payments of 422 billion €$_{2010}$ in the period from 2000 and 2032. In this context, it has to be pointed out, however, that renewable generation units that have been installed until the end of 2012 are responsible for almost three quarters of that sum. Hence, even if the FIT system was abolished today, substantial payments would still have to be made over a long period of time.

One of the defining features of the German FIT system for renewable electricity is the annual degression of tariffs for newly installed plants that is used to account for technological progress and the associated cost reductions for renewable technologies. Moreover, it has to be kept in mind that tariffs are held nominally constant such that with respect to the real tariff level an additional reduction of about 2 % p.a. occurs because of inflation.

In Figure 5-6 the average tariffs displayed for the different renewable sources comprise all installations generating electricity in the respective year (instead of only the newly installed ones). In real terms, a constant decrease in the average tariff level (across all sources) from 18 ct$_{2010}$/kWh in 2011 to 13.3 ct$_{2010}$/kWh in 2020 and 9 ct$_{2010}$/kWh in 2030 is realized. The tariff spread is also reduced: while in 2011 tariffs ranged between 9 and 39 ct$_{2010}$/kWh, in 2030 the highest tariff level amounts to about 13.6 ct$_{2010}$/kWh (geothermal energy) and the lowest tariffs are paid for offshore wind plants with 6.9 ct$_{2010}$/kWh. Here, it has to be considered that installations that would receive even lower tariffs have already opted out of the tariff system. This is illustrated by the fact that in 2030, no average tariffs can be calculated for onshore wind energy and hydropower.

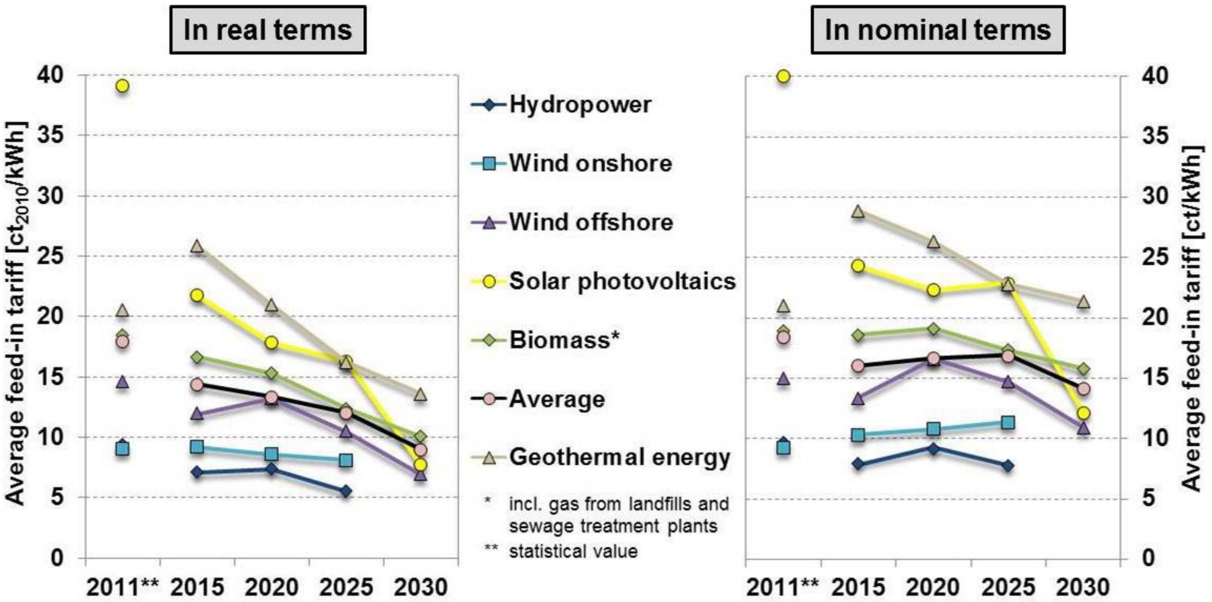

Figure 5-6: Average feed-in tariffs (for all installations covered by the FIT system in the respective year) in the reference case

Over the projected period, the strongest decrease in the tariff level can be observed for solar photovoltaics. Starting from an extremely high average level of 39 ct$_{2010}$/kWh in 2011, substantial annual tariff cuts lead to a reduction to less than 22 ct$_{2010}$/kWh in 2015. As a consequence, on average solar PV installations already receive a lower specific remuneration than geothermal energy in 2015. The decline continues afterwards with a specifically sharp drop between 2025 and 2030 where a large number of old plants with high tariff levels reach the end of the payment period. The slight increase in average tariffs for offshore wind plants between 2015 and 2020 can be attributed to the fact that in 2020 a large amount of plants using a special scheme with higher initial tariffs are installed. Looking at the tariff structure in nominal terms, the reduction is less pronounced with 23 % between 2011 and 2030 and an average level of around 14 ct/kWh in 2030. Accordingly, nominal tariffs by renewable source range between 11 and 21 ct/kWh in 2030.

While results on FIT payments and the tariff level provide information on the amount of support that renewable generators receive in the future, they do not correctly reflect the actual additional costs of the FIT scheme. That is why in addition, the differential costs of the FIT scheme are calculated for the reference case. In this cost term, the market value of the electricity generated under the FIT system is subtracted from the FIT payments presented above and therefore represents the additional financial burden that arises through the tariff scheme.

In light of the enormous rise in renewable electricity generation, FIT differential costs grow in real terms by 37 % from 12 billion €$_{2010}$ in 2011 to 16.5 billion €$_{2010}$ in 2015 in the reference case (cf. Figure 5-7). Despite the substantial tariff reduction, solar PV is responsible for over 40 % of this increase followed by biomass with 35 %. Thus, in 2015 generation from solar energy causes more than half of the entire differential cost while contributing only 23 % to total renewable electricity generation. In contrast, onshore wind farms cover 32 % of renewable generation and only 17 % of FIT differential cost.

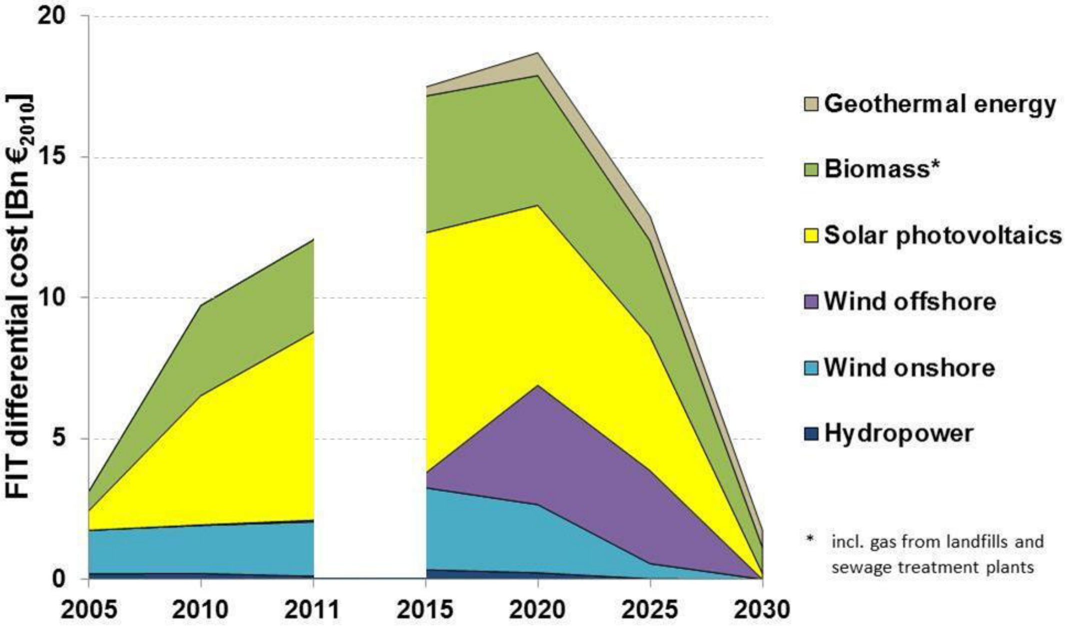

Figure 5-7: FIT differential cost in the reference case

The rise in differential cost between 2015 and 2020 of 2 billion €$_{2010}$ is clearly lower than the simultaneous increase in FIT payments since wholesale electricity prices grow considerably in this period. The differential costs for wind onshore, solar photovoltaics and biomass already exhibit a clear decline, whereas the share of offshore wind generation is raised to almost a quarter of total differential costs in 2020. After 2020, a rapid decrease sets in which can be ascribed to rising electricity prices, tariff reductions as well as a falling share of renewable generation participating in the tariff system. As a result, FIT differential costs amount to less than 2 billion $€_{2010}$ in 2030.

Additional insights on the cost burden caused by the FIT system for renewable electricity can be gained by looking at the cumulated differential costs accrued under the tariff system since its implementation in the year 2000 (cf. Table 5-11). In total, differential costs add up to 209 billion $€_{2010}$ (231 billion € in nominal terms, with an inflation rate of 2.3 % per year) until 2020 and 320 billion $€_{2010}$ (384 billion €) until 2032. With almost 127 billion $€_{2010}$, generation from solar photovoltaics is responsible for 40 % of total costs in the projected period. Due to the comparatively high tariff level, biomass follows in second place with a share of 27 %. Even though the contribution to renewable electricity of offshore wind farms is clearly lower than that of onshore wind energy when aggregated over the period 2000 to 2032, its importance in total real differential cost is only slightly lower (13 % as compared to 15 %). However, while in the case of onshore wind the majority of the cost arises until 2020, nearly two thirds of total costs for the support of offshore wind generation are incurred after 2020. Once again, it needs to be highlighted that renewable plants that came into operation until the end of 2012 and for which funding would have to be continued even if the tariff system was ended today play a dominant role in the cumulated differential cost of the FIT system in the modelling period (58 % until 2032, in real terms).

Table 5-11: Overview on the cumulated FIT differential cost in the reference case

Cumulated FIT differential cost	Hydro-power	Wind onshore	Wind offshore	Solar photovoltaics	Biomass*	Geothermal energy	Total
2000-2020 [Bn $€_{2010}$]	5.0	39.6	15.5	89.0	56.0	4.1	209.2
2000-2020 [Bn €]	5.1	42.2	18.6	98.4	61.9	4.8	231.1
2000-2032 [Bn $€_{2010}$]	5.5	47.2	40.5	126.6	86.9	13.1	319.7
2000-2032 [Bn €]	5.9	52.2	52.8	150.0	104.9	17.8	383.6

* incl. gas from landfills and sewage treatment plants

Based on the differential cost, the FIT surcharge, i.e. the levy on end-user electricity prices applied to finance the additional cost of the FIT system, can be calculated. The various operations required to arrive at the surcharge are given in Table 5-12. First of all, the special provisions for electricity-intensive manufacturing enterprises and rail operators who pay a reduced surcharge of 0.05 ct/kWh for the greater part of their electricity consumption need to be taken into account. In the model, it is assumed that the ceiling of 0.05 ct/kWh is held nominally constant such that in real terms the already negligible contribution of this privileged consumer group even declines further over the modelling period. In a second step, the cost sum that needs to be covered by the non-privileged consumers can be determined by subtracting the revenues from privileged consumption and from selling the renewable electricity to the market from total FIT payments. This is almost similar to the differential cost presented in

Figure 5-7. To obtain the surcharge, this cost term is then divided by the electricity consumption of the non-privileged consumers which decreases slightly over the projected period.

Table 5-12: Calculation of the FIT surcharge in the reference case

	Unit	2015	2020	2025	2030
1. Total FIT payments	Bn €$_{2010}$	24.1	28.9	23.1	8.4
2. Revenues from privileged electricity consumers	Bn €$_{2010}$	0.029	0.026	0.023	0.021
3. Revenues from marketing	Bn €$_{2010}$	7.6	10.2	10.2	6.7
4. Deficit to be covered by the surcharge (=1.-2.-3.)	**Bn €$_{2010}$**	**16.4**	**18.7**	**12.9**	**1.7**
5. Non-privileged electricity consumption	TWh	395	386	366	369
6. FIT surcharge (in real terms) (=4./5.)	**ct$_{2010}$/kWh**	**4.17**	**4.83**	**3.51**	**0.46**
7. FIT surcharge (in nominal terms)	**ct/kWh**	**4.66**	**6.05**	**4.92**	**0.72**

As a result, the FIT surcharge rises from 3.45 ct$_{2010}$/kWh in 2011 to 4.17 ct$_{2010}$/kWh in 2015 and 4.83 ct$_{2010}$/kWh in 2020, corresponding to an increase of 40 % between 2011 and 2020. An even stronger rise is prevented by the simultaneous upward trend in wholesale electricity prices[17]. Afterwards, in line with the reduction in FIT differential cost, the surcharge drops continuously to 0.46 ct$_{2010}$/kWh in 2030 which is comparable to the level that was reached in 2003. In nominal terms, the price peak amounts to 6.05 ct$_{2010}$/kWh in 2020, while in 2030 a value of 0.72 ct$_{2010}$/kWh is obtained.

5.3.3. Electricity consumption

The increase in end-user electricity prices associated with the charging of the FIT surcharge is likely to lead to adjustments in electricity consumption. In the reference scenario, only a slight decrease in total electricity consumption of 4 % from 516 TWh in 2010 to 496 TWh in 2030 occurs (cf. Figure 5-8). This development is in contradiction with the targets of the German Energy Concept aiming at a reduction in electricity consumption of 10 % until 2020 compared to 2008 (instead of the 3 % realized in the model results for this period). At the same time, it has to be paid attention to the fact that the enhanced use of electrical applications represents a viable emission abatement option in view of the ongoing decarbonisation of the power sector.

In the industry sector, a variety of contrasting trends result in a relatively constant electricity consumption until 2030. The general decline in energy consumption in the industry sector due to energy efficiency improvements is opposed to an increase in electricity consumption due to changes in production processes (e.g. a switch to electric arc furnaces in the iron and steel industry) and a stronger usage of electrical cross-sectional technologies. This rise can

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[17] It has to be noted that there are two main reasons why the level of the FIT surcharge in the model differs from the currently observed values (5.3 ct/kWh in 2013). First, it has to be kept in mind that the values for the wholesale electricity prices resulting from the model tend to be slightly higher than the values observed in the real word due to the fact that the model values, given as the dual variable of the electricity commodity balance, contain an investment and fixed operating cost share. As a result, the model calculations yield lower differential costs and FIT surcharges. Second, it is assumed that the amount of final electricity consumption under the special equalisation scheme is limited to a level of around 70 TWh (compared to the actual 96 TWh in 2013, cf. ÜNB 2012b).

also be explained by the need to comply with the reduction targets under the EU ETS. In the tertiary sector on the other hand, a clear decrease of 23 % in electricity consumption takes place between 2010 and 2030. In this case, energy savings in the areas lighting, office equipment and process energy as well as the reduced electricity demand for space heating (due to the ban on night storage heaters from 2020 onwards) outweigh the increased consumption for air-conditioning and electrical heat pumps. For private households, the same developments can be observed with respect to space heating, lighting and heat pumps. Yet, due to the trend to smaller household sizes and rising penetration rates with respect to information and communication technologies, electricity consumption for household appliances grows considerably. Therefore, on the whole electricity consumption in the household sector falls only by 7 % in the period from 2010 to 2030. In the transport sector, the goals of the National Electromobility Development Plan (cf. Bundesregierung 2009) of having at least one million electric vehicles in circulation by 2020 and five million by 2030 are accounted for in the model. Together with a slightly growing importance of rail transport, total electricity consumption in the transport sector increases by 80 % to 30 TWh in 2030. With less than 6 %, the share of transport in total electricity consumption remains, however, relatively low. Further information on how the FIT surcharge affects electricity consumption in the different end-user sectors will be obtained from the scenario comparisons in the following chapters.

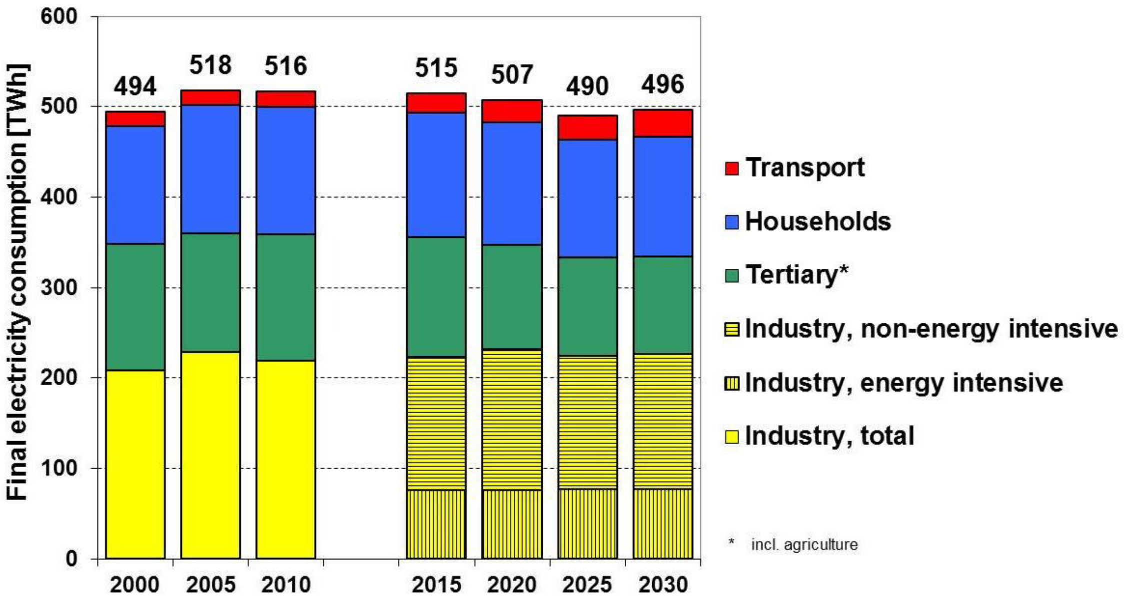
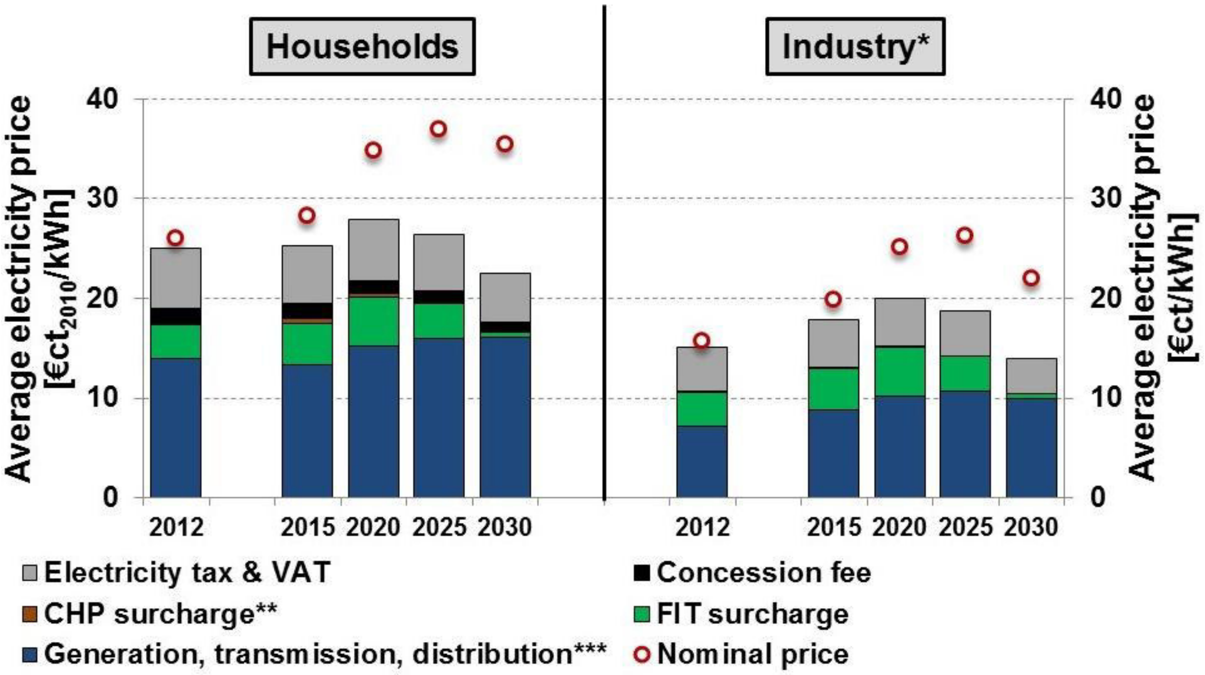


Figure 5-8: Electricity consumption by sector in the reference case

End-user electricity prices are composed of two broad components: one covering the costs for generation, transmission and distribution and the other one comprising the various governmental levies (FIT surcharge, levy resulting from the feed-in premium system for CHP electricity generation, concession fee as well as electricity and value added tax). Figure 5-9 illustrates the future development of electricity prices in Germany using the example of private households and the industry sectors which are not privileged with respect to the FIT surcharge.



* Calculation is based on the following category: Annual consumption of 24 GWh, annual peak load of 4000 kW and utilization time of 6000 hours, medium voltage, non-privileged in terms of FIT surcharge

** Surcharge resulting from feed-in premiums for CHP electricity generation

*** Including fee resulting from the Electricity Network Charges Ordinance (StromNEV, cf. Bundesgesetzblatt 2011b)

Figure 5-9: End-user electricity prices in the reference case (own calculations based on BNetzA and BKartA 2013, IER et al. 2010)

With respect to household consumers, electricity prices remain relatively constant in real terms until 2015 when compared to 2012. Until 2020 an increase of about 10 % occurs resulting in the highest price level in the modelling period of almost 28 ct_{2010}/kWh. Afterwards, prices decline gradually such that in 2030 the real household electricity price is nearly 10 % below the value of 2012. In nominal terms, the price peak is reached with 37 ct/kWh in 2025 and in the period from 2012 to 2030 the nominal price increase amounts to 36 %. The various price components exhibit, however, divergent developments. Between 2012 and 2015, costs for generation, transmission and distribution fall slightly which can be mainly explained by the merit-order effect induced by the strong expansion of renewable electricity generation (cf. Chapter 4.3.1). After 2015, growing fuel, grid expansion and carbon costs outbalance this effect resulting in a continuing rise in this cost component. The FIT surcharge increases its share in household electricity prices from 14 % in 2012 to 17 % in 2020. Yet, until 2030, given the rapid decline of the surcharge, this share drops to 2 %. Regarding the CHP surcharge, the concession fee and the electricity tax, it is assumed that the current level is held constant in nominal terms such that in real terms a slight decrease can be observed. As a consequence, together with the 19 percent value added tax, the total governmental share in household electricity prices adds up to 48 % in 2015 (as compared to 44 % in 2012) and falls gradually to 29 % in 2030.

Electricity prices for non-privileged industry consumers undergo the same developments as household prices albeit at a substantially lower overall price level. In real terms the price peaks at 20 ct_{2010}/kWh in 2020 and in nominal terms in 2025 with 26 ct/kWh. As non-privileged industry sectors are charged the same FIT surcharge as households, the relative weight of this surcharge is with almost a quarter in 2020 clearly higher than in the case of private households. In total, the governmental share in non-privileged industry prices is diminished from 51 % in 2015 to 29 % in 2030.

5.3.4. Emissions

Both policy instruments that are explicitly modelled in this scenario analysis have a significant effect on CO_2 emissions in Germany. In the reference case, total energy- and process-related CO_2 emissions decline by 37 % in 2020 and by 48 % in 2030 compared to 1990. That means that the target of the German Energy Concept is almost met for 2020 (40 %) but missed by 7 percentage points in 2030.

In light of the strong increase of renewable electricity generation, the energy conversion sector contributes the largest part to emission mitigation in absolute terms with a reduction of 232 Mt CO_2 or 55 % in 2030 with respect to 1990. As a result, the share of energy conversion in total emissions falls from 42 % in 2010 to 36 % in 2030. Slightly lower levels of CO_2 abatement are achieved in the industry sector. This can be mainly attributed to process-related emissions where only comparatively expensive abatement options are available. Compared to 1990, a reduction of 37 % is realized until 2020 und of 50 % until 2030 such that the industry's contribution to CO_2 emissions remains relatively constant at a level of 23 %. Disproportionally high mitigation efforts are implemented in the tertiary sector resulting in a slight drop in its share to 5 % in 2030, whereas the household sector is responsible for about 12 % of total emissions in the entire modelling period. As has been highlighted in a number of studies, transport represents the sector most difficult to decarbonise. Accordingly, in the reference case CO_2 emissions in this sector are only diminished by 12 % in 2020 and 18 % in 2030 when compared to 1990 and the share of the transport sector in total emissions rises from 16 % in 1990 to 25 % in 2030.

For the EU Emissions Trading System, the reference case applies the current target of lowering CO_2 emissions by 21 % until 2020 compared to 2005 and afterwards extrapolates the annual reduction rate of 1.74 % until 2030 resulting in a decline of 34 %. On the basis of the flexible modelling approach of the EU ETS, emission mitigation in the German ETS sectors amounts to 26 % until 2020 and 43 % until 2030 (cf. Figure 5-10). Hence, Germany's contribution to the burden sharing lies substantially above the EU average. For the sectors not covered by the EU ETS, a national target of -14 % until 2020 (with respect to 2005) has been assigned to Germany in the scope of the EU Effort Sharing Decision establishing an EU-wide mitigation target of -10 % for all non-ETS sectors. From the model results for the reference case it becomes obvious that with the policy instruments and support measures currently implemented in the non-ETS sectors in Germany this reduction level is significantly exceeded. Until 2020, non-ETS CO_2 emissions are lowered by 20 % and by 30 % in 2030, in relation to 2005.

The explicit modelling procedure applied for the EU ETS in this scenario analysis also makes it possible to calculate endogenously a certificate price for the entire ETS area. On the whole, a comparatively low price level prevails in the reference case. In real terms, ETS allowance prices rise gradually from 11.8 $€_{2010}$/t CO_2 in 2015 to 13.9 $€_{2010}$/t CO_2 in 2025 followed by a slight decrease to 13.4 $€_{2010}$/t CO_2 in 2030. This relates to a nominal level of 16 €/t CO_2 in 2020 and of 21 €/t CO_2 in 2030.

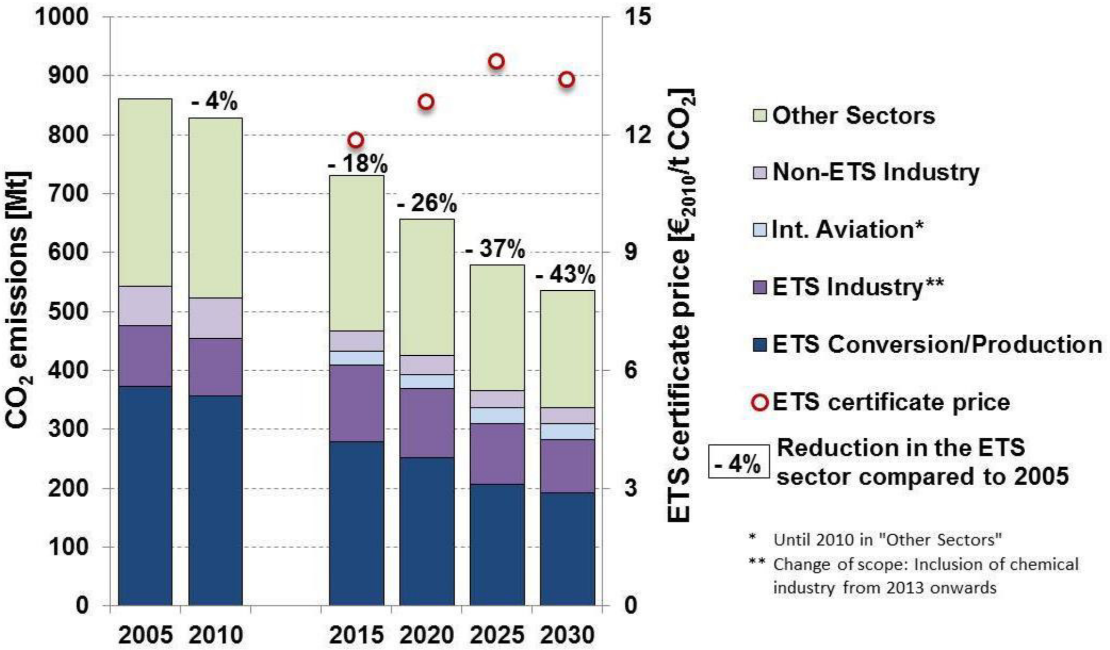


Figure 5-10: CO_2 emissions in Germany and ETS certificate prices in the reference case

5.4 Interaction between EU ETS and the Germany FIT system

In the following chapter, it will be illustrated how the flexible modelling approaches for both the EU ETS and the German FIT system for renewable electricity can be made use of to explore the interactions between these two policy instruments. The interdependencies between a supranational emission trading scheme and national instruments for the promotion of renewable electricity have been analysed in various studies in a theoretical manner (cf. for example Johnstone 2003, Sorrell and Sijm 2003, Walz 2005, Kemfert and Diekmann 2009, Matthes 2010, OECD 2011). Table 5-13 provides an overview on the potential interactions between the EU ETS and the German feed-in tariff system.

Interactions between the EU ETS and the FIT system occur because the affected target groups overlap. The electricity sector represents an area directly influenced by both instruments, while the energy-intensive industry is only directly affected by the Emissions Trading System. As both instruments have an impact on electricity prices, the different types of electricity consumers constitute the most important indirectly affected target group. The most relevant implication of this interdependency is usually seen in the fact that on EU-level no additional emission reduction can be attained with the help of the FIT system in view of the binding ceiling on total emissions set in the cap and trade system. Consequently, it has often been argued in theoretical literature that a support scheme for renewable electricity is only counterproductive with respect to the goal of a cost efficient emission reduction, as it usually leads to higher abatement costs while at the same time having no additional effect on emission reduction. Hence, the German FIT system can only be justified if it serves additional policy objectives (cf. Chapter 2.4 on policies promoting environmental technologies).

Table 5-13: Possible interactions between the EU ETS and the German FIT system for renewable electricity

Affected sector	Impacts
Direct interactions	
Electricity generation	The additional renewable generation caused by the FIT system replaces generation based on fossil fuels and reduces carbon emissions. Thus, ETS reduction targets (specified in absolute terms) are more easily attained, i.e. less allowances have to be purchased by German electricity generators, possibly resulting in a lower certificate price in the whole system.
Indirect interactions (within Germany)	
Energy-intensive industry	With the implementation of the FIT system, emission mitigation efforts may be shifted from the German energy-intensive industry branches to electricity production. With lower prices for ETS allowances, the energy-intensive industry has less incentive to reduce emissions.
Electricity consumers	Both instruments have the impact of raising electricity prices leading to adjustments within the electricity consuming sectors combined with feedbacks on electricity generation. The isolated effects of each instrument can, however, not be simply added in order to obtain the overall effect given the possible dampening influence of the FIT system on ETS CO_2 prices.
Indirect interactions (outside of Germany)	
Foreign ETS sectors	The ETS allowances not needed in the German electricity sector due to the FIT system are deployed elsewhere (either in the German energy-intensive industry or in foreign ETS sectors), resulting in a new market equilibrium with potentially lower certificate prices but the same level of CO_2 emissions in the ETS as a whole.
Electricity exchange	The additional renewable electricity generation in Germany may, in combination with the Emissions Trading System, also influence the electricity exchange between Germany and neighbouring countries.

The various impacts outlined in Table 5-13 are examined in a quantitative manner in the following scenario analysis. The interactions between the EU ETS and the German feed-in tariffs for renewable electricity are analysed for two different target levels of the Emissions Trading System: the current 21 %-target and an elevation to 34 % in 2020 compared to 2005. Accordingly, in both cases one scenario with both instruments (REF and ETS34+FIT) and one with only the EU ETS (ETS21 and ETS34) are calculated. Moreover, the sole effects of the FIT system without emission trading in place are explored (scenario FIT_Only) and as basis for comparison an additional scenario (No_Ins) with none of the instruments implemented is used.

5.4.1. Emissions

The impacts of introducing a support instrument for renewable electricity on a national level while having a supranational emissions trading system in place become clearly visible when looking at the emission reduction in Germany under the different scenario assumptions (cf. Figure 5-11). Both for the 21 %- and the 34 %-ETS reduction target, overall mitigation efforts in Germany (which are determined endogenously) are higher for those cases in which the FIT system is in place. The difference can be attributed to the electricity sector, where generation based on fossil fuels is substituted by renewable energies. For example, for the case of an ETS-target of 21 %, an additional emission reduction of 67 Mt CO_2 is realized in the electricity sector in 2020 when the feed-in tariffs are implemented (scenario REF versus ETS21). Given the generally higher mitigation level, this difference is with 40 Mt CO_2 less pronounced under an ETS reduction target of 34 %. In the scenario analysis at hand, no indirect effect of the FIT system on the German industry sectors participating in emission trading is discernible. Even though less ETS allowances are needed in electricity generation in Germany and, as will be shown more clearly in the following, certificate prices are lower, these allowances are not absorbed by the German ETS industry sectors such that emissions from these sectors are nearly the same in the comparable scenarios with our without FIT system.

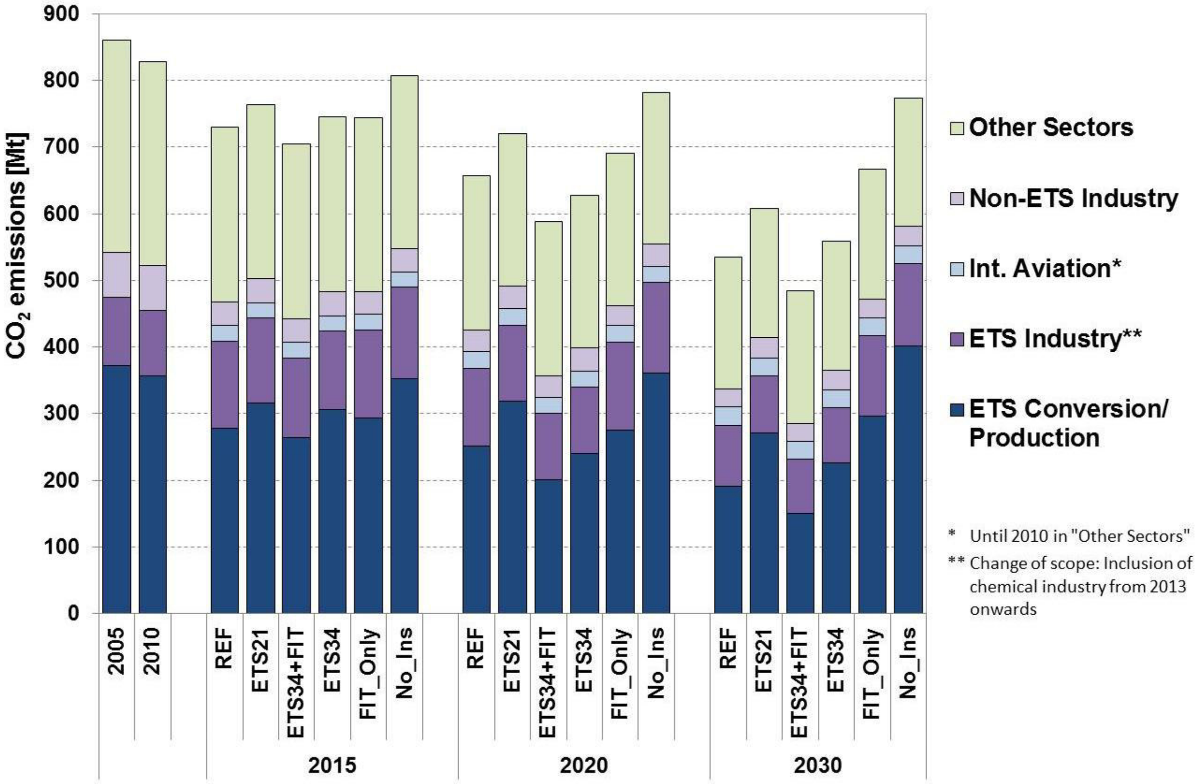


Figure 5-11: CO_2 emissions in Germany under different assumptions regarding the FIT scheme and the EU ETS

As can be expected, varying scenario assumptions on the EU ETS and the feed-in tariffs for renewable electricity have no noticeable influence on emission abatement in the non-ETS sectors. In all scenarios non-ETS emissions are lowered by about 20 % until 2020 and 30 %

until 2030 compared to 2005. As already mentioned, this clearly surpasses the national target value of 14 % for 2020 set on the basis of an EU-wide reduction target for total GHG emissions of 20 % for 2020 compared to 1990. If the overall abatement goal on the EU level was tightened to 30 % until 2020 with an associated distribution between the ETS and non-ETS sectors of 34 % and 16 %, the German contribution in the non-ETS sectors would have to be raised to 22.4 % - assuming that the burden sharing remains the same. Thus, some additional measures would have to be realized to fulfil this reduction target.

The feed-in tariff system also induces a relatively strong expansion of renewable electricity in the hypothetical case that the EU ETS is not in place (cf. scenario FIT_Only). Consequently, until 2020 even a slightly higher emission reduction than in scenario ETS21 is achieved. In 2030, however, total CO_2 emissions in Germany are only lowered by 36 % with respect to 1990 in this scenario, whereas for the scenarios with EU ETS, emission mitigation ranges between 41 % (ETS21) and 53 % (ETS34+FIT). By way of comparison, CO_2 emissions in Germany decline only by about 25 % between 1990 and 2030 if neither the EU ETS nor the FIT system is implemented.

As a consequence, the national system for the promotion of renewable electricity in Germany has an impact on the burden sharing among the participating states in the EU ETS. Germany's contribution to the fulfilment of the overall ETS cap rises when renewable electricity receives further support. Since the additional emission certificates are not utilized in the German industry sector, they are available for other EU ETS countries (cf. Figure 5-12).

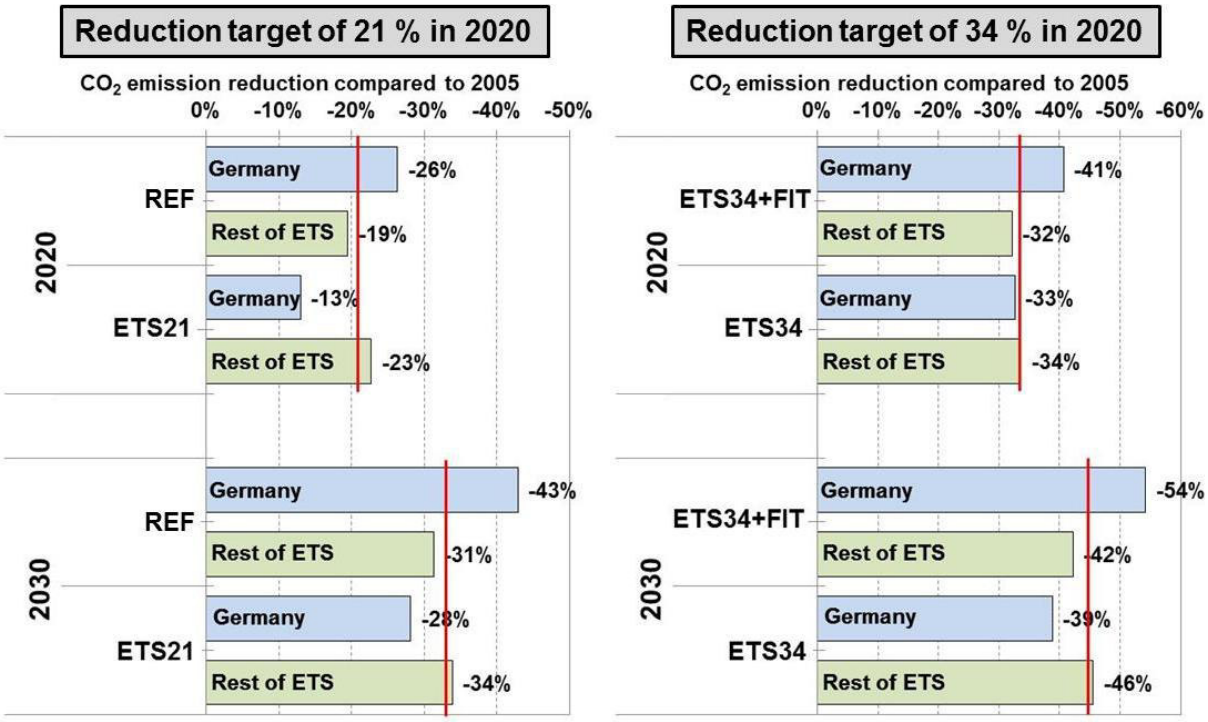


Figure 5-12: Burden sharing in the EU ETS under different assumptions regarding the FIT scheme and the EU ETS

For a reduction target of 21 % for 2020, emission mitigation in Germany varies in the model results between 26 % with the feed-in tariffs for renewable electricity (reference case) and 13 % without (scenario ETS21). Until 2030, this difference widens to 43 % versus 28 % based on an EU-wide reduction target of -33.7 %. Similar findings are obtained for the scenarios with a more ambitious mitigation objective of 34 % for 2020. Germany's contribution generally lies above the average for the entire ETS region if the support system for renewable electricity is in place and under the average (with varying degrees) if this is not the case. The share of the remaining ETS member states is adjusted accordingly. It has to be pointed out once more that irrespective of the national policy framework the ETS target is always exactly complied with as there is no incentive to go beyond this cap. Thus, from an EU-wide perspective, no additional emission abatement is stimulated with the help of national schemes for the promotion of renewable electricity.

Apart from changes in the burden sharing, the national FIT system for renewable electricity in Germany has an additional effect on EU level as it influences the price for ETS certificates. Since the demand for emission allowances is diminished in Germany, the certificate price for the entire system can be expected to fall. As mentioned above, a relatively low price level is observed in the reference case, with an ETS target of 21 % and the feed-in tariffs in place. Under the hypothetical assumption that the FIT system was abolished (scenario ETS21), an increase in ETS certificate prices between 5.5 and 6.1 $€_{2010}$/t CO_2 would result from the model calculations for the projected period (cf. Figure 5-13). Consequently, prices for emission allowance rise from 17.6 $€_{2010}$/t CO_2 in 2015 to 19.3 $€_{2010}$/t CO_2 in 2030 in the scenario ETS21.

A significantly higher price level is caused when the ETS reduction target for 2020 is raised to 34 %. When both this target and the FIT system are accounted for (scenario ETS34+FIT), certificate prices start at a comparatively moderate value of about 21 $€_{2010}$/t CO_2 in 2015, but experience a considerable upsurge to almost 34 $€_{2010}$/t CO_2 in 2020. This shows that tightening the ETS reduction level now for a relatively close point in time - considering the long investment periods and technical lifetimes in the energy industry - would come at substantial cost. In the long-term, with more flexibility to realize additional abatement options and ongoing cost reductions for these options, prices for ETS allowances drop again to 21 $€_{2010}$/t CO_2 in 2030 in the scenario ETS34+FIT and are therefore still nearly 8 $€_{2010}$/t CO_2 higher than in the comparable scenario with the reduction target of 21 %. With respect to the higher mitigation level, the difference between the case with FIT system and the one without (scenario ETS34) is less pronounced and ranges between 1.9 and 4.8 $€_{2010}$/t CO_2.

In nominal terms (cf. Table 5-14), certificate prices increase gradually until 2030 in both scenarios with the ETS target of 21 % - to 21 €/t CO_2 with feed-in tariffs in place and to 30 €/t CO_2 without them. In the case of the 34 %-mitigation target, the highest price level in nominal terms is reached in 2020 with 42 €/t CO_2 (scenario ETS34+FIT) and 48 €/t CO_2 (ETS34). Despite the strong decrease after 2020, nominal prices lie between 33 and 41 €/t CO_2 in 2030.

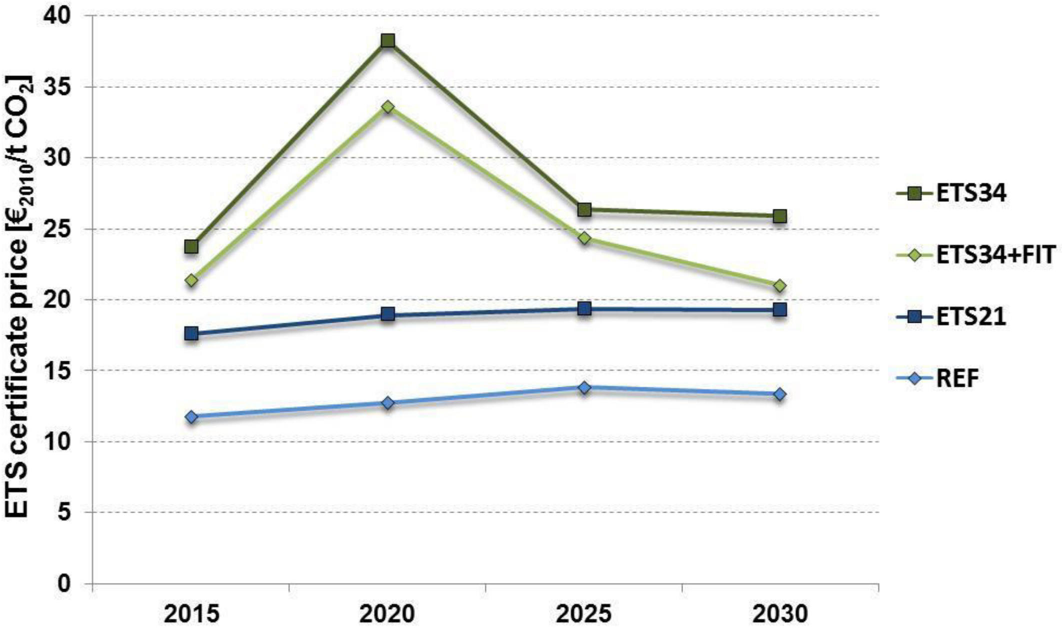


Figure 5-13: ETS certificate prices in real terms under different assumptions regarding the FIT scheme and the EU ETS

Table 5-14: ETS certificate prices in nominal terms under different assumptions regarding the FIT scheme and the EU ETS

	Unit	2015	2020	2025	2030
REF	€/t CO_2	13.2	16.1	19.5	21.1
ETS21	€/t CO_2	19.7	23.7	27.2	30.3
ETS34+FIT	€/t CO_2	23.9	42.1	34.3	33.1
ETS34	€/t CO_2	26.5	47.9	36.9	40.7

5.4.2. Electricity sector

Additional insights on how the EU ETS and the FIT scheme interact within Germany can be gained by looking at the development of electricity generation from renewable sources under the different scenario assumptions (cf. Figure 5-14). First of all, the importance of the feed-in tariffs for renewable electricity needs to be stressed. In the scenarios without the FIT system, the extension of renewable electricity generation remains rather limited, with shares in gross electricity consumption of at most 25 % in 2030. The only renewable technology that is competitive under the emissions trading system without the additional support of feed-in tariffs are onshore wind plants that reach in 2030 with around 70 TWh the same generation levels as in the scenarios with FIT system in place. Apart from that, only electricity generation based on solid biomass is slightly increased over the projected period, whereas in the case of offshore wind energy, solar photovoltaics, biogas and geothermal energy the EU ETS alone does not stimulate any additional expansion until 2030. In 2030 onshore wind generation covers more than half of the entire renewable generation in the scenarios without feed-in tariffs. Thus, these scenario results underline that supporting renewable electricity generation does not constitute a cost efficient emission abatement strategy for Germany.

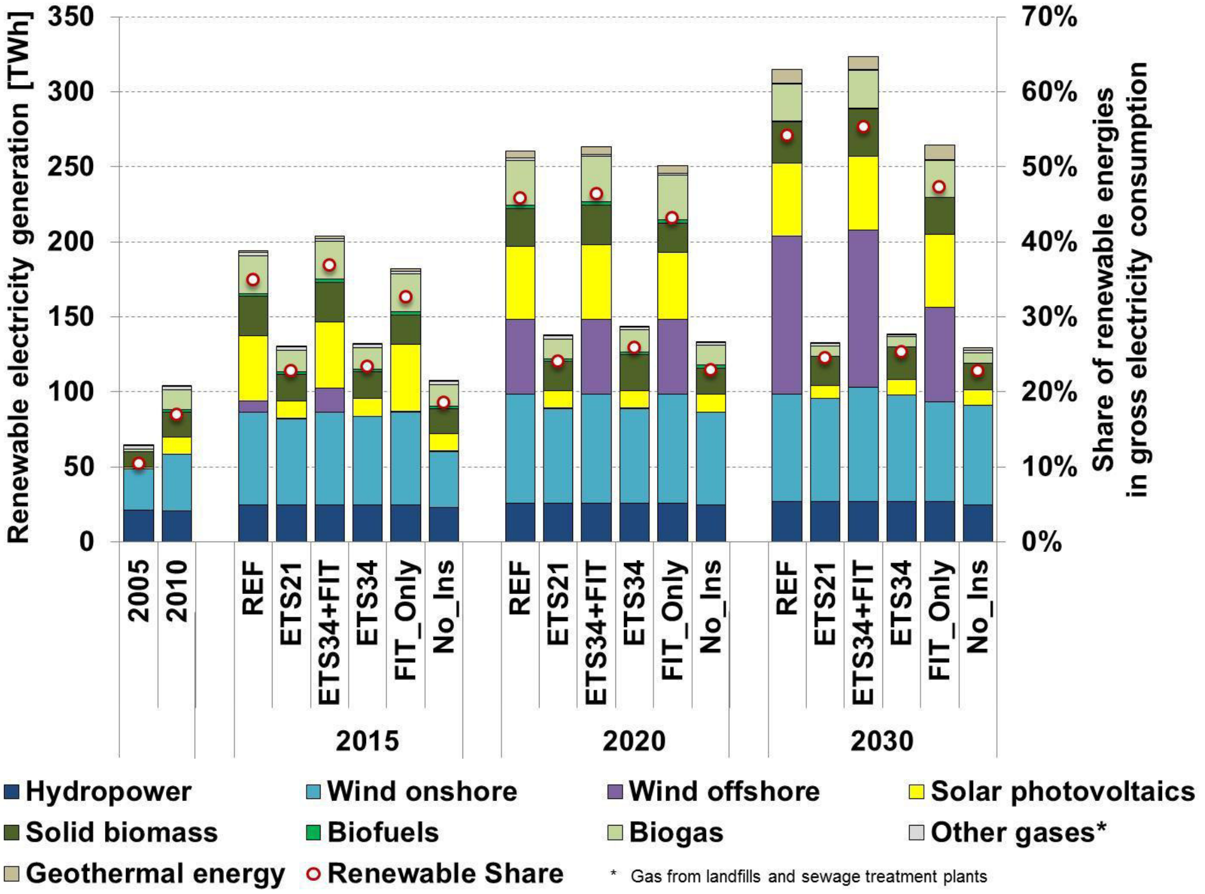


Figure 5-14: Renewable electricity generation under different assumptions regarding the FIT scheme and the EU ETS

Furthermore, the scenario comparison at hand can be used to explore whether in combination with the FIT system the EU ETS has a supporting effect on the expansion of renewable electricity in Germany by raising the generation costs for fossil fuel plants. Under the premises that only the FIT system but not the EU ETS is implemented (scenario FIT_Only), renewable electricity generation in Germany still rises considerably such that the share in gross electricity consumption in 2020 is with 43 % only three percentage points lower than in the reference case. In the long-term, however, growth rates slow down significantly when compared with the reference scenario, as the competitiveness of the renewable generation technologies is affected by the lower generation costs for installations based on fossil fuels. The lower renewable share in gross electricity consumption of 47 % in 2030 (as compared to 54 % in the reference case) can be mainly attributed to a reduced extension of offshore wind generation which is almost halved with respect to the level in the reference case.

In contrast, hardly any changes are discernible when the ETS emission reduction target is raised from 21 % to 34 % in 2020. Almost the same expansion of renewable electricity is realized in the scenarios REF and ETS34+FIT. Negligible increases in the generation based on onshore wind energy and biomass result in a rise of the renewable contribution to gross electricity consumption to 55 % in 2030, i.e. one percentage point above the reference level. Finally, it needs to be pointed out that with neither the EU ETS nor the FIT system in place (scenario No_Ins), renewable electricity is still extended slightly over the projected period, as additional onshore wind generation in favourable locations and repowering on already developed sites becomes competitive even under these conditions from 2020 onwards.

The lower prevalence of renewable energies in electricity generation in those scenarios that do not account for the feed-in tariffs needs to be compensated by other energy carriers. Thus, without the implementation of the FIT system, fossil fuels maintain a more dominant role in the German power sector with shares in net electricity supply rising gradually to around 70 % in 2030 due to the simultaneous phase-out of nuclear electricity - in contrast to 38 % in the reference case (cf. Figure 5-15). For both ETS target levels, generation based on natural gas is raised significantly. In 2020, the contribution of natural gas in absolute terms is almost doubled when compared to the respective scenario with FIT scheme, to 162 TWh in case of the ETS reduction target of 21 % and to 213 TWh for the 34 %-target. In both scenarios, natural gas covers about 44 % (240 TWh) of net electricity supply in 2030. Consequently, in relation to the reference case additional gas-fired capacities of about 13 GW need to be installed in these scenarios over the period 2013 to 2032.

As far as coal and lignite are concerned, clear differences can be observed between the scenarios with the 21 %- and the 34 %-mitigation target. In the scenario ETS21, installed capacity based on lignite is increased by 5 GW until 2022, such that the share of lignite in net electricity supply is raised to 28 % in 2020 and 20 % in 2030 (compared to 21 % and 11 % in the reference case). In contrast, considerably lower shares are realized for lignite-fired power plants and no additional capacities are installed over the projected period when the ETS reduction target of 34 % for 2020 is implemented. In this context, it needs to be pointed out that the scenario without FIT system (ETS34) constitutes the only constellation where CCS (in lignite power plants) gains in importance in Germany with a share of 6 % in total net electricity supply in 2030. In all scenarios, the significance of coal drops much more quickly than that of lignite. In the scenario ETS21, a slightly higher generation based on coal than in the reference case results from higher capacity utilization rates, while no additional capacities are installed after 2012. With the more ambitious ETS reduction target, the contribution of coal-fired plants to power supply falls to about 1 % in 2020, both with and without the FIT system in place. This rapid decrease is associated with extremely low capacity factors for these plants. Net electricity imports depend primarily on the emission mitigation level, with slightly higher net imports in case of the 34-% target. Yet, no clear trend in the amount of electricity imports with respect to the inclusion of the FIT scheme is discernible.

As mentioned above, due to the prevalence of fossil fuels, the scenarios without the feed-in tariffs exhibit significantly higher CO_2 emissions in electricity generation than the reference case or the scenario ETS34+FIT. Thus, if the national support scheme for renewable electricity is not in force, the German electricity sector mainly responds to the supranational ETS targets through a larger reliance on natural gas (and CCS in the case of a more ambitious reduction objective) and a larger purchase of emission allowances.

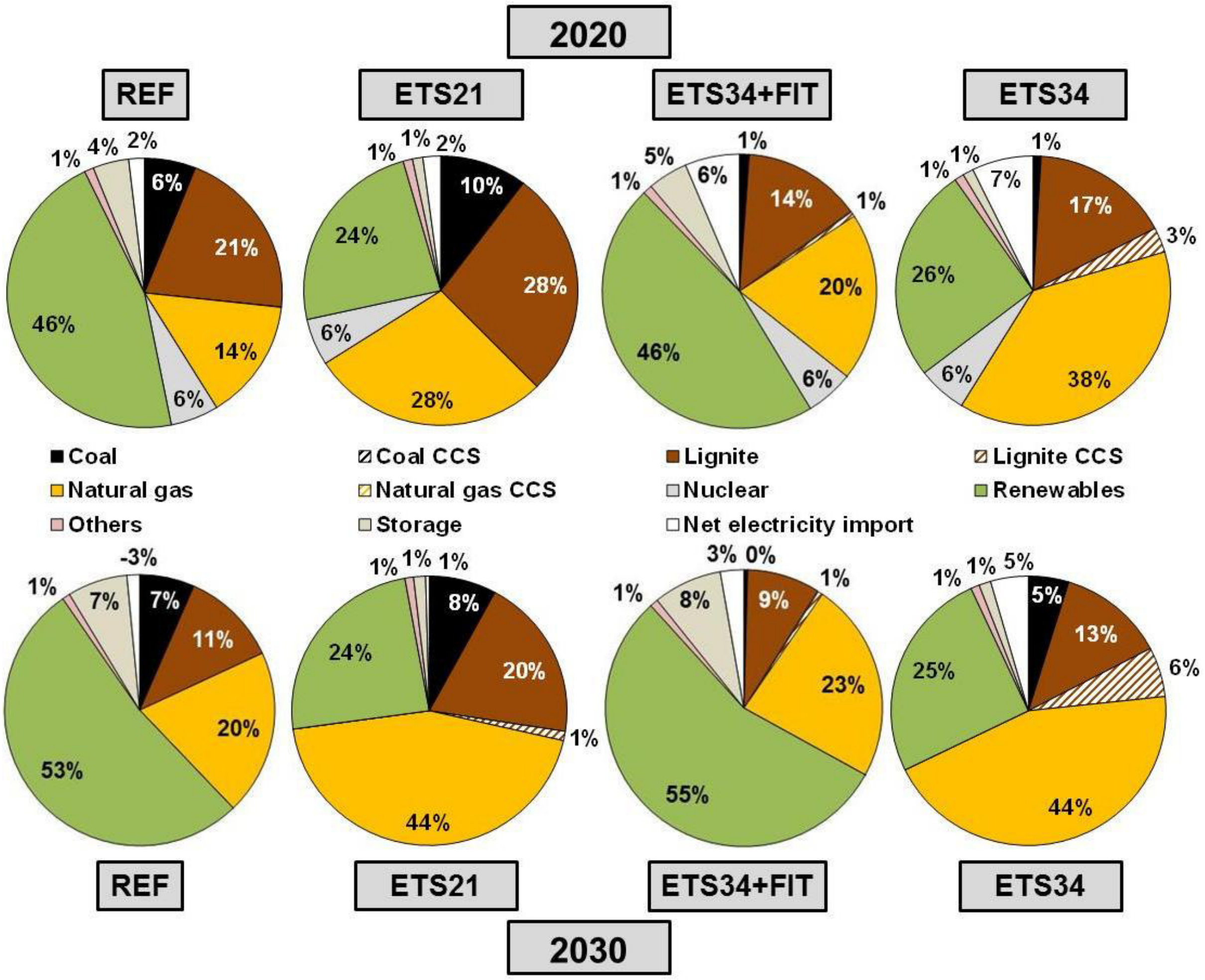


Figure 5-15: Structure of total net electricity supply under different assumptions regarding the FIT scheme and the EU ETS

With respect to electricity prices, various, and in some cases opposing, effects that arise from the interaction between the EU ETS and the national FIT scheme need to be taken into consideration. First of all, raising the share of renewable electricity generation has a dampening impact on wholesale prices as it replaces the conventional generation with the highest generation cost (so-called merit-order effect). Furthermore, the influence of the emissions trading system on electricity prices is lowered with the implementation of the feed-in tariffs as ETS certificate prices decline. These two effects lead to a decrease in wholesale electricity prices in the scenarios with FIT system of up to 22 % for the lower ETS reduction target and of up to 26 % for the higher target in relation to the respective scenarios without feed-in tariffs (cf. Figure 5-16).

In the case of end-user electricity prices, an additional influencing factor is discernible. Here, the extra costs of the FIT scheme are accounted for by means of the FIT surcharge. From the scenario results it can be deduced that the latter effect outweighs the two price-reducing ones such that household electricity prices are up to 23 % higher in the scenarios with feed-in tariffs than in those without. For non-privileged industry consumers this impact is even more pronounced since the FIT surcharge captures, in relative terms, a larger share of the electricity price. The difference in prices between the scenarios decreases until 2030 as the FIT surcharge falls as well. The influence is generally more pronounced for the 21 %-reduction target, because here, as will be shown below in more detail, the FIT surcharge is higher than in the scenario ETS34+FIT. An exemption needs to be made for the privileged industry sectors that only have to pay a limited FIT surcharge of 0.05 ct/kWh. In this case, the merit-order effect as well as the reduced certificate price outbalances the FIT surcharge resulting in a decline in electricity prices between 9 % and 22 % compared to the respective scenarios without feed-in tariffs.

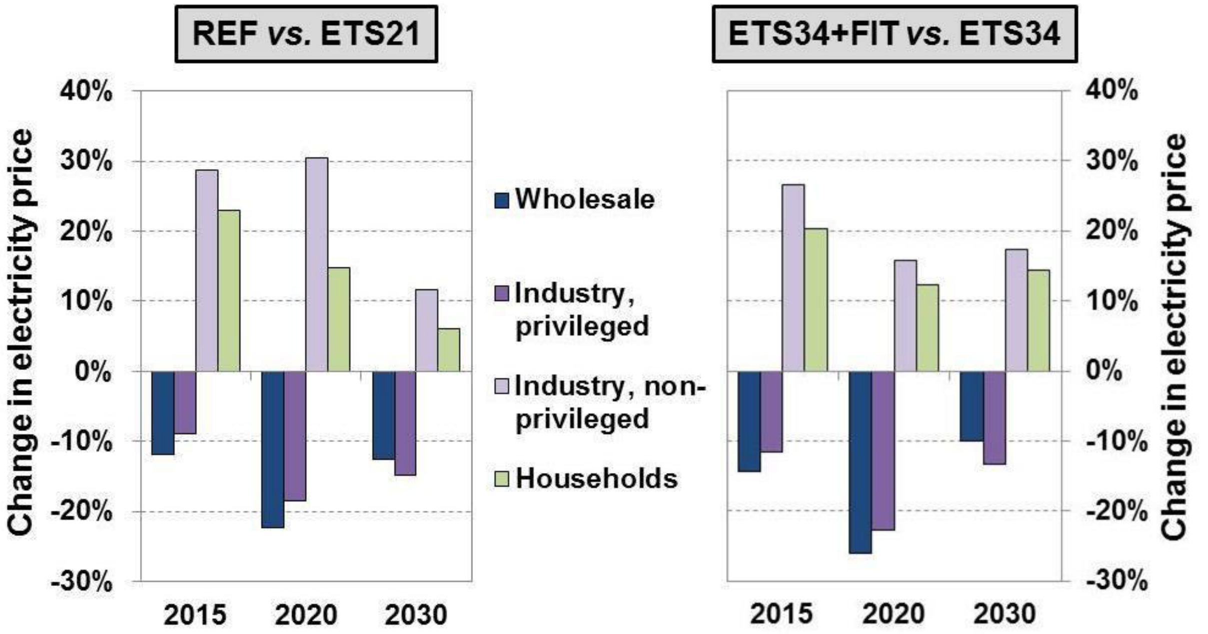


Figure 5-16: Comparison of electricity prices with and without FIT scheme in place under different assumptions regarding the EU ETS target

Changes in electricity prices can be expected to entail alterations in electricity consumption. In the model, electricity demand can either be modified by a change in technology choice (e.g. alternative production processes in industry or heating systems in private households) or by adjusting demand for energy services or useful energy for which own-price elasticities are laid down. The specifications chosen for this scenario analysis reflect the comprehensive empirical evidence that price elasticities of electricity demand are comparatively low (cf. for example Lafferty et al. (2001), Espey and Espey (2004), Narayan et al. (2007), Fan and Hyndman (2011), Kamerschen and Porter (2004)). Total electricity consumption is reduced by up to 4 % in 2020 when the feed-in tariffs for renewable electricity are taken into account (cf. Table 5-15). Until 2030, this influence is reduced to less than 2 % for both ETS target levels. The tertiary sector proves to be the most flexible in reacting to changes in electricity prices, with a reduction of up to 12 % in the reference case when compared to the scenario ETS21. In contrast, adjustments in electricity consumption of households and non-energy intensive industry sectors due to the introduction of the FIT scheme are considerably lower. The energy-intensive industry branches, which are in most parts privileged with respect to the

FIT surcharge, experience a slight increase in electricity demand when the feed-in tariffs are implemented. In addition, it has to be noted that from 2020 onwards, the lower electricity consumption does not relate to a lower electricity generation in the scenarios with FIT system, as in these scenarios more electricity is used in storage technologies given the rising share of fluctuating sources in electricity production.

Table 5-15: Electricity consumption by sector under different assumptions regarding the FIT scheme and the EU ETS

TWh	2010	2020				2030			
		REF	ETS21	ETS34 +FIT	ETS34	REF	ETS21	ETS34 +FIT	ETS34
Industry, energy intensive	219	76	73	79	76	77	75	77	77
Industry, non-energy intensive		156	160	153	155	149	152	149	150
Tertiary*	140	115	131	112	120	108	113	107	112
Households	141	136	140	133	135	132	135	131	135
Transport	17	24	24	24	24	30	30	30	30
Sum	**516**	**507**	**528**	**502**	**511**	**496**	**505**	**495**	**504**

* incl. agriculture

5.4.3. The FIT system under different EU ETS targets

The scenario analysis at hand can also be applied to examine whether the reduction level specified under the EU ETS has an impact on the long-term development of the German tariff system for renewable electricity. To do so, a number of parameters characterising the FIT scheme are contrasted for the reference case (ETS target of 21% for 2020) as well as the scenarios ETS34+FIT (ETS target of 34 % for 2020) and FIT_Only (no ETS reduction target).

In a first step, it is analysed whether different ETS mitigation targets influence the relevance of the FIT system in the development of renewable electricity in Germany. It has already been shown that the feed-in tariffs are indispensable if the goal consists in rapidly increasing the contribution of renewable energies to power generation. However, renewable plant operators who have made use of the tariffs when starting generation have the option to drop out of the tariff system whenever selling the generated electricity directly to the market is more profitable, i.e. when the wholesale electricity price is higher than the respective feed-in tariff.

The scenario results indicate that in the long-term the share of renewable electricity that still participates in the FIT scheme varies strongly with the target specification in the EU ETS (cf. Figure 5-17). Thus, in the scenario with the ambitious reduction target of 34 % and accordingly with the highest wholesale electricity prices, the relevance of the tariffs is reduced considerably. In comparison to the reference case, where in 2020 83 % and in 2030 45 % of renewable generation are covered by the FIT system, these shares drop to 57 % in 2020 and 24 % in 2030. On the other hand, if emission trading was not implemented, electricity prices and the associated incentives to leave the tariff system would be significantly lower resulting in high shares of renewable electricity in the FIT scheme of 87 % in 2020 and 61 % in 2030.

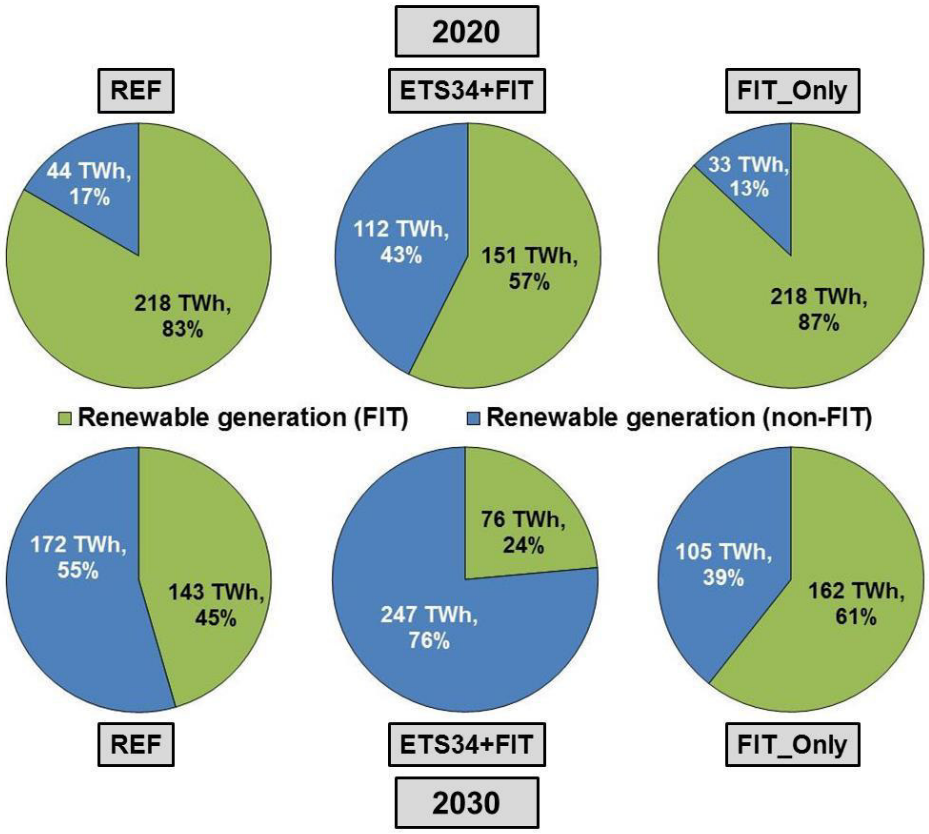


Figure 5-17: Relevance of the FIT system in renewable electricity generation under different assumptions regarding the EU ETS target

The difference in wholesale electricity prices and the importance of the tariff system between the scenarios also affects the relevant cost parameters of the German FIT scheme for renewable electricity (cf. Table 5-16). The payments to renewable plant operators under the system depend on the amount of electricity generated and the share that is still remunerated through the tariffs. Consequently, in 2015 the highest payments are made in the scenario with the 34 %-reduction target which also features the highest renewable generation in this year. In contrast, tariff payments in the scenario FIT_Only are slightly lower in 2015 than in the reference case. In the long-term, the share of renewable electricity still covered by the tariff system is more relevant in determining FIT payments. Hence, in 2030 tariff payments are lowest in the scenario ETS34+FIT even though the highest amount of renewable electricity is generated in this case. Looking at cumulated FIT payments for the period 2000 to 2032, it becomes apparent that with almost 20 billion €$_{2010}$ more than in the reference case, the highest payments arise in the scenario FIT_Only in which renewable electricity generation is lowest but the share participating in the FIT system is highest. As opposed to that, cumulated tariff payments are 14 billion €$_{2010}$ below the reference case in the scenario with the 34 %-target.

In addition to the amount of electricity generated and the relevance of the FIT scheme, FIT differential costs are determined by wholesale electricity prices. As a result, over the entire projected period differential costs are lowest in the scenario ETS34+FIT with the most ambitious ETS mitigation target, whereas without the EU ETS differential costs are constantly higher than in the reference case. Cumulated over the period 2000 to 2032, this results in a difference to the reference case of almost -98 billion €$_{2010}$ for the scenario ETS34+FIT and of +46 billion €$_{2010}$ for the scenario FIT_Only. Thus, due to the differences in wholesale electricity prices, the highest FIT surcharge needs to be paid in the scenario with the lowest renewable electricity generation (FIT_Only), whereas raising the ETS target to 34 % in 2020 helps to reduce the FIT surcharge by 1.3 ct$_{2010}$/kWh in 2020 and 0.1 ct$_{2010}$/kWh in 2030 in relation to the reference case. Yet, it has to be kept in mind that although the surcharge arising from the FIT system is slightly lower, end-user electricity prices are still highest in the scenario ETS34+FIT given the high ETS certificate prices.

Table 5-16: Cost parameters for the FIT system under different assumptions regarding the EU ETS target

		2011	2015	2020	2030	Cumulated (2000-2032)
FIT payments [Bn €$_{2010}$]	REF	16.38	24.1	28.9	8.4	422.4
	ETS34+FIT		25.3	24.4	7.3	408.3
	FIT_Only		22.9	28.6	10.1	442.0
FIT differential cost [Bn €$_{2010}$]	REF	12.05	16.5	18.7	1.7	319.7
	ETS34+FIT		15.8	13.4	1.4	222.0
	FIT_Only		17.5	22.4	4.1	365.8
FIT surcharge [ct$_{2010}$/kWh]	REF	3.45	4.17	4.83	0.46	-
	ETS34+FIT		4.04	3.55	0.37	
	FIT_Only		4.41	5.58	1.08	

5.4.4. Energy system cost

The additional system-wide cost burden that is caused by the implementation of the German FIT scheme for renewable electricity can be assessed in a consistent manner by looking at energy system costs for the different scenarios. These comprise the entire costs of a specific energy system in a certain region and a certain period, covering capital costs for energy conversion and transport technologies, fixed operating and maintenance costs as well as fuel and certificate costs. In general, it can be stated that introducing a specific support system for renewable electricity generation entails a rise in total system cost (cf. Table 5-17). In case of the ETS mitigation target of 21 % for 2020, system costs increase by 33 billion €$_{2010}$ in 2020 and 18 billion €$_{2010}$ in 2030 when the FIT system is accounted for (i.e. reference case compared to scenario ETS21). When cumulated over the period 2013 to 2030, the difference between the scenarios amounts to almost 520 billion €$_{2010}$ of total system cost. For the more ambitious ETS reduction target of 34 %, the impact is only slightly less significant. Once again, it should be noted that this considerable cost increase does not stimulate any additional emission reduction on the European level.

Table 5-17: Comparison of annual undiscounted energy system cost with and without FIT scheme in place under different assumptions regarding the EU ETS target

		2015	2020	2025	2030	Cumulated 2013-2030
REF *vs.* ETS21	Bn €$_{2010}$	31.4	32.9	28.4	18.4	518.6
ETS34FIT *vs.* ETS34	Bn €$_{2010}$	30.0	31.2	26.8	18.8	496.9

5.5 Comparison of different support systems for renewable electricity

In light of the substantial cost increases in the German FIT system in recent years, criticism has become stronger and the question has been raised whether the system could be reformed in a fundamental manner or even replaced by an alternative support measure. In the following, it will be illustrated how a scenario analysis based on the explicit modelling of support mechanisms for renewable electricity can be applied to compare the advantages and drawbacks of these instruments in a quantitative manner.

Therefore, in a first step, two sensitivity analyses are conducted on two critical issues that could be addressed without completely changing the current support mechanism. The cost for the expansion of generation based on solar PV has soared in the last few years such that in 2011 solar photovoltaics was responsible for more than half of total differential cost while generating only 21 % of electricity in the FIT system. Significant tariff cuts have already been executed - yet, in the first sensitivity an even more radical step of completely stopping support for solar PV after 2012 is proposed. It has to be kept in mind, however, that tariff payments for units that have been installed until the end of 2012 have to be continued according to the current FIT provisions.

In a second sensitivity, a look is taken at the special equalisation scheme for electricity-intensive enterprises and rail operators that pay a reduced FIT surcharge. The share of this privileged consumer group in total electricity consumption has risen in recent years, raising at the same time the cost burden on the remaining consumers. Thus, the effects of abolishing this special scheme - both on the privileged and non-privileged consumer groups - are examined in this sensitivity analysis.

In a second step, the performance of alternative support schemes for renewable electricity which could replace the current feed-in tariffs is analysed. The scenarios are established such that with each of them one specific effect relevant in the comparison of these instruments can be quantified. First of all, a technology-neutral FIT system it used to explore the impacts of promoting only the most cost efficient technologies as opposed to the current technology-specific variations in the support level without changing the absolute amount of renewable electricity generated (technology effect). Secondly, in the scope of a quantity-based, technology-neutral tradable green certificate (TGC) scheme the additional effects of reducing the total amount of renewable electricity to the target values of the German Energy Concept are examined (quantity effect). Thirdly, the high potential windfall gains under technology-neutral support systems are addressed by a third scenario with a technology-specific quota system in which the same shares in gross electricity consumption for each renewable source are reached as under the technology-neutral TGC scheme. Hence, in this scenario the targets of the German Energy Concept are still fulfilled in a cost efficient manner, but at the same time the profits of renewable electricity generators are limited (windfall effect).

For each of these sensitivities and alternative scenarios, the performance of the respective support system in terms of renewable electricity and generation cost, support costs, burden on electricity consumers, energy system costs, etc. is contrasted with the reference case. It has to be pointed out that in each case the historical development of the FIT system is accounted for, i.e. it is assumed that all plants installed until the end of 2012 remain in this system and continue to receive the fixed tariffs. The modified support mechanism only applies to new installations from 2013 onwards. For an overview of all the scenarios used to contrast different support schemes for renewable electricity, see Table 5-7.

5.5.1. Adjustments within the current FIT system

Sensitivity analysis: Ceasing the promotion of solar photovoltaics

If the support for solar photovoltaics through the FIT scheme was discontinued by the end of 2012 (sensitivity FIT2012_NoPV), no additional solar PV units would be installed in Germany over the projected period. Consequently, electricity generation from solar energy would remain on the level reached in 2012 of 28 TWh with a slight drop in 2030 as the first installations reach the end of their technical lifetime (cf. Figure 5-18). Thus, in 2015 solar PV generation is 16 TWh lower than in the reference case and the difference increases to almost 22 TWh in 2030. Since the electricity generation based on other renewable sources remains unchanged, the renewable share in gross electricity consumption declines to 43 % in 2020 and 51 % in 2030 - as compared to 46 % and 54 % in the reference case. Hence, the targets of the German Energy Concept are still overfulfilled.

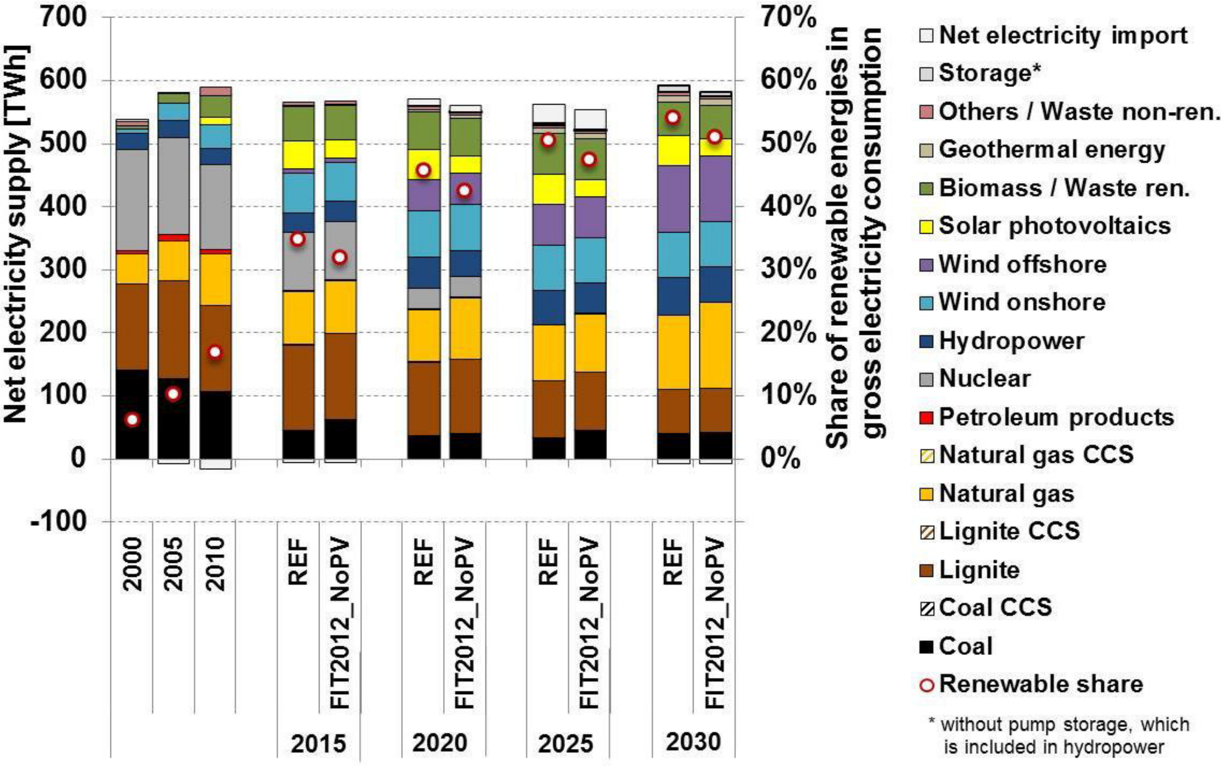


Figure 5-18: Effect of ceasing the promotion of solar photovoltaics on net electricity supply compared with the reference case

The gap in electricity generation caused by the reduced generation from solar energy is covered by fossil fuels. In 2015, generation based on coal is raised by 17 TWh in relation to the reference case by increasing the utilization of existing power plants without requiring new investments. Afterwards, a stronger reliance on natural gas can be observed with a rise of 19 TWh in generation and of 2.4 GW in installed capacity in 2030 when compared to the reference scenario. Moreover, in view of the reduced generation from fluctuating sources, less storage capacities are needed (-1.3 GW) resulting in a decrease in electricity output from storage systems of more than 7 TWh in 2030. This also explains the slightly lower net electricity supply in this sensitivity when contrasted with the reference case.

Ceasing the FIT support for solar photovoltaics could be justified by the goal to alleviate the cost burden of the system given the comparatively high tariff level for solar PV. Table 5-18 gives an overview on the impacts of this sensitivity analysis on the most important cost parameters of the FIT system. On the whole, the results indicate that the differences in relation to the reference case are relatively limited. Without further payments to new solar PV installations from 2013 onwards, total FIT payments would decline almost 25 billion $€_{2010}$ in the period from 2000 to 2032, while for cumulated FIT differential costs the difference amounts to nearly 12 billion $€_{2010}$ or 3.6 % of total differential costs in the reference case. With respect to the FIT surcharge, a significant reduction is only realized in 2020 with -0.46 ct_{2010}/kWh compared to the reference. This effect can be partly explained by a slightly higher wholesale electricity price in this sensitivity in 2020 resulting in a diminution in differential cost and the associated surcharge.

Table 5-18: Change in cost parameters for the FIT system in the sensitivity without promotion of solar photovoltaics compared with the reference case

		2015	2020	2030	Cumulated (2000-2032)
FIT payments	FIT2012_NoPV	23.4	28.0	7.2	397.8
[Bn $€_{2010}$]	*Difference to REF*	*-0.69*	*-0.89*	*-1.25*	*-24.6*
FIT differential cost	FIT2012_NoPV	16.4	16.9	1.5	308.2
[Bn $€_{2010}$]	*Difference to REF*	*-0.07*	*-1.82*	*-0.23*	*-11.5*
FIT surcharge	FIT2012_NoPV	4.14	4.37	0.40	-
[ct_{2010}/kWh]	*Difference to REF*	*-0.02*	*-0.46*	*-0.06*	

Hence, it can be concluded that terminating feed-in tariff payments for new solar PV units after 2012 would yield no substantial benefits in terms of reducing the overall costs of the FIT system. Looking at the results from Table 2-5 and Table 5-11 indicates that on the basis of the trajectory from the reference case, new solar PV installations from 2013 onwards would only be responsible for about 9 % of total cumulated FIT differential cost for solar energy over the period 2000 to 2032. Thus, the enormous tariff cuts - both those executed in recent years and those that can be expected in the near future - in combination with the absolute limit on capacity that will receive support at 52 GW have helped to keep down the cost burden caused by additional solar PV investments in the future. In contrast, considerable costs will still have to be incurred in the future for units that have been installed before 2013, assuming that tariff payments are guaranteed for existing installations.

Accordingly, comparatively insignificant impacts on end-user electricity prices and consumption arise when ceasing the support for solar photovoltaics from 2013 onwards (cf. Figure 5-19). With respect to private households and non-privileged industry consumers, the most noticeable effect takes place in 2020, where electricity prices fall by 2.5 % to 3.2 % compared to the reference case. In all other modelling periods, the differences remain below 0.5 %. The associated changes in electricity consumption are negligible over the entire projected period.

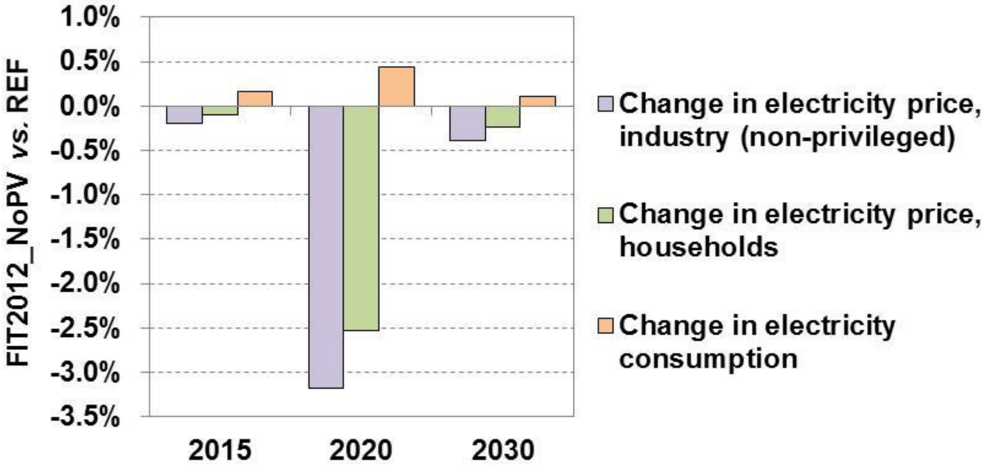


Figure 5-19: Effect of ceasing the promotion of solar photovoltaics on electricity prices and consumption compared with the reference case

Sensitivity analysis: Abolishing the special equalisation scheme for electricity-intensive enterprises and rail operators

A rise in electricity prices raises concerns regarding the competitiveness of the domestic industry. That is why in the German FIT system, an equalisation scheme has been implemented for electricity-intensive companies and rail operators that pay for the majority of their consumption a reduced FIT surcharge of 0.05 ct/kWh. However, the amount of electricity that is included in this privileged scheme has risen steadily in recent years from about 37 TWh in 2004 to 96 TWh in 2013 (cf. BMU 2012c and ÜNB 2012b) simultaneously raising the regular FIT surcharge for the remaining consumers. Thus, as part of a strategy to diminish the overall impact of the tariff system on electricity prices, a proposal has been launched by the German Minister of the Environment to reduce the number of beneficiaries of the special equalisation scheme (cf. BMWi and BMU 2013). The following sensitivity analysis (FIT2012_NoES) explores the extreme example of completely abolishing the special equalisation scheme such that all electricity consumers have to pay the same surcharge. It has to be pointed out that in the reference case the reduced surcharge is applied to all energy-intensive industry branches in the model whose electricity consumption amounts to about 70 to 76 TWh in this scenario in the projected period.

The scenario results show that ending the special equalisation scheme has, as can be expected, no impact on the amount of renewable electricity generation. Yet, differences arise when calculating the FIT surcharge (cf. Table 5-19).

Table 5-19: Impact of abolishing the special equalisation scheme for electricity-intensive enterprises and rail operators on the FIT surcharge compared with the reference case

	Unit	2015	2020	2025	2030
1. Total FIT payments	Bn €$_{2010}$	24.1	28.9	23.1	8.4
2. Revenues from privileged electricity consumers	Bn €$_{2010}$	0.000	0.000	0.000	0.000
3. Revenues from marketing	Bn €$_{2010}$	7.6	11.2	10.2	6.7
4. Deficit to be covered by the surcharge (=1.-2.-3.)	**Bn €$_{2010}$**	**16.5**	**17.7**	**12.9**	**1.7**
5. Total electricity consumption	TWh	469	464	444	445
6. FIT surcharge (in real terms) (=4./5.)	**ct$_{2010}$/kWh**	**3.52**	**3.81**	**2.90**	**0.39**
Difference to REF	***ct$_{2010}$/kWh***	***-0.65***	***-1.02***	***-0.61***	***-0.07***
7. FIT surcharge (in nominal terms)	**ct/kWh**	**3.93**	**4.77**	**4.07**	**0.61**
Difference to REF	***ct/kWh***	***-0.73***	***-1.28***	***-0.85***	***-0.11***

First of all, the revenues for privileged consumers drop to zero which results only in a negligible increase in the differential costs that need to be covered by the regular surcharge. More importantly, the electricity consumption over which these differential costs are spread is extended to include the energy-intensive industry and is therefore in the entire modelling period around 20 % or 75 TWh higher than in the reference case. The associated decrease in the FIT surcharge lies between 16 % and 21 % in relation to the reference case. In absolute terms, the largest reduction is realized in 2020 with 1.0 ct$_{2010}$/kWh. Hence, by abolishing the special equalisation scheme for electricity-intensive companies and rail operators, the peak in the FIT surcharge in 2020 can be lowered from 4.8 ct$_{2010}$/kWh (6.0 ct/kWh in nominal terms) in the reference case to 3.8 ct$_{2010}$/kWh (4.8 ct/kWh). Towards the end of the projected period, the differences get less pronounced in absolute terms as the FIT surcharge is declining in general.

Thus, the modelling results show that without the special equalisation scheme the costs for non-privileged consumers could be diminished considerably by raising at the same time the burden on energy-intensive industries. This is also reflected in the development of electricity prices (cf. Figure 5-20). A substantial increase in the previously privileged sectors between 31 % and 37 % is opposed to a slight decrease for the non-privileged consumer groups of 3 % to 5 % with respect to the reference case. The resulting changes in electricity consumption are also depicted in Figure 5-20. Relatively strong adjustments can be observed in the energy-intensive industry sectors. While in 2015, where due to the closeness in time the required flexibility to adapt production processes is not given, electricity consumption in these sectors drops by only 2.5 % in relation to the reference case, the relative difference rises to more than 9 % until 2030. These reductions occur mainly in the iron and steel as well as the pulp and paper industries. In contrast, given the less pronounced changes in the price level, the rise in electricity consumption in the non-privileged industry sectors and private households remains below 1 %. In total, electricity consumption is therefore slightly lower in the sensitivity without special equalisation scheme than in the reference case.

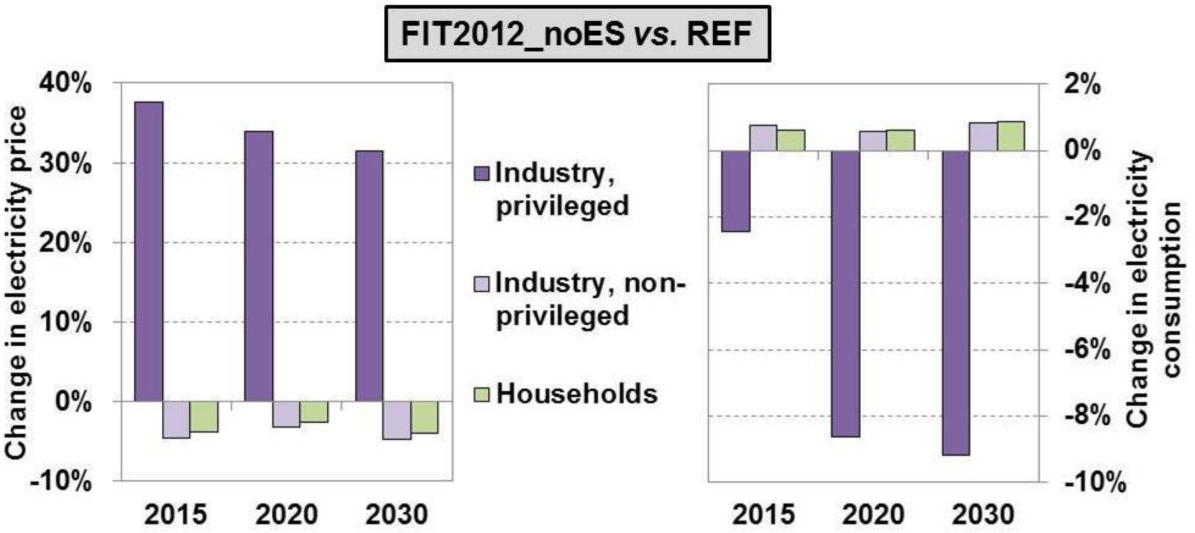


Figure 5-20: Change in electricity prices and consumption when abolishing the special equalisation scheme for electricity-intensive enterprises and rail operators compared with the reference case

Considering the already comparatively high electricity price level in Germany, an additional increase through the FIT surcharge entails the risk of energy-intensive industries migrating to other countries where production is less costly. In the model, the decline in production in Germany due to a loss in competitiveness can only be estimated in a rough manner on the basis of the own-price elasticities assigned to the various demand commodities. This approach yields rather low adjustments in the production level of the energy-intensive industry branches when they have to pay the full FIT surcharge (cf. Figure 5-21).

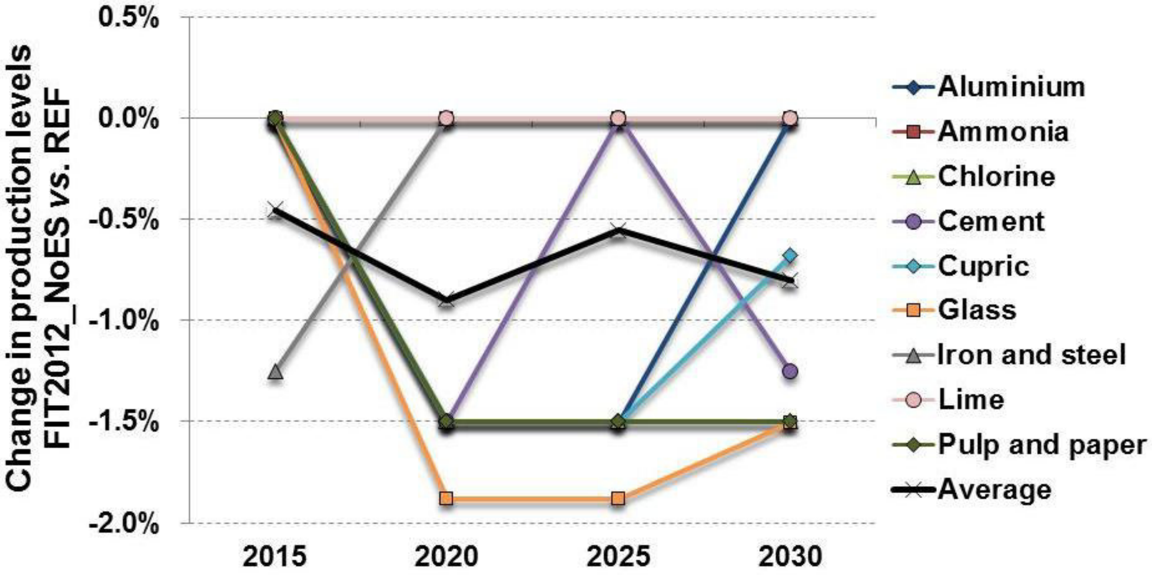


Figure 5-21: Change in production levels in energy-intensive industry branches when abolishing the special equalisation scheme for electricity-intensive enterprises and rail operators compared with the reference case

On average, the relative reduction compared to the reference case lies between 0.4 and 0.9 % over the projected period. The changes are more pronounced in sectors where the substitution of electricity by other energy carriers poses a greater difficulty, as for example in the glass industry. Yet, once again it has to be pointed out that these results only provide an indication of the impacts on production levels of energy-intensive industries when increasing the electricity price level due to the implementation of a national support scheme for renewable electricity. Additional modelling approaches, like for example CGE models, are required to evaluate issues concerning the international competitiveness of domestic industries.

5.5.2. Comparison of alternative support schemes for renewable electricity

The electricity sector

Instead of making adjustments in the current technology-specific FIT system in Germany, it could be considered to completely replace it with an alternative support scheme for renewable electricity. In the following analysis, it is assumed that this switch takes place in 2013, while all generation units that have been installed until the end of 2012 remain in the old tariff system. In order to compare the performance of the various modelled schemes with the feed-in tariffs in the reference case, first of all a look is taken at the generation side.

In the scenario FIT_Neut, a technology-neutral FIT system is implemented, meaning that all renewable sources receive a uniform tariff. The tariff level is set such that the same absolute amount of renewable electricity generation is stimulated in each modelling period as in the reference case. In that manner, the technology effect, i.e. the impact of promoting only the most cost efficient technologies, can be examined in an isolated fashion. In the model, such a support system is introduced by putting in a first step a lower bound on total renewable electricity generation containing the absolute amounts of generation from the reference case. Thus, the optimization approach is free to choose the most cost efficient way to fulfil these minimum requirements. From the results of this scenario run, the uniform tariff - given as the shadow price of the bound on renewable generation - and the associated surcharge on end-user electricity prices can be calculated. This FIT surcharge is then put into the model in order to account for the effects on the demand side. As it was the case in the reference scenario, an iterative process is required to balance the FIT payments and the surcharge.

From the scenario results on renewable electricity generation shown in Figure 5-22 it becomes apparent that switching to a technology-neutral support system leads to significant shifts in the structure of renewable electricity. Heavier reliance is put on comparatively low-cost technologies based on onshore wind energy and solid biomass. After 2015, onshore wind generation is raised considerably with a difference of 15 TWh (20 %) in 2020 and of 38 TWh (53 %) in 2030 in relation to the reference case. That means that also less favourable locations are exploited, which are not funded under the current German FIT scheme. In 2030, the ceiling of 110 TWh specified in the model for the maximum expansion of generation from onshore wind energy is reached. In the case of biomass, additional large energy-only and

CHP plants based on solid biomass that receive no or only relatively low tariffs in the present system are installed. Accordingly, electricity generation from solid biomass rises to 46 TWh until 2030 constituting an increase with respect to the reference case of 19 TWh (70 %). By contrast, fewer investments are made in more costly generation technologies. Most importantly, no additional solar PV units are installed after 2012 such that the generation from solar energy decreases by about 20 TWh in 2020 and 2030 when compared with the reference case. Small-scale biogas plants are also affected by the technology-neutral scheme with a decline of about 15 TWh in 2030. With respect to offshore wind energy, almost the same growth can be observed until 2025, whereas in 2030 generation remains about 17 TWh below the reference case. With the increase in onshore wind and the decrease in solar photovoltaics and offshore wind generation, the share of fluctuating sources in total renewable electricity generation remains with 71 % in 2030 almost unchanged in relation to the reference case. In general, the results show that even when the most cost efficient trajectory is chosen, the high shares of renewable electricity which result for the current German FIT system in this scenario analysis cannot be reached without some contribution from more costly technologies, like offshore wind farms.

That is why in a next step, the feed-in tariff systems are contrasted with quantity-based tradable green certificate schemes which have the advantage that compliance with the previously set target values can be guaranteed. Thus, in these scenarios, the effect of reducing renewable generation to the levels defined in a political decision-making process can be assessed. The relatively straightforward modelling approach is based on user-defined constraints specifying minimum renewable shares in total electricity generation. In the scenario QU_Neut, a single constraint is put on the entire renewable generation comprising the target values of the German Energy Concept[18]. In this way, through the optimization calculus the most cost efficient manner of achieving the targets is determined and a uniform certificate price, defined by the generation costs of the marginal (and most expensive) generation unit needed to fulfil the quota, arises. In contrast, in the scenario QU_Spec a technology-specific quota system is implemented. The model contains therefore a constraint for each renewable source stating its relative share in total electricity generation. These shares are taken from the scenario QU_Neut such that also with the technology-specific scheme the overall renewable targets are complied with in the most cost efficient manner. The difference consists, however, in the design of the support system. Based on the specific targets, a different certificate price is created for each renewable source reflecting its marginal generation costs. Consequently, with this scenario the advantages of a technology-specific scheme in terms of limiting the profits of renewable generators can be evaluated. Instead of a TGC scheme, these scenarios could also be understood as technology-neutral or -specific tendering procedures in which the renewable shares are assigned through a bidding process in each modelling period.

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[18] The German Energy Concept specifies target values for the renewable share in gross electricity consumption of 35 % for 2020 and 50 % in 2030. For 2015 and 2025, the values in the model are based on linear interpolation (between 2012 and 2020 / 2020 and 2030).

As can be observed in Figure 5-22, due to the scenario specifications the development of renewable electricity generation until 2030 is almost similar in the scenario QU_Neut and QU_Spec. As with the quantity-based support systems the targets of the German Energy Concept are precisely complied with, renewable electricity generation drops by a quarter (66 TWh) in 2020 and by 11 % (36 TWh) in 2030 compared to the reference case.

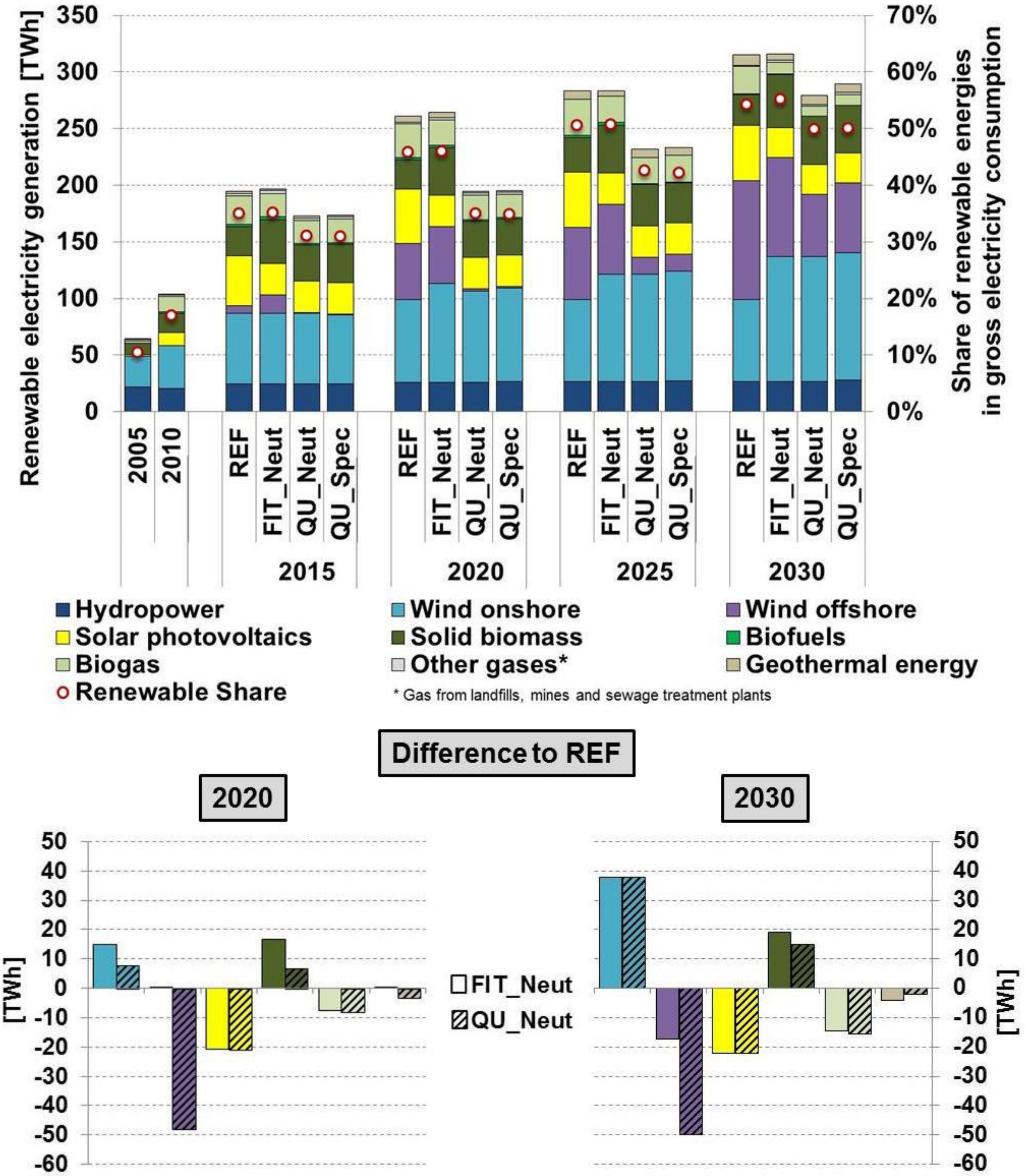

Figure 5-22: Comparison of renewable electricity generation in the scenarios with different support schemes for renewable electricity

With respect to the composition of renewable electricity generation, some similarities with the scenario featuring the technology-neutral FIT scheme (FIT_Neut) are discernible. The maximum growth potential for onshore wind generation is fully exploited, while the expansion of solar PV comes to a complete stop. The lower overall generation level compared to scenario FIT_Neut affects in particular the development of offshore wind energy. Until 2020, hardly any investments in offshore wind plants are realized; only in 2030 a significant increase to about 55 TWh occurs. Thus, with a quota system for renewable electricity, offshore wind generation remains about 50 TWh below the level of the reference case and 33 TWh below the level of the scenario with a technology-neutral FIT scheme in 2030. Accordingly, the contribution of onshore wind energy rises to 39 % in 2030 (compared to 23 % in the reference case), whereas offshore wind energy covers only 20 % (33 % in the reference case) of total renewable generation. At the same time, the scenario results show that with the chosen assumptions on the renewable potentials an exploitation of offshore wind energy is required even when reducing generation from renewable sources to the target levels of the German Energy Concept. With respect to biomass, the same trends are observable as in the scenario FIT_Neut, i.e. an increase in large-scale generation based on solid biomass at the cost of biogas. Since the assumed potentials for electricity generation from geothermal energy are rather limited, the differences between the scenarios are negligible. The slightly higher renewable generation level in the scenario QU_Spec compared to QU_Neut can be attributed to the somewhat higher electricity consumption in this scenario. On the whole, the scenario comparison at hand indicates that when strictly adhering to the principle of cost efficiency the development of renewable electricity in Germany changes considerably. With an increased contribution of onshore wind energy and solid biomass at the expense of solar photovoltaics, offshore wind energy and biogas, the heterogeneity of renewable generation is reduced slightly.

Furthermore, changing the support system for renewable electricity might have repercussions on conventional electricity generation. In accordance with the scenario definition, in the scenario featuring a technology-neutral FIT system the same absolute amounts of electricity are generated by renewable energies as in the reference case such that the rest of the generation remains almost entirely unchanged. Yet, the reduced renewable shares in the scenarios with the quantity-based TGC system require an increased contribution of conventional generation. In Figure 5-23, the differences to the reference case are exemplified on the basis of scenario QU_Neut, as between the scenarios with the technology-neutral and -specific quota system no notable deviations are discernible. With the quota system, the share of fossil fuels in total net electricity supply rises to 56 % in 2020 and 45 % in 2030 - as compared to 42 % and 38 % in the reference case. In 2020, the overall increase of 69 TWh is mainly based on coal (25 TWh) and natural gas (36 TWh), while in 2030 the difference of 34 TWh is mainly covered by natural gas. With respect to lignite, generation is expanded by about 8 TWh in both years. In the case of lignite and coal, no additional capacities need to be installed, whereas the installed capacity of gas-fired power plants is raised by 3 GW until 2030. Apart from that, the reduced share of fluctuating generation causes a decline in the electricity output from storage systems of 17 TWh in 2020 and 12 TWh in 2030 in relation to the reference case.

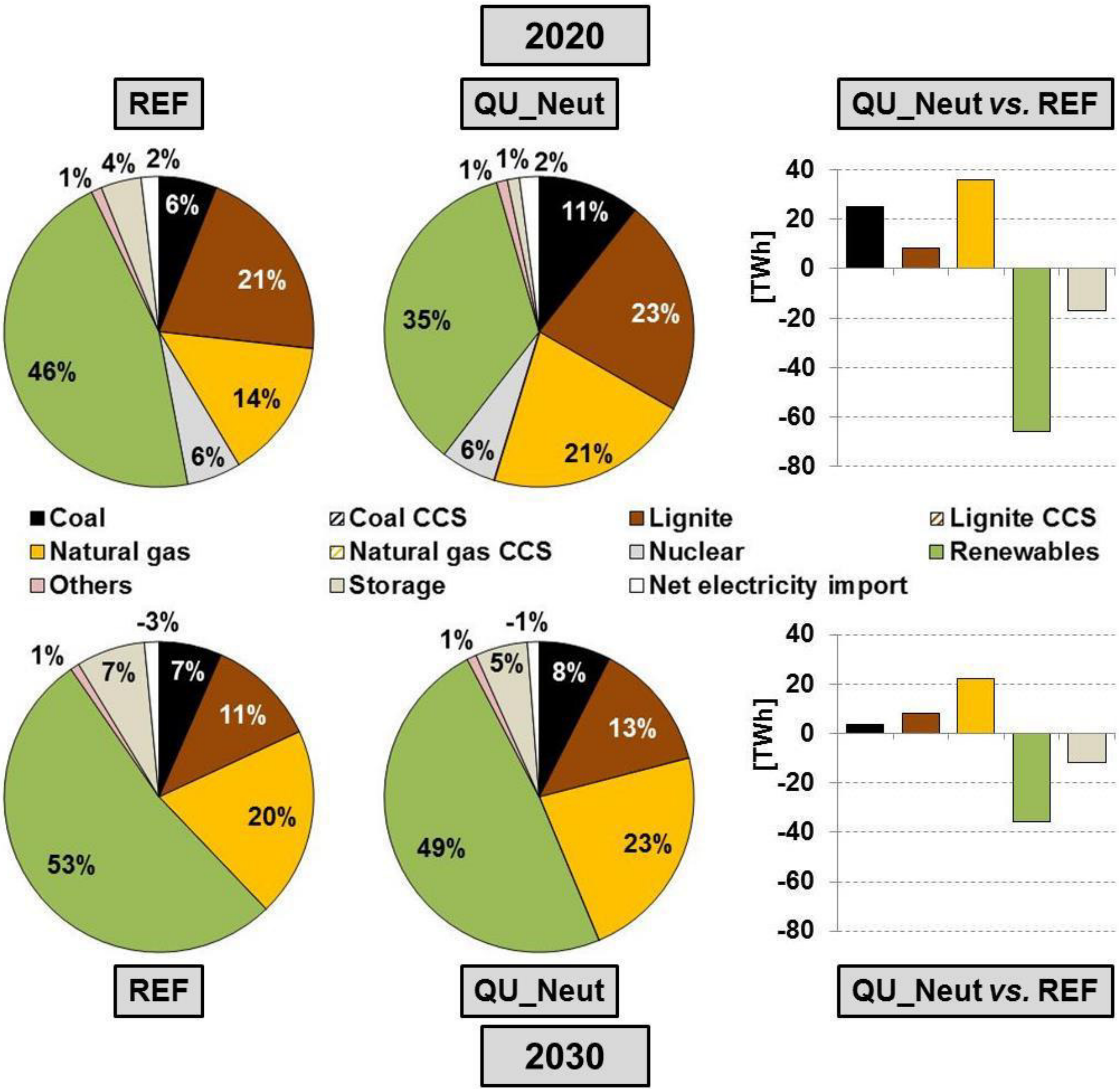

Figure 5-23: Comparison of the structure of total net electricity supply between the reference case and the scenario with a quota system for renewable electricity

One of the most important criteria that should be adhered to when designing a support system for renewable electricity is cost efficiency. Insights on how the different instruments modelled in this scenario analysis perform in this respect can be gained by looking at generation cost for renewable electricity. Figure 5-24 includes the cost of all generation units that have been installed from 2013 onwards[19]. The most substantial differences to the reference occur both with the technology-neutral FIT system and the TGC schemes for solar photovoltaics. In this case, generation costs are lowered between 6 and 7 billion €$_{2010}$ in each modelling period resulting in a cumulated reduction of around 120 billion €$_{2010}$ between 2013 and 2030. As far as offshore wind energy is concerned, considerable cost decreases of almost 6 billion €$_{2010}$ per year between 2020 and 2030 are only realized in the scenarios with quota system, in which generation based on offshore wind power falls significantly compared to the reference

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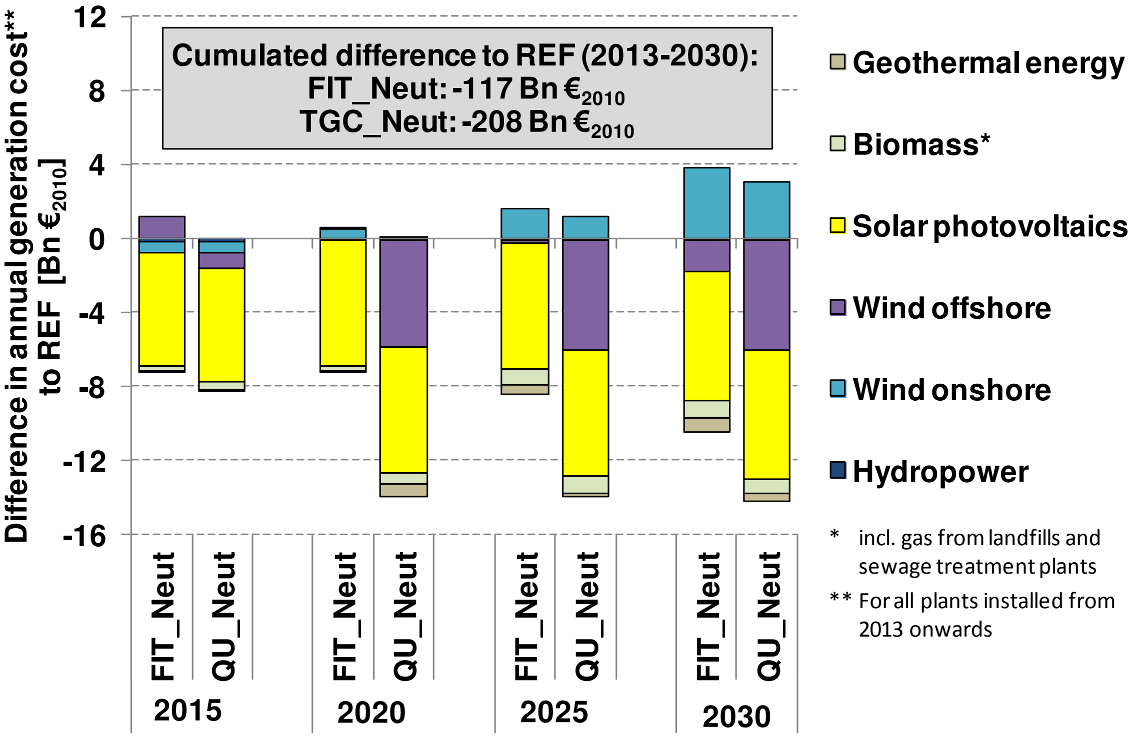
[19] With respect to the quota systems, Figure 5-24 depicts only scenario QU_Neut as per scenario definition renewable generation and the associated generation costs are almost similar in the scenarios with the technology-neutral and -specific TGC scheme.

case. These reductions are opposed to cost increases in the case of renewable sources where generation is raised. However, due to the fact that only the most cost efficient technologies are expanded, these increments are comparatively low. The additional installation of onshore wind farms entails a rise in cumulated generation costs of 19 billion €$_{2010}$ in the period from 2013 to 2030 in the scenario FIT_Neut in relation to the reference case. The fact that these costs are slightly lower in the scenario QU_Neut can be explained by the deferment of part of the expansion to later modelling periods, where investment costs have already fallen in line with the assumed learning rates.

With respect to biomass, two contrasting impacts have to be considered. Generation costs are raised in the case of large-scale units based on solid biomass, while cost savings are realized for biogas plants. Since the latter effect prevails, in total a slight cost reduction can be observed for electricity generation from biomass both in the scenario with technology-neutral FIT scheme and for the quota system. Altogether, generation costs for renewable electricity decrease considerably when the current German FIT system is replaced by an alternative support scheme that is more strongly oriented on the principle of cost efficiency. For all renewable generation units installed from 2013 onwards, cumulated generation costs are reduced by 117 billion €$_{2010}$ over the period from 2013 to 2030 in the scenario FIT_Neut in relation to the reference case. If, in addition, the amount of renewable generation is lowered to the targets of the German Energy Concept, this cost difference adds up to 208 billion €$_{2010}$.



* incl. gas from landfills and sewage treatment plants

** For all plants installed from 2013 onwards

Figure 5-24: Difference in generation cost for renewable electricity generation between the technology-neutral feed-in tariff scheme and quota system in relation to the reference case

Additional information on the cost differences between the scenarios can be obtained from the average (across all renewable sources) generation costs per unit of renewable electricity generated. Here, the values depicted in Figure 5-25 for each modelling period comprise only those generation units that have been installed in the respective period. With the exception of hydropower, cost reductions due to learning effects are assumed for all renewable technologies in the model. This is reflected in a steady decline in specific renewable generation cost in the reference case from 10.9 ct_{2010}/kWh in 2015 to 6.6 ct_{2010}/kWh in 2030. The relatively high level in 2015 could be clearly lowered if only the most cost efficient technologies were promoted. The reduction to 8.1 ct_{2010}/kWh with the technology-neutral FIT system and to 6.9 ct_{2010}/kWh with the quota systems in 2015 can be mainly attributed to the fact that no additional solar PV units are installed. In the scenario FIT_Neut, a slight increase in the average renewable generation costs occurs between 2015 and 2020 which can be explained by the strong expansion of offshore wind energy, which does not take place with the reduced overall growth in renewable generation under the quota systems. For all plants installed from 2025 onwards, specific generation costs are on average almost similar under the various alternative schemes. The difference to the reference case decreases to about 1.4 ct_{2010}/kWh in 2030.

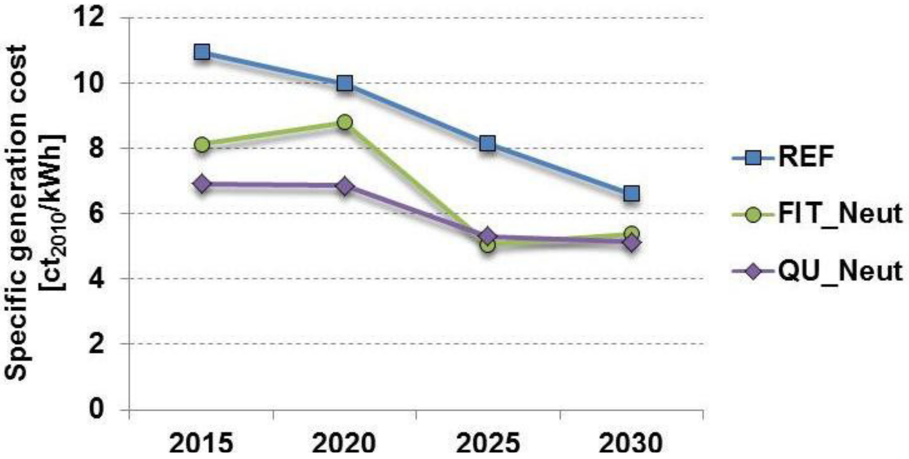


Figure 5-25: Average specific generation cost of all renewable electricity generation plants installed in the respective model year under different support schemes

The support system for renewable electricity

The expansion of renewable electricity generation in Germany causes additional costs for the electricity system - irrespective of the chosen support system. In the present scenario analysis it is assumed that under all modelled support instruments these costs are financed through a levy on end-user electricity prices, just as it is the case under the current German FIT scheme. Moreover, it has to be pointed out that the special equalisation scheme for electricity-intensive companies and rail operators, which constitutes a singular feature of the Germany system, is not taken into account in the alternative support systems. Thus, in some cases, the sensitivity FIT2012_NoES is used as basis for comparison instead of the reference case.

Figure 5-26 provides a comparison of the various forms of remuneration under the different promotional instruments which apply to all renewable generation plants that are installed from 2013 onwards. Until 2012, the present German FIT system is in force in all scenarios. For the case of the technology-neutral FIT scheme, the model calculations deliver a fixed feed-in premium which is paid on top of the wholesale electricity price. For the TGC schemes, the shadow price of the relative bound on renewable generation can be interpreted as the certificate price that would arise on the market for renewable certificates.

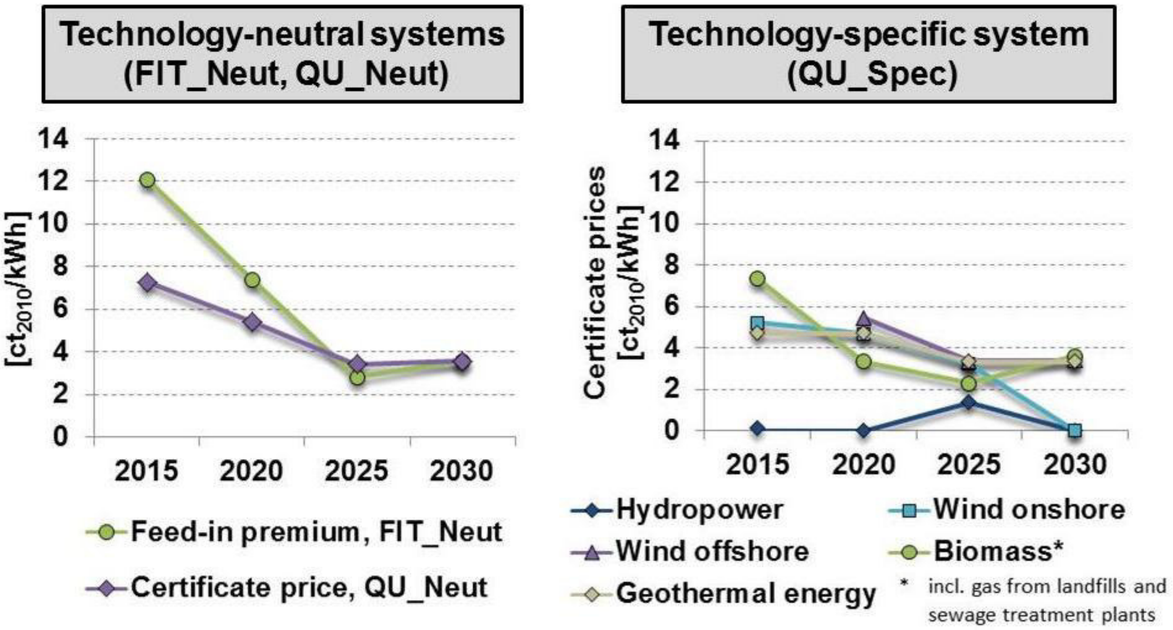


Figure 5-26: Additional remuneration for renewable electricity under different support schemes (feed-in premium in FIT_Neut and certificate prices in QU_Neut and QU_Spec)

In a technology-neutral support scheme, the remuneration per unit of renewable generation is defined by the generation costs of the marginal unit that is needed to satisfy the target. Hence, the uniform payment that all renewable plant operators receive is substantially higher than average renewable generation costs. Accordingly, a high initial feed-in premium of about 12 ct_{2010}/kWh is realized in the scenario with the technology-neutral FIT system. Afterwards, a rapid decline of the premium to 2.8 ct_{2010}/kWh in 2025 followed by a slight increase until 2030 can be observed. If renewable generation was reduced to the target level of the German Energy Concept, the remuneration for renewable generators could be lowered considerably. This is reflected in the difference between the feed-in premium in the scenario FIT_Neut and the uniform certificate price under the technology-neutral quota system of 4.8 ct_{2010}/kWh in 2015 and almost 2 ct_{2010}/kWh in 2020. After 2020, nearly the same remuneration level ensues in both scenarios.

In a technology-specific support system different payment levels arise for the various technology categories. In the technology-specific TGC scheme modelled in the scope of this scenario analysis, the certificate prices for each renewable source are determined by the marginal generation unit in each category. This gives rise to substantial variations in the remuneration level for renewable electricity. The payments needed to promote the exploitation of the remaining hydropower potential in Germany are close to zero over the entire projected period with the exemption of a certificate price of 1.4 ct_{2010}/kWh in 2025. In the case of onshore wind energy, the certificate price drops gradually from 5.2 ct_{2010}/kWh in 2015 to zero in

2030. As the expansion of offshore wind farms is delayed in the scenarios with quota system, a certificate price for this category is only created from 2020 onwards. It amounts in 2020 to 5.5 ct_{2010}/kWh and falls to 3.4 ct_{2010}/kWh in 2030. The highest price level of 7.3 ct_{2010}/kWh arises in 2015 for electricity generation based on biomass. This can be explained by the fact that since for most of the other (less expensive) renewable sources the potential limits are already reached in 2015, relatively costly options based on biogas need to be drawn upon in order to reach the renewable target. After a significant decrease in 2020 and 2025, biomass again sets the highest certificate price in 2030 with 3.6 ct_{2010}/kWh. Given the relatively low learning effects assumed for geothermal electricity generation in the model, the certificate price declines only slightly from 4.7 ct_{2010}/kWh in 2015 to 3.3 ct_{2010}/kWh in 2030. Moreover, on the basis of the technology-specific design of the quota system, it can be ascertained which renewable category determines the uniform certificate price in the technology-neutral quota scheme (biomass in 2015 and 2030, offshore wind in 2020 and 2025).

The additional remuneration that is required to stimulate renewable electricity generation in Germany defines the differential costs that electricity consumers need to incur under the different support systems. In the following, it will be shown that implementing a system which causes lower renewable generation costs does not automatically entail a lower cost burden for consumers. In this context, it has to be noted that under a technology-neutral FIT system and under different types of quota systems, renewable plant operators have no incentive to leave the support scheme as long as the uniform feed-in tariff is higher than the wholesale electricity price or as long as the certificate price is above zero.

Accordingly, in the scenarios that feature a technology-neutral system (FIT_Neut and QU_Neut) the entire renewable electricity generation from units that are installed from 2013 onwards remains in this system and receives the corresponding payments. Due to the relatively high uniform FIT premium or certificate price, this leads to considerable increases in differential costs in the case of renewable technologies with relatively low investment costs (cf. Figure 5-27). For onshore wind energy, for example, higher differential costs than under the current German FIT system emerge in the scenarios FIT_Neut and QU_Neut from 2020 onwards. The cost difference rises to around 3.9 billion €$_{2010}$ in 2030, when under the present technology-specific scheme in Germany the entire onshore wind generation has dropped out of the system. The same applies to hydropower, although the cost increase is rather limited. These increments can be largely avoided with a technology-specific quota system where the certificate prices for onshore wind energy and hydropower drop to zero in 2030.

A differentiated picture arises for offshore wind energy. Until 2025, differential costs for the expansion of offshore wind farms can be reduced with respect to the reference case in the various alternative support schemes, with the lowest cost savings in the scenario FIT_Neut and the highest in QU_Spec. However, in 2030 differential costs for offshore wind energy rise between 2.1 and 3.1 billion €$_{2010}$ compared to the current German FIT scheme. This is due to the fact that under all the alternative support systems the entire offshore wind generation is still covered by the system, while in the reference case for part of the wind farms that have been installed in or before 2020 and have already reached the low basic tariff there is an incentive to directly sell the electricity to the market. Clear cost savings in the entire modelling period are achieved in the case of solar photovoltaics as no additional units are installed after 2012 under any of the alternative instruments. For biomass, a strong increase in differential costs occurs in 2015 under the technology-neutral FIT system due to the high uniform tariff level in this scenario. Apart from that, limited cost reductions with respect to the reference case prevail in all scenarios given the comparatively high remuneration for electricity generation based on biomass in the current German FIT scheme. On the whole, with the technology-neutral feed-in tariffs, differential costs are higher than in the reference case in all modelling periods except 2025, while for the quota systems cost savings can be realized until 2025 followed by a substantial cost increase in 2030.

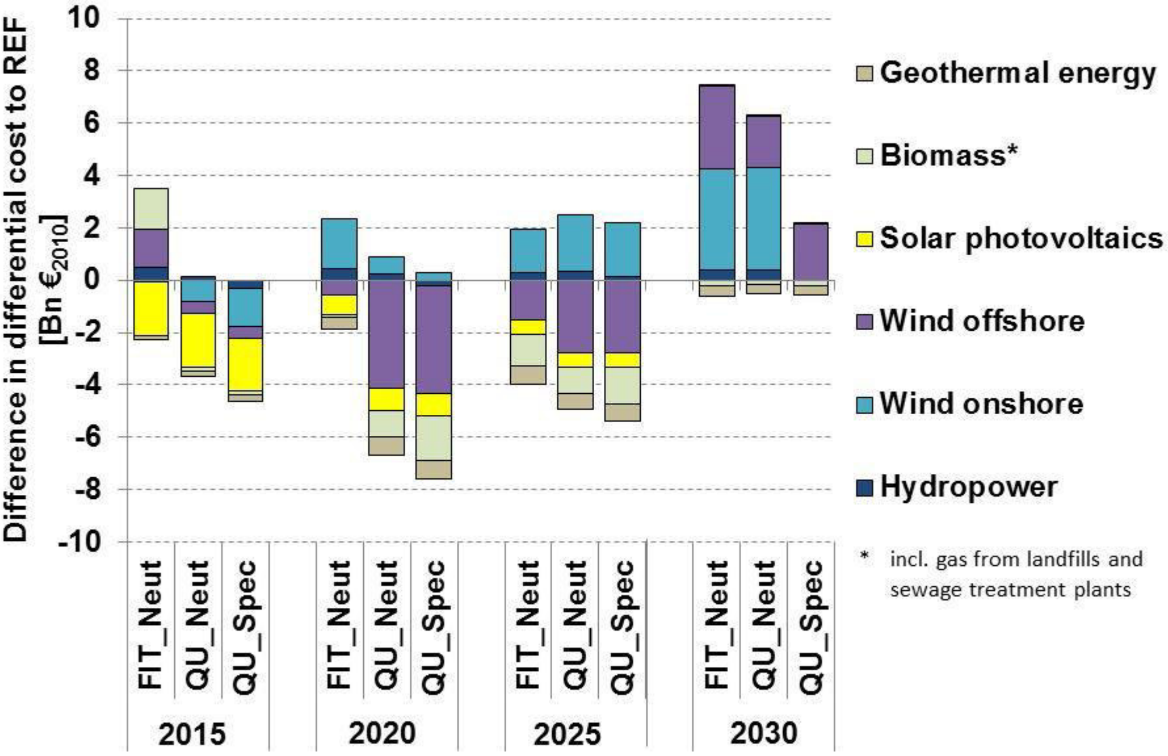


Figure 5-27: Difference in differential cost arising from the various support schemes for renewable electricity compared to the reference case

In order to obtain a clearer picture on the impacts of changing the support system for renewable electricity on the cost burden for electricity consumers, the cumulated differential costs for the period 2000 to 2032 are put together in Table 5-20. It has to be noted that in all scenarios the costs arising from the current FIT system for units installed until the end of 2012 are included for the entire model period. As far as the scenario with the technology-neutral tariff scheme is concerned, cumulated differential costs exceed those that result from the existing German system for all renewable sources except solar photovoltaics and geothermal energy. In light of the high uniform tariff level, increases occur especially for low-cost technologies based on onshore wind energy (+37 billion $€_{2010}$) and hydropower (+8 billion $€_{2010}$).

Thus, in total, cumulated differential costs rise by almost 33 billion €$_{2010}$ when substituting the current tariff scheme by a technology-neutral FIT system - as opposed to a reduction in generation costs for renewable electricity of 117 billion €$_{2010}$ from 2013 to 2030 between the two scenarios.

An increment in cumulated differential costs for the low-cost categories hydropower and onshore wind energy can also be observed for the technology-neutral quota system. Yet, cost savings are realized for all other renewable sources, most strikingly in the case of offshore wind energy with 27 billion €$_{2010}$. The resulting decline in total cumulated differential costs over the period 2000 to 2032 of 30 billion €$_{2010}$ is, however, rather limited when compared with the reduction in renewable generation costs of 208 billion €$_{2010}$ between the scenario QU_Neut and the reference case. Based on the differentiation in the tariff structure, differential costs can be lowered substantially under the technology-specific quota system, with only a slight increase for onshore wind power. Altogether, the reduction in cumulated differential costs in relation to the reference case adds up to 68 billion €$_{2010}$ from 2000 to 2032.

Table 5-20: Cumulated differential cost under different support schemes for renewable electricity compared to the reference case

Cumulated differential cost, 2000-2032 [Bn €$_{2010}$]	**Hydro-power**	**Wind onshore**	**Wind offshore**	**Solar photovoltaics**	**Biomass***	**Geothermal energy**	**Total**
FIT_Neut	13.5	84.1	52.9	110.1	87.3	4.7	**352.5**
Difference to REF	*7.9*	*36.9*	*12.4*	*-16.5*	*0.4*	*-8.4*	***32.8***
QU_Neut	11.3	76.5	13.9	109.3	74.9	3.8	**289.7**
Difference to REF	*5.8*	*29.3*	*-26.6*	*-17.3*	*-12.0*	*-9.3*	***-30.0***
QU_Spec	3.4	51.7	14.7	109.3	69.3	3.4	**251.8**
Difference to REF	*-2.2*	*4.5*	*-25.8*	*-17.3*	*-17.6*	*-9.7*	***-68.0***

* incl. gas from landfills and sewage treatment plants

The changes in differential costs are reflected in the development of the surcharge that is levied on electricity consumption to finance the additional costs of the respective support scheme for renewable electricity (cf. Table 5-21). Here, the sensitivity featuring the current German FIT system without special equalisation scheme for electricity-intensive companies and rail operators is more suitable as basis for the comparison as this special scheme is not accounted for in the scenarios with the alternative support systems. In addition, the differences to the reference case, reflecting the actual regulation in force, are presented as well.

When replacing the current feed-in tariffs (without special equalisation scheme) with a technology-neutral FIT system, the renewable surcharge on final electricity prices rises in all modelling periods except 2025. With 1.5 ct$_{2010}$/kWh the increase is most pronounced in 2030, when under the present tariff scheme more than half of the renewable generation is no longer covered by the system. In 2015 and 2020, the differences amount to less than 0.5 ct$_{2010}$/kWh. A more positive picture arises from the comparison with the reference case. This does, however, only reflect the additional effect of abolishing the special equalisation scheme already described in the sensitivity analysis FIT2010_NoES. In nominal terms, the surcharge reaches a peak of 5.1 ct/kWh in the scenario FIT_Neut in 2020.

Table 5-21: Surcharge on final electricity prices arising from different support schemes for renewable electricity compared to the reference case (with and without special equalisation scheme)

FIT_Neut					
	Unit	**2015**	**2020**	**2025**	**2030**
In real terms	**ct$_{2010}$/kWh**	**3.99**	**4.08**	**2.40**	**1.91**
Difference to FIT2012_NoES	*ct$_{2010}$/kWh*	*0.48*	*0.27*	*-0.51*	*1.52*
Difference to REF	*ct$_{2010}$/kWh*	*-0.17*	*-0.75*	*-1.11*	*1.45*
In nominal terms	**ct/kWh**	**4.46**	**5.10**	**3.36**	**3.00**
QU_Neut					
	Unit	**2015**	**2020**	**2025**	**2030**
In real terms	**ct$_{2010}$/kWh**	**2.97**	**2.75**	**2.34**	**1.71**
Difference to FIT2012_NoES	*ct$_{2010}$/kWh*	*-0.54*	*-1.07*	*-0.57*	*1.33*
Difference to REF	*ct$_{2010}$/kWh*	*-1.19*	*-2.09*	*-1.18*	*1.25*
In nominal terms	**ct/kWh**	**3.32**	**3.44**	**3.27**	**2.69**
QU_Spec					
	Unit	**2015**	**2020**	**2025**	**2030**
In real terms	**ct$_{2010}$/kWh**	**2.71**	**2.40**	**2.13**	**0.74**
Difference to FIT2012_NoES	*ct$_{2010}$/kWh*	*-0.81*	*-1.42*	*-0.77*	*0.36*
Difference to REF	*ct$_{2010}$/kWh*	*-1.46*	*-2.44*	*-1.38*	*0.28*
In nominal terms	**ct/kWh**	**3.03**	**3.00**	**2.99**	**1.17**

Lowering the expansion of renewable electricity to the target values defined in the German Energy Concept helps to reduce the additional burden on electricity consumption. In the scenario with a technology-neutral quota system, the surcharge decreases between 0.5 and 1.1 ct$_{2010}$/kWh in the period from 2015 to 2025 compared to the sensitivity without special equalisation scheme. The peak in 2020 in nominal terms is lowered to 3.4 ct/kWh. In 2030, the effect that with a technology-neutral design the entire renewable generation remains in the support system is dominant such that the surcharge is raised by 1.3 ct$_{2010}$/kWh in relation to the sensitivity FIT2010_NoES. Additional reductions can be achieved with a technology-specific design of the quota system. The most striking difference to the sensitivity without special equalisation scheme is realized in 2020 with -1.4 ct$_{2010}$/kWh. Yet, even with this specification, a slightly higher surcharge than in the reference case ensues in 2030. In nominal terms, the highest level is already reached in 2015 with 3.0 ct/kWh.

Hence, the scenario analysis at hand shows that it is not guaranteed that consumers benefit from a support system that promotes the most cost efficient renewable technologies. A technology-neutral design can ensure a cost efficient expansion of renewable electricity, but at the same time allows renewable generators to generate high profits, especially in the case of technologies with comparatively low investment costs. These windfall profits can be reduced with the technology-specific quota system. However, with the even more detailed tariff structure of the current German FIT system the possibility to make large profits is even more limited and renewable plant operators tend to drop out of the system more quickly. Thus, aligning the support for renewable electricity more strongly to the principle of cost efficiency can help to diminish the cost burden, but in addition attention should be paid to implementing a clearly differentiated tariff structure. At the same time, it needs to be pointed out that the effects of the scenario comparison would be more pronounced if the different support systems were contrasted from the starting point of the promotion of renewable electricity in Germany in the year 2000. Here, only a shift to another system from 2013 onwards is considered such that in each scenario the first 12 years of the German FIT system have to be accounted for.

Electricity consumption

In the end, what is decisive for electricity consumers is the impact of the instrument promoting renewable electricity on electricity prices. In the present scenario analysis, differences between the modelled support schemes cannot only arise from the variance in the surcharge but also from differing levels of wholesale electricity prices. As before, the sensitivity without special equalisation scheme is used as the reference point in the comparison in order to focus solely on the effect of switching the support system for renewable electricity.

Because of the similarity in the absolute amount of renewable electricity generation, the scenario with the technology-neutral FIT system exhibits almost the same wholesale electricity prices as the reference case or the sensitivity FIT2012_NoES. Consequently, deviations from this reference are caused only by the changes in the FIT surcharge described above. Accordingly, end-user electricity prices rise in comparison to the sensitivity without special equalisation scheme in all modelling periods except 2025, where a slight reduction between 2 % and 4 % is realized (cf. Figure 5-28). The most significant increase occurs in 2030 with 8 % in the case of private households and more than 11 % for the industry sector, while in 2015 and 2020 the changes are considerably lower.

The reduction of renewable electricity generation and the associated stronger reliance on fossil fuels lead to slightly higher wholesale electricity prices in the scenarios with TGC schemes. Hence, the reductions that can be achieved with respect to the renewable surcharge are not fully translated into end-user electricity prices. Under the technology-neutral quota system, household electricity prices decrease between 0.6 % and 4.7 % and industry prices between 2.4 % and 6.9 % in the period from 2015 to 2025 when compared to the sensitivity FIT2012_NoES. Yet, in 2030 electricity prices are even slightly higher than in the scenario with the technology-neutral FIT scheme due to the increase in the wholesale electricity price level. With the technology-specific quota scheme, electricity prices are lowered to a somewhat greater extent with a maximum in 2020 of 6.6 % in the case of households and almost 10 % in the industry sector compared to the sensitivity without special equalisation scheme. Still, even in this scenario end-user electricity prices exceed the here chosen reference in 2030 by 3 % to nearly 5 %.

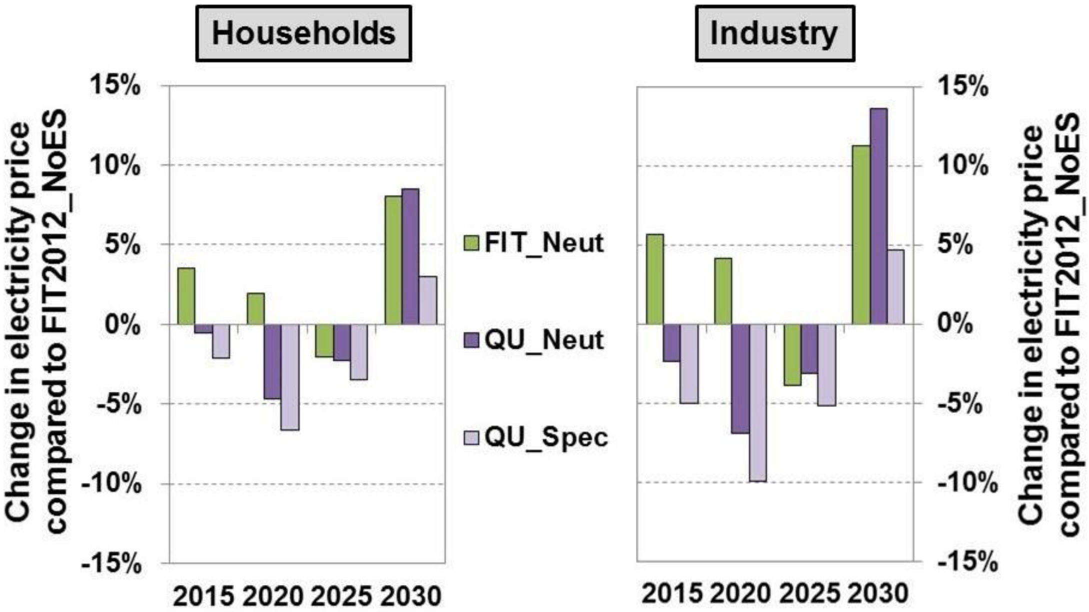


Figure 5-28: Change in end-user electricity prices under different support schemes for renewable electricity compared to the reference case (without special equalisation scheme)

As mentioned before, the model results on the effects on electricity consumption are in line with the empirical evidence that electricity demand is relatively price-inelastic. Accordingly, the differences in electricity consumption between the scenarios with alternative support schemes for renewable electricity and the sensitivity FIT2012_NoES turn out to be rather limited (cf. Table 5-22). When replacing the current German feed-in tariffs with a technology-neutral FIT system, declines in total electricity consumption can be observed both in 2020 and 2030, although only the reduction in 2030 reaches a non-negligible level of almost 11 TWh (2 %). With respect to the TGC schemes, in accordance with the changes in end-user electricity prices, increases in electricity consumption between 12 and 17 TWh in 2020 are opposed to reductions of 3 to 13 TWh in 2030. The fact that in the scenario QU_Neut the differences in electricity consumption are less pronounced in 2030 than in 2020 despite of the larger change in electricity prices can be ascribed to path dependencies as in previous modelling years investments in electricity-using equipment have been made. On the whole, the adjustments in electricity consumption can be mainly attributed to private households and the tertiary sector, while the industry sector, especially energy-intensive branches where the use of electricity constitutes a viable emission reduction option, proves to be less flexible.

Table 5-22: Electricity consumption by sector under different support schemes for renewable electricity

TWh	2010	2020				2030			
		FIT2012 _NoES	FIT_ Neut	QU_ Neut	QU_ Spec	FIT2012 _NoES	FIT_ Neut	QU_ Neut	QU_ Spec
Industry, energy intensive	219	69	69	70	72	70	69	69	70
Industry, non-energy intensive		157	156	160	161	150	149	148	150
Tertiary*	140	115	116	123	123	110	105	104	108
Households	141	136	134	137	138	133	129	129	132
Transport	17	24	24	24	24	30	30	30	30
Sum	**516**	**502**	**500**	**514**	**519**	**492**	**482**	**480**	**489**

* incl. agriculture

Emissions

Extending the use of renewable energy sources in electricity generation represents one of the major emission abatement strategies. Thus, reducing the share of renewable electricity, like it is done in the scenarios with quantity-based quota systems, has implications for emission reduction and the participation of Germany in the EU ETS. That is why, in Figure 5-29 the development of CO_2 emissions by sector in Germany and the associated ETS certificate prices are contrasted for the reference case and the scenario featuring the technology-neutral TGC scheme for renewable electricity.

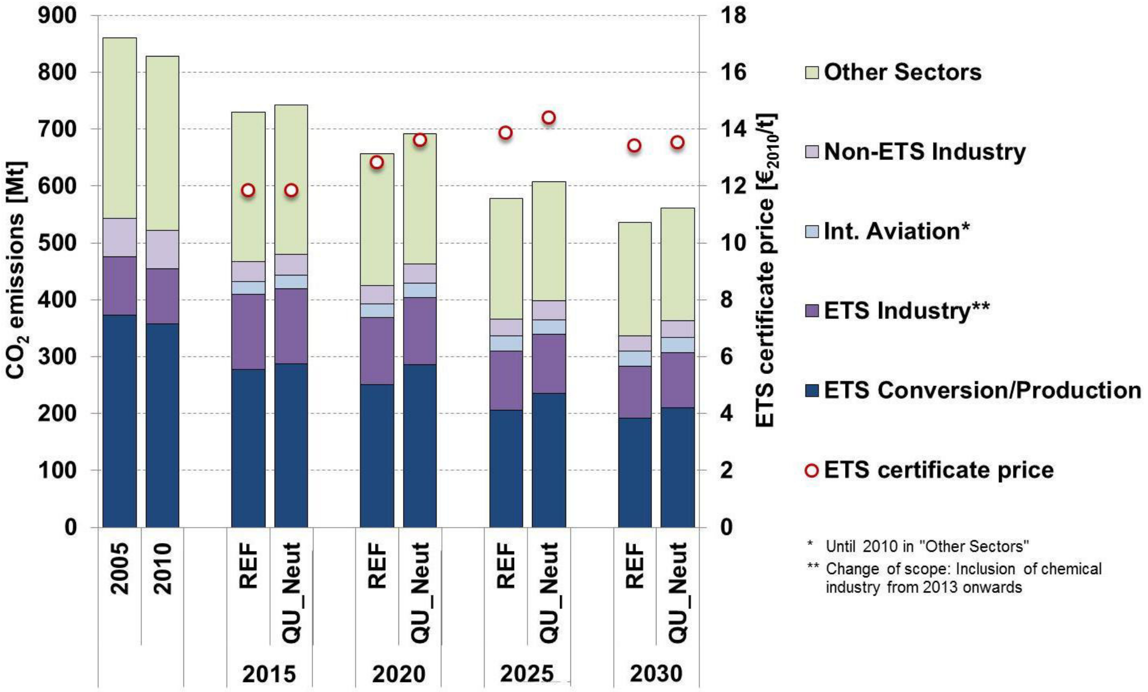


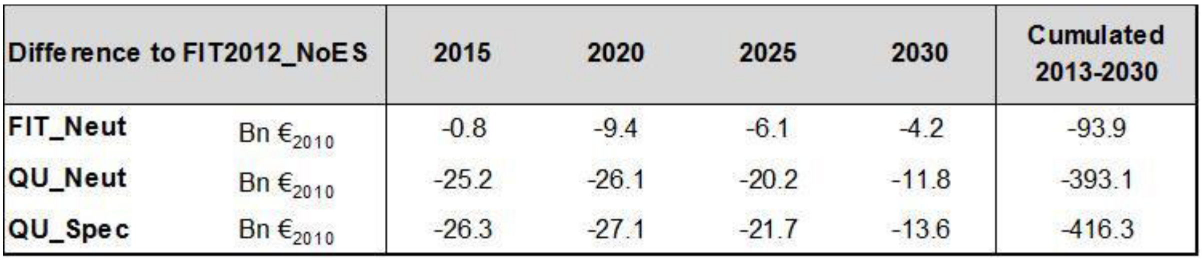
Figure 5-29: Comparison of CO_2 emissions in Germany and ETS certificate prices between the reference case and the scenario with a quota system for renewable electricity

CO_2 emissions from electricity generation in Germany rise by 34 Mt CO_2 in 2020 and 18 Mt CO_2 in 2030 when renewable generation is reduced to the target levels of the German Energy Concept. In the industry sector, a slight increase in CO_2 emissions can be observed as well which can be mainly attributed to the reduced electricity consumption in the energy-intensive industry branches in the scenario QU_Neut (without special equalisation scheme) in relation to the reference case and the lower use of renewable energies in industrial CHP plants. No significant changes occur in the emission levels of the remaining sectors. As a result, total CO_2 emissions decline by 33 % until 2020 and 46 % until 2030 with respect to 1990 in the scenario with the technology-neutral quota system - as compared to 37 % and 48 % in the reference case. Hence, the targets of the Energy Concept are clearly missed. Moreover, Germany's contribution to the burden sharing under the EU ETS falls as the emission reduction in the German ETS sectors drops from 26 % in the reference case to 19 % in 2020 and from 43 % to 38 % in 2030 compared to 2005. This causes a slight increase in the price for emission certificates of about 1 $€_{2010}$/t CO_2 in 2020. Until 2030, however, this difference to the reference case disappears almost completely.

Energy system cost

With the aim to have a final assessment of the system-wide cost burden that different instruments for the promotion of renewable electricity entail, a look is taken at energy system cost. Based on the higher cost efficiency of renewable electricity generation, reductions in annual undiscounted energy system costs compared to the reference case (without special equalisation scheme) can be achieved with all the alternative support systems modelled in this scenario analysis (cf. Table 5-23). With a cumulated difference of 94 billion €$_{2010}$ over the period from 2013 to 2030, these savings are comparatively limited if only the principle of cost efficiency is applied with the help of a technology-neutral FIT system while still reaching the same high expansion of renewable electricity as in the reference case (technology effect). Considerably higher reductions are realized when in addition the quantity of renewable generation is lowered to the targets of the Germany Energy Concept (quantity effect). Such target compliance can be guaranteed under a quantity-based support system. When switching to a technology-neutral quota system, cumulated energy system costs diminish by 393 billion €$_{2010}$ between 2013 and 2030 in relation to the reference case. In terms of system-wide cost, the additional benefit of implementing a technology-specific TGC scheme and thereby limiting the potential windfall profits of renewable generators amounts only to 23 billion €$_{2010}$ cumulated over the period from 2013 to 2030. In this context, it needs to be pointed out, however, that energy system costs do not contain any information on the distribution of these costs across the system. Thus, for electricity consumers the benefits of using a technology-specific design instead of a uniform support level are higher, as has been shown above when contrasting the differential costs of the support systems in the scenarios QU_Neut and QU_Spec. Since at the same time renewable plant operators generate less profits, the difference in energy system costs between these two scenarios is less pronounced.

Table 5-23: Difference in annual undiscounted energy system cost between the scenarios with different support schemes for renewable electricity compared to the reference case (without special equalisation scheme)



Difference to FIT2012_NoES		2015	2020	2025	2030	Cumulated 2013-2030
FIT_Neut	Bn €$_{2010}$	-0.8	-9.4	-6.1	-4.2	-93.9
QU_Neut	Bn €$_{2010}$	-25.2	-26.1	-20.2	-11.8	-393.1
QU_Spec	Bn €$_{2010}$	-26.3	-27.1	-21.7	-13.6	-416.3

Sensitivity analysis: Higher hurdle rates for investments in renewable electricity under a quota system

The high planning security for renewable investors constitutes one of the major advantages of fixed feed-in tariff systems. In contrast, under quantity-based support schemes the risk for renewable plant operators increases substantially as future revenues are unpredictable. Therefore, criticism has been expressed that under such systems a higher remuneration in the form of a risk premium is required to compensate for this more uncertain investment environment.

That is why in the scope of this scenario analysis an additional sensitivity (QU_Spec_hh) with higher financing costs for investments in renewable electricity is calculated for the scenario with the technology-specific quota system. Here, on the basis of Redpoint Energy (2010), the hurdle rates (or discount rates) for renewable technologies are raised from 7 % to 9 %, while all other assumptions and input data are adopted from the scenario QU_Spec. With this increase of 2 percentage points, a comparatively extreme scenario regarding the impacts of higher uncertainty on financing costs is explored.

The results for this sensitivity show that higher discount rates for renewable investments cause a rise in generation costs for renewable electricity of almost 14 billion €$_{2010}$ (10.6 %) cumulated over the period from 2013 to 2030 in relation to the scenario QU_Spec (cf. Table 5-24). As a consequence, the certificate prices for the different renewable sources need to be raised on average between 0.15 and 0.44 ct$_{2010}$/kWh over the projected period. This implies a higher cost burden on electricity consumers represented by additional cumulated differential costs of 5.6 billion €$_{2010}$ (3.1 %) and an increase in the surcharge on final electricity prices of around 0.1 ct$_{2010}$/kWh. Finally, the higher hurdle rates for renewable electricity generation are reflected in an increment of undiscounted energy system costs of 70 billion €$_{2010}$ (0.8 %) cumulated from 2013 to 2030 when compared with the scenario QU_Spec.

Thus, the sensitivity analysis at hand indicates that the higher uncertainty for renewable investments under quantity-based support schemes can lead to a slight increase in the cost burden that such a system induces. At the same time, one must not forget that even though renewable generators benefit from greater investment security under fixed tariff schemes, the risk does not disappear from the system, but is transferred to electricity consumers as the amount of renewable electricity that has to be financed through the system in the future is unknown.

Table 5-24: Impact of higher hurdle rates for renewable investments under a technology-specific quota system on important cost parameters

Difference between QU_Spec_hh and QU_Spec	**Unit**	**2015**	**2020**	**2025**	**2030**	**Cumulated 2013-2030**
Generation cost for renewable electricity*	M€$_{2010}$	175	575	746	2075	13703
	%	8.1%	12.2%	8.1%	12.7%	10.6%
Average certificate price	ct$_{2010}$/kWh	0.37	0.44	0.24	0.15	-
	%	6.5%	11.4%	8.4%	10.3%	-
Differential cost	M€$_{2010}$	244	357	357	282	5633
	%	1.9%	3.1%	3.7%	8.5%	3.1%
Surcharge on final electricity prices	ct$_{2010}$/kWh	0.07	0.09	0.09	0.07	-
	%	2.4%	3.9%	4.1%	9.8%	-
Annual undiscounted energy system cost	Bn €$_{2010}$	3.90	4.13	4.49	2.41	70
	%	0.9%	0.9%	1.0%	0.5%	0.8%

6 Conclusion and outlook

In light of the issue of climate change and the associated efforts for a transition to a more sustainable energy supply, the future development of energy systems in Europe and around the world is strongly influenced by the implementation of a wide range of energy and climate policy instruments. Hence, it becomes increasingly important to account for the impact of such instruments when conducting energy system analyses. As outlined in the introduction, the present thesis was focused on three research targets: (1) the evaluation of the strength and weaknesses of conventional bottom-up energy system models for policy evaluation, (2) the development of endogenous model approaches for the explicit representation of different policy instruments in energy system models and (3) a comparative scenario analysis incorporating this modelling techniques.

The suitability of energy system models for the assessment of climate and energy policy instrument is appraised on the basis of the approach by Jaccard et al. (2003) which defines three dimensions for an ideal energy model for policy evaluation: technological explicitness, microeconomic realism and macroeconomic completeness. Accordingly, bottom-up energy system models can provide an appropriate framework to analyse the effects of policy instruments due to their high level of technological detail and process orientation. Moreover, such a comprehensive approach has the advantage that all interactions and repercussions within the energy system are taken into account. In contrast, drawbacks have been identified in the area of representing the decision-making behaviour of different economic agents in a realistic manner as well as of taking macroeconomic feedbacks into consideration. Keeping these shortcomings in mind and stating them openly can already improve the transparency of a quantitative model analysis. Apart from that, considerable research efforts are currently dedicated to finding solutions for these issues, which is particularly reflected in the significant progress made in the field of hybrid modelling.

As far as the specific modelling techniques for the endogenous representation of different policy instruments are concerned, the promotion of renewable electricity in Germany has been chosen as a case study in view of the strong controversy that currently surrounds this topic. For the first time, flexible modelling approaches for the two most important instruments presently influencing the expansion of renewable sources in electricity generation in Germany - the feed-in tariff (FIT) system and the European Emissions Trading System (EU ETS) – have been developed. This methodology allows to evaluate all impacts and repercussions of these policy measures on the energy system in an endogenous manner. From this modelling exercise several general lessons can be drawn:

- The real-world application of climate and energy policy instruments often differs substantially from the abstract, theoretical representation in textbooks. This additional complexity has to be accounted for in the modelling approach in order to arrive at a realistic depiction of the policy impact.

- Quantity-based measures, like emissions trading systems or tradable green certificate schemes, are generally much more straightforward to model than price-based instruments like feed-in tariffs as in the latter case additional cost terms have to be introduced.
- When using a comprehensive energy system model for policy evaluation, one has to make sure that all effects a policy instrument causes are included in the modelling approach. For example, when modelling a FIT system for renewable electricity, the impacts on electricity demand as well as on the electricity grid and the required storage capacity need to be taken into consideration.
- In general, it needs to be pointed out that in order to ensure that policy instruments are represented in a realistic manner, a highly detailed model, comprising a large variety of technologies and (in the case of the electricity sector) a high time resolution, is required.

With the help of the comparative scenario analysis on the long-term development of the German energy system a number of advantages of the endogenous modelling approaches for policy evaluation were highlighted. First of all, when including all policy instruments in their current version, a baseline scenario reflecting the business-as-usual case can be calculated. In the next step the flexible modelling techniques allow to explore how changing scenario assumptions, for example on fossil fuel prices, affect the outcomes of the respective policy instrument. In addition, the explicit integration of policy measures provides the possibility to evaluate the interactions between different policy instruments. Finally, these modelling approaches can be applied for quantitative comparisons of alternative policy instruments which can be applied for the same political target.

With respect to the reference case, it has been shown that based on the current feed-in tariff system a strong expansion of renewable electricity is realized, which clearly exceeds the target values of the German Energy Concept. It is therefore associated with a considerable cost burden on electricity consumers and puts additional strain on the electricity system. At the same time, a relatively moderate price level can be observed in the projected period for emission certificates in the European Emissions Trading System.

The scenario analysis on the interaction between the EU ETS and the German FIT system illustrates that if countries are joined through an emission trading system, national policy tools can have an impact on all participating countries. The German support scheme for renewable electricity can facilitate compliance with the ETS reduction targets as it entails a dampening effect on certificate prices. At the same time, however, no additional emission reduction on the EU level is induced and emission reduction becomes less cost efficient given the fact that the expansion of renewable electricity generation in Germany constitutes a comparatively expensive abatement option. Given the widespread use of support mechanisms for renewable electricity in Europe, it is essential that their effect on emission mitigation is taken into account when setting the reduction targets under the EU ETS.

With the comparative analysis on different policy instruments for renewable electricity it can be shown that with technology-neutral support schemes that strictly adhere to the principle of cost efficiency the generation cost of renewable electricity in Germany could be reduced considerably. Additional saving could be achieved if the expansion of renewable generation was adjusted to the targets of the German Energy concept with the help of a quantity-based support mechanism. Yet, at the same time it has to be kept in mind that since technology-neutral systems are associated with high profits for renewable generators, it cannot be ensured that electricity consumers benefit from such schemes. Thus, countries implementing a new support system for renewable electricity should pay attention both to promoting the most cost efficient technologies and to limiting the cost burden on consumers with the help of a clearly differentiated remuneration structure. Apart from cost efficiency and distributional impacts, however, the decision for the appropriate support instrument will be guided by issues like the market integration of renewables, the target to promote technology diffusion, distribution of risk, transaction costs, etc.

For the case of Germany, it needs to be pointed out that the effects of the scenario comparison would be more pronounced if the different support systems were contrasted from the starting point of the promotion of renewable electricity in Germany in the year 2000. Here, only a shift to another system from 2013 onwards is considered such that in each scenario the first 12 years of the German FIT system have to be accounted for. At the same time, one must not forget that the transition from a FIT system to a tradable green certificate (TGC) scheme or tender mechanism might be politically difficult to realize and might entail high transaction costs, as given the necessity to “grandfather” existing installations both systems would have to be maintained side-by-side for a certain period of time. In the long term, with renewable energies becoming the dominant source in electricity generation, reform strategies will be necessary for the entire market design optimizing both renewable and conventional generation.

On the whole, this thesis has shown that bottom-up energy system models can provide a valuable contribution to the quantitative evaluation of the long-term impacts of different types of policy instruments on the energy system. If the aim consists in integrating all effects of a certain measure into the model in an endogenous manner, the modelling approach can prove to become relatively complex. So, it needs to be highlighted that the choice of the modelling tool and the sophistication of the methodology should always depend on the specific research question that is analysed. Furthermore, one has to bear in mind that there never will be a universal model that can be applied to all energy-related research topics.

Due to the complexity of research on energy policy further efforts are needed in the area of coupling different types of energy models and the development of hybrid models. Moreover, evaluating energy and climate policy instruments in a comprehensive manner will also require an increased communication across different academic disciplines on energy-related questions and the incorporation of research results from other disciplines, e.g. the social sciences, into the modelling process. This thesis has mainly focused on measures that affect the energy supply side (as well as industry) where the assumption of decision-making based on cost minimisation is generally applicable. Further research is needed on methodological approaches which allow to integrate policy instruments which target the demand-side, e.g. the residential sector, into optimising energy system models where a large variety of factors can influence the impact of such instruments. Apart from that, endeavours of raising the level of detail in a modelling approach are often restricted by the limited availability of reliable data. In this context, the research on the empirical foundation of energy system models and the integration of different types of data sources into such models should be strengthened.

Additional attention should also be paid in the future to stating the advantages and drawbacks of the chosen modelling approach in a transparent manner and to establishing appropriate ways of communicating modelling results to policy makers. With the sustained interested in energy-related policy questions around the world, energy modelling will continue to play a crucial role in informing the political decision-making process.

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Annex: Additional scenario assumptions

Table A-1: Long-term own-price elasticities for the different demand categories (used from 2020 onwards; based on the 2010 version of the ETSAP-TIAM model (cf. ETSAP 2011))

Demand category	Price increase	Price reduction
Industry	-0.1	-0.1
Tertiary sector		
Space heat	-0.1	0
Hot water	-0.1	0
Lighting	-0.15	0
ICT	-0.05	0
Air conditioning	-0.15	-0.05
Other appliances	-0.05	0
Residential sector		
Space heat	-0.05	0
Hot water	-0.05	0
Lighting	-0.1	0
Cooking	0	0
Refrigeration	-0.05	-0.03
Clothes Washing	-0.05	0
Air conditioning	-0.15	-0.05
Other appliances	-0.2	-0.05
Transport		
Passenger transport	-0.15	-0.05
Freight transport	-0.15	-0.05

Table A-2: Technological and economic parameters for renewable electricity generation technologies - hydro power (based on Kaltschmitt et al. 2006, Remme 2006)

New installation (large)				
		2015	**2020**	**2030**
Capacity	MW	20	20	20
Lifetime	a	80	80	80
Availability	h/a	5500	5500	5500
Investment cost[a]	€$_{2007}$/kW	5800	5800	5800
Fix O&M cost	€$_{2007}$/kWa	87.0	87.0	87.0
New installation (small)				
		2015	**2020**	**2030**
Capacity	MW	3	3	3
Lifetime	a	80	80	80
Availability	h/a	5000	5000	5000
Investment cost	€$_{2007}$/kW	4140	4140	4140
Fix O&M cost	€$_{2007}$/kWa	103.5	103.5	103.5
Modernisation				
Investment cost	€$_{2007}$/kW	1500	1500	1500

[a] Higher investment costs for larger plants are mainly due to strict environmental protection requirements (cf. Kaltschmitt et al. 2006, p. 378).

Table A-3: Technological and economic parameters for renewable electricity generation technologies - solar photovoltaics (based on Wissel et al. 2010, BSW-Solar 2013, BMU 2012f, BMU 2011c)

Rooftop installation				
		2015	**2020**	**2030**
Lifetime	a	25	25	25
Availability	h/a	930	930	930
Investment cost	€$_{2007}$/kW	1800	1550	1450
Fix O&M cost	€$_{2007}$/kWa	27.0	23.3	21.8
Freestanding installation				
		2015	**2020**	**2030**
Lifetime	a	25	25	25
Availability	h/a	1000	1000	1000
Investment cost	€$_{2007}$/kW	1640	1415	1245
Fix O&M cost	€$_{2007}$/kWa	24.6	21.2	18.7

Table A-4: Technological and economic parameters for renewable electricity generation technologies - wind onshore (based on Blesl et al. 2012, Wissel et al. 2010, Remme 2006)

New installation				
		2015	**2020**	**2030**
Lifetime	a	20	20	20
Availability (wind velocity 4-5 m/s)	h/a	1500	1500	1500
Availability (wind velocity 5-6 m/s)	h/a	2200	2200	2200
Availability (wind velocity > 6 m/s)	h/a	2900	2900	2900
Investment cost	€$_{2007}$/kW	1000	940	870
Ancillary cost (grid connection,…)	€$_{2007}$/kW	320	320	320
Fix O&M cost	€$_{2007}$/kWa	50	50	50
Repowering				
Assumption:	Ancillary investment cost is reduced by one third (as the infrastructure of the original installation is used).[a]			

[a] cf. Rehfeldt und Gerdes (2005)

Table A-5: Technological and economic parameters for renewable electricity generation technologies - wind offshore (based on Blesl et al. 2012, IER et al. 2010, BMU 2012f)

Location type 1				
		2015	**2020**	**2030**
Distance to shore	km	40	40	40
Water depth	m	25	25	25
Lifetime	a	20	20	20
Availability	h/a	3600	3600	3600
Investment cost	€$_{2007}$/kW	2800	2300	2050
Ancillary cost (grid connection & foundation)	€$_{2007}$/kW	226	226	226
Fix O&M cost	€$_{2007}$/kWa	166	139	125
Location type 2				
		2015	**2020**	**2030**
Distance to shore	km	30	30	30
Water depth	m	30	30	30
Lifetime	a	20	20	20
Availability	h/a	3500	3500	3500
Investment cost	€$_{2007}$/kW	2800	2300	2050
Ancillary cost (grid connection & foundation)	€$_{2007}$/kW	231	231	231
Fix O&M cost	€$_{2007}$/kWa	167	139	125
Location type 3				
		2015	**2020**	**2030**
Distance to shore	km	80	80	80
Water depth	m	35	35	35
Lifetime	a	20	20	20
Availability	h/a	3800	3800	3800
Investment cost	€$_{2007}$/kW	2800	2300	2050
Ancillary cost (grid connection & foundation)	€$_{2007}$/kW	443	443	443
Fix O&M cost	€$_{2007}$/kWa	178	151	137
Location type 4				
		2015	**2020**	**2030**
Distance to shore	km	120	120	120
Water depth	m	40	40	40
Lifetime	a	20	20	20
Availability	h/a	4000	4000	4000
Investment cost	€$_{2007}$/kW	2800	2300	2050
Ancillary cost (grid connection & foundation)	€$_{2007}$/kW	621	621	621
Fix O&M cost	€$_{2007}$/kWa	188	161	147

Table A-6: Technological and economic parameters for renewable electricity generation technologies - solid biomass (based on Blesl et al. 2012, IER et al. 2010, BMU 2012f)

Condensing plant				
		2015	**2020**	**2030**
Capacity	MW	20	20	20
Lifetime	a	30	30	30
Efficiency	%	34	35	36
Availability	h/a	7000	7000	7000
Investment cost	€$_{2007}$/kW	750	700	700
Fix O&M cost	€$_{2007}$/kWa	37.5	35.0	35.0
Variable O&M cost	€$_{2007}$/MWh	2.8	2.8	2.8
CHP plant				
		2015	**2020**	**2030**
Capacity	MW	6	6	6
Lifetime	a	30	30	30
Max. electrical efficiency	%	26	26	27
Electrical efficiency at max. heat extraction	%	20	20	21
Thermal efficiency at max. heat extraction	%	61	62	62
Availability	h/a	5000	5000	5000
Investment cost	€$_{2007}$/kW	3150	2900	2850
Fix O&M cost	€$_{2007}$/kWa	171	171	171
Variable O&M cost	€$_{2007}$/MWh	3.2	3.2	3.2
ORC block heating and power station				
		2015	**2020**	**2030**
Capacity	MW	0.5	0.5	0.5
Lifetime	a	30	30	30
Electrical efficiency	%	15	16	17
Thermal efficiency	%	71	71	71
Availability	h/a	4500	4500	4500
Investment cost	€$_{2007}$/kW	5300	4900	4700
Fix O&M cost	€$_{2007}$/kWa	160	160	160
Variable O&M cost	€$_{2007}$/MWh	2.6	2.6	2.6
CHP, wood gasification (circulating fluidized bed)				
		2015	**2020**	**2030**
Capacity	MW	2	2	2
Lifetime	a	30	30	30
Max. electrical efficiency	%	41	41	42
Electrical efficiency at max. heat extraction	%	36	36	38
Thermal efficiency at max. heat extraction	%	45	45	45
Availability	h/a	5000	5000	5000
Investment cost	€$_{2007}$/kW	4150	3650	3400
Fix O&M cost	€$_{2007}$/kWa	300	150	150
Variable O&M cost	€$_{2007}$/MWh	3.0	3.0	3.0

Table A-7: Technological and economic parameters for renewable electricity generation technologies - biogas (based on IER et al. 2010, Wissel et al. 2010, BMU 2012f)

Condensing plant				
		2015	**2020**	**2030**
Capacity	MW	2	2	2
Lifetime	a	20	20	20
Efficiency	%	38	38	39
Availability	h/a	6000	6000	6000
Investment cost	€$_{2007}$/kW	760	713	713
Fix O&M cost	€$_{2007}$/kWa	49.4	46.3	46.3
Variable O&M cost	€$_{2007}$/MWh	2.3	2.3	2.3
Block heating and power station				
		2015	**2020**	**2030**
Capacity	MW	0.5	0.5	0.5
Lifetime	a	15	15	15
Electrical efficiency	%	33	34	34
Thermal efficiency	%	50	51	52
Availability	h/a	4500	4500	4500
Investment cost	€$_{2007}$/kW	800	750	750
Fix O&M cost	€$_{2007}$/kWa	52.0	48.8	48.8
Variable O&M cost	€$_{2007}$/MWh	2.4	2.4	2.4
Fuel cell (MCFC)				
		2015	**2020**	**2030**
Capacity	MW	0.3	0.3	0.3
Lifetime	a	10	10	10
Electrical efficiency	%	48	48	49
Thermal efficiency	%	34	36	36
Availability	h/a	4500	4500	4500
Investment cost	€$_{2007}$/kW	6000	3250	1000
Fix O&M cost	€$_{2007}$/kWa	490	105	105
Variable O&M cost	€$_{2007}$/MWh	24.0	24.0	24.0

Table A-8: Technological and economic parameters for renewable electricity generation technologies - liquid biomass (based on IER et al. 2010, Wissel et al. 2010, BMU 2012f)

Vegtable oil block heating and power station				
		2015	**2020**	**2030**
Capacity	MW	0.11	0.11	0.11
Lifetime	a	15	15	15
Electrical efficiency	%	36	37	37
Thermal efficiency	%	46	47	47
Availability	h/a	4500	4500	4500
Investment cost	€$_{2007}$/kW	1100	1100	1050
Fix O&M cost	€$_{2007}$/kWa	71.5	71.5	68.3
Variable O&M cost	€$_{2007}$/MWh	1.9	1.9	1.9

Table A-9: Technological and economic parameters for renewable electricity generation technologies - geothermal energy (based on Wissel et al. 2010, Kruck et al. 2009, Fritsch 2008)

ORC power plant, Hot-Dry-Rock				
		2015	**2020**	**2030**
Capacity	MW$_{el}$	4.5	4.5	4.5
Lifetime	a	25	25	25
Efficiency	%	10.5	11.5	12.5
Availability	h/a	6000	6500	6500
Investment cost	€$_{2007}$/kW$_{el}$	7839	7839	6626
Fix O&M cost	€$_{2007}$/kW$_{el}$a	314	314	265
Var. O&M cost	€$_{2007}$/MWh	1.2	1.2	1.2
ORC CHP plant, Hot-Dry-Rock				
		2015	**2020**	**2030**
Capacity	MW$_{el}$	4.5	4.5	4.5
Lifetime	a	25	25	25
Max. electrical efficiency	%	10.5	11.5	12.5
Electrical efficiency at max. heat extraction	%	10.0	11.0	12.0
Thermal efficiency at max. heat extraction	%	55.0	55.0	60.0
Availability	h/a	6000	6500	6500
Investment cost[a]	€$_{2007}$/kW$_{el}$	7939	7939	6726
Fix O&M cost	€$_{2007}$/kW$_{el}$a	318	318	269
Var. O&M cost (electricity)	€$_{2007}$/MWh	1.2	1.2	1.2
ORC power plant, hydrothermal				
		2015	**2020**	**2030**
Capacity	MW$_{el}$	4.5	4.5	4.5
Lifetime	a	25	25	25
Efficiency	%	9.5	10.5	11.5
Availability	h/a	6000	6500	6500
Investment cost	€$_{2007}$/kW$_{el}$	6980	6980	5900
Fix O&M cost	€$_{2007}$/kW$_{el}$a	279	279	236
Var. O&M cost	€$_{2007}$/MWh	1.2	1.2	1.2
ORC CHP plant, hydrothermal				
		2015	**2020**	**2030**
Capacity	MW$_{el}$	4.5	4.5	4.5
Lifetime	a	25	25	25
Max. electrical efficiency	%	9.5	10.5	11.5
Electrical efficiency at max. heat extraction	%	9.0	10.0	11.0
Thermal efficiency at max. heat extraction	%	49.5	50.0	55.0
Availability	h/a	6000	6500	6500
Investment cost[a]	€$_{2007}$/kW$_{el}$	7080	7080	6000
Fix O&M cost	€$_{2007}$/kW$_{el}$a	283	283	240
Var. O&M cost (electricity)	€$_{2007}$/MWh	1.2	1.2	1.2

[a] Investment cost for additional heat generation are assumed at 100 €/kW, based on Kabus et al. (2003).

Table A-10: Technological and economic parameters for electricity storage technologies (based on BMU 2010b, dena 2010a, dena 2010b, VDI 2009, ISE et al. 2009)

Pump storage power plant				
		2015	**2020**	**2030**
Lifetime	a	80	80	80
Availability factor	%	98	98	98
Efficiency	%	73	76	76
Investment cost	€$_{2007}$/kW	650	650	650
Fix O&M cost	€$_{2007}$/kWa	19.5	19.5	19.5
Diabatic compressed air energy storage (CAES)				
		2015	**2020**	**2030**
Lifetime	a	40	40	40
Availability factor	%	95	95	95
Plant efficiency	%	54	54	54
Energy input for 1kWh$_{el}$	kWh	0.69 (elec) / 1.17 (gas)	0.69 (elec) / 1.17 (gas)	0.69 (elec) / 1.17 (gas)
Investment cost	€$_{2007}$/kW	600	600	600
Fix O&M cost	€$_{2007}$/kWa	18.0	18.0	18.0
Advanced adiabatic compressed air energy storage (AA-CAES)				
		2015	**2020**	**2030**
Lifetime	a	40	40	40
Availability factor	%	95	95	95
Efficiency	%	68	70	70
Investment cost	€$_{2007}$/kW	750	750	750
Fix O&M cost	€$_{2007}$/kWa	22.5	22.5	22.5
Sodium–sulfur battery (NaS)				
		2015	**2020**	**2030**
Lifetime	a	8	8	8
Availability factor	%	98	98	98
Efficiency	%	82.5	85	90
Investment cost	€$_{2007}$/kW	1200	1100	1000
Fix O&M cost	€$_{2007}$/kWa	12	11	10
Redox flow battery				
		2015	**2020**	**2030**
Lifetime	a	12	12	12
Availability factor	%	98	98	98
Efficiency	%	77.5	80	80
Investment cost	€$_{2007}$/kW	2000	1900	1600
Fix O&M cost	€$_{2007}$/kWa	20	19	16
Hydrogen storage				
		2015	**2020**	**2030**
Lifetime (converter)	a	30	30	30
Lifetime (storage)	a	40	40	40
Availability factor	%	95	95	95
Efficiency (converter)	%	67	70	70
Investment cost (converter)	€$_{2007}$/kW	1485	1250	750
Investment cost (storage)	€$_{2007}$/kW	300	300	300
Fix O&M cost (converter)	€$_{2007}$/kWa	44.6	37.5	22.5
Fix O&M cost (storage)	€$_{2007}$/kWa	9	9	9

Table A- 11: Electricity grid expansion cost due to the increase in generation from wind energy and solar photovoltaics - transmission grid (based on dena 2005, dena 2010a, EC 2011c)

	Capacity of PV and wind (onshore+offshore) plants [MW]	Specific grid expansion costs [$€_{2007}$/kW]
Step1	≤ 32500	0
Step2	> 32500; ≤ 45400	97.5
Step3	> 45400; ≤ 61000	195
Step4	> 61000	400

Table A- 12: Electricity grid expansion cost due to the increase in generation from wind energy and solar photovoltaics - distribution grid (based on BDEW 2011, EC 2011c)

	Capacity of PV and wind onshore plants [MW]	Specific grid expansion costs [$€_{2007}$/kW]
Step1	≤ 32500	0
Step2	> 32500	500

Table A-13: District heat potential from geothermal energy and associated grid expansion cost (based on Blesl 2011)

	District heat potential from geothermal energy [TWh]	Expansion cost for district heat grid [$€_{2007}$/kW]	Grid losses
Step 1	4.4	0	5%
Step 2	21.8	562	10%
Step 3	29.0	692	15%
Step 4	45.9	930	20%

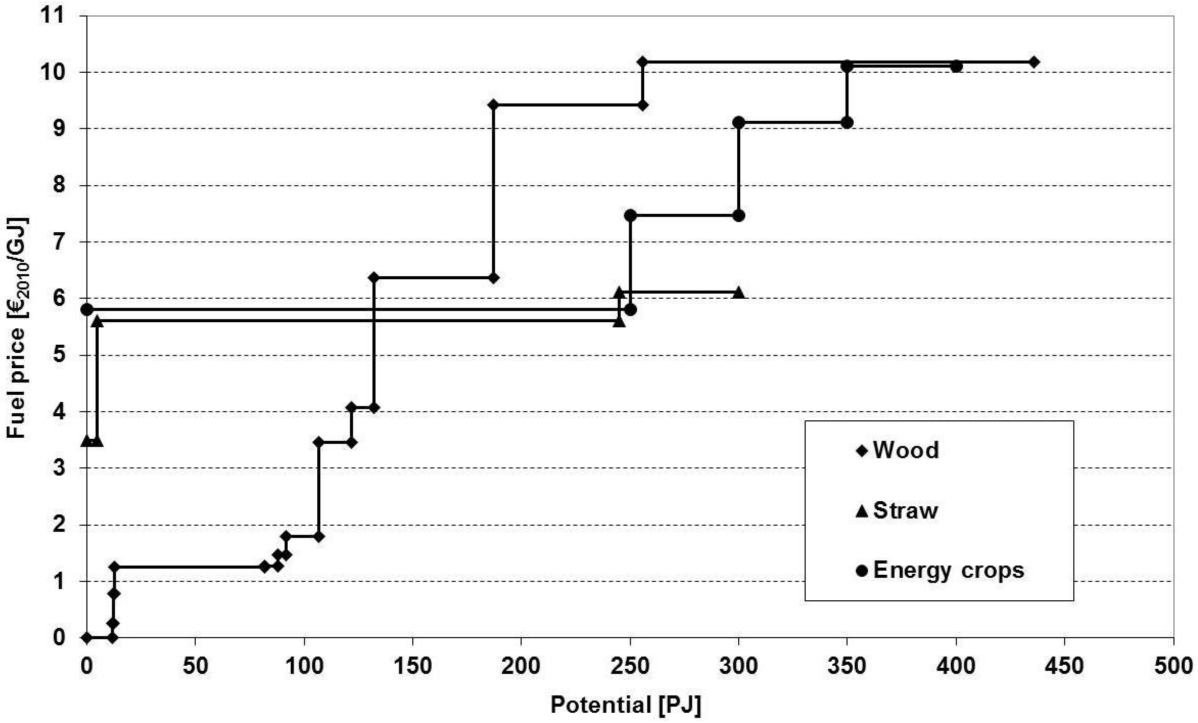

Figure A-1: Cost potential curves for the provision of various types of solid biomass (based on Remme 2006)

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