Moving towards socio-technical scenarios of the German energy transition – lessons learned from integrated energy scenario building

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Supplementary Material (SM)

SM-(1) Overview about the workflow of the scenario analysis

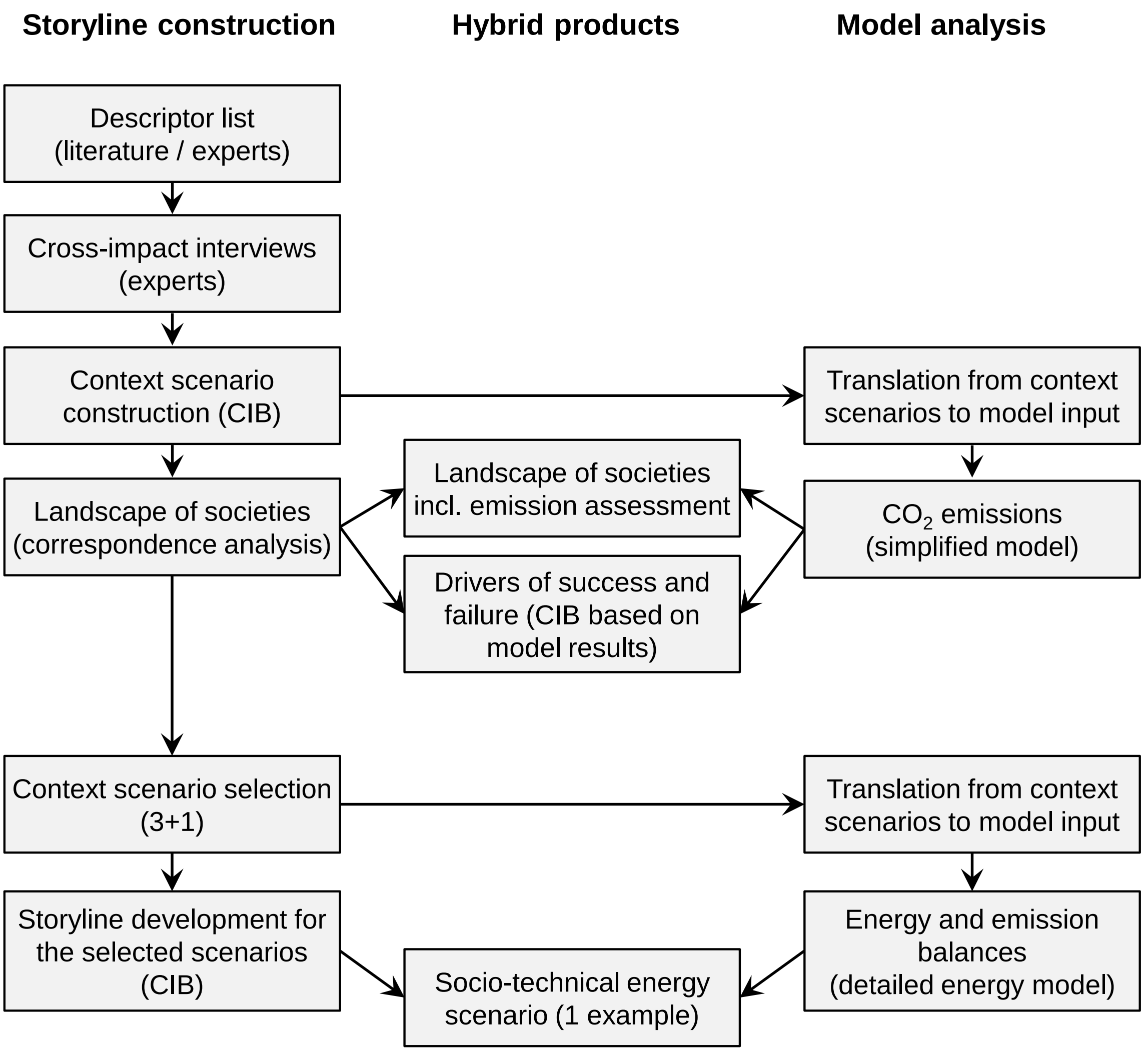

Figure 1: Workflow of the integrated scenario analysis.

SM-(2) Data survey design

CIB context scenarios can be more or less constructed over four steps:

1. context definitions (finding descriptors),
2. definition of uncertainty (describing different descriptor developments),
3. interdependency analysis (survey of cross-impact judgments) and finally
4. the construction of context scenarios (applying the balance algorithm to generate consistent scenarios) (Weimer-Jehle et al. 2016)

The operationalization of these steps can be done very differently. This case describes a rather comprehensive application of the context scenario approach, meaning that a considerable amount of data was collected, processed and reflected. Thus, the methodology for generating context scenarios of the German energy system involved applying many additional methods and steps for each of the above-mentioned ones. They are described as follows.

Step 1)

The selection of descriptors for analysis is a very important step, as they determine which aspects of a context are considered and excluded. Therefore, this step was considered carefully and with much deliberation. We adopted a 5-step procedure to produce the final descriptor list. Without describing the steps in detail, a short overview is provided below.

To define energy transition context:

- i) A **literature review** of 45 scenarios (societal, energy,…) was conducted and descriptors used were filtered and analyzed (Gallego Carrera et al, 2013). This formed the basis for the
- ii) 23 **unstructured expert interviews,** which were mainly carried out with interdisciplinary ENERGY-TRANS experts. Out of the 19 projects executed in ENERGY-TRANS, 17 involved descriptor consultation. All of the interviews were recorded and were processed afterwards. The descriptor list developed was then refined and structured by
- iii) applying **sociological theory and a developed structuring tool** (Prehofer, forthcoming). As a final step, descriptors were selected and
- iv) an **expert rating** was applied to form the basis of
- v) **additional selection criteria**. Twenty-eight ENERGY-TRANS experts representing seven ‘disciplines’ (energy economics, economics, politics, law, sociology, psychology, and ‘comprehensive topics’) and 16 of the 19 ENERGY-TRANS projects participated. In addition to the expert rating, selection rules about ‘must-haves for modelers’, ‘theoretical completeness’, ‘balance between context and energy descriptors’ and ‘balance between disciplinary participation’ were applied to compile the final descriptor list of 39 descriptors (a complete list of the descriptors used can be found in Weimer-Jehle, Prehofer, Hauser (2015)).

Step 2)

For all 39 descriptors, short essays were prepared on the basis of a

- i) **literature review** and
- ii) **written reviews of domain experts** to describe the content of each social and technical descriptor. To take account of future uncertainties, two to four plausible future developments for each descriptor were defined depending on the ‘bandwidth’ of uncertainty determined from our literature review and from domain experts (all of the descriptors are described in Weimer-Jehle, Prehofer, Hauser (2015)).

Fifteen of the 39 descriptors are quantitative in nature and needed to be quantified for modeling purposes. For this project we decided to find quantifications for the different future variables in this early phase of scenario construction (i.e., before judgments on interrelations are made). In turn, the experts could make judgments on the basis of concrete numbers and not only based on qualitative concepts. To apply adequate quantifications representing future uncertainties, we

i) searched for quantifications used in existing energy scenario studies. As a result we were able to **assess the bandwidth of uncertainty estimated for the energy scenario community**. Using these bandwidths, we

ii) **adopted the applied quantifications** to the descriptor developments. As a last step we

iii) **discussed and refined** these quantifications in cooperation with the modelers of this project.

Step 3)

Expert judgments about the interdependencies between all descriptor developments ("cross-impacts") are the core of our data survey. To collect these expert judgments we

i) conducted **1-3 two-hour interviews per descriptor with domain experts** (67 in total) with knowledge of a specific field. This allowed not only for the integration of an enormous amount of domains and of appropriate descriptors but also of different experts' opinions. To obtain more valid statements,

ii) the domain experts of each separate descriptor were allowed to **underpin or adapt their judgments through a Delphi-style consultation** (i.e., when divergent judgments emerged (divergent signs) the experts were informed of the judgments and explanations of the other experts and were asked to reconsider their statements). Finally, the context scenario team

iii) checked and in certain cases concretized impact judgments due to their methodical correctness.

Step 4)

The above steps build the basis for the final construction of consistent context scenarios. Thirty-nine descriptors with a total of 108 futures represent societal and energy-related topics. More precisely, the considered system includes 4 international, 10 economic, 6 political, 5 societal, 3 cultural and 11 energy-related descriptors, creating approximately 10^{14} possible scenario configurations for the context descriptors (approximately $3{\cdot}10^{18}$ when the eleven energy related descriptors are included). To limit the configuration set to consistent scenarios, the

i) **balance algorithm of the CIB is applied** (cf. Weimer-Jehle 2006) to identify 182 fully consistent scenarios (1725 scenarios when fully and nearly consistent scenarios are accepted) based on the impact judgments of the expert interviews. Still, the number of consistent scenarios is high and not each of those could be calculated in detail using the energy model. Thus, to select scenarios for the modeling exercise illuminating different facets of the societal possibility space,

ii) **some additional methods** are applied to explore the context and its interrelations with the energy system in more depth. This is described in more detail in chapter 3 of the article.

The expert elicitation process designed and applied for our project to prepare a descriptor list can be compared to expert processes used in other CIB studies. For instance, Schweizer and O'Neil (2014) based their descriptor selection method on an online survey inviting 74 experts to participate, 25 of whom responded. The experts were given a list of socioeconomic factors and were asked to prioritize them (the prioritization of multiple factors was allowed). After the survey was completed, the percentage of respondents prioritizing a factor was calculated, and all factors selected by at least 25% of the respondents were included in the study.

Procedures applied by Schweizer and O'Neil and in our study are similar in their basic approaches. A difference lies in the inclusion of measures applied in our study to balance the number of descriptors addressing different science domains. This is the case due to our goal of representing both societal and energy futures in our scenarios and the very broad range of science domains to be covered to this aim. As we relied on the ENERGY-TRANS team (approx. 60 persons) for descriptor prioritization (yet not for the cross-impact interviews) and as science domains were not equally represented by the team, biases in the representation of science domains included in the descriptor list may have occurred without the use of balancing measures.

A remarkably different approach is presented by Kemp-Benedict et al. (2014). The authors aimed at finding a list of prerequisites for sustainable forest management to be used as a descriptor list. They applied text analysis software to search through SSP (shared socio-economic pathway) storylines and related documents for respective text elements. The list of prerequisites gained by this analysis was edited to exclude factors that can be expected to be dominated by other factors. The resulting list was used for the CIB analysis.

This approach is less subjective and can be used to exploit large knowledge databases. It is an innovative approach that will likely be used more in CIB studies in the future, as it renders CIB studies more independent from (direct) expert elicitation. Schweizer and Kriegler (2012) also showed that cross-impact data can be derived (at least on some topics) from a literature review. The approach may present also challenges when applied for *context* scenario analysis. As one challenge text analysis can be expected to reveal direct drivers of a system under investigation but it may struggle to find indirect ones, which are the specific focus of a context scenario analysis. Another challenge emerges when a CIB study is designed to motivate experts to reconsider a problem and to identify ‘unconventional’ connections between science domains, as a text analysis can only return connections already recognized by scholars. However, such challenges may in part be remedied by the use of appropriate analysis methods or advantages may be found to overweigh related challenges.

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For more references see main text.

SM-(3) List of experts involved in the cross-impact interviews

Experts participating in the descriptor identification survey

Gregor Betz	Karlsruhe Institute of Technology / ITAS
Robert Brandt	Free University of Berlin
Jens Buchgeister	Karlsruhe Institute of Technology / ITAS
Marc Deissenroth	German Aerospace Center (DLR), Stuttgart / TT-STB
Gerhard Fuchs	University of Stuttgart / ZIRIUS
Armin Grunwald	Karlsruhe Institute of Technology / ITAS
Volker M. Haug	University of Stuttgart / Institute of Economy and Law
N.N.	
Max Kleemann	Karlsruhe Institute of Technology / ITAS
Wolfgang Köck	Center for Environmental Research, Leipzig (UFZ) / EP
Jürgen Kopfmüller	Karlsruhe Institute of Technology / ITAS
Paul Lehmann	Center for Environmental Research, Leipzig (UFZ) / Economy
Georg Licht	Centre for European Economic Research (ZEW), Mannheim
N.N.	
Birgit Mack	University of Stuttgart / ZIRIUS
Ellen Matthies	University of Magdeburg
Tobias Naegler	German Aerospace Center (DLR), Stuttgart / TT-STB
Michael Nast	German Aerospace Center (DLR), Stuttgart / TT-STB
Dörte Ohlhorst	Free University of Berlin
Witold-Roger Poganietz	Karlsruhe Institute of Technology / ITAS
Thomas Pregger	German Aerospace Center (DLR), Stuttgart / TT-STB
Ortwin Renn	University of Stuttgart / ZIRIUS
Klaus Rennings	Centre for European Economic Research (ZEW)
Andreas Rieder	Karlsruhe Institute of Technology / ITAS
Christine Rösch	Karlsruhe Institute of Technology / ITAS
Jens Schippl	Karlsruhe Institute of Technology / ITAS
Yvonne Scholz	German Aerospace Center (DLR), Stuttgart / TT-STB
Pia-Johanna Schweizer	University of Stuttgart / ZIRIUS
Kerstin Tews	Free University of Berlin
Elke Uhl	University of Stuttgart / IZTK
Stefan Vögele	Research Center Jülich (FZJ) / STE
Sandra Wassermann	University of Stuttgart / ZIRIUS
Annika Weiss	Karlsruhe Institute of Technology / ITAS

Experts interviewed for cross-impact matrix construction:

Marian Adolf	Zeppelin University
Christian Arndt	Nürtingen-Geislingen University (HfWU)
Annika Arnold	University of Stuttgart / ZIRIUS
Timo Baas	University of Duisburg-Essen
Stefan Bach	German Institute for Economic Research (DIW), Berlin
Sophia Becker	University of Stuttgart / ZIRIUS
Martin Biewen	University of Tübingen
Frieder Borggrefe	German Aerospace Center (DLR), Stuttgart / TT-STB
Jens Buchgeister	Karlsruhe Institute of Technology / ITAS
Marc Deissenroth	German Aerospace Center (DLR), Stuttgart / TT-STB
Thomas Eckert	Ludwig-Maximilian University München
Henriette Engelhardt-Wölfler	University of Bamberg, Chair for Demography
Gerhard Fuchs	University of Stuttgart, Institute of Social Sciences
Julian Hahmann	Friedrich-Wilhelms-University Bonn
Patrick Hansen	Research Center Jülich (FZJ) / STE
Eva Hauser	Institute for Sustainable Energy and Material Flow Systems (IZES)
Dirk Heinrichs	German Aerospace Center (DLR), Berlin / VF
Reiner Höft-Dzemski	German Association for Public and Private Welfare, Berlin
Patrick Jochem	Karlsruhe Institute of Technology / LfE
Max Kleemann	Karlsruhe Institute of Technology / ITAS
Wolfgang Köck	Center for Environmental Research, Leipzig (UFZ) / PP
Wilhelm Kohler	University of Tübingen, International Economie
Raimund Krumm	Institute of Applied Economic Research (IAW), Tübingen
Paul Lehmann	Center for Environmental Research, Leipzig (UFZ) / Economy
N.N.	
Birgit Mack	University of Stuttgart / ZIRIUS
Ellen Matthies	University of Magdeburg
Tobias Naegler	German Aerospace Center (DLR), Stuttgart / TT-STB
Dörte Ohlhorst	Free University of Berlin / FFU
Ilona Ostner	Georg-August-University, Göttingen
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Gerhard Pfister	Nürtingen-Geislingen University (HfWU)
Thomas Pregger	German Aerospace Center (DLR), Stuttgart / TT-STB
Andreas Pyka	University of Hohenheim
Wilhelm Rall	McKinsey

Mathias Reeg	German Aerospace Center (DLR), Stuttgart / TT-STB
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Mike Schäfer	University of Zürich UZH
Susanne Schmid	University of Stuttgart / Institute of Economy and Law
Dominik Schober	Centre for European Economic Research (ZEW), Mannheim
Yvonne Scholz	German Aerospace Center (DLR), Stuttgart / TT-STB
Regina Schröter	University of Stuttgart / ZIRIUS
Sophia Schubert	Free University of Berlin
Kai Schulze	University of Potsdam
Karin Schürmann	Research Center Jülich (FZJ) / STE
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Kerstin Tews	Free University of Berlin / FFU
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Gisela Wachinger	University of Stuttgart / ZIRIUS
Sandra Wassermann	University of Stuttgart / ZIRIUS
Johannes Weyer	University of Dortmund
Oliver Woll	Centre for European Economic Research (ZEW), Mannheim
Michael Zwick	University of Stuttgart / ZIRIUS

N.N. represents experts asking for anonymity

SM-(4) Description of pole representative selection (main text, chapter 3)

For in depth modeling, three scenarios out of the full set of 1725 context scenarios were used to represent poles of societal landscapes of the ‘Inertia’, ‘Market’ and ‘Value Shift’ scenarios (see Fig. 2 of the main text). Each representative was selected from all scenarios in the vicinity of each pole. The selection procedure was as follows: For each pole,

- Step 1: Frequencies of the descriptor developments based on all scenarios in the vicinity of the pole were calculated.
- Step 2: As an indicator for being typical for the pole vicinity, the sum of frequencies of all descriptors was calculated for each scenario in the pole vicinity.
- Step 3: the scenario with the highest indicator value was chosen to represent the pole.

This procedure prevents one from selecting a scenario that is rather untypical of a given pole vicinity. Nevertheless, there are heterogeneities within each pole vicinity and the representative quality of each scenario is limited but optimized by the selection procedure.

SM-(5) Approach used to couple context scenarios with the energy system model

The following considerations apply for both the simplified scenario calculation tool based on Microsoft Excel and the scenario development method employed using Mesap/PlaNet (unless otherwise stated).

General comments

Our coupling of context scenarios with the energy model was based on four different principles on determining technical scenario parameters, which differ in how they are determined by the given context scenario:

1. **Coupling of ‘hard’ coupling factors:** ‘Hard’ coupling factors are context descriptors that directly determine a quantitative model parameter. ‘Hard’ coupling factors can for instance cover the total amount of renewable electricity or heat supplied in 2050 or the average development of energy intensities of different sectors for 2015 to 2050. ‘Hard’ coupling factors leave very limited room for scenario modeler interpretations.
2. **Coupling of ‘soft’ coupling factors:** In contrast to ‘hard’ coupling factors, ‘soft’ coupling factors do not directly correspond with a (quantitative) model parameter. However, ‘soft’ coupling factors show a clear relationship to quantitative model parameters such that a plausible interpretation can be made based on background knowledge. One example is context descriptor ‘central or decentralized electricity generation and storage’, which can be interpreted in terms of the technology mix for electricity generation (see below). Although the interpretation of ‘soft’ coupling factors in terms of scenario parameters leaves room for modeler interpretation, his choice of parameter values must be well justified.
3. Determination of **relevant scenario parameters not considered by the context scenario**: Context scenarios do not determine most parameters relevant to further describe the technical storyline of the given scenario. Such undetermined parameters cover, e.g., the technology mix of conventional power plants or of heat generation technologies, the blending quotas of biofuels, etc. For such parameters, two different approaches can be applied:
    i. For some parameters (e.g., shares of individual conventional power generation technologies of total conventional power generation), plausible values can be chosen

based on technical constraints of the power system (e.g., rising demand for flexible power generation with rising shares of intermittent renewables, which are well identified from other more detailed scenario modeling studies). As a consequence, room for scenario modeler interpretation is limited.

ii. Values for other parameters (e.g., the blending quota for biofuels) have to be chosen according to the 'spirit' of the given scenario (e.g., societal views of nature conservation). In these cases, there is more room for modeler interpretation than in the cases discussed above.

4. Determination of **techno-economic parameters of energy technologies**: The techno-economic parameters for all relevant energy technologies (e.g., efficiencies or specific investment costs for power generation, heat generation, cogeneration, power-to-gas systems, transport technologies, etc.) are identical across all scenarios and are based on DLR's standard techno-economic database on energy technologies (see, e.g., Nitsch et al. (2012) and Pregger et al. (2013)). The only exceptions are descriptors (b) and (c) (reduction of the specific energy demand of electric vehicles and of vehicles with combustion engines), which are adjusted according to the context scenario.

In the paragraphs below we discuss the coupling of 'hard' and 'soft' coupling factors with the scenario model and our determination of parameter values in more detail.

Information on 'hard' and 'soft' coupling factors in this study

Table 1 to Table 4 document variants of all context descriptors for all four scenarios considered (the 'Target, 'Inertia', 'Market Forces', and 'Value Shift' scenarios). Hard coupling factors are highlighted in dark grey and soft coupling factors are highlighted in light grey. Further information on the coupling of hard/soft coupling factors with the scenario model is given for each descriptor.

descriptor A(II): 'global fossil price pathway'

Soft coupling factor. This descriptor refers to the international market price of 1 barrel of crude oil, but it is used to describe trends in the development of prices for all fossil fuels including natural gas, hard coal and diesel/gasoline for end users. For each of the three variants (100 $/bbl, 166 $/bbl, and 210 $/bbl), a corresponding price for those fossil energy carriers is assumed. However, price effects are not discussed in the paper.

descriptor A(III): 'global interest rate'

Hard coupling factor. This factor is used to calculate capital costs of energy technologies in the model. However, price effects are not discussed in the paper.

descriptor C: 'population'

Hard coupling factor. This factor is used to calculate living space, energy demand for space heat and electric applications in households, and passenger transport services.

descriptor D: 'GDP growth'

Hard coupling factor. 'GDP growth' determines (in combination with descriptor F 'tertiarization of the economy') the growth of value added in the industrial, trade and commerce sectors and thus indirectly the final energy demand of these sectors.

descriptor F: 'tertiarization of the economy'

Soft coupling factor. All scenarios assume that only 20% of all jobs are of the industrial sector, which corresponds to 27% of the gross value added (GVA).

descriptor K: ‘expansion of renewable energies in the electricity sector’

Hard coupling factor. This determines power generation from renewable sources in the model. However, the share of individual technologies is also determined by descriptor L ‘central/decentralized electricity generation and storage’) (see below).

descriptor L: ‘central/decentralized electricity generation and storage’

Soft coupling factor. All scenarios assume an increase in renewable electricity generation. The ‘trend towards central electricity generation and storage’ is thus interpreted as a trend towards the use of offshore wind and large onshore wind parks and central (public) cogeneration plants, whereas a trend towards ‘decentralized electricity generation and storage’ is interpreted as a trend towards PV and decentralized cogeneration use in households and small enterprises.

descriptor a: ‘reduction energy demand – household appliances’

Hard coupling factor. This descriptor describes the development of per-capita electricity demand in private households. In combination with population development it determines the power demand of private households for electric applications (no heating or transport).

descriptor b: ‘reduction energy demand – PC electric vehicles’

Hard coupling factor. This descriptor describes the reduction of average specific energy demand (per passenger kilometer) of an electric vehicle fleet (passenger cars, BEVs, PHEVs and hydrogen fuel cell electric vehicles). In combination with the development of passenger transport services and the share of ‘new’ cars in the passenger vehicle fleet (see descriptor h ‘investment in new vehicle concepts and infrastructure’), it determines the power and hydrogen demand of individual passenger transport.

descriptor c: ‘reduction in energy demand – PC engines’

Hard coupling factor. This descriptor describes the reduction in the average specific energy demand (per passenger kilometer) of internal combustion engines of private cars. In combination with the development of passenger transport services and the share of ‘new’ cars in the passenger vehicle fleet (see descriptor h ‘investment in new vehicle concepts and infrastructure’), it determines the gasoline and diesel demand of individual passenger transport.

descriptor d(I): ‘renovation rate – buildings (private)’

Soft coupling factor. In combination with descriptor d(II), descriptor d(I) determines specific energy demand for space heating in private houses. In combination with descriptors C (‘population development’ and i (‘living trends’), this determines final energy demand for space heating in private households.

At an annual renovation rate of 1% and a renovation depth of 30% (reduction of specific energy demand per living space due to renovation), we assume that the average specific energy demand per living space of the building stock can be reduced to 100 kWh/m^2/yr (from today’s value of 150 kWh/m^2/yr). At a renovation rate of 1.5% and a renovation depth of 50%, the specific energy demand can be reduced to 76 kWh/m^2/yr, and at a renovation rate of 2% and a renovation depth of 70%, the average specific energy demand of the building stock can be reduced to 41 kWh/m^2/yr by 2050.

descriptor d(II): ‘renovation depth – buildings (private)’

Soft coupling factor. See descriptor d(I).

descriptor e: ‘reduction of energy demand – industry’

Hard coupling factor. This descriptor describes the reduction in the energy intensity (final energy demand per gross value added) of the German industry. In combination with descriptors D (‘GDP development’) and E (‘tertiarization of the economy’) it allows one to estimate the final energy demand of the industry.

descriptor f: ‘reduction of energy demand – commercial sector’

Hard coupling factor, similar to descriptor e.

descriptor g: ‘expansion of district heating’

Soft coupling factor. Descriptor variant ‘no change’ is interpreted as a continuation of the current stagnation of district heating (ca. 500 PJ/yr in Germany) and as an eventual reduction due to reduced space heating demand. Descriptor variant ‘strong expansion’ implies an increase in public district heating generation to 600-700 PJ/yr.

descriptor h: ‘investment in new vehicle concepts and infrastructures’

Hard coupling factor. This descriptor directly describes the share of ‘new’ technologies (BEVs, PHEVs, and hydrogen fuel cell vehicles) of all transport services of individual passenger cars.

descriptor i: ‘living trends’

Hard coupling factor. In combination with descriptor C (‘population development’), the descriptor determines living spaces and in turn in combination with descriptors d(I) and d(II) final energy demand for space heating in private households.

descriptor j: ‘expansion of renewables for heating’

Hard coupling factor. In combination with descriptor g (‘expansion of district heating’), descriptor j determines the expansion of renewable heat (in TWh/yr) for individual buildings (heat pumps, biomass, and solar thermal) and district heating (biomass, solar thermal, geothermal and heat pumps).

descriptor k: ‘rebound effects of individual energy demand’

Soft coupling factor. In the case of a ‘moderate rebound’, the energy demand of private households (electric appliances) is 7% higher than in the case of a ‘small rebound’. In the case of a ‘strong rebound’, energy demand for electric appliances used in private households is 15% higher than that of the ‘small rebound’ case.

			descriptor	unit	type	Target
international factors		A (I)	global development in general	-	i	Market forces
		A (II)	global fossil price pathway	$/bbl	d	166
		A (III)	global interest rate	%	s	0.025
		B	EU integration	-	i	EU-Renaissance
national factors	general	C	population in 2050	million	d	67.4
	economy	D	GDP growth	%/yr	d	1.2
		E	employment market development	-	i	employment market bifurcation
		F	tertiarisation of the economy	-	s	0.8
		G	innovative ability of the economy	-	i	stable
		H	transnational flows of trade	-	i	European Germany - focus on services
		I	international integration of electricity grids	-	i	trend towards national self-reliance (regarding capacities)
		J	development of infrastructures in power transmission & distribution grids	-	i	delayed
		K	expansion of renewable energies in the electricity sector (generation 2050)	TWh/yr	d	450
		L	trends central / decentralised electricity generation and storage	-	s	trend towards mixed structures
		M	regulation electricity market	-	i	modifications of existing markets (security of supply via market)
national factors	politics	N	policy stability in the energy field	-	i	constant
		O	governance in the energy field	-	i	preference for non-technology-specific economic instruments
		P	governance of infrastructure expansion	-	i	trend towards non-coordinated expansion
		Q	planning legislation / public infrastructure planning	-	i	compromise
		R	governmental targets of organisation	-	i	focus on market mechanisms
		S	welfare state development	-	i	more emphasis on liberal welfare elements
national factors	society	T	income distribution	-	i	increasing inequality / increasing average income
		U	technology acceptance (energy technologies)	-	i	slightly increasing
		V	individual energy consuming behaviour	-	i	trend towards non-involvement
		W	educational development	-	i	strong focus on MINT / strong limitation on access
national factors	culture	X	public attitude towards the energy transition / NIMBY	-	i	no trend visible
		Y	value orientation and objectives in economic development	-	i	trend towards materialism and performance
		Z	media discourse	-	i	slight plurality of opinion / strong trend for tabloidisation
national factors	passive descriptors for energy system	a	reduction energy demand - household appliances	%/yr	d	0.6
		b	reduction energy demand - PC electric vehicles	%/yr	d	1.7
		c	reduction energy demand - PC engines	%/yr	d	0.8
		d (I)	renovation rate - buildings (private)	%/yr	s	2.0
		d (II)	renovation depth - buildings (private)	%	s	70
		e	reduction energy demand - industry	%/yr	d	2.3
		f	reduction energy demand - commercial sector	%/yr	d	3.4
		g	expansion district heating	-	s	strong expansion
		h	investments new vehicle concepts and infrastructures	-	s	high (~100% of vehicle market)
		i	living trends	m^2/cap	d	60
		j	expansion of renewable energies for heating	TWh/yr	d	400
		k	rebound effects individual energy demand	-	s	moderate

Table 1: Descriptor variants for the ‘Target’ scenario (direct/hard coupling descriptors highlighted in dark grey, soft coupling descriptors highlighted in light grey).

			descriptor	unit	type	Inertia
international factors		A (I)	global development in general	-	i	Fortress world
		A (II)	global fossil price pathway	$/bbl	d	210
		A (III)	global interest rate	%	s	0.025
		B	EU integration	-	i	EU under threat
national factors	general	C	population in 2050	million	d	67.4
	economy	D	GDP growth	%/yr	d	0.6
		E	employment market development	-	i	employment market bifurcation
		F	tertiarisation of the economy	-	s	0.8
		G	innovative ability of the economy	-	i	decreasing
		H	transnational flows of trade	-	i	European Germany - focus on services
		I	international integration of electricity grids	-	i	trend towards national self-reliance (regarding capacities)
		J	development of infrastructures in power transmission & distribution grids	-	i	strongly delayed
		K	expansion of renewable energies in the electricity sector (generation 2050)	TWh/yr	d	300
		L	trends central / decentralised electricity generation and storage	-	s	trend towards integrating decentralised units into centralised system
		M	regulation electricity market	-	i	introduction of new markets (security of supply via state)
national factors	politics	N	policy stability in the energy field	-	i	decreasing
		O	governance in the energy field	-	i	preference for administrative regulations
		P	governance of infrastructure expansion	-	i	trend towards non-coordinated expansion
		Q	planning legislation / public infrastructure planning	-	i	focus on legitimation and acceptance
		R	governmental targets of organisation	-	i	focus on state / public governance
		S	welfare state development	-	i	more emphasis on liberal welfare elements
national factors	society	T	income distribution	-	i	increasing inequality / continuing weak or no growth of average income
		U	technology acceptance (energy technologies)	-	i	decreasing
		V	individual energy consuming behaviour	-	i	trend towards non-involvement
		W	educational development	-	i	strong focus on MINT / strong limitation on access
national factors	culture	X	public attitude towards the energy transition / NIMBY	-	i	trend towards negative attitude
		Y	value orientation and objectives in economic development	-	i	trend towards materialism and performance
		Z	media discourse	-	i	high plurality of opinion / strong trend for tabloidisation
national factors	passive descriptors for energy system	a	reduction energy demand - household appliances	%/yr	d	1.3
		b	reduction energy demand - PC electric vehicles	%/yr	d	0.8
		c	reduction energy demand - PC engines	%/yr	d	0.8
		d (I)	renovation rate - buildings (private)	%/yr	s	2.0
		d (II)	renovation depth - buildings (private)	%	s	70
		e	reduction energy demand - industry	%/yr	d	1.0
		f	reduction energy demand - commercial sector	%/yr	d	3.4
		g	expansion district heating	-	s	no change
		h	investments new vehicle concepts and infrastructures	-	s	small (20% of vehicle market)
		i	living trends	m^2/cap	d	60
		j	expansion of renewable energies for heating	TWh/yr	d	250
		k	rebound effects individual energy demand	-	s	moderate

Table 2: Descriptor variants for the 'Inertia' scenario (direct/hard coupling descriptors highlighted in dark grey, soft coupling descriptors highlighted in light grey).

			descriptor	unit	type	Market
international factors		A (I)	global development in general	-	i	Market forces
		A (II)	global fossil price pathway	$/bbl	d	166
		A (III)	global interest rate	%	s	0.025
		B	EU integration	-	i	Nobody cares
national factors	general	C	population in 2050	million	d	67.4
	economy	D	GDP growth	%/yr	d	1.8
		E	employment market development	-	i	low unemployment / strong transition to flexible working hours
		F	tertiarisation of the economy	-	s	0.8
		G	innovative ability of the economy	-	i	stable
		H	transnational flows of trade	-	i	global Germany
		I	international integration of electricity grids	-	i	stronger European transmission network with European self-reliance
		J	development of infrastructures in power transmission & distribution grids	-	i	delayed
		K	expansion of renewable energies in the electricity sector (generation 2050)	TWh/yr	d	450
		L	trends central / decentralised electricity generation and storage	-	s	trend towards mixed structures
		M	regulation electricity market	-	i	modifications of existing markets (security of supply via market)
national factors	politics	N	policy stability in the energy field	-	i	constant
		O	governance in the energy field	-	i	preference for non-technology-specific economic instruments
		P	governance of infrastructure expansion	-	i	trend towards non-coordinated expansion
		Q	planning legislation / public infrastructure planning	-	i	compromise
		R	governmental targets of organisation	-	i	focus on market mechanisms
		S	welfare state development	-	i	more emphasis on liberal welfare elements
national factors	society	T	income distribution	-	i	increasing inequality / increasing average income
		U	technology acceptance (energy technologies)	-	i	slightly increasing
		V	individual energy consuming behaviour	-	i	trend towards non-involvement
		W	educational development	-	i	strong focus on MINT / strong limitation on access
national factors	culture	X	public attitude towards the energy transition / NIMBY	-	i	no trend visible
		Y	value orientation and objectives in economic development	-	i	trend towards materialism and performance
		Z	media discourse	-	i	high plurality of opinion / strong trend for tabloidisation
national factors	passive descriptors for energy system	a	reduction energy demand - household appliances	%/yr	d	0.6
		b	reduction energy demand - PC electric vehicles	%/yr	d	1.7
		c	reduction energy demand - PC engines	%/yr	d	1.55
		d (I)	renovation rate - buildings (private)	%/yr	s	2.0
		d (II)	renovation depth - buildings (private)	%	s	70
		e	reduction energy demand - industry	%/yr	d	2.3
		f	reduction energy demand - commercial sector	%/yr	d	3.4
		g	expansion district heating	-	s	strong expansion
		h	investments new vehicle concepts and infrastructures	-	s	moderate (50% of vehicle market)
		i	living trends	m^2/cap	d	60
		j	expansion of renewable energies for heating	TWh/yr	d	400
		k	rebound effects individual energy demand	-	s	moderate

Table 3: Descriptor variants for the 'Market' scenario (direct/hard coupling descriptors highlighted in dark grey, soft coupling descriptors highlighted in light grey).

			descriptor	unit	type	Value Shift
international factors		A (I)	global development in general	-	i	Policy reform
international factors		A (II)	global fossil price pathway	$/bbl	d	100
international factors		A (III)	global interest rate	%	s	0.025
international factors		B	EU integration	-	i	EU-Renaissance
national factors	general	C	population in 2050	million	d	78.7
national factors	economy	D	GDP growth	%/yr	d	1.8
national factors	economy	E	employment market development	-	i	low unemployment / strong transition to flexible working hours
national factors	economy	F	tertiarisation of the economy	-	s	0.8
national factors	economy	G	innovative ability of the economy	-	i	increasing
national factors	economy	H	transnational flows of trade	-	i	European Germany - focus on services
national factors	economy	I	international integration of electricity grids	-	i	stronger European transmission network with European self-reliance
national factors	economy	J	development of infrastructures in power transmission & distribution grids	-	i	undelayed
national factors	economy	K	expansion of renewable energies in the electricity sector (generation 2050)	TWh/yr	d	700
national factors	economy	L	trends central / decentralised electricity generation and storage	-	s	trend towards the transition to a decentralised system
national factors	economy	M	regulation electricity market	-	i	modifications of existing markets (security of supply via market)
national factors	politics	N	policy stability in the energy field	-	i	increasing
national factors	politics	O	governance in the energy field	-	i	preference for non-technology-specific economic instruments
national factors	politics	P	governance of infrastructure expansion	-	i	trend towards coordinated expansion
national factors	politics	Q	planning legislation / public infrastructure planning	-	i	focus on legitimation and acceptance
national factors	politics	R	governmental targets of organisation	-	i	focus on public participation and transparency
national factors	politics	S	welfare state development	-	i	more emphasis on corporatist-statist welfare elements
national factors	society	T	income distribution	-	i	constant or decreasing inequality / increasing average income
national factors	society	U	technology acceptance (energy technologies)	-	i	slightly increasing
national factors	society	V	individual energy consuming behaviour	-	i	trend towards technophilia
national factors	society	W	educational development	-	i	strong focus on MINT / slight limitation on access
national factors	culture	X	public attitude towards the energy transition / NIMBY	-	i	trend towards positive attitude
national factors	culture	Y	value orientation and objectives in economic development	-	i	trend towards post-materialism
national factors	culture	Z	media discourse	-	i	high plurality of opinion, weak trend for tabloidisation
national factors	passive descriptors for energy system	a	reduction energy demand - household appliances	%/yr	d	0.6
national factors	passive descriptors for energy system	b	reduction energy demand - PC electric vehicles	%/yr	d	1.7
national factors	passive descriptors for energy system	c	reduction energy demand - PC engines	%/yr	d	1.55
national factors	passive descriptors for energy system	d (I)	renovation rate - buildings (private)	%/yr	s	2.0
national factors	passive descriptors for energy system	d (II)	renovation depth - buildings (private)	%	s	70
national factors	passive descriptors for energy system	e	reduction energy demand - industry	%/yr	d	2.3
national factors	passive descriptors for energy system	f	reduction energy demand - commercial sector	%/yr	d	3.4
national factors	passive descriptors for energy system	g	expansion district heating	-	s	strong expansion
national factors	passive descriptors for energy system	h	investments new vehicle concepts and infrastructures	-	s	high (~100% of vehicle market)
national factors	passive descriptors for energy system	i	living trends	m^2/cap	d	50
national factors	passive descriptors for energy system	j	expansion of renewable energies for heating	TWh/yr	d	500
national factors	passive descriptors for energy system	k	rebound effects individual energy demand	-	s	moderate

Table 4: Descriptor variants for the ‘Value Shift’ scenario (direct/hard coupling descriptors highlighted in dark grey, soft coupling descriptors highlighted in light grey).

Information on model parameters not directly determined by the context scenario:

The ‘hard’ and ‘soft’ coupling factors described above to a large extent determine the final energy demand of the industrial, household, commerce and trade, and transport sectors. They further determine the amount of electricity and heat generated from renewable sources. However, the coupling factors do not determine all relevant input parameters characterizing a scenario’s technical storyline. In particular, context scenarios neither define technologies used for conventional and renewable power and heat generation nor biomass consumed for energy purposes (e.g., a blended quota for biofuels). Thus, remaining relevant scenario parameters must be determined based on the two principles discussed above (3i and 3ii). This is illustrated by the three examples shown below (Figure 2 to Figure 4):

Figure 2 shows installed capacities for power generation of the four scenarios and the share of (intermittent) RES of total power generation capacity. For the three scenarios with shares of intermittent renewable power generation of greater than 60-70% (the ‘Target’, ‘Market’, and ‘Value Shift’ scenarios), typical base and medium load power plants (e.g., lignite and hard coal power plants) are driven back by the system’s flexibility requirements. In contrast, gas power plants serve as the backbone of conventional installed capacity, as they are capable of providing the required levels of flexibility at high shares of renewable energy.

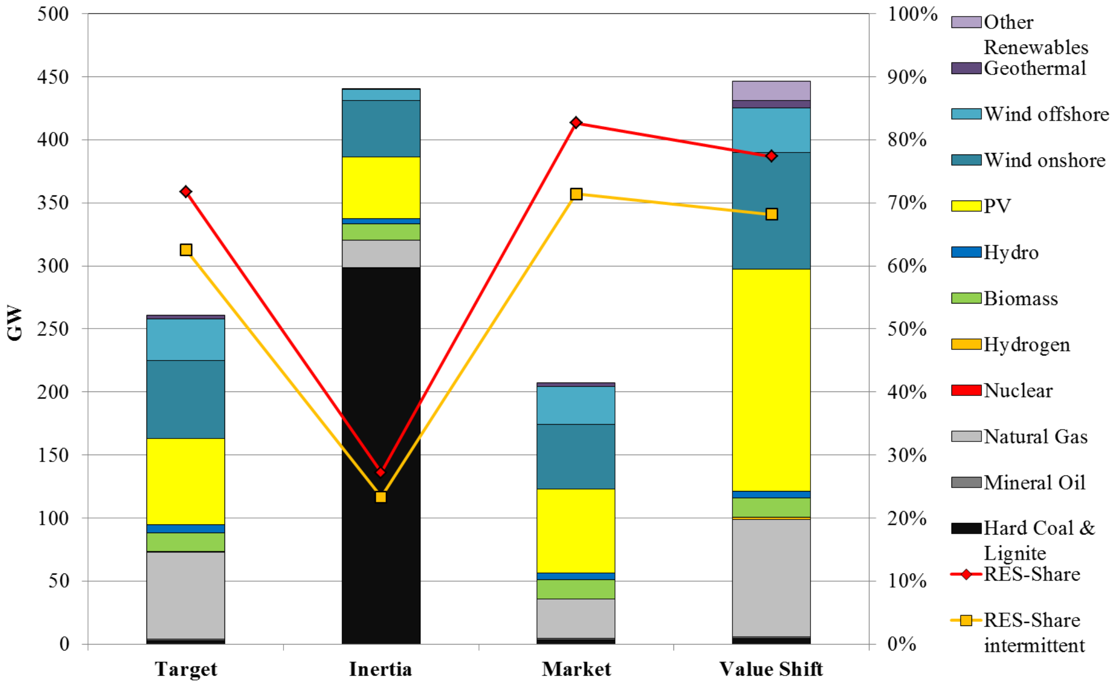

Figure 2: Installed capacities of power generation by technology and (intermittent) RES share for 2050.

Figure 3 shows the final energy demand for space heat and hot water (SH/HW) of the residential sector differentiated by energy carrier respective technologies used. Figure 3 also shows the RES share of final energy demand for SH/HW for this sector. Total demand is mainly constrained by the development of living space, the renovation rate and renovation depth of buildings and population development for the four scenarios (see Table 1 to Table 4). The RES share is determined from energy demand for SH/HW and the degree of RES heat expansion observed in the scenarios. The share of district heat is determined by descriptor g (‘expansion of district heat’). Among the scenarios, ‘Target’ ‘Market’, and ‘Value Shift’ district heating networks are considerably expanded. Accordingly, the share of district heat increases significantly from approximately 10% today to 28% (‘Market’) and 42% (‘Target’). For the ‘Inertia’ scenario, the district heat share of total final energy consumption for SH/HW in the residential sector remains nearly constant (12% in 2050). Shares of other heat technologies are shaped by each scenario. Biomass consumption is lowest in the ‘Target’ and ‘Value Shift’ scenarios, as overall attitudes regarding sustainability are the strongest in these scenarios. Thus, concerns about the sustainable use of biomass for energy purposes limit bioenergy consumption in the two scenarios. Note that societal views of sustainability are not directly constrained by the context scenario descriptors. However, it is assumed that the combination of descriptors X (‘public attitudes towards the energy transition’) and Y (‘value orientation and objectives of economic development’) allows for an assessment of views of sustainability. In the ‘Value Shift’ scenario, the share of electric heat pumps is the highest of all scenarios. This corresponds to a strong expansion of renewable power generation (700 TWh/yr in 2050), which allows for high levels of electrification and which in turn decreases CO_2 emissions generated from the heating sector.

Thus, the technology share of SH/HW for the residential sector is determined by both ‘soft’ and ‘hard’ coupling factors but also by technical constraints (principle 3i) and by constraints set by the ‘spirit’ of a given scenario (principle 3ii).

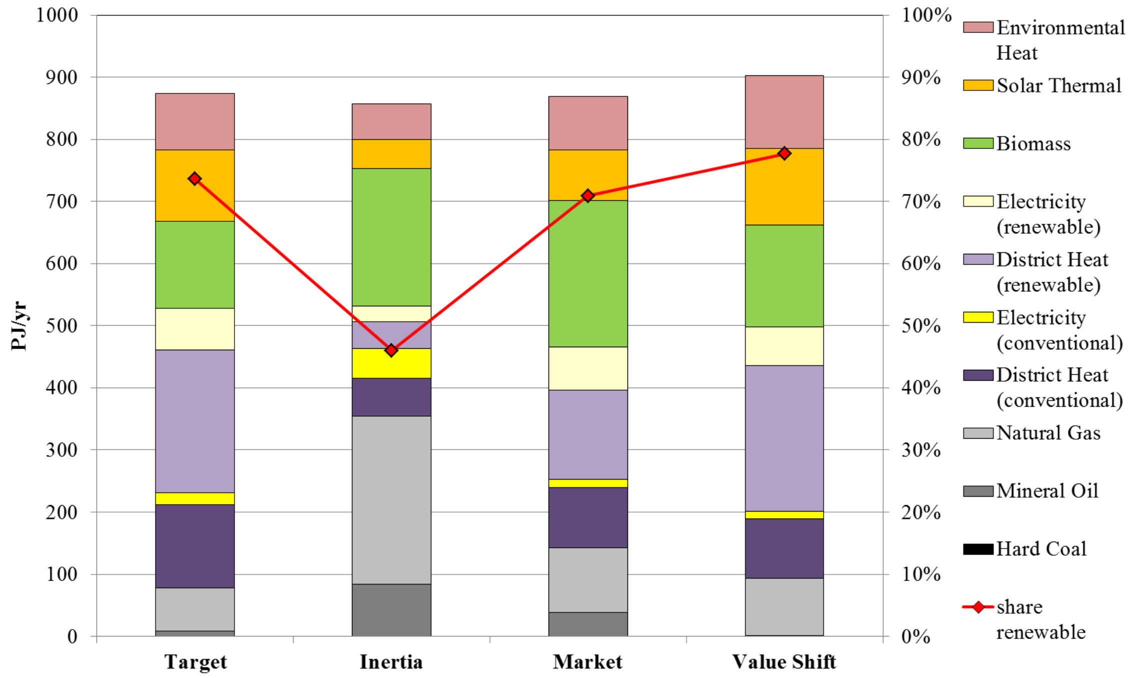

Figure 3: Final energy demand and RES share for space heat and hot water (residential sector) by energy carrier for 2050.

Figure 4 shows the final energy demand of each energy carrier for individual passenger transport and the biofuel blending quota for total diesel and gasoline. Total final energy demand is mainly determined by population development (descriptor C) and by improvements made in internal combustion engine and electric motor efficiency (descriptors b and c). The share of ‘new’ technologies (electric and hydrogen vehicles) is determined by descriptor h (‘investment in new vehicle concepts and infrastructures’). In the ‘Value Shift’ scenario, sustainability concerns limit biofuel consumption. Although the blending quota for this scenario is higher than it is today, low demand for diesel or gasoline results in low levels of biofuel demand. In contrast, an absence of sustainability concerns in the ‘Inertia’ scenario allows for a high biofuel quota with high demand for diesel and gasoline, resulting in the highest levels of biofuel consumption observed across all four scenarios. In the ‘Value Shift’ scenario, the share of hydrogen cars observed of all ‘new’ car concepts is highest. This reflects growing levels of technological acceptance (descriptor U), a trend towards technophilia (descriptor V) and improved capacities of innovation (descriptor G) observed in this scenario relative to the other scenarios.

Regarding SH/HW of the residential sector, the technology mix for individual passenger transport is determined by both ‘soft’ and ‘hard’ coupling factors but also by additional technical constraints (principle 3i) and by constraints set by the ‘spirit’ of a given scenario (principle 3ii).

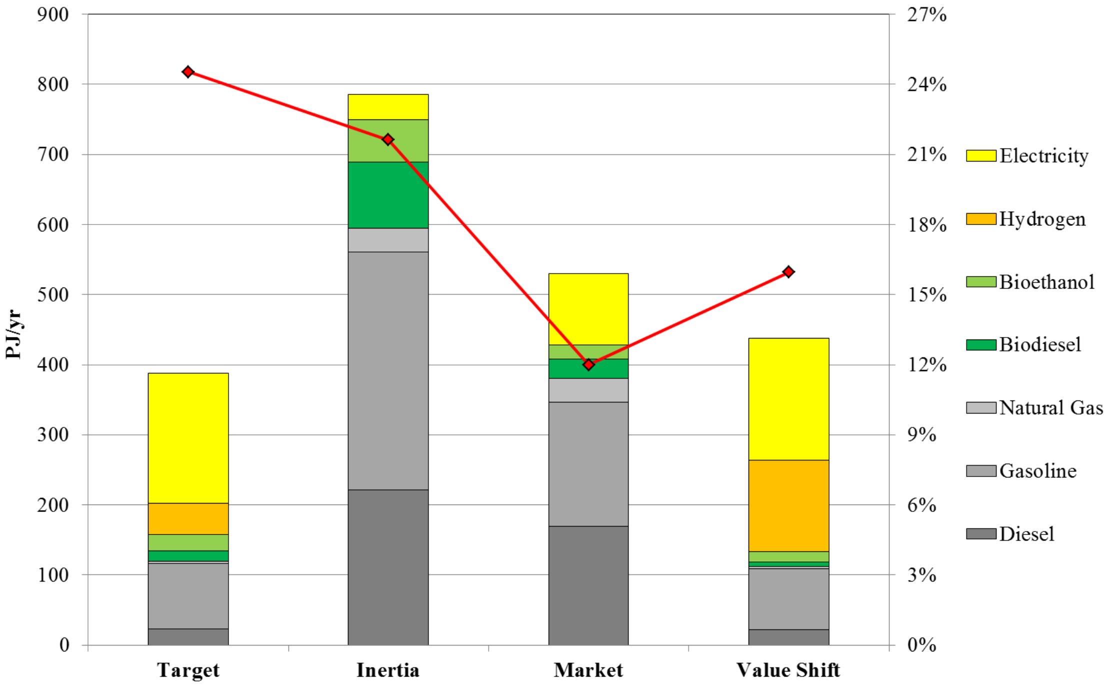

Figure 4: Final energy demand per fuel/energy carrier and biofuel blending quota for individual passenger transport for 2050.

Main differences between the scenario development using the simplified Excel tool and Mesap/PlaNet

- **Temporal resolution**: The Excel tool calculates a scenario only for the target year of 2050 while the detailed scenarios developed with Mesap/PlaNet illustrate the full transformation pathway for 2015 to 2050.
- **Demand differentiated by applications:** The simple Excel tool distinguishes between heat and electricity demand for private households, industry, and trade and commerce. The detailed Mesap/PlaNet model further distinguishes between space heat, process heat, hot water, air conditioning, process cooling, mechanical energy, illumination, information and communication. Furthermore, the Excel tool considers power and district heat losses, consumption, etc. in an aggregated manner.
- **Technologies considered**: The simple Excel tool considers fewer technologies for heat, power, and combined heat and power generation than the full Mesap/PlaNet model. With respect to heat generation, the simplified model does not differentiate between sectors. In a similar way, transport technologies are less differentiated than those considered in Mesap/PlaNet.
- Principle 3ii (**determination of scenario parameters from the 'spirit' of the context scenario**) cannot be applied using the Excel tool, as the modeler's interpretation of consequences of the 'spirit' of a given context scenario is not automatable.

References

Nitsch J et al. (2012) Long-term scenarios and strategies for the deployment of renewable energies in Germany in view of European and global developments. Report to the German Federal Ministry for the Environment (BMU). DLR, FhG IWES, IfnE. (in German).

Pregger T, Nitsch J, Naegler T (2013) Long-term scenarios and strategies for the deployment of renewable energies in Germany. Energy Policy, 59(0):350–360.

SM-(6) Examples of very low emission scenarios

The set of 380 scenarios involving very low CO_2 emissions (<130 Mt/yr) includes a variety of storylines and driving forces and societal conditions leading to this emission level. Some scenarios can be associated with intact societies deliberately seeking very low emissions. Others must be described as societies driven towards very low emissions by a combination of uncomfortable external pressures and internal dysfunction. However, one descriptor development is shared by all very low emissions scenarios: a small population (cf. Table 1 of the main text). This does not mean that a small population automatically leads to very low emissions; rather, the subset of 'small population' scenarios taken from the complete set of 1725 scenarios covers 73 to 734 Mt CO_2 emissions for the year 2050 (Figure 5) (i.e., the maximum and minimum emission scenarios are related to small populations). On the other hand, moderate or large populations do not exclude substantial emission mitigation efforts. The lowest emission scenario for a moderate or large population involves the emission of 132 Mt/yr and only narrowly misses the (arbitrary) qualification for the very low emission category. In summary, a small population serves as a sort of prerequisite for very low emission scenarios. However, additional stimuli must be involved to lead society towards very low emissions. These stimuli may result from (demand driven) high fossil fuel prices, from environmental concerns, or from energy carrier supply risks as a consequence of international crises. As examples we describe the following two scenarios.

One represents the case of an **intact society** (Table 5, 126 Mt) that successfully responds to a strong increase in fossil fuel prices. The application of a market-oriented approach, a favorable setting for global prosperity and a reinvigorated EU enables strong economic growth in Germany despite its weak demographic development. This is also attributable to the presence of a highly skilled and innovative workforce and to high levels of workforce mobilization. Potential workforce scarcity ensures the strong positioning of employees within the labor market and a satisfactory yet divided pattern of income development. As a consequence, the economy and population are ready and able to assume the burdens of an energy transformation. The materialistic value orientation of this society constitutes no barrier to its capacity to manage such a transformation, as the core stimulus (strong increase of prices for fossil fuels) is an economic one and is perceived as a threat to materialistic welfare.

Table 5: Very low emission scenario. Example: Intact society

A(I). Global development - General	: A(I)1 Market Forces
A(II). Global development - Price for fossil fuels	: A(II)3 Strong growth of prices
A(III). Global development - Interest rate level	: A(III)2 Moderate recovery of interest rates
B. EU integration	: B1 EU Renaissance
C. Population development	: C1 Strongly decreasing
D. GDP growth	: D3 Strong development
E. Labor market development	: E1 Low unemployment / pro-worker flexibility
F. Tertiarization of the economy	: F2 Strong tertiarization
G. Innovation capabilities	: G3 Increasing
H. Transnational trade flows	: H1 European Germany
I. International power line integration	: I2 Trend European power grid / European autarky
J. Infrastructure expansion of power lines	: J1 Appropriate expansion
K. Renewable electricity expansion	: K3 Strong expansion
L. Centralized/decentralized power generation and -storage	: L3 Conversion to decentralized system architecture
M. Electricity market regulations	: M1 Market in charge of security of supply
N. Energy policy stability	: N3 Increasing policy stability
O. Energy policy instruments	: O3 Technology-unspecific economic instruments
P. Governance in the field of infrastructure expansion	: P1 Coordinated expansion
Q. Planning law / public infrastructure planning	: Q2 Focus legitimacy and acceptance
R. Political design model	: R3 Market mechanisms
S. Social welfare state design	: S1 Liberal welfare state
T. Private income development	: T3 Increasing inequality / high income growth
U. Acceptance of energy technologies	: U3 Slightly increasing
V. Energy consumption behavior (individual)	: V2 Trend towards being economical
W. Education development	: W1 Focus MINT / low access barriers
X. Public attitude towards the 'Energiewende'	: X1 Trend towards positive attitude
Y. Value shift	: Y1 Trend materialism and performance
Z. Media discourse	: Z1 Opinion diversity and tabloidization
a. Consumption trend - Household appliances	: a2 Strong efficiency trend
b. Efficiency trend - E-cars	: b3 Strong efficiency trend
c. Efficiency trend - Combustion cars	: c2 Strong efficiency trend
d. Efficiency trend - Private buildings	: d3 Strong efficiency trend
e. Efficiency trend - Industry	: e2 Strong efficiency trend
f. Efficiency trend - Trade/Services	: f3 Strong efficiency trend
g. Local heating networks	: g2 Accelerated expansion
h. New car concepts and infrastructure	: h3 High investments
i. Residential space trends	: i1 Weakly increasing
j. Renewable heat production	: j3 Very strongly increasing
k. Rebound in individual energy consumption	: k2 Moderate rebound

The second scenario involves a society that becomes out of step under transformative pressures (**Society under pressure**, Table 6, 110 Mt). A series of severe international crises leads to strong growth in fossil fuel prices and to uncertainties regarding constant access to energy resources. This stimulates an energy transition in Germany. At the same time, global defragmentation together with a European Union in abeyance undermines the German 'business model' of economic success. Thus, the German economy and German society are weakened just when it hurts most: in the face of an urgent need for transformation. In this critical situation, the state must at least take control of pivotal elements of the transformation to ensure a sufficient dynamic, a shift that leads in a liberalized economy to a coexistence of diverging control paradigms, spurring conflicts and frictions. Nevertheless, Germany achieves strong level of emission mitigation, albeit this is due in part to its successful energy transformation and in part to derailed efforts towards economic development.

Table 6: Very low emission scenario. Example: Society under pressure

A(I). Global development - General	: A(I)3 Fortress World
A(II). Global development - Price for fossil fuels	: A(II)3 Strong growth of prices
A(III). Global development - Interest rate level	: A(III)2 Moderate recovery of interest rates
B. EU integration	: B3 EU under threat
C. Population development	: C1 Strongly decreasing
D. GDP growth	: D1 Weak development
E. Labor market development	: E3 Division of labor market
F. Tertiarization of the economy	: F2 Strong tertiarization
G. Innovation capabilities	: G2 Constant
H. Transnational trade flows	: H2 European Germany - focus on services
I. International power line integration	: I1 Trend national capacity autarky
J. Infrastructure expansion of power lines	: J1 Appropriate expansion
K. Renewable electricity expansion	: K3 Strong expansion
L. Centralized/decentralized power generation & -storage	: L3 Conversion to decentralized system architecture
M. Electricity market regulations	: M3 State in charge of security of supply
N. Energy policy stability	: N1 Decreasing policy stability
O. Energy policy instruments	: O1 Regulatory instruments
P. Governance in the field of infrastructure expansion	: P2 Uncoordinated expansion
Q. Planning law / public infrastructure planning	: Q4 Compromise
R. Political design model	: R1 State control
S. Social welfare state design	: S1 Liberal welfare state
T. Private income development	: T1 Increasing inequality / low income growth
U. Acceptance of energy technologies	: U3 Slightly increasing
V. Energy consumption behavior (individual)	: V4 Trend towards sustainability
W. Education development	: W2 Focus MINT / strong access barriers
X. Public attitude towards the 'Energiewende'	: X1 Trend towards positive attitude
Y. Value shift	: Y1 Trend materialism and performance
Z. Media discourse	: Z1 Opinion diversity and tabloidization
a. Consumption trend - Household appliances	: a2 Strong efficiency trend
b. Efficiency trend - E-cars	: b3 Strong efficiency trend
c. Efficiency trend - Combustion cars	: c1 Weak efficiency trend
d. Efficiency trend - Private buildings	: d3 Strong efficiency trend
e. Efficiency trend - Industry	: e2 Strong efficiency trend
f. Efficiency trend - Trade/Services	: f3 Strong efficiency trend
g. Local heating networks	: g2 Accelerated expansion
h. New car concepts and infrastructure	: h3 High investments
i. Residential space trends	: i3 Strongly increasing
j. Renewable heat production	: j2 Strongly increasing
k. Rebound in individual energy consumption	: k2 Moderate rebound

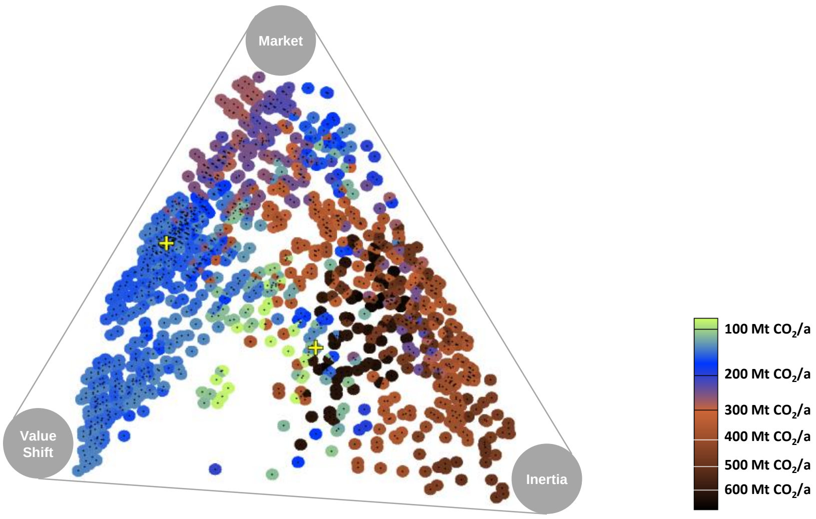

Figure 5: Landscape of societies and the selected very low emission scenarios. Yellow cross left: 'Intact society', center: 'Society under pressure'.

SM-(7) The world behind the 'Target' scenario – A socio-technical energy scenario describing the energy transformation in Germany by the year 2050

Introduction

Among the many storylines put forth by the CIB analysis (see main article) and describing varieties of success and failure stories of different origins, this storyline features a case of success mainly driven by internal developments in Germany, though these are only possible against the background of certain international developments. This 'Target' scenario storyline (see Figure 6 and Table 1) was selected out of the full sample of approximately 1,700 CIB storylines generated by the project because its energy-economic outcomes resembles the DLR 'Long-term scenarios' (Nitsch et al. 2012 and preceding 'Leitszenarien' mentioned there), energy scenarios widely used in the German energy discourse after its publication[1]. Therefore, the storyline for the 'Target' scenario can broadly be seen as a *reconstruction of the socio-technical background story* behind the 'Long-term scenarios' revealing which societal and international framework conditions are well fitted to provoke their energy-economic developments. However, it has to be kept in mind that the 'Target' scenario presented in the main article and discussed here in the following paragraphs only resembles the 'Long-term scenarios' in many features, but is a distinct scenario for itself. Thus, the quantitative results from the 'Target' scenario shown below are not identical with the results from (Nitsch et al. 2012).

This means that the following example demonstrates a special (inverted) usage of the data provided by a CIB-plus-model analysis: Instead of selecting a certain societal development and asking for the energy-economic consequences, we are starting by a predefined normative energy scenario and inquire into the societal implications hidden behind the model results. Both directions of analysis are possible and meaningful depending on the goals of the study: they are connected to an explorative versus normative understanding of scenarios as an analytical tool.

It should be noted that the 'Target' scenario follows defined minimum targets of the German Energy Concept ('Energiekonzept', BMWi 2010) (see Table 8) reducing GHG emissions by 80% by 2050 compared to 1990. This represents a reduction of 85% of energy-related CO_2 emissions. Compared to the ambitious goals of the Paris Agreement (UNFCCC 2015), the 'Target' scenario is still a failure. Nevertheless, fundamental developments of a successful energy transition are achieved, such as significant efficiency improvements in all sectors and a massive expansion of renewable energies. These developments would have to be intensified for the target 'well below 2°C temperature increase' and supplemented, for example, by greater use of synthetic fuels.

A format for presenting socio-technical energy scenarios

A scenario, in the end, is a narrative about the possible future development of a system, may this narrative be expressed by numbers, illustrations or text. Common model-based energy scenarios usually are depicted using quantitative data (tables and diagrams) and explanatory text. In the case of a socio-technical energy scenario the energy narrative is expanded by a supplementing narrative about the societal developments, taking place in parallel and being intertwined with the energy developments: the 'context scenarios'. The strength of CIB based context scenarios lies in the fact that there exists (in form of the cross-impact matrix) an explicit yet qualitative 'model' about the processes which shape the societal part of the socio-technical scenarios. This model connects the societal part to the energy-economic developments.

So the probably most modest (yet not the only) way to expand the 'classical' format of an energy scenario narration is to follow the usual course of an energy scenario report and going step by step through the energy-economic sectors. The common quantitative and verbal explanations about the technical changes are then complemented with an explanation how societal changes intervene in the

[1] A few other storylines were also found with high conformity with the framework assumptions of the 'Long-term scenarios', all of them very similar in their societal trend. One of them was selected here as an example for demonstrating the idea of a socio-technical energy scenario.

sector, e.g. by exhibiting the partial impact models suggested by the cross-impact matrix. Following this concept, the socio-technical energy scenario presented here consists of the following elements:

- After a preliminary statement about the framework conditions, e.g. concerning the international background, each energy sector is considered step-by-step.
- In each sector, model results are shown describing the techno-economic changes using quantitative tables, diagrams, and textual explanations.
- In addition, qualitative impact diagrams show how societal drivers act on the techno-economic factors in the sector, explaining the connection between societal and technical dynamics by citing the expert statements collected during the expert interviews. To achieve lucid impact diagrams, only the most relevant promoting drivers and short summaries of their explanation text are shown. Weak promoters and also counteracting impacts are not displayed for sake of clarity (the latter are always outvoted in a consistent CIB scenario).

This format of a socio-technical energy scenario can be played out to very different text sizes. The authors may choose to present all partial impact models or only a selection. They can confine themselves to show the impact diagrams or deliver more details about the socio-technical interactions in the text, e.g. by citing the expert statements about the cross-impacts. On the energy-economic side authors can decide about the aggregation level of the model results shown and explained, ending up in short or extensive descriptions also on the techno-economic part of the narrative. In the following example we choose a rather low level of detail in order to get a reasonable text size.

The ‘Target’ scenario: Expanding an energy-economic scenario towards a socio-technical perspective

Preliminary remarks on the context scenario identified as a consistent background storyline:

As mentioned before the scenario analyzed here in more detail was selected out of approximately 1700 context scenarios. It can be seen as a broadly consistent societal background story behind the DLR ‘Long-term scenarios’ (Nitsch et al. 2012) as it matches with their framework assumptions. The descriptor configuration in this context scenario is shown in Figure 6 and in Table 13. In the heart of the storyline and its internal logical structure lies the symbiotic self-enforcement of two societal developments: constant stability of energy politics and, more or less, a preservation of the currently affirmative public attitude towards the 'Energiewende', failing in increasing this approval, but also avoiding erosion of today’s positive attitudes due to coming hardships of the transformation process (see Figure 7).

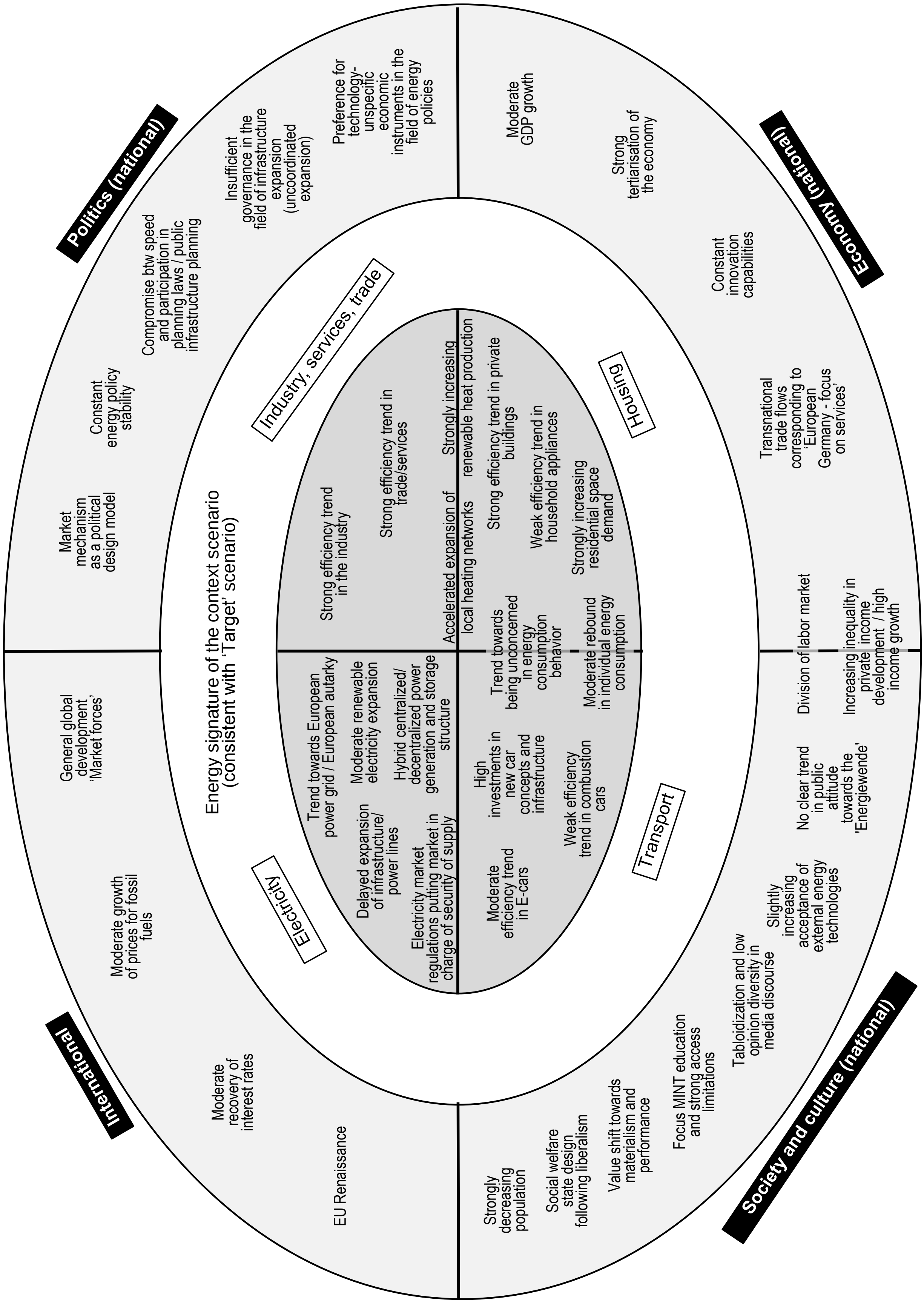

Figure 6: A context scenario describing a consistent socio-economic-political background of the 'Target' scenario.

The power of this pair of developments as a storyline driver lies in its self-stabilizing quality: policy stability encourages a positive attitude towards a political project, or as an expert interviewed during the CIB analysis put it: ‘People appreciate reliability and planning security. They prefer to place their trust in institutions whose words and deeds go hand in hand.’ Vice versa, public approval eases the way for political actors to stand by their energy goals and to keep a steady hand. This self-stabilizing pair of developments builds the ground for transformative developments in many different action fields, which together form this scenario and describe a targeted pathway towards the year 2050. As a consequence of its role as a major driver of the storyline, this signature stimulates many of the other context scenario elements and, by this, it is a direct or indirect driver in many of the impact diagrams shown below.

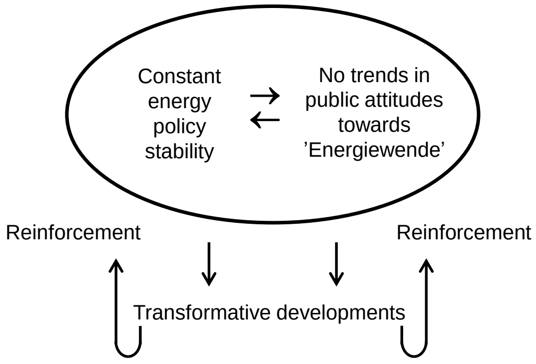

Figure 7: Signature of the storyline.

Despite the self-stabilizing quality of this pair of developments it probably will not be easy to establish this scenario signature and make it unfolding its enabling effects on the transformation process in reality: Only a very small share of the 1725 context scenarios are coined by this signature – as a rule obstructive framework conditions prevent its development or, even when established, curtail its effects. The secret of success of this scenario lies in the fact that, under the specific conditions described in this scenario, the signature produces a bundle of developments that, after unfolding, stabilize the signature instead of undermining it in the long term.

An encouraging aspect in the perspective of supporters of the 'Energiewende' is that the storyline does not assume a 'rose-colored' (i.e. overoptimistic) world: in an ideal world, policy stability as well as public affirmation would increase instead of only being stable (though on a fairly high level). In this respect (and in others) the described storyline represents a sort of 'second best world', and, as the analysis shows, a second best world is good enough for reaching at least the minimum 'Energiewende' goals if it only manages to show strength in some pivotal aspects.

International background

	2030	2050
Oil	126 $/b	166 $/b
Gas	11 €/GJ	13,8 €/GJ
Coal	108 €/SKE	131 €/SKE

Table 7: Energy carrier prices (UBA 2013).

On the global stage, the market and growth paradigm defends its role as a dominating factor. Trade barriers are removed, and developing and emerging countries are integrated more and more into the global economic structures. Global population as well as global inequality rises. The price of fossil energy carriers are significantly rising, avoiding extreme price levels, however. Interest rates recover and increase to a level of 2.5 % real interest rates for long-term government bonds. In Europe, the EU recovers and the integration process gains strength again. This leads to productivity growth in the member states and the strengthening of integrated and coordinated climate and energy policies across the Union. With regard to the energy system this includes a European power grid integration following the goal of European energy markets (instead of national energy autarky).

These international developments serve as framework assumptions for the national context analysis. They are only one example of possible sets of international framework assumptions represented in the full sample of context scenarios. The assumptions shown above are distinguished by the fact that they were identified by the CIB analysis as a plausible international background of the national storyline described below.

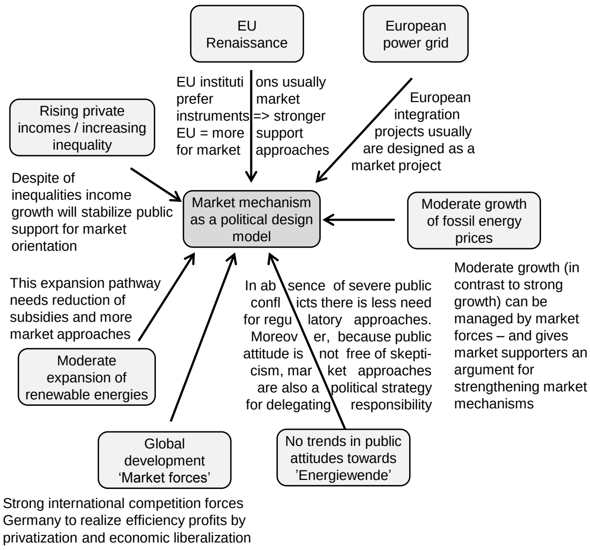

Figure 8: Partial impact model 'Political design model: market mechanism'. Only strong drivers shown.

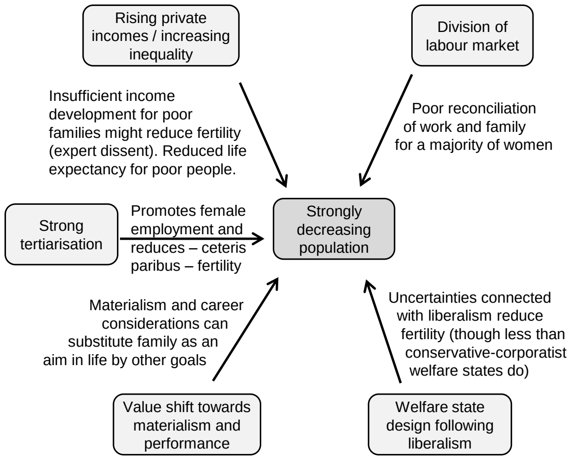

Figure 9: Partial impact model 'Strongly decreasing population'. Only strong drivers shown.

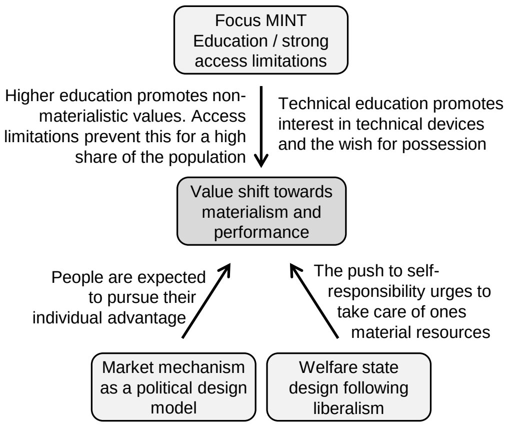

Figure 10: Partial impact model 'Direct drivers of materialism and performance values'. Only strong drivers shown.

General societal development

In a world in which the market paradigm dominates on the global scale, Germany is among the countries that follow the principles of free markets and liberalization, encouraged in parts by a reinvigorating EU. The German government trusts, as a rule, in market mechanism (Figure 8), e.g. when reorganizing the electricity market. It follows market-liberal welfare principles, prefers technology-unspecific economic instruments in energy politics (where appropriate) and tolerates an education system with significant social access barriers.

Consequences are growing income disparity, a divided labor market with high workers' flexibility (in particular for the low-skill sector), low birth rates (the aging population shrinks to 67.4 Mio. till 2050, Figure 9), a dominance of materialistic and performance oriented values in the population (Figure 10), weak intrinsic consumer interest in energy saving behavior, and by concentration effects and decreasing education level, tabloidization and a poor plurality of opinions in the media. Effective coordination of the energy infrastructure expansion is hampered too because infrastructure location decisions are more influenced by profit aspects than by balanced multilevel governance.

On the plus side Germany manages to stabilize MINT education for a sufficient share of students, innovation capacities and GDP growth on a moderate level of 1.2 % per year – the latter promoted by a strong economic growth on the European and global level, increasing European trade flows. Tertiarization proceeds helping to promote female employment and partly compensating decreasing labor force in Germany. The sustained economic growth ensures that incomes are generally growing, though with different speed. Also favorable for the energy transition, public acceptance of energy technologies slightly increases, promoted among others by structural changes in the energy infrastructure and as a positive side-effect of the otherwise hindering materialistic value orientation (Figure 11).

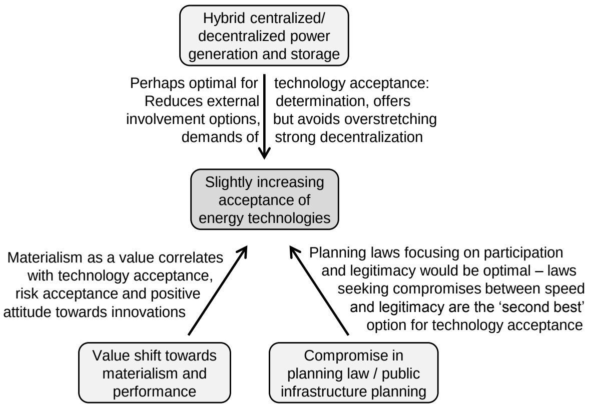

Figure 11: Partial impact model 'Direct drivers of slightly increased acceptance of energy technologies'. Only strong drivers shown.

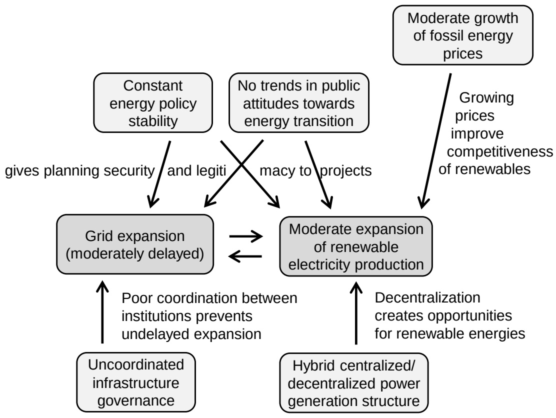

Figure 12: Partial impact model 'Direct drivers of infrastructure & renewable electricity production'. Only strong drivers shown.

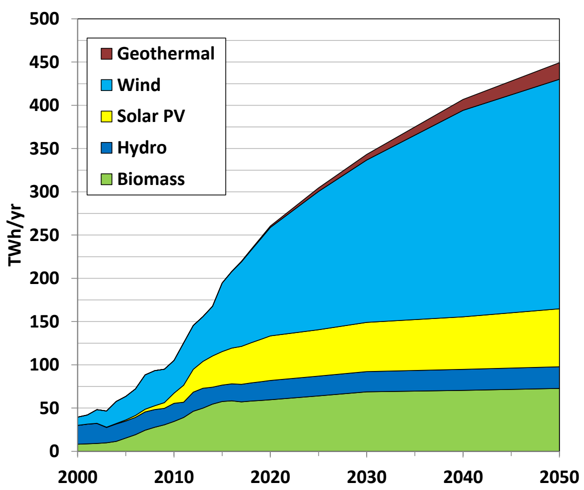

Figure 13: Renewable electricity production 2000–2050.

Renewable energy production

Renewable electricity production succeeds in maintaining the pace of the past and the production increases by approximately 8 TWh per year on average. Major drivers of the expansion are rising prices for fossil energies, a reasonable continuing political support which results, among others, in a somewhat delayed, but steady grid extension and a public attitude which tends to be supportive, at least in principle (Figure 12 and Figure 13). Occasional attempts to further speed-up the expansion fail, however, due to the limits of support of a mediocre energy policy stability. Moreover, the option of an ultra-high expansion of renewable electricity production would have needed the boost of definitely high fossil energy prices and/or a clear paradigm shift towards a widely decentralized energy system, both absent in this scenario. Further limiting factors are a limited public interest and also ability – against a background of growing income disparity – to actively engage in the energy transformation as a prosumer (limiting decentralization).

Renewable heat production, in parallel to renewable electricity production, follows a strong, yet not extreme expansion pathway, increasing at a rate of approximately 6.5 TWh per year and partly coupled with an expansion also of heat distribution nets. Among the drivers supporting the expansion are rising prices for fossil energies, a slightly rising technology acceptance and new opportunities for renewable heat supply coming from efficiency developments in housing. A higher expansion is prevented by the low population development and a (only) stable state of energy policy stability and public attitude towards the 'Energiewende' goals.

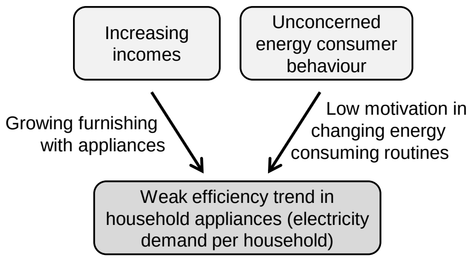

Figure 14: Partial impact model 'Direct drivers of weak efficiency trend in household appliances'. Only strong drivers shown.

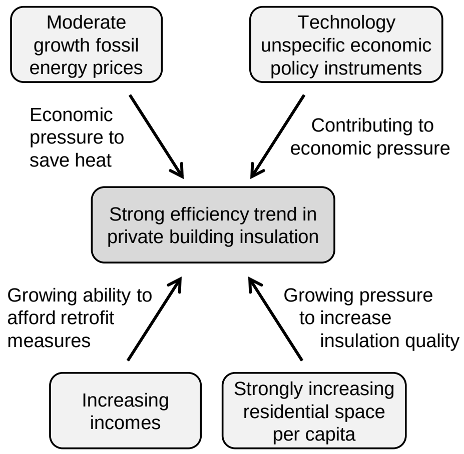

Figure 15: Partial impact model 'Direct drivers of strong efficiency trend in private building insulation'. Only strong drivers shown.

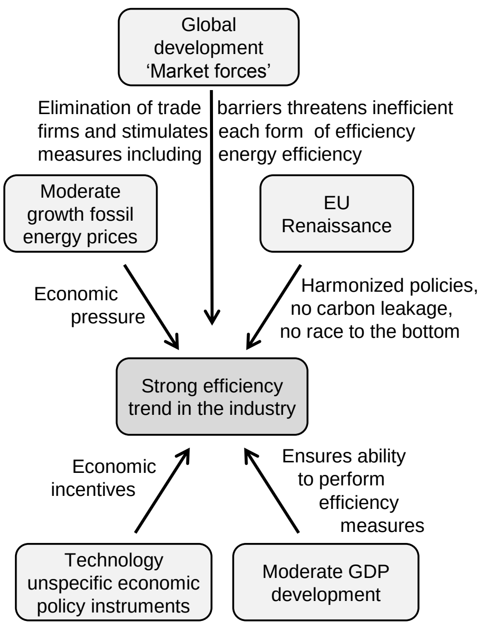

Figure 16: Partial impact model 'Direct drivers of strong energy efficiency trend in the industry'. Only strong drivers shown.

Efficiency

The societal framework conditions produce a non-uniform efficiency development across the sectors. The materialistic and consumption oriented attitudes in the majority of the population limits efficiency development where it depends on personal engagement and behavior, but enables progress where strong economic reasons advocate efficiency measures. Household appliances contribute less to the personal energy budget and in lack of other motivations efficiency growth is weak in this field (electricity consumption per household decreases by 0.6 % per year, Figure 14). A stronger efficiency development is achieved in buildings (2% of buildings are renovated each year, reducing the energy demand of the renovated building by 70% on average, Figure 15): space heating defines a major part of the personal energy budget and against the background of rising energy prices and policy measures intensifying this effect efficiency measures are just simply a means to make the growing desire for large dwellings affordable. In the industry and in service and trade holds the same (Figure 16): the impacts of growing energy prices, growing international competition and energy policies supporting this effect speed efficiency developments to 2.3 % per year (industry) and 3.4 % per year (service and trade sector).

The overall effect of those efficiency efforts can be seen in Figure 17: The total final energy consumption in the sectors residential, service and trade, and industry decreases by 43% between 2015 and 2050 (2015: around 6200 PJ, 2050: 3500 PJ).

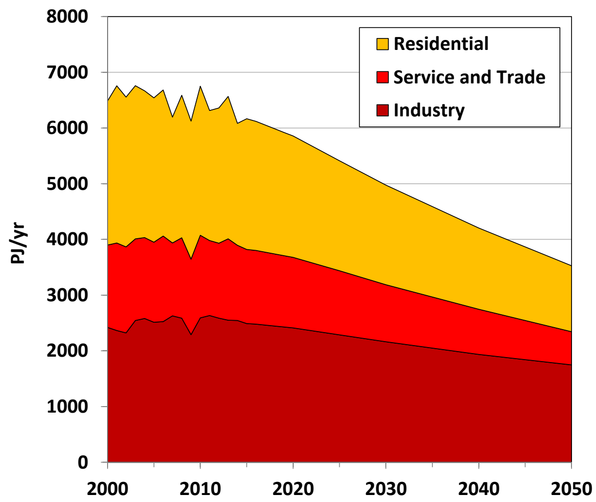

Figure 17: Total final energy demand by sector 2000–2050.

Transport

A transition of the transport sector is an indispensable part of a successful transition of the German energy system as a whole, and the considerable emissions reduction of this scenario implies that it includes also significant changes in mobility structures and technologies. The overall pattern of the scenario, however – strongly market oriented society, consumption focused, materialistic population, the energy transition rather being a government's project – imprints itself also in the way the transport transformation takes place.

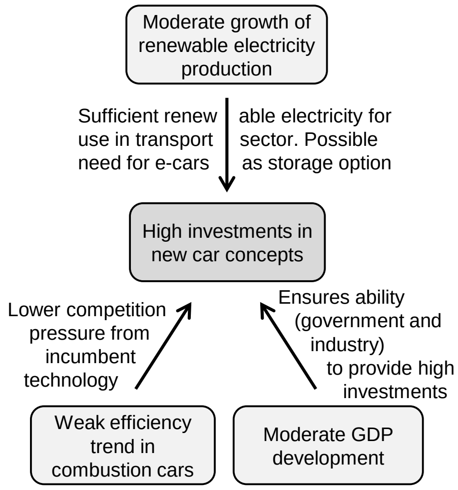

Figure 18: Partial impact model 'Direct drivers of high investments in new car concepts'. Only strong drivers shown.

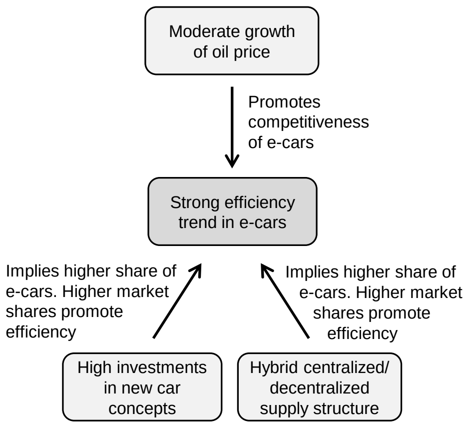

Figure 19: Partial impact model 'Direct drivers of strong efficiency trend in e-cars'. Only strong drivers shown.

One formative element of the developing transport sector is that a considerable part of the population is well-off and focused on consumption enough to ignore growing fuel prices and the appeals of the government. Car manufactures respond to their demands for some time more: technological progress in combustion engines is mainly converted in size, performance and comfort and specific consumptions of traditional cars decrease only at a slow rate of 0.8 % per year.

On the other hand, the goals of the energy transition make it clear to manufacturers and investors that a system transition towards e-mobility, biofuels and/or hydrogen cars will be unavoidable sooner or later. The steady extension of renewable electricity production makes it predictable when large capacities will be available also for supplying the additional demand from transportation and the storage capacity of e-car batteries or hydrogen systems will even be of systemic relevance. The satisfactory economic growth produces enough capital for broad infrastructure investments, provided investors could be convinced. It is the direction of the development of combustion cars far off the demands of the energy transition and the vacuum it creates on the field of environmental-friendly mobility that gives the needed huge investments in new car concepts the necessary security (Figure 18). Also the growing market shares of e-cars ensure fast efficiency progress for this technology (Figure 19). Figure 20 shows how these developments play out in terms of final energy demands and final energy carriers in the transport sector: final energy demand in the transport sector decreases by 46% from nearly 2600 PJ in 2015 to slightly more than 1400 PJ in 2050. At the same time, the share of fossil fuels in the transport energy demand decreases from 93% in 2015 to 46% in 2050, when biofuels, electricity, and hydrogen make up 22%, 19%, and 13% of the energy demand, respectively (see Figure 20).

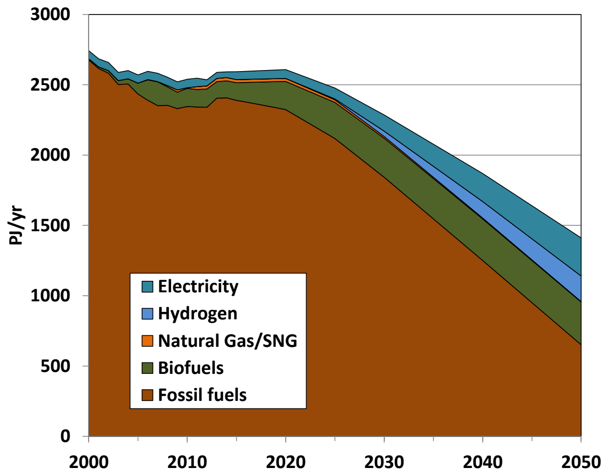

Figure 20: Final energy demand of the transport sector 2000–2050 (passengers and freight).

Primary energy demand and CO_2 emissions

Figure 21 shows the resulting primary energy consumption[2] in the 'Target' scenario differentiated by sectors. Primary energy demand decreases by 43% from approximately 13,000 PJ in 2015 to 7070 PJ in 2050. This is a consequence of significant efficiency efforts in households, transport, industry, and in the service and trade sector (see discussion above), reducing final energy consumption (FEC) in these sectors. Furthermore, the shift from fossil and nuclear power production to renewable power production from mainly wind and photovoltaics (Figure 13) reduces thermal conversion losses and – consequently – primary energy demand.

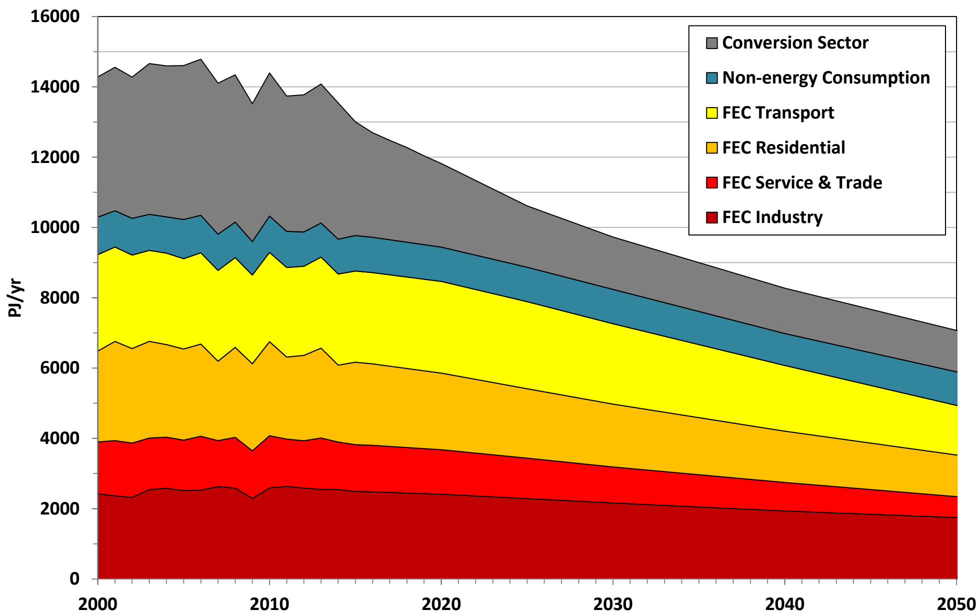

Figure 21: Primary energy demand 2000-2050 by sector.

Figure 22 shows the resulting primary energy consumption differentiated by energy carrier respectively energy source: fossil fuels – mainly natural gas and mineral oil – still contribute to 46% of the primary energy demand. They are mainly used in the transport sector, for high temperature process heat and power generation. The major renewable contributions to primary energy demand are solar (photovoltaics and solar thermal), wind, geothermal energy and biomass.

[2] primary energy demand calculated with the physical energy content method

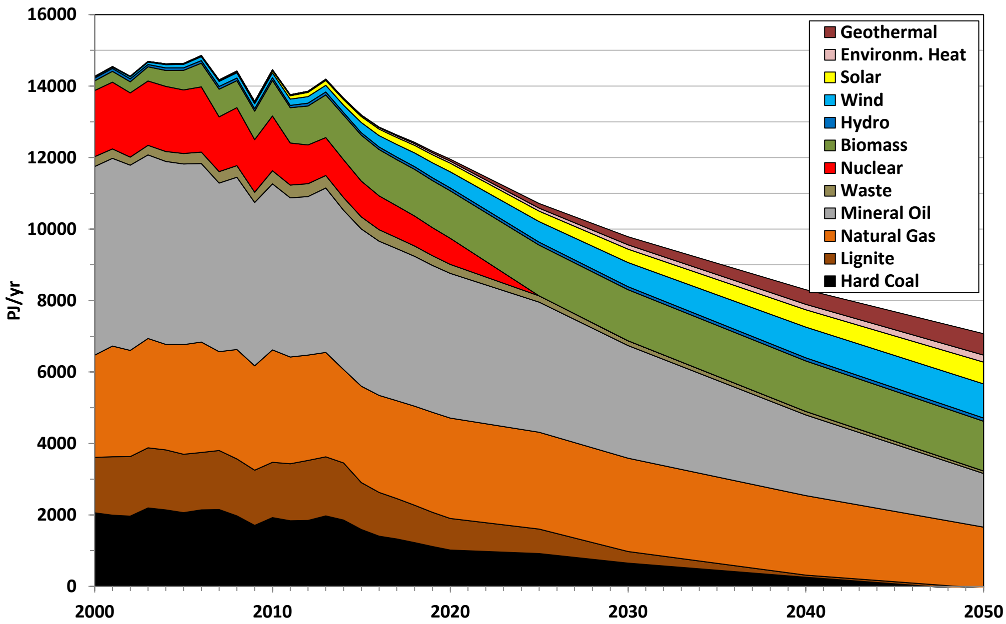

Figure 22: Primary energy demand 2000-2050 by energy carrier.

The efficiency gains, technology shifts in particular in the transport sector, and a moderate-to-strong expansion of renewable energies discussed above, result in a reduction of the annual energy-related CO_2 emissions to 140 Mt in 2050 (Figure 23). This is a reduction of more than 85% since 1990 (the reference year for the reduction target in the German 'Energiekonzept'). The 2050 targets of the 'Energiekonzept' are thus met in this scenario (Table 8). Roughly one third of all emissions stem from the transport and conversion sectors each. Industry contributes 25% to total energy-related CO_2 emissions, whereas the contributions of the residential and the service and trade sectors are small (<5%).

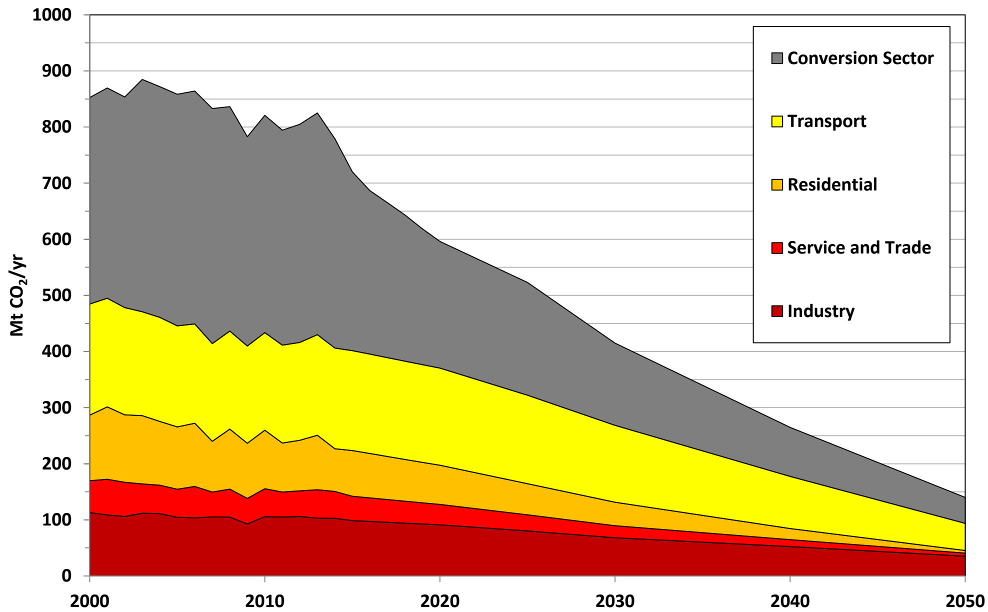

Figure 23: Energy related CO_2 emissions 2000–2050.

Table 9 to Table 12 provide some more quantitative details on the 'Target' scenario. Table 13 summarizes the context scenario configuration underlying the socio-technical 'Target' scenario.

Table 8: (minimum) targets of the energy transition according to the German 'Energiekonzept' (BMWi 2010).

	2020	2030	2040	2050
GHG emissions reduction (referring to 1990)	-40%	-55%	-70%	-80 to -95%
nuclear phase out	until 2022			
RE share (gross) final energy demand	18%	30%	45%	60%
RE share gross electricity demand	35%	50%	65%	80%
reduction primary energy demand	- 20%			- 50%
reduction electricity demand	- 10%			- 25%
reduction final energy				
demand of transport sector	-10%			- 40%
reduction heat demand (2020) resp. primary energy demand (2050) of buildings	-20%			- 80%

Table 9: details on gross power generation in the 'Target' scenario, [1] including biogenic waste, [2] solid and liquid biomass, biogas, landfill and sewage gas.

gross power generation in TWh per year	2015	2030	2050
nuclear	91.8	0.0	0.0
lignite	155.0	42.5	0.0
of which cogeneration (CHP)	5.4	2.5	0.0
hard coal	121.7	55.7	8.2
of which cogeneration (CHP)	13.4	8.0	6.3
natural gas	63.6	110.0	117.1
of which cogeneration (CHP)	60.6	84.7	69.8
oil	5.4	2.0	1.0
of which cogeneration (CHP)	2.4	0.8	0.0
waste [1]	31.9	14.6	9.4
of which cogeneration (CHP)	2.0	4.2	5.0
hydrogen	0.0	0.0	3.5
of which cogeneration (CHP)	0.0	0.0	3.5
photovoltaics	38.7	56.9	67.0
of which rooftop systems	36.9	54.1	64.0
of which ground-mounted systems	1.9	2.8	3.0
wind energy	79.2	187.7	265.3
of which onshore	70.9	120.7	141.3
of which offshore	8.3	67.0	124.0
hydro power	19.0	23.4	25.0
geothermal energy	0.1	6.5	19.2
ocean energy	0.0	0.0	0.0
biomass [2]	51.8	62.9	66.9
of which cogeneration (CHP)	26.1	45.4	59.2
of which biogas (in total biomass)	31.6	32.0	32.4
of which solid biomass (in total biomass)	18.1	28.9	32.5
total generation	**658.2**	**562.1**	**582.6**

Table 10: Transport services (passenger transport) in the 'Target' scenario.

transport services - passenger transport in billion pkm per year	2015	2030	2050
individual road transport	**903**	**859**	**740**
gasoline engine	473	280	0
gasoline engine (hybrid)	0	67	279
diesel engine	418	438	0
diesel engine (hybrid)	0	15	97
gas engine	12	8	3
battery electric vehicle (BEV)	0	43	287
hydrogen fuel cell vehicle (H2 FCEV)	0	7	74
motorcycles	**19**	**19**	**17**
gasoline engine	19	17	13
battery electric vehicle (BEV)	0	3	4
trains, trams etc.	**92**	**94**	**88**
electric drive	83	84	80
diesel engine	10	10	8
public road transport	**76**	**69**	**64**
diesel engine	75	62	40
diesel engine (hybrid)	0	2	4
battery electric vehicle (BEV)	1	5	12
hydrogen fuel cell vehicle (H2 FCEV)	0	1	8
aviation	**59**	**74**	**69**
total	**1150**	**1114**	**978**

Table 11: Transport services (freight transport) in the 'Target' scenario.

transport services - freight transport in billion tkm per year	2015	2030	2050
road transport	**487**	**617**	**620**
diesel engine	431	480	337
gasoline engine	57	62	24
diesel engine (hybrid)	0	30	70
gasoline engine (hybrid)	0	7	25
battery electric vehicle (BEV)	0	9	23
hydrogen fuel cell vehicle (H2 FCEV)	0	29	141
trains	**117**	**183**	**242**
electric drive	107	174	233
diesel engine	10	9	9
navigation	**65**	**83**	**102**
aviation	**2**	**3**	**3**
total	**671**	**886**	**967**

Table 12: prices for crude oil, natural gas and hard coal (for industry & power plants), CO_2 emission certificates (model inputs) and levelized costs of electricity (LCOE, model output).

cost assumptions and results	unit	2015	2030	2050
crude oil	$/bbl	115	142	166
natural gas	€ct/kWh	3.23	4.86	5.98
hard coal	€ct/kWh	1.61	2.18	2.73
CO_2 emission certificates	€/t	7	28	50
electricity (LCOE)	€ct/kWh	5.67	9.59	9.09

Table 13: Context scenario configuration underlying the socio-technical 'Target' scenario.

A(I). Global development - General	A(I)1 Market forces
A(II). Global development - Price for fossil fuels	A(II)2 Moderate growth of prices
A(III). Global development - Interest rate level	A(III)2 Moderate recovery of interest rates
B. EU integration	B1 EU Renaissance
C. Population development	C1 Strongly decreasing
D. GDP growth	D2 Moderate development
E. Labor market development	E3 Division of labor market
F. Tertiarization of the economy	F2 Strong tertiarization
G. Innovation capabilities	G2 Constant
H. Transnational trade flows	H2 European Germany - focus on services
I. International power line integration	I2 Trend European power grid / European autarky
J. Infrastructure expansion of power lines	J2 Delayed expansion
K. Renewable electricity expansion	K2 Moderate expansion
L. Central/decentralized power generation & -storage	L2 Hybrid structure
M. Electricity market regulations	M1 Market in charge of security of supply
N. Energy policy stability	N2 Constant policy stability
O. Energy control instruments	O3 Technology-unspecific economic instruments
P. Governance in the field of infrastructure expansion	P2 Uncoordinated expansion
Q. Planning law / public infrastructure planning	Q4 Compromise
R. Political design model	R3 Market mechanisms
S. Social welfare state design	S1 Liberal welfare state
T. Private income development	T3 Increasing inequality / high income growth
U. Acceptance of energy technologies	U3 Slightly increasing
V. Energy consumption behavior (individual)	V1 Trend towards being unconcerned
W. Education development	W2 Focus MINT / strong access limitations
X. Public attitude towards the 'Energiewende'	X2 No clear trend
Y. Value shift	Y1 Trend materialism and performance
Z. Media discourse	Z3 Tabloidization
a. Consumption trend - Household appliances	a1 Weak efficiency trend
b. Efficiency trend - E-cars	b2 Moderate efficiency trend
c. Efficiency trend - Combustion cars	c1 Weak efficiency trend
d. Efficiency trend - Private buildings	d3 Strong efficiency trend
e. Efficiency trend - Industry	e2 Strong efficiency trend
f. Efficiency trend - Trade/Services	f3 Strong efficiency trend
g. Local heating networks	g2 Accelerated expansion
h. New car concepts and infrastructure	h3 High investments
i. Residential space trends	i3 Strongly increasing
j. Renewable heat production	j2 Strongly increasing
k. Rebound in individual energy consumption	k2 Moderate rebound

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