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EWI Working Paper, No 12/13

September 2012

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ISSN: 1862-3808

Decarbonizing Europe's power sector by 2050 - Analyzing the implications of alternative decarbonization pathways

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Abstract

In this paper, the implications of alternative decarbonization pathways for Europe's power sector up until the year 2050 are analyzed. In specific, an electricity system optimization model is used to investigate the minimal costs of decarbonization under a stand-alone CO_2 reduction target and to quantify the excess costs associated with renewable energy targets and politically implemented restrictions on alternative low-carbon technologies, such as nuclear power. Our numerical simulations confirm the theoretical argumentation concerning counterproductive overlapping regulation. The decarbonization of Europe's power sector is found to be achieved at minimal costs under a stand-alone CO_2 reduction target (171 bn €$_{2010}$). Additionally implemented RES-E targets lead to significant excess costs of at least 237 bn €$_{2010}$. Excess costs of a complete nuclear phase-out in Europe by 2050 are of the same order of magnitude (274 bn €$_{2010}$).

Keywords: Electricity, CO_2 target, renewable target, excess costs, optimization model

JEL classification: C61, Q40, Q50

ISSN: 1862-3808

1. Introduction

In October 2009, the European Council endorsed the EU objective to reduce greenhouse gas (GHG) emissions by 80-95 % (compared to the levels in 1990) by 2050. Given the power sector's comparatively high technological and economic potential for cutting CO_2 emissions, the transition towards a low carbon economy implies an almost complete decarbonization of Europe's power sector - a target, which could be

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achieved along different pathways (EC (2011)). EU member states currently build on the promotion of renewable energy technologies, which are supposed to supply at least 34 % of the EU's electricity consumption by 2020 (EREC (2011)). Regarding the target year 2050, it is not yet clear whether a stand-alone GHG reduction target or additional renewable energy targets will be defined.

If the main objective of both instruments (legally binding GHG reduction and RES-E targets) is to reduce GHG emissions, the issue of counterproductive overlapping regulation arises (Tinbergen (1952)). Naturally, GHG reduction targets could be achieved at least-cost by the implementation of a stand-alone cap-and-trade system covering all sources of GHG emissions. Trading GHG emissions promotes cost-efficiency as it establishes a uniform GHG emission price, which serves as a benchmark for the marginal costs of each potential abatement option. Additional instruments, such as binding renewable energy targets, interfere with this least-cost idea by exempting a particular abatement option from the common benchmark price. As such, implementing additional renewable energy targets within a cap-and-trade system for GHG emissions is not only ineffective with regard to the decarbonization target (as the maximum amount of GHG emissions is set by the cap), but also inefficient in tackling CO_2 emission reductions.[1]

In addition to binding renewable energy targets, politically implemented restrictions on alternative low-carbon technologies, such as nuclear power or thermal power plants equipped with carbon capture and storage (CCS) technology, would exempt possible CO_2 abatement options and thus lead to excess costs in comparison to a stand-alone CO_2 target. However, nuclear energy and CCS are associated with risks that some EU member states are not willing to accept. Currently, 15 out of 27 EU member states are using nuclear energy for power generation, supplying in total around one third of the EU's electricity consumption. While France, the United Kingdom and Slovakia are still pursuing plans to expand their nuclear energy capacities, Germany, Belgium and Switzerland have decided to phase out their existing nuclear power plants after the Fukushima disaster in March 2011. Similarily, CCS currently faces strong headwinds in several EU member states, as CCS demonstration projects are postponed or cancelled, primarily due to constrained financial conditions.[2]

In this paper, an electricity system optimization model is used to investigate the minimal costs of decarbonizing Europe's power sector by 2050 under a stand-alone CO_2 reduction target and to quantify the excess

[1]While climate protection is emphasized as the primary justification for implementing binding renewable energy targets in current policy debates, the EU also refers to enhanced security of energy supply, technological innovation and job creation as arguments for promoting renewables (EU (2009)). From this perspective, one may refer to the excess costs as the implicit cost of using binding renewable energy targets for other goals than climate protection. In this case, however, the question arises whether renewable energy targets are the best instrument available to the regulatory authorities to address supplementary policy targets such as decreased import dependency on fossil fuels, product innovation and job creation.

[2]In addition, CCS often lacks public acceptance regarding the transportation and storage of CO_2 .

costs associated with renewable energy targets and politically implemented restrictions on alternative low-carbon technologies. For reasons of policy relevance, an EU-wide CO_2 reduction target of 90 % until 2050 (compared to 1990 levels) constitutes our benchmark of comparison. Based on these results, we quantify the excess costs associated with overlapping regulation of renewable energy targets and politically implemented restrictions on the use of nuclear power and CCS. Main findings of our paper include that the decarbonization of Europe's power sector could be achieved in 2050 at moderate additional costs of 171 bn $€_{2010}$ – in comparison to the case of no politically implemented CO_2 reduction targets – if the political framework ensures competition between all low-carbon technologies. However, if renewables are exempt from competition with other low-carbon technologies by prescribing explicit RES-E targets, substantial excess costs arise. In comparison to a stand-alone CO_2 target, the costs of decarbonizing Europe's power sector increase by at least 237 bn $€_{2010}$ or 16 %. Interestingly, the excess costs associated with a complete nuclear phase-out in Europe by 2050 lie in the same range as the excess costs associated with RES-E targets (274 bn $€_{2010}$ or 18 %).

The structure of the paper is as follows: Section 2 gives an overview of related research. Section 3 provides a detailed description of the electricity system optimization model for Europe's power sector used in the analysis and defines the scenarios of our simulation. In Section 4, we summarize the results of our analysis: Section 4.1 discusses the excess costs associated with politically implemented renewable energy targets and restrictions on other low-carbon technologies, while Section 4.2 investigates the specific marginal costs of compliance. In Section 5, we draw conclusions and provide an outlook for further possible research.

2. Related literature and contribution of current works

Various papers have recently focused on quantifying the excess costs associated with overlapping EU climate policy regulations for 2020, either using macroeconomic equilibrium or energy system optimization models.

Böhringer et al. (2009) use a multi-sector, multi-region computable general equilibrium model of global trade and energy use to investigate the excess costs of emission market segmentation and overlapping climate policy regulation up to 2020. They find that the current segmentation of the EU GHG emission market causes substantial excess costs as compared to a uniform GHG emission pricing through a comprehensive EU-wide cap-and-trade system. The excess costs of an EU-wide RES-E target of 30 % by 2020 are, however, rather modest due to the fact that the stand-alone GHG emission regulation already induces a substantial increase in RES-E generation in the scenarios depicted in the study.

Table 1: Literature on the quantification of excess costs associated with EU climate policy regulations

	Model type	Quantification	Time horizon
Böhringer et al. (2009)	Equilibrium model	Excess costs of EU-wide RES-E targets and GHG emission market segmentation	2020
Aune et al. (2011)	Equilibrium model	Excess costs of differentiated national renewable energy targets	2020
Boeters and Koorneef (2011)	Equilibrium model	Excess costs of EU-wide renewable energy targets	2020
Möst and Fichtner (2010)	Optimization model	Excess costs of national RES-E promotion schemes and EU-wide RES-E targets	2030

Aune et al. (2011) assess the excess costs associated with the additional implication of differentiated national renewable energy targets for all EU member states as part of the EU climate policy (EC (2010)) for 2020. In specific, they employ a multi-market energy equilibrium model to analyse the impact of various designs of green certificate schemes in addition to the overall GHG emission reduction target of 20 % by 2020. Their model simulations indicate large gains from the trading of green certificates: Excess costs amount to nearly 20 bn €$_{2007}$ if green certificates can only be traded on a national (instead of an EU-wide) level, whereas excess costs decrease by 70 % to 6 bn €$_{2007}$ if an EU-wide trade of green certificates is allowed.

Boeters and Koorneef (2011) use a multi-region, multi-sector recursively dynamic computational general equilibrium model to assess the excess costs of a separate 20 % renewable energy target in gross final energy consumption by 2020 as part of the EU climate policy (EU (2009)).[3] The authors find that the excess costs critically depend on the assumed costs of renewable energy technologies. In their base-case calibration, total costs associated with the 20 % renewable energy target for 2020 are only 6 % (4 bn €$_{2005}$) higher than without the renewable energy target. If, however, the slope of the assumed supply curve is doubled, excess costs amount to more than 32 %.

While macroeconomic equilibrium models have their strength when it comes to examining the broader economy – as they account for feedback effects between different sectors triggered by policy induced changes in relative prices and incomes – they often lack technological details of energy production and conversion, which are a key advantage of energy system optimization models. Due to their technological richness and explicitness, energy system optimization models are particularly well suited to analyze sector-specific policy implications.

[3]For this study, the model has been extended with a module of the electricity sector representing a number of alternative electricity generation technologies through marginal cost curves.

Möst and Fichtner (2010) use a multi-periodic linear energy system optimization model for the power sector of the EU-15 and six neighbouring European countries to determine the economically optimized future evolution of the electricity system under different climate policy regulations until 2030. Simulation results show that under a stand-alone CO_2 regulation, only a few RES-E investments are cost-efficient by 2030. Hence, incentivising RES-E generation while continuing CO_2 emission trading – with a reduction target of 30 % in 2030 (compared to the emissions in 2005 values) – causes significant excess costs. In the case of a prolongation of current national RES-E promotion schemes until 2030, excess costs amount to 72 bn €$_{2005}$. If, however, EU-wide RES-E targets (instead of national RES-E promotion schemes) are implied, excess costs decrease to 63 bn €$_{2005}$ due to the relocation of renewable electricity capacities to regions with less expensive renewable energy potentials.[4]

Our analysis complements the work of Böhringer et al. (2009), Boeters and Koorneef (2011) and Möst and Fichtner (2010). In contrast to the aforementioned literature, we take the 2050 horizon into perspective and analyze the implications of alternative decarbonization pathways for Europe's power sector. In specific, we use an electricity system optimization model to derive the costs of compliance with an EU-wide CO_2 reduction target of 90 % and an EU-wide RES-E target of 85 % up to 2050. Based on the simulation results, we are able to quantify the excess costs of overlapping regulation.

Moreover, in contrast to the existing literature, we quantify the excess costs associated with politically implemented restrictions on the use of nuclear power and CCS – two low-carbon technologies that are currently facing strong headwinds in several EU member states. However, given that the costs of compliance with politically implemented targets (CO_2 and RES-E) and restrictions (nuclear power and CCS) crucially depend on the future economic development, we examine a sensible range of alternative model assumptions. In specific, we account for a 'Low-cost' and a 'High-cost' scenario, which differ with regard to the future development of Europe's total electricity demand, renewable energy investment costs and fossil fuel prices. As such, we identify a robust interval of possible costs of compliance, giving important insights on the implications of alternative decarbonization pathways for Europe's power sector by 2050.

3. Model description and scenario definition

3.1. Electricity system optimization model

The model used in this analysis is an extended version of the long-term investment and dispatch model for conventional, storage and transmission technologies from the Institute of Energy Economics (University

[4]Note that excess costs decrease, although the assumed RES-E target of 1600 TWh for 2030 is about 20 % higher then the endogeneous RES-E production under the prolongation of current national RES-E promotion schemes.

of Cologne) which covers 29 countries (EU27 plus Norway and Switzerland).[5] Endogenous investments in renewable energy technologies have recently been added to the model (Fürsch et al. (2012), Nagl et al. (2011)), including roof and ground photovoltaic systems (PV), wind (onshore and offshore), biomass (solid and gas), biomass CHP (solid and gas), geothermal, hydro (storage and run-of-river) and CSP technologies. For CSP, only facilities including thermal energy storage devices are considered. Biomass, geothermal and hydro technologies are modeled as dispatchable renewables similar to conventional power plants.

Demand characteristics are represented by modeling the dispatch for three days (Saturday, Sunday and a weekday) per season on an hourly basis (scaled to 8760 hours). Three days per season are used to account for the different demand structures on weekends and weekdays. Moreover, typical feed-in structures of fluctuating renewable energies (wind and solar technologies) are modeled for each season, reflecting the weather dependent availability of wind and solar technologies. A maximum possible feed-in of wind and solar power plants is assumed for each hour including days with both very low and very high wind speeds and solar radiation. This approach allows for wind and solar power curtailment when needed to meet demand or when total system costs can be reduced by saving ramping costs of thermal power plants.[6] To account for local weather conditions, the model considers several wind and solar power regions (subregions) within the single countries based on hourly meteorological wind speed and solar radiation data (EuroWind (2011)). Overall, 47 onshore wind, 42 offshore wind and 38 photovoltaic subregions are modeled.

The objective of the model (shown in Eq. (1)) is to minimize accumulated discounted total system costs while assuming that demand is met at all times. An overview of all model sets, parameters and variables is given in Table 2.

[5] A full model description can be found in Richter (2011).

[6] The model chooses offshore wind curtailment first, since transaction costs for curtailing are assumed to be the lowest.

Table 2: Model abbreviations including sets, parameters and variables

Abbreviation	Dimension	Description
Model sets		
a ∈ A		Technologies
s ∈ A	Subset of a	Storage technologies
r ∈ A	Subset of a	RES-E technologies
c ∈ C (alias c')		Countries
e ∈ C	Subset of c	Subregions
d ∈ D		Days
h ∈ H		Hours
y ∈ Y		Years
Model parameters		
ac_a	€$_{2010}$/MWh_{el}	Attrition costs for ramp-up operation
an_a	€$_{2010}$/MW	Annuity for technology specific investment costs
$\mathrm{av}_{c,a}^{d,h}$	%	Availability
$\mathrm{de}_{y,c}^{d,h}$	MW	Demand
dr_y	%	Discount rate
cc_y	t CO_2	Cap for CO_2 emissions
ef_a	t CO_2 /MWh_{th}	CO_2 emissions per fuel consumption
fc_a	€$_{2010}$/MW	Fixed operation and maintenance costs
$\mathrm{fu}_{y,a}$	€$_{2010}$/MWh_{th}	Fuel price
$\mathrm{fp}_{y,c,a}$	MWh_{th}	Fuel potential
hp_y	€$_{2010}$/MWh_{th}	Heating price for end-consumers
hr_y	MWh_{th}/MWh_{el}	Ratio for heat extraction
$\mathrm{nr}_{y,c,r}$	MWh	National technology-specific RES-E targets
$\mathrm{pd}_{y,c}^{d,h}$	MW	Peak demand (increased by a security factor)
$\mathrm{sp}_{r,e}$	km^2	Space potential
sr_r	$\mathrm{MW/km}^2$	Space requirement
η_a	%	Net efficiency (generation)
β_s	%	Net efficiency (load)
$\tau_{y,c,a}^{d,h}$	%	Capacity factor
ω_y	%	Quota on RES-E generation
Model variables		
$\mathrm{AD}_{y,c,a}$	MW	Commissioning of new power plants
$\mathrm{CU}_{y,c,a}^{d,h}$	MW	Ramped-up capacity
$\mathrm{GE}_{y,c,a}^{d,h}$	MW_{el}	Electricity generation
$\mathrm{IM}_{y,c,c'}^{d,h}$	MW	Net imports
$\mathrm{IN}_{y,c,a}$	MW	Installed capacity
$\mathrm{ST}_{y,c,s}^{d,h}$	MW	Consumption in storage operation
TCOST	€$_{2010}$	Total system costs

Total system costs are defined by investment costs, fixed operation and maintenance (FOM) costs, variable production costs and costs due to ramping thermal power plants. Investment costs occur for new investments in generation units and are annualized with a 5 % interest rate for the depreciation time. The FOM costs represent staff costs, insurance charges, rates and maintenance costs. For CCS power plants, FOM costs include fixed costs for CO_2 -storage and transportation. Variable costs are determined by fuel prices, the net efficiency and the total generation of each technology. Ramp-up costs are simulated by referring to the power plant blocks and by setting a minimum load restriction. Depending on the minimum load and start-up time of thermal power plants, additional costs for ramping occur. Combined heat and power (CHP) plants can generate income from the heat market, thus reducing the objective value. In specific, the generated heat in CHP plants is remunerated by the assumed gas price (divided by the conversion efficiency of the assumed reference heat boiler), which roughly represents the opportunity costs for households and industries. However, only a limited amount of generation in CHP plants is compensated by the heating market.[7]

$$\min \; TCOST = \sum_{y\in Y}\sum_{c\in C}\sum_{a\in A}\Bigg[dr_y \cdot \Bigg(AD_{y,c,a}\cdot an_a + IN_{y,c,a}\cdot fc_a \tag{1}$$

$$+\sum_{d\in D}\sum_{h\in H}\left(GE^{d,h}_{y,c,a}\cdot\left(\frac{fu_{y,a}}{\eta_a}\right) + CU^{d,h}_{y,c,a}\cdot\left(\frac{fu_{y,a}}{\eta_a}+ac_a\right) - GE^{d,h}_{y,c,a}\cdot hr(a)\cdot hp(y)\right)\Bigg)\Bigg]$$

s.t.

$$\sum_{a\in A} GE^{d,h}_{y,c,a} + \sum_{c'\in C} IM^{d,h}_{y,c,c'} - \sum_{s\in A} ST^{d,h}_{y,c,s} = de^{d,h}_{y,c} \tag{2}$$

$$\sum_{a\in A}\left[\tau^{d,h}_{y,c,a}\cdot IN_{y,c,a}\right] + \sum_{c'\in C}\left[\tau^{d,h}_{y,c,c'}\cdot IM^{d,h}_{y,c,c'}\right] \geq pd^{d,h}_{y,c} \tag{3}$$

$$GE^{d,h}_{y,c,a} \leq av^{d,h}_{c,a}\cdot IN_{y,c,a} \tag{4}$$

$$\sum_{r\in A} sr_r \cdot IN_{y,e,r} \leq sp_{r,e} \tag{5}$$

$$\sum_{d\in D}\sum_{h\in H}\frac{GE^{d,h}_{y,c,a}}{\eta_a} \leq fp_{y,c,a} \tag{6}$$

$$\sum_{a\in A}\left[\sum_{c\in C}\sum_{d\in D}\sum_{h\in H}\frac{GE^{d,h}_{y,c,a}}{\eta(a)}\cdot ef_a\right] \leq cc_y \tag{7}$$

$$\sum_{c\in C}\sum_{r\in A}\sum_{d\in D}\sum_{h\in H} GE^{d,h}_{y,c,r} \geq \omega_y \cdot \sum_{c\in C}\sum_{d\in D}\sum_{h\in H} de^{d,h}_{y,c} \tag{8}$$

$$\sum_{d\in D}\sum_{h\in H} GE^{d,h}_{y,c,r} \geq nr_{y,c,r} \tag{9}$$

Total system costs are minimized, subject to several techno-economic restrictions: The hourly demand within each country has to be met (Eq. (2)) and the peak demand (increased by a security margin of 10 %) has to be ensured by securely available installed capacities and net imports in the peak demand hour (Eq. (3)). Further important model equations bind the electricity infeed and/or the construction of technologies. The

[7] We account for a maximum potential for heat in co-generation within each country, which is depicted in Table B.15 of the Appendix.

infeed and construction can, for example, be limited by a restricted hourly availability of plants (Eq. (4)), the scarcity of construction sites (Eq. (5)) and the scarcity of the used fuels (Eq. (6)). The hourly availability of dispatchable power plants (thermal, nuclear, storage and dispatchable RES-E technologies such as biomass and geothermal power plants) is limited due to unplanned or planned shut-downs e.g. because of repairs, which are reflected in the parameter $\mathrm{av}_{c,a}^{d,h}$ in Equation (4). The infeed of storage technologies is additionally restricted by the storage level of a particular hour. Unlike dispatchable power plants, the hourly availability of fluctuating RES-E technologies depends on meteorological conditions and varies on a very narrow spatial scale. Hence, in the case of wind and solar power technologies, the parameter $\mathrm{av}_{c,a}^{d,h}$ represents the (maximum possible) feed-in within each hour. Equation (5) depicts the space potential restriction for wind and solar power technologies within a subregion. For other technologies, not the scarcity of the space but rather the scarcity of the used fuels is crucial. Equation (6) restricts the fuel use to a yearly potential in MWh_{th} per country, with different potentials applying for lignite, solid biomass and gaseous biomass sources.

In addition to techno-economic restrictions, the electricity infeed and/or investment in technologies can also be bound by politically implied restrictions. Equation (7) states that the EU-wide CO_2 emissions in Europe's power sector may not exceed a certain CO_2 cap per year. Given the formulation of an EU-wide CO_2 cap, the CO_2 abatement target is achieved at minimal costs, i.e. at equalized marginal costs per ton of CO_2 additionally abated within Europe's power sector. Hence, the model results reflect the market solution of an EU-wide trading system with CO_2 allowances within Europe's power sector. In particular, the marginal costs of compliance with the EU-wide CO_2 cap correspond to the equilibrium prices of CO_2 allowances. Equation (8) formalizes an EU-wide (technology-neutral) RES-E quota in percentage of Europe's electricity demand. Given the formulation of an EU-wide (technology-neutral) RES-E quota, RES-E technologies are used where they are the cheapest option, i.e. at equalized marginal costs per additional unit power generation from RES-E technologies. As such, the model results correspond to the market solution of an EU-wide tradable green certificate system within Europe's power sector. In specific, the marginal costs of compliance with the EU-wide (technology-neutral) RES-E quota can be interpreted as the equilibrium price of green certificates. Besides EU-wide (technology-neutral) RES-E quotas, national technology-specific RES-E targets can also be defined. Equation (9) formalizes the politically implemented restriction that each country must achieve commitment with technology-specific RES-E targets, as prescribed by the EU member states' National Renewable Energy Action Plans (NREAP's) for 2020.

In addition to CO_2 reduction and RES-E targets, political restrictions regarding the construction of new nuclear power plants or conventional power plants equipped with CCS can be implied by limiting the option to invest in those technologies. As such, the modelling approach is a profound tool to derive a comprehensive set of technically feasible and economically efficient development pathways for Europe's power sector by 2050. Specifically, the implications of alternative decarbonization pathways can be analyzed by varying politically implemented restrictions for the given economic framework conditions.

3.2. Scenario definitions

The decarbonization of Europe's power sector in 2050 can be achieved along different pathways. To systematically analyze the implications of alternative political targets and restrictions under different economic conditions, a matrix of 32 scenarios is defined (Table 3).

Table 3: Scenario matrix

Political scenario			Economic scenario		
CO_2 and RES-E	Nuclear	CCS	Low-cost	Base	High-cost
No target	not restricted	not restricted	1-I-L	1-I-B	1-I-H
	not restricted	restricted	1-II-L	1-II-B	1-II-H
	restricted	not restricted	1-III-L	1-III-B	1-III-H
	restricted	restricted	1-IV-L	1-IV-B	1-IV-H
CO_2 target	not restricted.	not restricted	2-I-L	2-I-B	2-I-H
	not restricted	restricted	2-II-L	2-II-B	2-II-H
	restricted	not restricted	2-III-L	2-III-B	2-III-H
	restricted	restricted	2-IV-L	2-IV-B	2-IV-H
CO_2 & RES-E target	not restricted	not restricted	3-I-L	3-I-B	3-I-H
	not restricted	restricted	3-II-L	3-II-B	3-II-H
	restricted	not restricted	3-III-L	3-III-B	3-III-H
	restricted	restricted	3-IV-L	3-IV-B	3-IV-H

Along the row dimension of Table 3, the scenarios differ with regard to politically implemented regulations. In specific, the scenarios vary with regard to the existence of legally binding CO_2 reduction and RES-E targets as well as with regard to restrictions on the usage of nuclear power and CCS. Along the line dimension, however, the scenarios differ with regard to the economic conditions in place. Below, the exact specifications of both the alternative political targets (and restrictions) and the economic conditions assumed in the different scenarios are presented. These include:

- **No target**: Neither CO_2 nor RES-E quotas are implemented.
- **CO_2 target**: EU-wide CO_2 quotas are implemented until 2050 and formulated with respect to 1990 CO_2 emission levels (see Table 4).

- **CO_2 & RES-E target**: In addition to EU-wide CO_2 quotas, EU-wide (technology-neutral) RES-E quotas are implemented until 2050, which are are formulated with respect to Europe's gross electricity demand (see Table 4).

Table 4: EU-wide CO_2 and EU-wide (technology-neutral) RES-E quotas

	2020	2030	2040	2050
CO_2 reduction in comparison to 1990 levels	20 %	42 %	65 %	90 %
RES-E generation in % of Europe's electricity demand	36 %	50 %	66 %	85 %

- **Nuclear not restricted**: No political restrictions on the usage of nuclear power are implemented. As such, investments in new nuclear power plants are possible across Europe by 2050.

- **Nuclear restricted**: While the usage of existing nuclear power plants is not restricted, investments in new nuclear reactors are. This leads to a complete nuclear phase-out in Europe until 2050.[8]

- **CCS not restricted**: CCS becomes a commercially available investment option after 2030.

- **CCS restricted**: Investments in CCS are not possible.

Due to the fact that the costs of decarbonization under alternative political targets (CO_2 and RES-E quotas) or restrictions (nuclear power and CCS) critically depend on the economic conditions in place, we control for three economic scenarios. As shown in Table 5, the difference between the economic scenarios refers to the level of RES-E investment costs, fossil fuel prices and total electricity demand. The scenario specifications serve the purpose of deriving an upper and lower bound of decarbonization costs. The 'Low-cost' scenario implies lower costs of decarbonization, while the 'High-cost' scenario implies higher costs of decarbonization compared to the 'Base' scenario. A detailed listing of all scenario-specific parameters assumed can be found in Table A.9, A.8 and A.10 of the Appendix.

[8]While Germany is assumed to phase-out its existing nuclear power plants before 2022, as current legislation stipulates, all other existing nuclear power plants throughout Europe are assumed to remain in operation until the end of their technical lifetimes.

Table 5: Specification of economic parameters

	'Low-cost'' scenario	'Base' scenario	'High-cost' scenario
RES-E investment costs	low	medium	high
Gas-to-coal spread	low	medium	high
Europe's electricity demand	decrease	constant	increase

In all three economic scenarios, RES-E investment costs are assumed to decrease over time, with the less mature RES-E technologies (such as PV, CSP and offshore wind) realizing higher cost degression rates towards 2050 than technically mature RES-E technologies (such as biomass power plants). The specific level of future investment cost degression rates, however, significantly differs between the scenarios. For example, while investment costs of offshore wind power plants are assumed to decrease by up to 60 % by 2050 (compared to 2010 levels) in the 'Low-cost' scenario, investment costs decrease by 34 % in the 'Base' scenario and by only 8 % in the 'High-cost' scenario. In contrast, due to limited ressources, fossil fuel prices are assumed to increase over time in all three scenarios. The specific increase of fossil fuel prices, however, differs across the scenarios. While the 'Low-cost' scenario exhibits a lower increase in the gas-to-coal spread as the 'Base' scenario, the 'High-cost' scenario assumes a higher increase.[9] Europe's electricity demand is assumed to either decrease by 15 % up to 2050 (compared to 2010 levels)('Low-cost'), to stay constant at 2010 levels ('Base') or to increase by 15 % up to 2050 (compared to 2010 levels) ('High-cost').

Except for RES-E investment costs, fossil fuel prices and electricity demand, all other parameters are kept constant throughout the scenarios. In particular, the development of Europe's electricity grid up to 2050 is assumed to be the same in all scenarios. While power transfers within the single market regions are assumed to face no transmission constraints – as market regions are modeled as copper plates – power transfers between the market regions are limited by the interconnection capacities. In total, these are assumed to increase by a factor of 2.5 up until 2050 (compared to 2010 levels). Specifically, interconnection capacity extensions are limited to projects which have already entered the planning or permission phase today based on the ENTSO-E's 10-Year Network Development Plan (ENTSO-E (2010)), but whose commissioning is assumed to be delayed. A detailed listing of all parameters common to the scenarios can be found in Table B.13, B.12, B.14 and B.16 of the Appendix.

4. Scenario results

The subsequent analysis of our scenario results is structured as follows: Section 4.1 investigates the total (accumulated) system costs associated with alternative political targets and restrictions under different

[9]The higher the gas-to-coal spread is, the higher the costs of decarbonization will be.

economic conditions. In specific, we first analyse the costs of compliance with a stand-alone CO_2 reduction target of 90 % in 2050 (compared to 1990 levels) (4.1.1). Based on these results – which serve as our benchmark of comparison – we quantify the excess costs associated with additionally implemented RES-E targets (4.1.2) and restrictions on the use of nuclear power (4.1.3) and CCS (4.1.4). Section 4.2 analyses the marginal costs of compliance with the annual CO_2 and RES-E targets per decade up to 2050 to gain a better understanding of the consequences of overlapping regulation.

The general focus of the analysis is on total system costs, excess costs and marginal costs of compliance with politically implemented targets and restrictions, rather than the cost-efficient development of regional capacities or generation throughout Europe. Nevertheless, an overview of the cost-efficient capacity and generation mix in 2050 for the different scenarios can be found in Table C.17 of the Appendix.

4.1. Total system costs

Total system costs are defined as the sum of discounted investment, fixed operation and maintenance and variable generation costs of the electricity generation system accumulated from 2010 until 2050.[10] They do not include investment costs for the necessary infrastructure and operational costs for grid management. Table 6 depicts the discounted scenario-specific total system costs accumulated until 2050 in billion €$_{2010}$.

Table 6: Total system costs (discounted and accumulated until 2050) in bn €$_{2010}$

Political scenario				Economic scenario		
CO_2 and RES-E	Nuclear	CCS		Low-cost [L]	Base [B]	High-cost [H]
No target	No restriction	No restriction	[1-I]	1,248	**1,331**	1,415
	No restriction	Restriction	[1-II]	1,248	1,331	1,415
	Restriction	No restriction	[1-III]	1,261	1,345	1,430
	Restriction	Restriction	[1-IV]	1,261	1,345	1,430
CO_2 target	No restriction	No restriction	[2-I]	1387	**1502**	1588
	No restriction	Restriction	[2-II]	1394	**1518**	1616
	Restriction	No restriction	[2-III]	1506	**1776**	1948
	Restriction	Restriction	[2-IV]	1541	1858	2051
CO_2 & RES-E target	No restriction	No restriction	[3-I]	1466	**1739**	1879
	No restriction	Restriction	[3-II]	1469	1741	1882
	Restriction	No restriction	[3-III]	1512	1811	1984
	Restriction	Restriction	[3-IV]	1546	1873	2063

Three general conclusions can be drawn from the scenario matrix: First, total system costs are the lowest

[10]Total system costs also include the annualized investment costs of all existing conventional, renewable and storage capacities in 2010, which are assumed not to be completely depreciated by the year 2010.

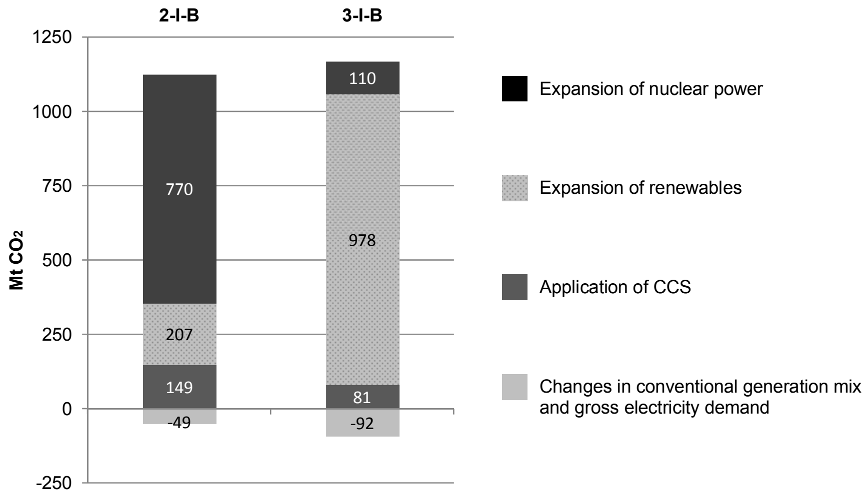

Figure 1: Total CO_2 savings in 2050 compared to 2010 levels

in scenarios with no politically implemented targets or restrictions.[11] Second, total system costs significantly rise as the number of political targets and restrictions increases. Third, total system costs decisively depend on the economic scenario assumed. Overall, the impact of the economic scenario on total system costs increases with the number of political targets and restrictions in place.

4.1.1. Costs of compliance with EU-wide CO_2 targets

Given stand-alone CO_2 reduction targets of up to 90 % by 2050 (compared to 1990 levels) and no restrictions on the usage of nuclear power and CCS, the decarbonization of Europe's power sector may be achieved at moderate additional costs. Total system costs increase from 1,331 bn €$_{2010}$ in scenario 1-I-B (which assumes no politically implemented CO_2 reduction targets) to 1,502 bn €$_{2010}$ in scenario 2-I-B. As such, the compliance with the CO_2 reduction targets up until 2050 is achieved at additional costs of 171 bn €$_{2010}$ or 13 %.

As shown in Figure 1, the 90 % CO_2 reduction target in 2050 is accomplished through the expansion of nuclear power, renewable energies and CCS technologies (scenario 2-I-B). In specific, the expansion of nuclear power accounts for 770 Mt CO_2 or 71 % of total CO_2 savings in 2050 (1,077 Mt CO_2), the expansion of renewables for 207 Mt CO_2 (19 %), and the application of CCS for 149 Mt CO_2 (14 %).[12]

These scenario results point out the comparative (electricity generation) cost advantage of nuclear power

[11] Due to a massive increase of electricity generation in low-cost coal-fired power plants across Europe up until 2050, CO_2 emissions increase by 25-68 % by 2050 (compared to 1990 levels).

[12] The CO_2 savings are derived by comparing the CO_2 emissions of Europe's electricity generation mix in 2050 with the emissions in 2010.

in low-carbon power systems. However, our cost assumptions for nuclear power do not account for the costs associated with the final disposal of nuclear waste or potential nuclear accidents.

Compared to 2008 levels, nuclear power capacities increase by 61 % in 2050 – with the largest expansions occuring in Italy, Great Britain, Germany and Spain. As shown in Figure 2,[13] total installed nuclear power capacities in scenario 2-I-B amount to 221 GW, supplying 48 % of Europe's total electricity demand by 2050.

Aside from nuclear power, renewables play an important role in achieving commitment with the stand-alone CO_2 targets at minimal costs. By 2050, total onshore wind capacities amount to 130 GW, supplying about 377 TWh or 11 % of Europe's electricity demand. In addition to onshore wind capacities, biomass-fired and geothermal capacities are significantly expanded across Europe up until 2050. Conversely, offshore wind and solar power technologies (PV and CSP) are not depicted as cost-efficient investment option, given the unconstrained availability of nuclear power across Europe. In total, renewables account for 36 % of Europe's electricity demand in 2050, given a stand-alone CO_2 reduction target of 90 % in scenario 2-I-B.

CCS applied to thermal power plants plays a crucial role in countries with traditionally high shares of lignite-fired power generation, such as Germany, Poland and the Czech Republic. By 2050, installed capacities of lignite-CCS power plants amount to over 23 GW in Germany, 9 GW in Poland and 7 GW in the Czech Republic. However, CCS applied to coal- and gas-fired power plants is not a cost-efficient investment option. This is due to the fact that renewables depict a lower cost CO_2 abatement option to achieve commitment with the EU-wide CO_2 reduction targets in the long run compared to coal- and gas-fired power plants equipped with the CCS technology. In total, lignite-fired power plants supply 11 % of Europe's electricity demand by 2050 in scenario 2-I-B.

Overall, the costs of decarbonization in the 'Low-cost' (2-I-L) and 'High-cost' scenario (2-I-H) hardly differ from the cost of decarbonization in the 'Base' scenario (2-I-B), given that nuclear power is depicted as an unrestricted investment option. On average across all scenarios, the CO_2 reduction targets of up to 90 % in 2050 are achieved at moderate additional costs of 161 bn €$_{2010}$ or 12 %.

[13] The historical 2008 values are based on EURELECTRIC (2009) and Eurostat (2010)

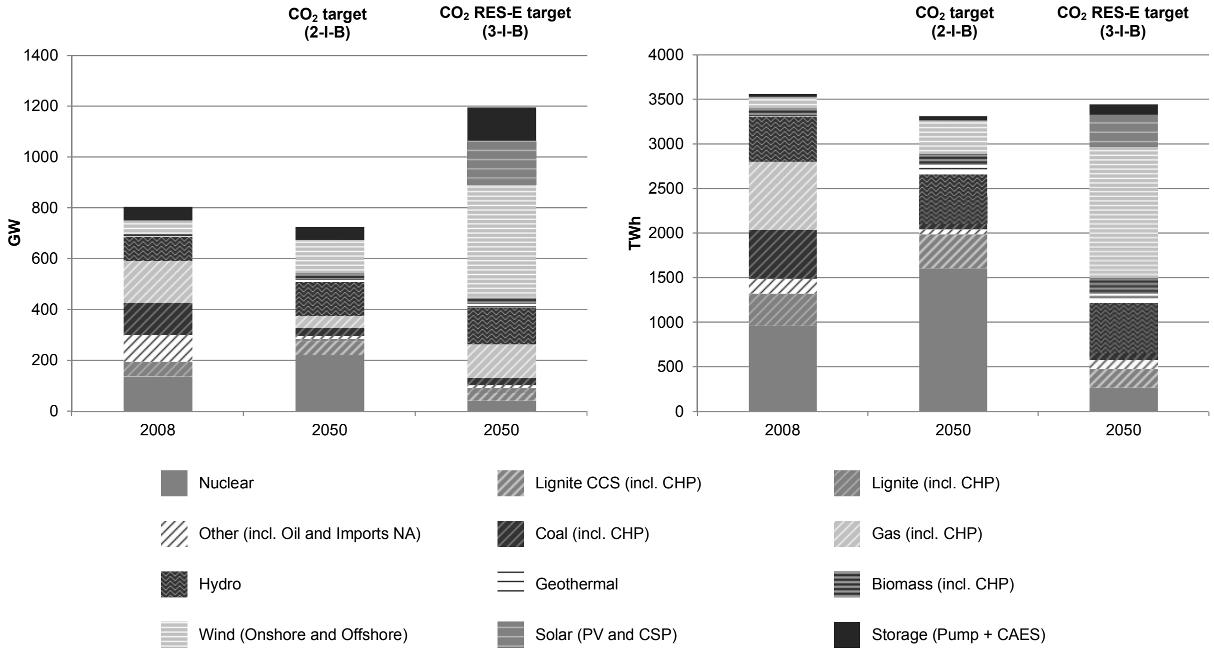

Figure 2: Scenario specific capacity and generation mix in 2050

4.1.2. Excess costs of additionally implemented RES-E targets

CO_2 reduction targets could be achieved at least-cost by the implementation of a stand-alone cap-and-trade system for CO_2 emissions. Additional instruments, such as legally binding RES-E targets, interfere with this least-cost idea by exempting a particular CO_2 abatement option from the common benchmark price, which leads to excess costs in comparison to a stand-alone CO_2 target.

Our numerical analysis shows that the excess costs associated with additionally implemented EU-wide RES-E targets are substantial.[14] Total system costs increase from 1,502 bn €$_{2010}$ in scenario 2-I-B to over 1,739 bn €$_{2010}$ in scenario 3-I-B. Hence, achieving commitment with EU-wide RES-E targets (which increase from 36 % in 2020 to 85 % in 2050) leads to excess costs of 237 bn €$_{2010}$ or 16 % up to 2050.[15]

As shown in Figure 2, the excess costs are based on the large-scale replacement of nuclear power (scenario 2-I-B) through more expensive RES-E technologies up until 2050. Overall, renewables account for 978 Mt CO_2 or 91 % of total CO_2 savings in 2050 (See scenario 3-I-B in 2).[16] In addition to onshore wind turbines, biomass-fired and geothermal power plants, offshore wind turbines and solar power capacities are deployed

[14]Note that the RES-E targets are expressed in percentage of Europe's electricity demand.

[15]However, given the fact that we do not take into account the costs associated with the final disposal of nuclear waste or potential nuclear accidents the excess costs of additionally implemented RES-E targets represent an upper bound estimate.

[16]Nuclear power: 110 Mt CO_2 ; CCS: 81 Mt CO_2 .

to achieve commitment with the EU-wide RES-E targets. However, unlike onshore wind, investments in offshore wind and solar power capacities do not take place before 2020. Overall, 245 GW of onshore wind turbines, 197 GW of offshore wind turbines, 121 GW of photovoltaic systems, 53 GW of concentrating solar power plants, 26 of GW biomass power plants (incl. CHP-plants) and 16 GW of geothermal power plants are installed by 2050 in scenario 3-I-B.

Given the formulation of EU-wide RES-E targets, the deployment of capacities takes place at the most favorable sites across Europe. Onshore and offshore wind turbines are primarily deployed in northern European countries with good wind conditions such as Great Britain (97 GW), (northern) France (96 GW), Germany (78 GW), the Netherlands (36 GW) and Norway (23 GW). Photvoltaic systems are primarily installed in southern European countries such as Italy (52 GW), Spain (17 GW) and (southern) France (20 GW). Moreover, 45 GW of CSP plants equipped with thermal storage devices are deployed across southern Europe by 2050 (mostly in Spain).

However, the excess costs associated with the EU-wide RES-E targets significantly depend on the assumed economic development. While in the 'Base' scenario excess costs amount to 237 bn €$_{2010}$ (16 %), excess costs in the 'Low-cost' scenario (3-I-L) amount to only 79 bn €$_{2010}$ (5 %), and to more than 291 bn €$_{2010}$ (18 %) in the 'High-cost' scenario (3-I-H). These results are primarily driven by the assumptions regarding the future development of RES-E investment costs. Obviously, excess costs of compliance with EU-wide RES-E targets decrease as the level of RES-E investment costs decreases. Moreover, given a limited potential of favorable renewable energy sites across Europe, excess costs of EU-wide RES-E targets decrease as the level of Europe's electricity demand decreases – assuming that the RES-E targets are formulated as a percentage of Europe's total electricity demand.

On average across the 'Low-cost', 'Base' and 'High-cost' scenarios, excess costs of EU-wide RES-E targets amount to 202 bn €$_{2010}$ (13 %) by 2050. However, due to the formulation of EU-wide (technology-neutral) RES-E targets for each decade (which increase from 36 % in 2020 to 85 % in 2050), the estimations present a lower bound of the possible excess costs.

Sensitivity analysis on national technology specific RES-E targets

For reasons of policy relevance, a sensitivity analysis of scenario 3-I-B is simulated by considering national technology-specific RES-E targets instead of an EU-wide (technology-neutral) RES-E target for 2020. In particular, we assume that the EU member states achieve commitment with the national technology-specific RES-E targets specified in their National Renewable Energy Action Plans (NREAPs) for 2020 instead of an

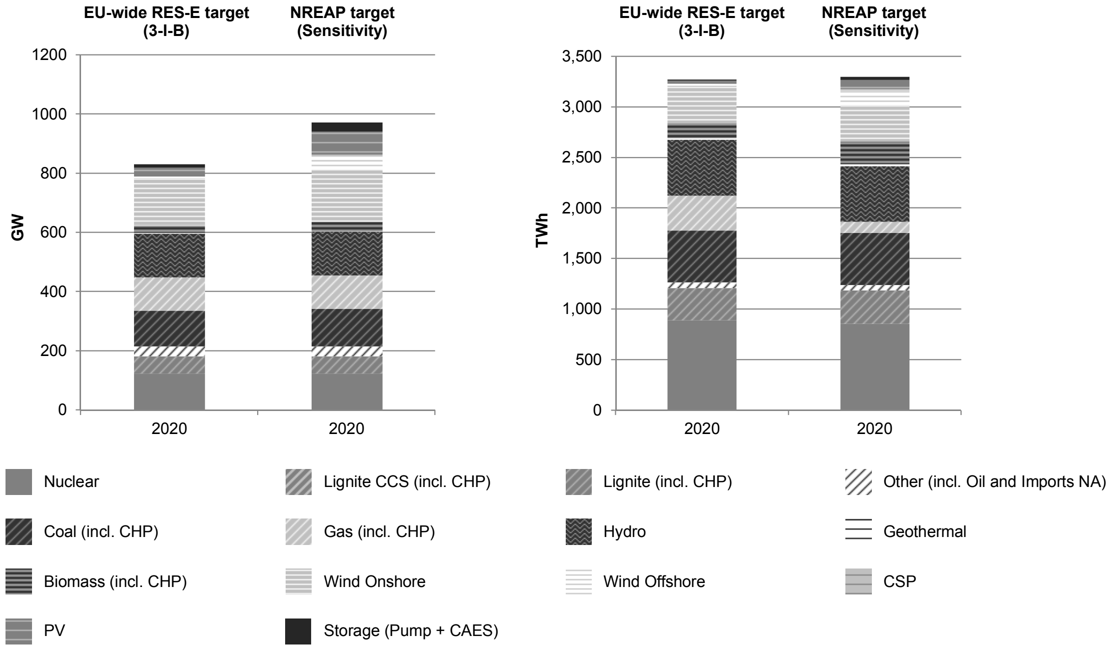

Figure 3: Scenario specific capacity and generation mix in 2020

EU-wide (technology-neutral) RES-E target of 36 % in 2020.[17] In comparison to the EU-wide (technology-neutral) RES-E targets, national technology-specific RES-E targets may lead to substantial excess costs for two reasons: First, technology-specific targets may prevent the utilization of the least-cost RES-E technologies. Second, national targets may prevent the allocation of RES-E technologies at the most favorable sites in Europe (with the highest full load hours).

Our simulation results show that the total system costs increase from 1,739 bn €$_{2010}$ to 1,929 bn €$_{2010}$ if the EU member states achieve commitment with their technology-specific NREAP targets in 2020, instead of the EU-wide RES-E target of 36 % (scenario 3-I-B). The excess costs associated with the national technology-specific NREAP targets amount to over 190 bn €$_{2010}$ by 2050.

As shown in Figure 3, the sub-optimal choice of RES-E technologies is reflected by a significant expansion of photovoltaics and offshore wind up to 2020. While the EU member states' NREAPs forsee a strong increase

[17] All other assumptions are kept constant. In specific, we assume that the national technology-specific RES-E targets of the EU member states' NREAPs only exist until 2020 and are replaced by the EU-wide (technology-nutral) RES-E targets of scenario 3-I-B from 2020 onwards. Hence, both scenarios achieve commitment with a 85 % RES-E target by 2050. They only differ with regard to the 2020 RES-E target. Table A.11 of the Appendix lists the technology-specific RES-E targets (in TWh) assumed.

of PV electricity generation in Europe (83 TWh in the EU, of which 41 TWh in Germany), no additional PV capacities are deployed in Europe until 2020 in scenario 3-I-B, assuming an EU-wide (technology-neutral) RES-E target of 36 % for 2020. A similar case holds for offshore wind power. While the NREAP targets forsee a total offshore wind electricity generation of 142 TWh in 2020, only 15 TWh offshore wind power is generated in scenario 3-I-B. These results reflect the significant cost advantage of onshore wind power in comparison to offshore wind power and PV before the year 2020.

In addition to the sub-optimal choice of RES-E technologies, excess costs also occur due to an inefficient regional allocation of RES-E technologies. For example, although total onshore wind capacities in 2020 are 5 % lower in scenario 3-I-B than in the 'Sensitivity' scenario with the NREAP targets, total onshore wind electricity generation is 5 % higher.[18] As opposed to the national technology-specific NREAP targets, the EU-wide (technology-neutral) RES-E target ensures the deployment of wind power turbines at the most favorable sites in Europe until 2020. As a consequence, the average full load hours achieved by the onshore/offshore wind turbines deployed across Europe in 2020 are 11 %/14 % higher in scenario 3-I-B than in the 'Sensitivity' scenario using the NREAP targets.

Overall, the scenario results show that the national technology-specific RES-E targets prevent the cost-efficient choice and allocation of RES-E technologies across Europe. Consequently, significant excess costs arise. In the case of the EU member states' NREAP targets for 2020, the excess costs are primarily due to two reasons: First, the NREAP targets forsee a large-scale deployment of photovoltaic systems and offshore wind power turbines, which are characterized by comparatively high investment costs up to 2020. Second, the NREAP targets prescribe the allocation of wind power turbines (onshore and offshore) and photovoltaic systems at comparatively unfavorable sites across Europe.

4.1.3. Excess costs of political restrictions on the use of nuclear power

After the Fukushima disaster in March 2011, several EU member states decided to either phase out their existing nuclear power plants, postpone plans to construct new nuclear power plants or reinforced the decision to stay a nuclear-free country. Given the current policy situation, we analyse the excess costs associated with a complete nuclear phase-out in Europe by 2050 by restricting the option to invest in new nuclear power plants across Europe.[19]

[18] In scenario 3-I-B: 162 GW and 370 TWh respectively; in 'Sensitivity' scenario with NREAP targets: 170 GW and 352 TWh respectively. Note that the implied national technology-specific onshore wind targets in the 'Sensitivity' scenario for 2020 are exceeded in Denmark and Ireland.

[19] While Germany is assumed to phase-out its existing nuclear power plants before 2022, as current legislation stipulates, all other existing nuclear power plants throughout Europe are assumed to remain in operataion until the end of their technical lifetimes.

Our numercial analysis shows that the excess costs associated with a complete nuclear phase-out in Europe by 2050 are in the same range as the excess costs associated with EU-wide RES-E targets of up to 85 % in 2050. In comparison to stand-alone CO_2 targets and no politically implied restrictions on the use of nuclear power across Europe up to 2050 (scenario 2-I-B), total system costs increase from 1,502 bn €$_{2010}$ to 1,776 bn €$_{2010}$ in scenario 2-III-B. Hence, an EU-wide phase-out of nuclear power by 2050 leads to excess costs of about 274 bn €$_{2010}$ or 18 %. These excess cost primarily occur due to the large-scale replacement of nuclear power by more expensive RES-E technologies.

As opposed to scenario 2-I-B – in which nuclear power accounts for around 48 % of Europe's electricity demand in 2050 – renewables in scenario 2-II-B account for 893 Mt CO_2 or 83 % of total CO_2 savings in 2050 (1,077 Mt CO_2). The application of CCS, in contrast, accounts for 152 Mt CO_2 or 14 %, which corresponds to the contribution of CCS in scenario 2-I-B.

In comparison to scenario 2-I-B, total installed capacities across Europe significantly increase in scenario 2-III-B (plus 63 %) due to the large scale expansion of fluctuating wind (on- and offshore) and solar power (PV) plants, which exhibit significant lower full load hours than nuclear power plants. While total installed capacities amount to 726 GW in the case of no political restrictions on the use of nuclear power across Europe (scenario 2-I-B), total installed capacities amount to 1,185 GW given a complete nuclear phase-out in Europe by 2050. In specific, 221 GW of nuclear capacities are replaced by 144 GW of additional onshore wind capacities, 172 GW of additional offshore wind capacities and 136 GW of additional PV capacities in 2050. Moreover, 189 GW of gas-fired power plants and 45 GW of storage capacities (CAES) are additionally deployed by 2050 to ensure the countinuous balance of supply and demand.

Overall, the simulation results show that the excess costs of a complete nuclear phase-out in Europe by 2050 correspond to the excess costs of additionally implied EU-wide RES-E targets (of up to 85 % in 2050). In both cases, the decarbonization of Europe's power sector is achieved through a massive expansion of renewables up to 2050.

4.1.4. Excess costs of political restrictions on the use of CCS

Carbon capture and storage (CCS) technology could play an important role in the transition towards a decarbonized economy in Europe. However, it remains uncertain whether CCS will be commercially available for application in conventional power plants after 2030, primarily due to public concerns regarding the transportation and storage of CO_2 . Against this background, we analyze the potential excess costs associated with a restriction on the application of CCS technology in conventional power plants in Europe after 2030.

Our numercial analysis shows that the excess costs associated with a restriction of CCS are rather moderate. In comparison to scenario 2-I-B – which assumes stand-alone CO_2 targets and no restrictions on the use of CCS – total system costs increase by 16 bn €$_{2010}$ (from 1502 bn €$_{2010}$ to 1,518 bn €$_{2010}$) if CCS becomes not commercially available after 2030. This moderate increase is due to the assumption of an unconstrained availability of nuclear power in scenario 2-I-B, which depicts a comparatively low-cost CO_2 abatement option. Hence, the contribution of nuclear power to total CO_2 emission savings in 2050 increases from 770 Mt CO_2 (scenario 2-I-B) to 889 Mt CO_2 in the absence of CCS (scenario 2-II-B). In specific, Germany, Poland and the Czech Republic replace their 39 GW of lignite-CCS power plants (scenario 2-II-B) with 27 GW of additional nuclear capacities, 6 GW of additional gas capacities and 10 GW of additional lignite power plants (scenario 2-I-B).

Interestingly, the excess costs associated with a restriction on the use of nuclear power significantly increase if Europe pursues a complete nuclear phase-out by 2050. This increase is due to the fact that lignite-CCS power plants are replaced with more expensive renewable technologies instead of nuclear power. In comparison to scenario 2-III-B – which assumes no restriction on the use of CCS – total system costs rise by 82 bn €$_{2010}$ to 1,858 bn €$_{2010}$ in scenario 2-IV-B.

After having analyzed the total costs of compliance with EU-wide CO_2 reduction targets, as well as the specific excess costs associated with additionally implemented RES-E targets and restrictions on the use of nuclear power and CCS, Section 4.2 investigates the marginal costs of compliance with the annual CO_2 and RES-E targets for each decade up to 2050 to gain a better understanding about the consequences of overlapping regulation.

4.2. Marginal costs of compliance

In addition to the difference in total system costs, the impact of politically implemented targets can also be identified by the marginal costs of compliance. In the case of the EU-wide CO_2 reduction targets, the marginal costs of compliance – depicted in Table 7 – reflect the total system costs associated with the abatement of the last ton of CO_2 needed to achieve commitment with the CO_2 reduction target for a specific year. As such, the marginal costs of compliance present the additional costs of the last CO_2 abatement option chosen compared to that of the replaced technology.

As per assumption, the politically implied CO_2 reduction targets become more restrictive over time (CO_2 target increases from 20 % in 2020 to 90 % in 2050), whereas the costs of existing low-carbon technologies decrease over the years and new technologies become available. Hence, the marginal costs of compliance do not need to increase steadily over time. An example for the impact of new technologies on the marginal costs of compliance is the introduction of CCS from 2030 onwards, which causes the marginal costs of compliance in scenario 3-I-L to drop from 18 €$_{2010}$/t CO_2 to 7 €$_{2010}$/t CO_2 between 2020 and 2030. Conversely, in scenario 3-II-L, where CCS depicts no investment option, marginal costs of compliance decrease only from 18 €$_{2010}$/t CO_2 to 17 €$_{2010}$/t CO_2 between 2020 and 2030.[20]

Table 7: Marginal costs of compliance with EU-wide CO_2 reduction and (technology-neutral) RES-E targets

		CO_2 target [€$_{2010}$/t CO_2]				RES-E target [€$_{2010}$/MWh]			
Scenario		2020	2030	2040	2050	2020	2030	2040	2050
CO_2 target	2-I-L	36	16	29	62	-	-	-	-
	2-I-B	41	19	28	78	-	-	-	-
	2-I-H	39	17	36	82	-	-	-	-
	2-II-L	36	29	41	68	-	-	-	-
	2-II-B	41	34	32	76	-	-	-	-
	2-II-H	35	35	72	83	-	-	-	-
	2-III-L	36	27	65	65	-	-	-	-
	2-III-B	41	27	103	91	-	-	-	-
	2-III-H	41	26	101	177	-	-	-	-
	2-IV-L	36	50	79	73	-	-	-	-
	2-IV-B	42	58	128	99	-	-	-	-
	2-IV-H	38	61	129	197	-	-	-	-
CO_2 & RES-E target	3-I-L	18	7	54	37	18	33	19	31
	3-I-B	23	7	49	42	18	49	71	60
	3-I-H	28	6	37	50	0	55	95	71
	3-II-L	18	17	68	37	17	32	12	28
	3-II-B	22	12	68	42	18	46	60	56
	3-II-H	27	13	66	55	0	54	80	72
	3-III-L	35	19	58	55	2	23	9	3
	3-III-B	39	18	69	80	6	36	51	2
	3-III-H	39	22	79	94	0	38	63	20
	3-IV-L	35	43	79	72	3	8	0	0
	3-IV-B	38	46	95	97	7	23	32	0
	3-IV-H	38	54	104	159	0	17	45	0

Moreover, the availability of nuclear power, as a comparatively low-cost CO_2 abatement option, has a significant impact on the marginal costs of compliance with the EU-wide CO_2 reduction targets. The effects can, for example, be seen when comparing scenario 2-III-H with scenario 2-I-H. If no restrictions on the usage of nuclear power across Europe are implemented, then the marginal costs of compliance in 2050 amount

[20]The small decrease is due to the fact that both the investment costs of existing RES-E technologies decrease and more advanced RES-E technologies become available. For example, to account for technological progress expected in the wind power sector, 8 MW onshore and offshore wind turbines can be built from 2030 onwards, which are characterized by higher full load hours, lower specific investment costs and a lower space requirement per MW installed (km^2/MW).

to only 82 €$_{2010}$/t CO_2 . However, if Europe pursues a complete nuclear phase-out by 2050, marginal costs increase to over 177 €$_{2010}$/t CO_2 .

Apart from the politically implemented restrictions on nuclear power and CCS, the marginal costs of compliance with the yearly EU-wide CO_2 reduction targets also depend on the additional implication of EU-wide RES-E targets. Overall, the additionally implemented RES-E targets have a clear downward pressure on the marginal costs of compliance with the CO_2 reduction targets across the scenarios. Nevertheless, the marginal costs of compliance are always greater than zero in the case of EU-wide RES-E targets (scenario 3-I-L to 3-IV-H), meaning the implied CO_2 reduction targets are binding in all years.

Moreover, the marginal costs of compliance with the EU-wide CO_2 reduction targets also depend on the assumed economic scenario. The more critical the economic conditions are, especially concerning higher RES-E investment costs or total electricity demand, the higher the marginal costs of compliance with the EU-wide CO_2 reduction targets will be. The marginal costs of compliance with the EU-wide RES-E targets per decade reflect the total system costs associated with the supply of the last MWh of RES-E electricity production needed to achieve commitment with the RES-E target in a specific year. As can be seen in Table 7, the marginal costs of compliance with the EU-wide RES-E targets significantly depend on the EU-wide CO_2 reduction targets in place and on the politically implemented restrictions on other low-carbon technologies. For example, the marginal costs of compliance with the EU-wide RES-E targets can drop to zero in scenarios that combine challenging CO_2 reduction targets with restrictions on the usage of nuclear power and CCS. Thus, the additionally implemented EU-wide RES-E targets are rendered non-binding. This is, for example, the case in scenario 3-IV-L for the years 2040 and 2050.

Overall, the simulation results illustrate the consequences of overlapping regulation. On average, additionally implemented RES-E targets have a clear downward pressure on the marginal costs of compliance with the EU-wide CO_2 reduction targets.

5. Conclusion

The numerical simulations confirm the theoretical argumentation concerning counterproductive overlapping regulation. The decarbonization of Europe's power sector is achieved at minimal costs under a stand-alone CO_2 reduction target (171 bn €$_{2010}$). Additionally implemented RES-E targets lead to significant excess costs of at least 237 bn €$_{2010}$. The excess costs associated with a complete phase-out of nuclear power in Europe by the year 2050 are in the same order of magnitude (274 bn €$_{2010}$).

Based on the given results, several policy implications can be concluded. Ideally, to minimize the costs of decarbonizing Europe's power sector by 2050, competition between all low-carbon technologies must be ensured. However, if renewables are exempt from competition by legally binding RES-E targets, the targets should be defined as EU-wide technology-neutral instead of national technology-specific to ensure the utilization of the least-cost renewable technologies across Europe. Moreover, given substantial uncertainties on the future development of RES-E investment costs and Europe's electricity demand, excess costs should be limited by the formulation of absolute (technology-neutral) RES-E targets instead of RES-E targets that are related to the level of Europe's electricity demand.

The approach of our analysis could be extended and improved in several ways. First, our approach does not account for other potential benefits of renewable energy sources, such as lower import dependencies of fossil fuels, as well as the potential risks associated with nuclear power electricity generation. Second, the role of grid extensions for the cost-efficient decarbonization of Europe's electricity system could be analyzed by varying the assumptions regarding the future extension of net transfer capacities in the model. Third, by neglecting weather uncertainty in the model, excess costs associated with RES-E targets may be underestimated (Nagl et al. (2012)). In specific, forecast errors of wind and solar power are not included. All aspects present interesting areas of further research.

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Appendix A. Scenario-specific model parameters

Table A.8: Scenario-specific fuel prices in €$_{2010}$/MWh$_{th}$ based on IEA (2011)

	Economic scenario	Nuclear	Lignite	Coal	Gas
2020	Low-cost	3.60	1.40	12.00	23.70
	Base	3.70	1.45	12.50	25.20
	High-cost	3.70	1.50	12.80	26.60
2030	Low-cost	3.60	1.40	12.10	25.60
	Base	3.70	1.45	12.80	28.30
	High-cost	3.90	1.50	13.50	30.50
2040	Low-cost	3.60	1.40	12.20	26.50
	Base	3.80	1.45	13.00	29.80
	High-cost	4.10	1.50	14.00	32.50
2050	Low-cost	3.60	1.40	12.20	27.40
	Base	3.90	1.45	13.10	31.30
	High-cost	4.20	1.50	14.50	34.60

Table A.9: Scenario-specific RES-E investment costs in €$_{2010}$/kW based on EWI (2010), EWI/Energynautics (2011), IEA (2010a) and IEA (2010b)

	Economic scenario	2020	2030	2040	2050
Biomass gas	Low-cost	2,306	2,249	2,225	2,224
	Base	2,353	2,324	2,313	2,312
	High-cost	2,400	2,400	2,400	2,400
Biomass gas - CHP	Low-cost	2,498	2,436	2,412	2,409
	Base	2,549	2,518	2,506	2,505
	High-cost	2,600	2,600	2,600	2,600
Biomass solid	Low-cost	3,170	3,092	3,061	3,058
	Base	3,235	3,196	3,181	3,179
	High-cost	3,300	3,300	3,300	3,300
Biomass solid - CHP	Low-cost	3,362	3,279	3,247	3,243
	Base	3,431	3,390	3,373	3,372
	High-cost	3,500	3,500	3,500	3,500
Geothermal (hot dry rock)	Low-cost	10,821	7,980	7,036	6,692
	Base	12,616	11,017	10,475	10,303
	High-cost	14,410	14,054	13,914	13,914
Geothermal (high enthalpy)	Low-cost	2,164	1,596	1,407	1,338
	Base	2,523	2,203	2,095	2,061
	High-cost	2,882	2,811	2,783	2,783
PV ground	Low-cost	1,234	739	574	546
	Base	1,571	1,276	1,185	1,171
	High-cost	1,907	1,813	1,795	1,795
PV roof	Low-cost	1,372	821	638	606
	Base	1,745	1,418	1,316	1,301
	High-cost	2,118	2,015	1,995	1,995
CSP	Low-cost	3,319	2,206	1,803	1,715
	Base	4,484	3,858	3,629	3,585
	High-cost	5,649	5,510	5,455	5,455
Onshore wind	Low-cost	1,108	1,002	929	906
	Base	1,166	1,107	1,071	1,060
	High-cost	1,225	1,213	1,213	1,213
Offshore wind (deep)	Low-cost	2,453	1,809	1,595	1,517
	Base	2,860	2,497	2,374	2,335
	High-cost	3,266	3,186	3,154	3,154
Offshore wind (shallow)	Low-cost	2,236	1,649	1,454	1,383
	Base	2,607	2,277	2,165	2,129
	High-cost	2,978	2,905	2,876	2,876

Table A.10: Scenario-specific electricity demand per country in TWh based on Capros et al. (2010)

	2010	2020		2030		2040		2050	
		Low-cost	High-cost	Low-cost	High-cost	Low-cost	High-cost	Low-cost	High-cost
Austria	57.3	56.8	57.9	55.4	59.0	52.7	61.4	48.8	65.9
Belgium	81.4	80.6	82.2	78.6	83.9	74.8	87.3	69.3	93.6
Bulgaria	26.3	26.1	26.6	25.4	27.1	24.2	28.2	22.4	30.2
Czech Republic	57.6	57.1	58.2	55.7	59.4	52.9	61.8	49.1	66.2
Denmark	35.6	35.2	35.9	34.3	36.6	32.6	38.1	30.3	40.8
Estland	6.3	6.3	6.4	6.1	6.5	5.8	6.8	5.4	7.2
Finland	84.9	84.1	85.8	82.0	87.5	78.0	91.0	72.3	97.6
France	421.8	417.6	426.0	407.3	434.6	387.4	452.3	359.3	485.0
Germany	528.8	523.5	534.1	510.6	544.9	485.6	567.1	450.4	608.1
Great Britain	340.4	337.1	343.8	328.7	350.8	312.7	365.0	290.0	391.4
Greece	54.0	53.5	54.5	52.2	55.6	49.6	57.9	46.0	62.1
Hungary	33.0	32.7	33.3	31.9	34.0	30.3	35.4	28.1	37.9
Ireland	24.7	24.5	24.9	23.9	25.5	22.7	26.5	21.1	28.4
Italy	300.7	297.7	303.7	290.3	309.8	276.1	322.5	256.1	345.8
Latvia	5.9	5.8	6.0	5.7	6.1	5.4	6.3	5.0	6.8
Lithuania	8.1	8.1	8.2	7.9	8.3	7.5	8.7	6.9	9.3
Luxemburg	6.6	6.6	6.7	6.4	6.8	6.1	7.1	5.7	7.6
Netherlands	106.7	105.6	107.8	103.0	109.9	98.0	114.4	90.9	122.7
Norway	104.3	103.3	105.3	100.7	107.5	95.8	111.9	88.9	119.9
Poland	115.4	114.3	116.6	111.5	118.9	106.0	123.8	98.3	132.7
Portugal	46.3	45.8	46.8	44.7	47.7	42.5	49.7	39.4	53.2
Romania	41.0	40.6	41.4	39.6	42.2	37.7	44.0	34.9	47.1
Slovakia	24.8	24.5	25.0	23.9	25.6	22.8	26.6	21.1	28.5
Slovenia	13.4	13.3	13.5	12.9	13.8	12.3	14.4	11.4	15.4
Spain	247.4	244.9	249.9	238.9	254.9	227.2	265.3	210.7	284.5
Sweden	131.8	130.5	133.1	127.3	135.8	121.1	141.3	112.3	151.6
Switzerland	57.5	56.9	58.1	55.5	59.2	52.8	61.7	49.0	66.1
Total	2,962.4	2,932.9	2,991.7	2,860.4	3,052.0	2,720.6	3,176.3	2,523.3	3,405.8

Table A.11: National technology-specific RES-E targets for 2020 in TWh based on ECN (2011)

	Onshore Wind	Offshore Wind	PV	Biomass	Geothermal	CSP
Austria	4.8		0.3	5.1	0.002	
Belgium	4.3	6.2	1.1	11.0	0.029	
Bulgaria	2.6		0.4	0.9		
Czech Republic	1.5		1.7	6.2	0.018	
Denmark	74.8	34.4	41.4	52.4		
Estland	1.0	0.6		0.3		
Finland	3.5	2.5		12.9		
France	39.9	18.0	5.9	17.2	0.5	1.0
Germany	72.7	31.8	41.4	49.5	1.7	
Great Britain	34.2	44.1	2.2	26.2		
Greece	16.1	0.7	2.9	1.3	0.7	0.7
Hungary	1.5		0.1	3.3	0.4	
Ireland	10.2	1.7		1.0		
Italy	18.0	2.0	9.7	18.8	6.8	1.7
Latvia	0.5	0.4	0.004	1.2		
Lithuania	1.3		0.015	1.2		
Luxemburg	0.2		0.1	0.3		
Netherlands	13.4	19.0	0.6	16.6		
Poland	13.2	1.5	0.003	14.2		
Portugal	14.4	0.2	1.5	3.5	0.5	
Romania	8.4		0.3	2.9		
Slovakia	0.6		0.3	1.7	0.0	
Slovenia	0.2		0.1	0.7		
Spain	70.5	7.8	14.3	10.0	0.3	15.4
Sweden	12.0	0.5	0.004	6.0		
Total	419.7	171.4	124.4	264.5	10.9	18.7

Appendix B. Model parameters common to all scenarios

Table B.12: Investment costs of conventional and storage technologies in €$_{2010}$/kW based on IEA (2011), EWI/Energynautics (2011) and PROGNOS/EWI/GWS (2010)

Technologies	2010	2020	2030	2040	2050
CCGT	1,250	1,250	1,250	1,250	1,250
CCGT - CCS	-	-	1,550	1,500	1,450
CCGT - CHP	1,500	1,500	1,500	1,500	1,500
CCGT - CHP and CCS	-	-	1,700	1,650	1,600
Hard Coal	1,500	1,500	1,500	1,500	1,500
Hard Coal - innovative	2,500	2,250	1,875	1,750	1,650
Hard Coal - CCS	-	-	2,000	1,900	1,850
Hard Coal - innovative CCS	-	-	2,475	2,300	2,200
Hard Coal - innovative CHP	2,650	2,650	2,275	2,150	2,050
Hard Coal - innovative CHP and CCS	-	-	2,875	2,700	2,600
Lignite	1,850	1,850	1,850	1,850	1,850
Lignite - innovative	1,950	1,950	1,950	1,950	1,950
Lignite - CCS	-	-	2,550	2,500	2,450
Nuclear	3,157	3,157	3,157	3,157	3,157
OCGT	700	700	700	700	700
CAES	850	850	850	850	850
Pump storage	-	-	-	-	-
Hydro storage	-	-	-	-	-

Table B.13: Economic-technical parameters for conventional and storage technologies based on IEA (2011), EWI/Energynautics (2011) and PROGNOS/EWI/GWS (2010)

	η [%]	β [%]	ef [t CO_2 /MWh_{th}]	av [%]	FOM-costs [€$_{2010}/kW$]	Lifetime [a]
CCGT	60.0	-	0.201	84.50	28.2	30
CCGT - CCS	53.0	-	0.020	84.50	40.0	30
CCGT - CHP	36.0	-	0.201	84.50	88.2	30
CCGT - CHP and CCS	36.0	-	0.030	84.50	100.0	30
Hard Coal	46.0	-	0.335	83.75	36.1	45
Hard Coal - innovative	50.0	-	0.335	83.75	36.1	45
Hard Coal - CCS	42.0	-	0.034	83.75	97.0	45
Hard Coal - innovative CCS	45.0	-	0.034	83.75	97.0	45
Hard Coal - innovative CHP	22.5	-	0.335	83.75	55.1	45
Hard Coal - innovative CHP and CCS	18.5	-	0.050	83.75	110.0	45
Lignite	43.0	-	0.406	86.25	43.1	45
Lignite - innovative	46.5	-	0.406	86.25	43.1	45
Lignite - CCS	43.0	-	0.041	86.25	103.0	45
Nuclear	33.0	-	0.000	84.50	96.6	60
OCGT	40.0	-	0.201	84.50	17.0	25
CAES	86.0	82.0	0.0	95.00	9.2	40
Pump storage	87.0	83.0	0.0	95.00	11.5	100
Hydro storage	87.0	-	0.0	95.00	11.5	100

Table B.14: Economic-technical parameters for RES-E technologies based on EWI/Energynautics (2011), EWI (2010), IEA (2010a) and IEA (2010b)

	η [%]	av [%]	Secured capacity [%]	FOM costs [€$_{2011}/kW$]	Lifetime [a]
Biomass gas	40.0	85	85	120	30
Biomass gas - CHP	30.0	85	85	130	30
Biomass solid	30.0	85	85	165	30
Biomass solid - CHP	22.5	85	85	175	30
Concentrating solar power	-	-	40	120	25
Geothermal (hot dry rock)	22.5	85	85	300	30
Geothermal (high enthalpy)	22.5	85	85	30	30
PV ground	-	-	0	30	25
PV roof	-	-	0	35	25
Run-off-river hydropower	-	-	50	11.5	100
Offshore wind 5MW (deep)	-	-	5	152	20
Offshore wind 8MW (dep)	-	-	5	160	20
Offshore wind 5MW (shallow)	-	-	5	128	20
Offshore wind 8MW (shallow)	-	-	5	136	20
Onshore wind 6MW	-	-	5	41	20
Onshore wind 8MW	-	-	5	41	20

Table B.15: Maximum potential for heat generated in CHP plants in TWh

	2020	2030	2040	2050
Austria	41.2	41.5	41.8	42.0
Belgium	14.7	14.8	14.9	14.9
Bulgaria	6.9	7.0	7.0	7.1
Czech Republic	55.1	55.7	56.4	57.0
Denmark	54.7	55.1	55.4	55.7
Estland	1.4	1.4	1.4	1.4
Finland	65.2	65.7	66.1	66.5
France	31.6	31.8	32.0	32.2
Germany	192.4	192.9	192.9	192.9
Great Britain	68.1	68.6	69.0	69.3
Greece	17.4	17.7	17.9	18.2
Hungary	14.2	14.4	14.5	14.7
Ireland	3.2	3.3	3.3	3.3
Italy	169.2	171.7	174.1	176.5
Latvia	6.5	6.6	6.7	6.7
Lithuania	4.8	4.9	4.9	5.0
Luxemburg	0.9	0.9	0.9	0.9
Netherlands	114.3	115.1	115.8	116.4
Norway	3.6	3.6	3.7	3.7
Poland	93.3	94.4	95.5	96.6
Portugal	13.9	14.1	14.3	14.5
Romania	93.3	94.4	95.5	96.6
Slovakia	17.0	17.2	17.4	17.6
Slovenia	1.2	1.2	1.3	1.3
Spain	59.0	59.9	60.7	61.5
Sweden	29.3	29.5	29.6	29.8
Switzerland	0.7	0.7	0.7	0.7
Total	1173.1	1184.0	1193.7	1203.1

Table B.16: Assumed NTC extensions per decade in GW based on ENTSO-E (2010)

	AT CH	AT CZ	AT DE	AT HU	AT IT	AT SI	AT SK	BE DE	BE FR	BE GB	BE LU	BE NL	BG GR	BG RO
2010-2020				0.20					0.30				0.97	
2020-2030							0.97			1.00	0.40			
2030-2040			1.94						0.97					1.94
2040-2050	0.77		0.77		2.63			0.89						

	CH AT	CH DE	CH FR	CH IT	CZ AT	CZ DE	CZ PL	CZ SK	DE AT	DE BE	DE CZ	DE CH	DE DK-E	DE DK-W
2010-2020													0.60	
2020-2030														0.50
2030-2040				0.97		0.97			0.77		0.97			0.97
2040-2050	0.77	0.77	0.20						1.94	0.89		0.77		

	DE FR	DE LU	DE NL	DE NO	DE PL	DE SE	DK-E DE	DK-E DK-W	DK-E NO	DK-E PL	DK-E SE	DK-W DE	DK-W DK-E	DK-W NL
2010-2020					0.77	0.60	0.60				0.60			
2020-2030			1.94									0.50		0.70
2030-2040				0.70	0.97			1.40				0.97	1.40	
2040-2050														

	DK-W NO	DK-W SE	EE FI	EE LV	EE SE	ES FR	ES NA	ES PT	FI EE	FI NO	FI SE	FR BE	FR CH	FR DE
2010-2020	0.70		0.65				0.30	1.80	0.65		1.77	0.30		
2020-2030						1.60				0.97				
2030-2040							4.10							
2040-2050						1.20	10.00					0.97	0.20	

	FR ES	FR GB	FR IT	FR LU	GB BE	GB FR	GB IE	GB NL	GB NO	GR BG	GR IT	GR NA	HU AT	HU RO
2010-2020				0.20			1.47	1.00		0.97			0.20	
2020-2030	2.30	1.00	0.60		1.00	1.00			1.40		0.50			
2030-2040														
2040-2050	1.20		1.00											

	HU SI	HU SK	IE GB	IT AT	IT CH	IT FR	IT GR	IT NA	IT SI	LT LV	LT PL	LT SE	LV EE	LV LT
2010-2020	1.94		1.47							0.20	3.34	0.70		0.20
2020-2030		2.91				0.60	0.50							
2030-2040					0.97				1.94					
2040-2050				2.63		1.00								

	LV SE	LU BE	LU DE	LU FR	NA ES	NA GR	NA PT	NA IT	NL BE	NL DE	NL DK-W	NL NO	NL GB	NO DE
2010-2020				0.20									1.00	
2020-2030		0.20								1.94	0.70	1.40		
2030-2040					4.10									0.70
2040-2050					10.00									

	NO DK-E	NO DK-W	NO FI	NO GB	NO NL	NO SE	PT ES	PT NA	PL CZ	PL DE	PL DK-E	PL LT	PL SK	PL SE
2010-2020		0.70				2.17	1.80			0.77		3.34		
2020-2030			0.97	1.40	1.40									
2030-2040										0.97				
2040-2050														

	RO BG	RO HU	SE DE	SE DK-E	SE DK-W	SE EE	SE FI	SE LT	SE LV	SE NO	SE PL	SI AT	SI HU	SI IT
2010-2020			0.60	0.60			1.77	0.70		2.17			1.94	
2020-2030	1.94													
2030-2040														1.94
2040-2050														

	SK AT	SK CZ	SK HU	SK PL
2010-2020				
2020-2030	0.97		2.91	
2030-2040				
2040-2050				

Appendix C. Scenario results

Table C.17: Scenario-specific capacity and generation mix in Europe by 2050

	1-I-L	1-I-B	1-I-H	1-II-L	1-II-B	1-II-H	1-III-L	1-III-B	1-III-H	1-IV-L	1-IV-B	1-IV-H
	Capacity [GW]											
Nuclear	0	0	0	0	0	0	1	1	1	1	1	1
Lignite (incl. CHP)	52	53	54	52	51	54	51	53	54	51	53	54
Lignite-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Coal (incl. CHP)	234	284	340	234	234	340	234	284	340	234	284	340
Coal-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Gas (incl. CHP)	32	42	54	32	32	54	32	41	54	32	41	54
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	51	51	51	51	51	51	51	51	51	51	51	51
Hydro	133	136	139	133	134	139	134	136	139	134	136	139
Biomass (incl. CHP)	11	12	12	11	11	12	11	12	12	11	12	12
Wind onshore	72	85	102	72	72	102	72	87	102	72	87	102
Wind offshore	0	0	0	0	0	0	0	0	0	0	0	0
PV	1	0	0	1	1	0	1	0	0	1	0	0
CSP	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal	3	3	3	3	3	3	3	3	3	3	3	3
Other	11	11	11	11	11	11	11	11	11	11	11	11
Total	600	677	766	600	600	766	600	678	767	600	678	767
	Generation [TWh]											
Nuclear	0	0	0	0	0	0	3	3	3	3	3	3
Lignite (incl. CHP)	385	397	405	385	397	385	382	395	405	382	395	405
Lignite-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Coal (incl. CHP)	1,480	1,893	2,268	1,480	1,893	1,480	1,480	1,888	2,264	1,480	1,888	2,264
Coal-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Gas (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	5	25	34	5	25	5	5	23	33	5	23	33
Hydro	552	552	552	552	552	552	552	552	552	552	552	552
Biomass (incl. CHP)	84	87	87	84	87	84	84	87	87	84	87	87
Wind onshore	234	255	317	234	255	234	233	259	319	233	259	319
Wind offshore	0	0	0	0	0	0	0	0	0	0	0	0
PV	1	0	0	1	0	1	1	0	0	1	0	0
CSP	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal	18	18	18	18	18	18	18	18	18	18	18	18
Other	56	56	56	56	56	56	56	56	56	56	56	56
Imports North Africa	0	0	0	0	0	0	0	0	0	0	0	0
Total	2814	3282	3737	2814	3282	2814	2814	3280	3736	2814	3280	3736

	2-I-L	2-I-B	2-I-H	2-II-L	2-II-B	2-II-H	2-III-L	2-III-B	2-III-H	2-IV-L	2-IV-B	2-IV-H
	Capacity [GW]											
Nuclear	152	221	273	183	258	300	1	1	1	1	1	1
Lignite (incl. CHP)	12	10	10	21	24	27	9	5	9	28	17	17
Lignite-CCS	53	55	57	0	0	0	55	55	59	0	0	0
Coal (incl. CHP)	26	32	40	25	25	25	18	10	10	7	5	3
Coal-CCS	0	0	0	0	0	0	0	0	2	0	0	0
Gas (incl. CHP)	51	45	58	57	61	83	164	234	258	198	272	300
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	51	52	55	51	54	59	57	97	132	59	99	150
Hydro	138	135	138	139	135	138	145	142	146	144	142	146
Biomass (incl. CHP)	14	19	21	16	19	23	17	22	32	19	25	37
Wind onshore	152	130	163	183	134	205	296	244	385	347	258	397
Wind offshore	0	0	0	0	11	6	81	172	205	96	194	221
PV	12	0	0	19	0	0	149	136	124	224	209	199
CSP	0	0	0	3	0	0	55	40	40	66	60	59
Geothermal	15	15	13	16	15	15	16	16	16	17	17	16
Other	11	11	11	11	11	11	11	11	11	11	11	11
Total	688	726	837	725	747	891	1072	1185	1430	1217	1310	1558
	Generation [TWh]											
Nuclear	1,086	1,606	1,965	1,306	1,873	2,148	3	5	5	5	5	5
Lignite (incl. CHP)	8	6	6	45	44	49	0	0	0	110	5	0
Lignite-CCS	373	374	374	0	0	0	378	380	378	0	0	0
Coal (incl. CHP)	62	64	65	63	63	58	51	1	0	0	0	0
Coal-CCS	0	0	0	0	0	0	0	2	13	0	0	0
Gas (incl. CHP)	0	0	0	0	6	11	65	286	288	105	385	398
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	32	46	49	38	52	59	36	43	58	32	42	64
Hydro	552	552	552	552	552	552	552	552	551	552	552	551
Biomass (incl. CHP)	90	125	134	101	127	139	117	155	216	132	172	252
Wind onshore	443	377	473	525	387	570	754	657	928	834	684	953
Wind offshore	0	0	0	0	52	30	340	700	831	404	780	881
PV	18	0	0	28	1	0	191	184	165	275	268	257
CSP	0	0	0	12	0	0	199	149	149	240	224	216
Geothermal	105	105	86	107	107	101	110	110	108	110	110	109
Other	56	56	56	56	56	56	56	56	56	56	56	56
Imports North Africa	35	0	0	36	3	0	31	48	47	22	45	63
Total	2860	3313	3761	2869	3322	3774	2882	3327	3794	2877	3327	3804

	3-I-L	3-I-B	3-I-H	3-II-L	3-II-B	3-II-H	3-III-L	3-III-B	3-III-H	3-IV-L	3-IV-B	3-IV-H
	Capacity [GW]											
Nuclear	34	43	58	57	70	85	1	1	1	1	1	1
Lignite (incl. CHP)	16	18	19	26	27	30	12	12	12	27	24	22
Lignite-CCS	29	30	34	0	0	0	52	56	59	0	0	0
Coal (incl. CHP)	32	31	40	28	25	30	30	32	30	9	7	8
Coal-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Gas (incl. CHP)	110	131	148	112	129	147	141	166	216	193	231	277
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	80	131	178	77	134	192	64	106	145	60	100	151
Hydro	141	143	143	141	142	142	145	145	147	144	144	146
Biomass (incl. CHP)	17	26	41	18	27	40	18	26	37	19	27	35
Wind onshore	311	245	390	328	246	390	320	245	391	356	257	394
Wind offshore	83	197	232	73	196	233	89	196	221	96	203	233
PV	154	121	99	150	127	110	148	142	145	228	198	188
CSP	56	53	30	61	51	29	54	58	37	67	67	62
Geothermal	15	16	15	16	16	15	16	16	16	17	17	16
Other	11	11	11	11	11	11	11	11	11	11	11	11
Total	1089	1196	1439	1096	1201	1453	1101	1211	1466	1227	1285	1542
	Generation [TWh]											
Nuclear	195	270	372	370	457	561	3	4	5	5	5	5
Lignite (incl. CHP)	0	0	5	9	5	22	4	0	0	111	31	0
Lignite-CCS	193	205	217	0	0	0	355	380	373	0	0	0
Coal (incl. CHP)	77	77	73	84	86	76	62	49	27	1	0	0
Coal-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Gas (incl. CHP)	0	0	0	0	0	0	19	78	186	98	316	398
Gas-CCS	0	0	0	0	0	0	0	0	0	0	0	0
Oil (incl. CHP)	0	0	0	0	0	0	0	0	0	0	0	0
Storage (Pump + CAES)	74	116	223	67	106	196	43	52	76	34	46	67
Hydro	552	552	552	552	552	552	552	552	552	552	552	552
Biomass (incl. CHP)	120	180	257	126	190	255	120	181	229	130	186	235
Wind onshore	781	655	928	805	656	932	790	650	933	840	669	937
Wind offshore	352	806	945	314	800	939	371	793	890	402	817	919
PV	204	168	141	197	175	154	190	188	192	279	254	244
CSP	204	200	112	221	192	110	198	216	135	241	245	224
Geothermal	108	108	107	108	110	107	110	110	108	110	110	109
Other	55	55	56	55	54	54	55	56	56	56	56	56
Imports North Africa	32	57	60	30	51	55	22	36	63	22	47	64
Total	2946	3448	4048	2937	3434	4012	2895	3343	3825	2879	3333	3810