Supporting Online Material for the PNAS manuscript submission

“The economics of nuclear power and climate change mitigation policies”

by Nico Bauer, Robert J. Brecha and Gunnar Luderer

1. Description of the ReMIND-R model

1.1. Overview

REMIND-R is a global energy-economy-climate model. This model description is based on the introduction of the REMIND-R model [1], as well as the technical description in [2,3]. More information is also available from the ReMIND-website[1].

Fig. S1 provides an overview of the general structure of ReMIND-R. The macro-economic core of ReMIND-R is a set of regional Ramsey-type optimal growth models that solve for general equilibrium by maximizing the intertemporal welfare subject to equilibrium constraints. It considers 11 world regions and explicitly represents trade in final goods, primary energy carriers, and, in the case of climate policy, emission allowances. The multi-regional model is solved using the Negishi-approach such that it yields a distinguished Pareto-optimal solution which corresponds to the market equilibrium, if there are no externalities that are not yet internalized. For macro-economic production, capital, labor and energy are considered as input factors. The macro-economic output is available for investment into the macro-economic capital stock, consumption, trade, and costs incurred from the energy system.

The macro-economic core is hard-linked to the energy system module. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for the stationary end-uses. The demand for final energy is determined via nested constant elasticity of substitution (CES) production function (cf. Section 1.2.1). The energy system module considers endowments of exhaustible primary energy resources as well as renewable energy potentials. A substantial number (~50) of technologies are available for the conversion of primary energies to secondary energy carriers. Moreover, capacities for transport and distribution of secondary energy carriers for final end use are represented. The costs for the energy system, including investments into capacities, operation and maintenance costs as well as extraction and fuel costs appear in the macroeconomic budget function, thus reducing the amount of economic output available for consumption.

The model system also includes a climate module. In addition to CO_2 emissions from the combustion of fossil fuels, other greenhouse gas emissions are determined via marginal abatement costs curves or by assuming exogenous scenarios. A rather simple reduced

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[1] At http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1 the technical description of REMIND-R is available. REMIND-R is programmed in GAMS.

form climate model is used in the current version of ReMIND-R (cf. Section 1.4). The integration of the more complex climate module [4] is under way, but its deployment is subject to computational constraints.

In the present version of the ReMIND-R model climate change impacts and damages are not represented. Hence, the costs metrics that are presented with this version of the ReMIND-R model only consider the mitigation costs and do not account for the damages and their avoidance.

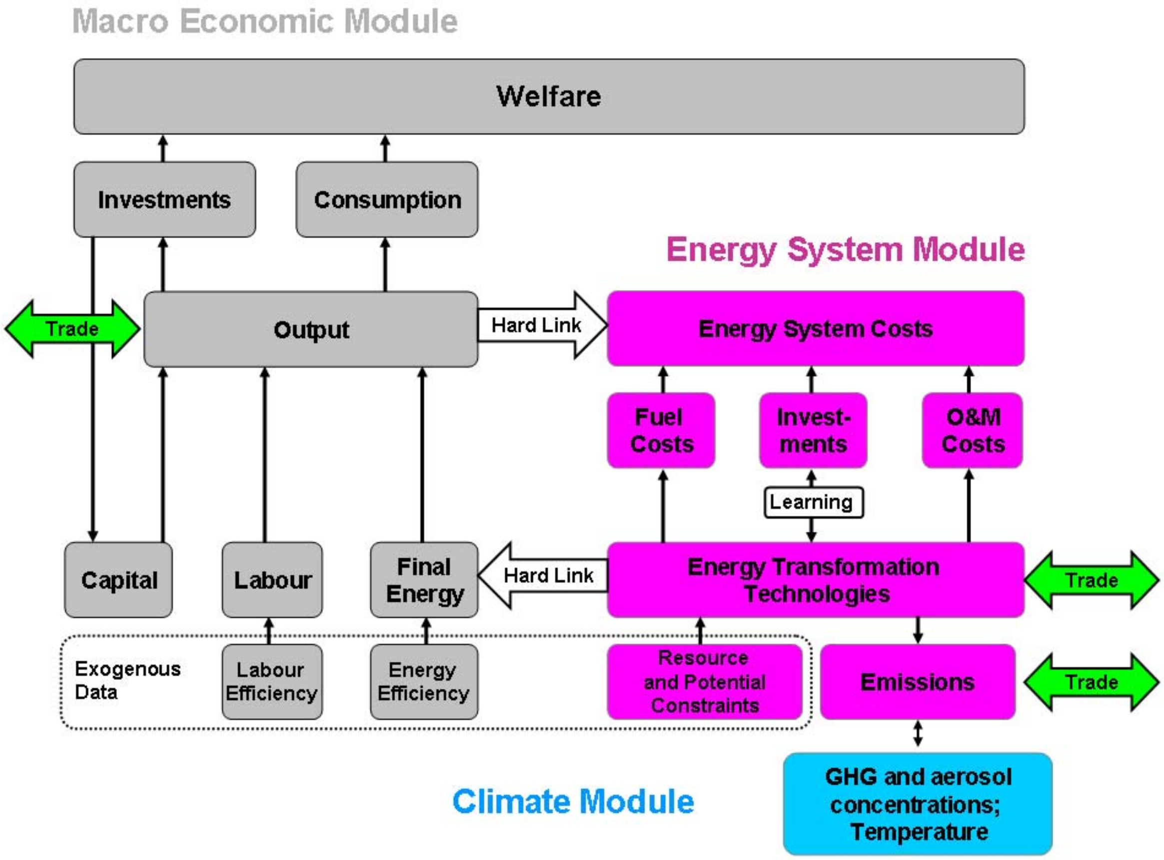

Fig. S1: Overall structure of the ReMIND-R model

In particular in terms of its macro-economic formulation, REMIND-R resembles well-known energy-economy-climate models [5,6,7]. REMIND-R is distinguished from these models by a high technological resolution of the energy system and intertemporal trade relations between regions. This results in a high degree of where-flexibility (abatement can be performed where it is cheapest) and what-flexibility (optimal allocation of abatement among end-use sectors) for the mitigation effort

Tab. S1 provides an overview of the key features of the model. The individual modules along with relevant parameters and assumptions are described in more detail in the following sections.

Tab. S1: Overview of key characteristics of the ReMIND-R model.

Key distinguishing feature	**ReMIND-R**
Macro-economic core and solution concept	Intertemporal optimization: Ramsey-type growth model, Negishi approach for regional aggregation
Expectations/Foresight	Default: perfect foresight.
Substitution possibilities within the macro-economy / sectoral coverage	Nested CES function for production of generic final good from basic factors capital, labor, and different end-use energy types
Link between energy system and macro-economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly.
Production function in the energy system / substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors) introduce convexities.
Land use	MAC curves for deforestation
International macro-economic linkages / Trade	Single market for all commodities (fossil fuels, final good, permits)
Implementation of climate policy targets	Pareto-optimal achievement of concentration, forcing or temperature climate policy targets under full when-flexibility. Allocation rules for distribution of emission permits among regions. Other options: Emission caps & budgets, taxes equivalent.
Technological Change / Learning	Learning by doing (LbD) for wind and solar. A global learning curve is assumed. LbD spillovers are internalized. Labor productivity and energy efficiency improvements are prescribed exogenously.
Representation of end-use sectors	Three energy end-use sectors: Electricity production, stationary non-electric, transport
Cooperation vs. non-cooperation	Pareto: full cooperation
Discounting	Constant rate of pure time preference (3%)
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion in the energy system

1.2. The Macro-Economic Kernel and Solution Concept

REMIND-R as introduced [1] is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model. The hard-link between the energy system and the macroeconomic system follows the method by [2]. Assuming perfect foresight and aiming at welfare maximization, REMIND-R simulates the world-economic dynamics over the time horizon 2005 to 2150 with a time step of five years. In order to avoid distortions due to end-effects, our analysis focuses on the results for the time span 2005-2100.

In its present version, ReMIND-R distinguishes 11 world regions (Fig. S2):

- USA - USA
- EUR - EU27
- JAP - Japan
- CHN - China
- IND - India
- RUS - Russia
- AFR - Sub-Saharan Africa (excl. Republic of South Africa)
- MEA - Middle East, North Africa, central Asian countries
- OAS - Other Asia (mostly South East Asia)
- LAM - Latin America
- ROW - Rest of the World (Canada, Australia, New Zealand, Republic of South Africa, Rest of Europe).

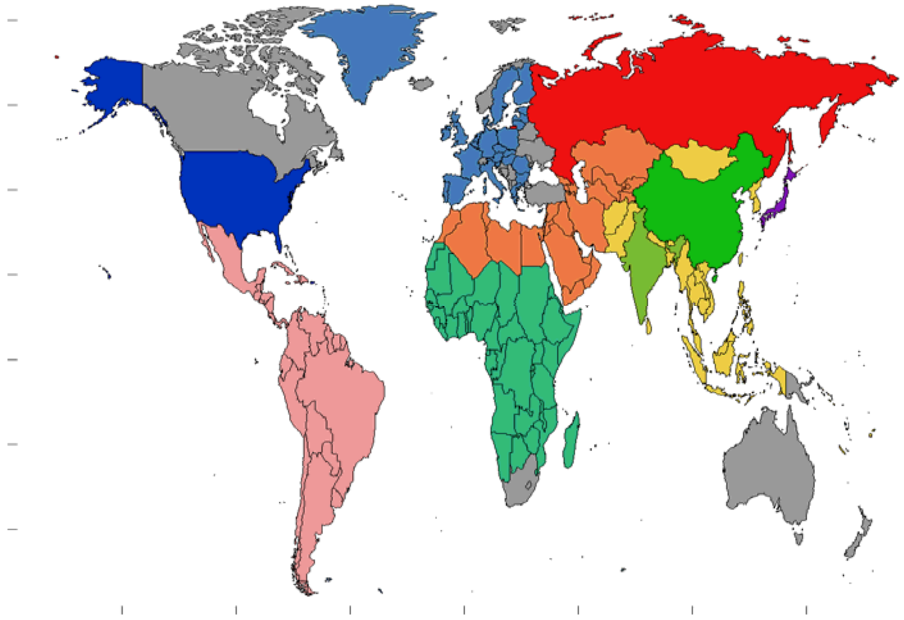

Fig. S2: ReMIND-R region definitions.

1.2.1. Objective function and production structure

A major assumption to the ReMIND-R model is the exogenous scenario on the development of the population. It is shown in Fig. S3. The scenario assumption is the same as in the RECIPE project [8].

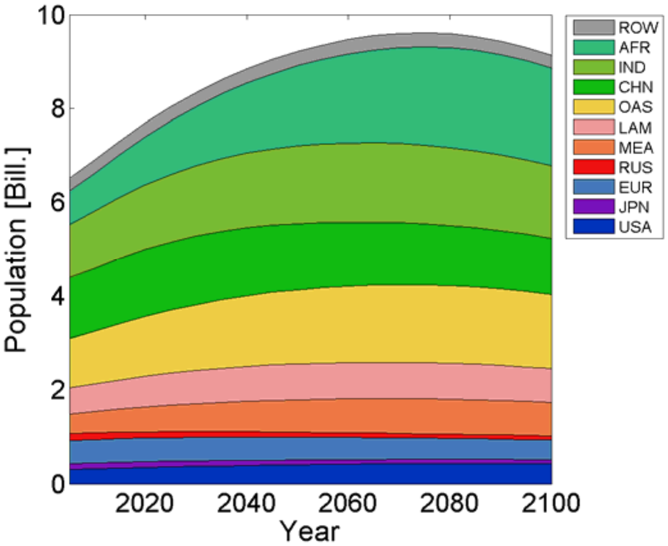

Fig S3: Population scenario differentiated by regions.

Each region is modeled as a representative household with a utility function that depends upon per capita consumption:

$$U_r = \sum_t e^{-\rho t} L_{rt} \log\left(\frac{C_{rt}}{L_{rt}}\right),$$

where L_t and C_t are population and consumption and time t, respectively. Utility calculation is subject to discounting. We assume a pure rate of time preference ρ of 3 %. The logarithmic functional relation between per-capita consumption and utility implies an elasticity of marginal consumption of 1. Thus, in line with the Keynes-Ramsey-Rule, ReMIND-R yields an endogenous interest rate in real terms of 5-6% for an economic growth rate of 2-3%. This is well in line with interest rates typically observed on capital markets.

It is the objective of REMIND-R to maximize a global welfare function that results as a weighted sum of the regional utility functions:

$$W = \sum_r n_r U_r \, .$$

The weights n_r (also called Negishi weights) are chosen such that the sum of the discounted value of exports equals that of the imports over the time horizon considered. Numerically, this clearing of each region’s intertemporal trade balance is achieved via an iterative algorithm. It ensures that the Pareto-optimal solution of the model corresponds to the market equilibrium in absence of non-internalized externalities (cf. Section 1.2.2). Marco-economic output, i.e. gross domestic product (GDP), of each region is determined by a "constant elasticity of substitution" (CES) function of the production factors labor, capital and end use energy. The end use energy of the upper production level is calculated as a production function which comprises transportation energy and stationary used energy. Both are connected by a substitution elasticity of 0.3. These two energy types are in turn determined by means of nested CES functions of more specific final energy types (see Fig. S4). Substitution elasticities between 2.5 and 3 hold for the lower levels of the CES nest. An efficiency parameter is assigned to each production factor in the various macroeconomic CES functions. Changes in the efficiency of the individual production factors for each region are given by exogenous scenarios.

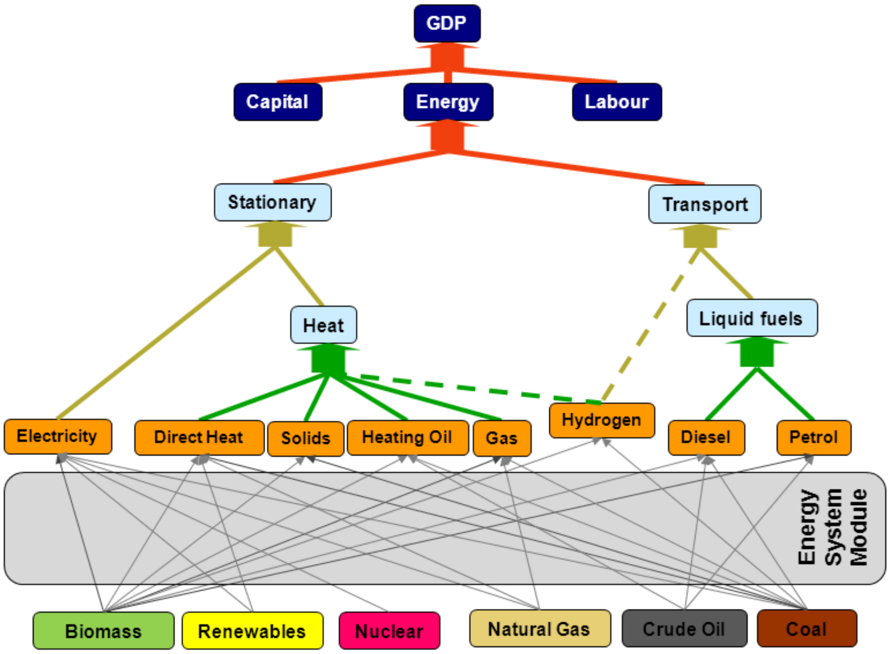

Fig. S4: Production structure of ReMIND. The conversion of primary energy (lowest level) to secondary energy is represented in the energy system module based on linear production functions. Aggregation of secondary energy to final energy carriers and aggregated macro-economic energy input is represented via nested CES structures.

In each region, produced GDP $Y(t)$ is allocated to consumption $C(t)$, investments into the macroeconomic capital stock $I(t)$, energy system expenditures and for the export of composite goods X_G. Energy system expenditure consist of fuel costs $G_F(t)$, investment costs $G_I(t)$ and operation & maintenance costs $G_O(t)$. Imports of the composite good M_G increase the available GDP:

$$Y(t) - X_G(t) + M_G(t) \geq C(t) + I(t) + G_F(t) + G_I(t) + G_O(t)$$

This balance of GDP distribution forms the budget constraint each region is subjected to. Macroeconomic investments enter a conventional capital stock equation with an assumed depreciation rate of 5 %.

1.2.2. Trade

In following the classical Heckscher-Ohlin and Ricardian models [9], trade between regions is induced by differences in factor endowments, demand and technologies. In

ReMIND-R, this is supplemented by the possibility of intertemporal trade. However, there is no bilateral trade, but exports in and imports from a common pool. Trade is modeled in the following goods:

- Coal
- Gas
- Oil
- Uranium
- Composite good (aggregated output of the macro-economic system)
- Permits (emission rights), in the case of climate policy

Intertemporal trade and the capital mobility implied by trade in the composite good cause factor price equalization and provide the basis for an intertemporal and interregional equilibrium.

In REMIND-R, the balance between exports and imports for each kind of goods in each period is guaranteed by adequate trade balance equations. However, the question whether a chosen trade structure is intertemporally balanced depends on how the welfare weights are adjusted. A distinguished Pareto-optimal solution, which in the case of missing externalities also corresponds to a market solution, can be obtained by adjusting the welfare weights according to the intertemporal trade balances.

The intertemporal budget constraint each region is subject to means that each composite goods export qualifies the exporting region for a future import (of the same present value), but implies for the current period a loss of consumption. Trade with emission permits works in a similar way. In the default setting, the presence of a global carbon market is assumed: Initial allocation of emission rights are determined by a burden sharing rule, and permits can be traded freely among world regions. A permit constraint equation ensures that each unit of CO_2 emitted by combusting fossil fuels is covered by emission certificates.

The representative households in REMIND-R are indifferent regarding domestic and foreign goods as well as indifferent among foreign goods of different origin. This can potentially lead to a strong specialization and, related to the cooperative setting implied by the solution concept, to rather optimistic results. For climate policy assessments this is less critical as it applies to both baseline and policy scenarios.

The physical trade of energy carriers assumes integrated markets, which corresponds to a global market place at which all demands and supplies are traded at an equilibrium price. The transportation to and from the global market, however, is subject to trade costs that are differentiated between regions and energy carriers.

1.2.3. Climate policy analysis

The ReMIND model is usually run in two modes.

- A “business as usual” mode in which the global welfare function is optimized without constraints. This resembles a situation where the occurrence of climate change would have no effect on the economy and the decisions of the representative households in the regions.
- A “climate policy” mode where an additional climate policy constraint is imposed on the welfare optimization. The constraint can take the form of a

limit on temperature, forcing (from Kyoto gases or all radiative substances), CO_2 concentration, cumulative carbon budget, or CO_2 emissions over time. The mitigation costs of achieving the policy goal to meet the climate constraint are calculated as an absolute or percentage reduction of net present value consumption or GDP w.r.t. to the business as usual case over a certain time horizon.

The impact of a pre-specified carbon tax can also be studied in ReMIND, although it is less straightforward. For such scenarios, the tax is implemented as a penalty on emissions. This tax revenue as part of each region's budget constraint is counterbalanced by a fixed amount of recycling the tax revenues. The model is solved iteratively with adjusted tax revenues until these match the tax payments.

1.3. The energy system

The energy system module (ESM) of ReMIND-R comprises a detailed description of energy carriers and conversion technologies. The ESM is embedded into the macroeconomic growth model: the techno-economic characteristics[2] and the system of balance equations that set up the energy system are constraints to the welfare maximization problem of the macroeconomic module.

The energy system can be regarded as an economic sector with a heterogeneous capital stock that demands primary energy carriers and supplies final energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The macro-economy demands final energy as an input factor for the production of economic output. In return, the energy sector requires financial resources from the capital market that are allocated among a portfolio of alternative energy conversion technologies. The techno-economic characteristics of the technologies and endogenously evolving prices of energy and CO_2 emissions determine the size and structure of the energy sector capital stock. Hence, the energy sector develops according to an equilibrium relationship to the remaining economy with which it is interrelated through capital and energy markets.

1.3.1. Primary energy resources

The primary energy carriers available in the ESM include both exhaustible and renewable resources:

- Coal
- Oil
- Gas
- Uranium
- Hydro
- Wind
- Solar
- Geothermal

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[2] In the following we report the investment costs according to the overnight concept and conversion efficiencies are based on LHV and gross production.

- Biomass

The exhaustible resources (coal, oil, gas and uranium) are characterized by extraction costs that increase over time as cheaply accessible deposits become exhausted. In ReMIND-R, this is represented via region-specific extraction cost curves which prescribe increasing costs of production with increasing cumulative extraction. In addition, adjustment costs are applied that represent short-term price markups in case of rapid expansion of resource production. While resources are assumed to be tradable across regions, resource trade is subject to region and resource-specific trade-costs.

By contrast, renewable energy sources do not deplete over time. They are represented via region-specific potentials. For each renewable energy type, the potentials are classified into different grades, each of which is characterized by a specific capacity factor. Superior grades feature high capacity factors and will produce more energy for a given installed capacity, while inferior grades will have lower yields. As a result of the optimization, this grade structure leads to a gradual expansion of renewable energy deployment over time.

The following tables Tab. S2 – S4 report the assumptions for various categories of fossil fuels based on [10]. The assumptions on conventional oil reserves have been up-dated by more recent estimates by [11]. Please note that the availability of factor in the last but second line shows large differences across the various categories. The reason is that numbers for some categories are given as recoverable amounts and others as amount in place. In the latter case also a factor that combines deposit availability and a technical recovery factor have to be assumed. The extraction cost assumptions are taken from Rogner and the price were deflated to the 2005$US unit.

Tab. S2: Assumptions for the availability of oil in EJ.

	Conventional Oil				Unconventional Oil	
	Recoverable amounts				Original oil in place	
	Proved recoverable	Estimated additional	Additional Speculative	Enhanced recovery	Recoverable reserve	Resources	Additional Occurrence
RUS	432	442	627	760	107	630	1105
MEA	4862	817	1067	2535	959	1809	3165
ROW	102	225	209	417	318	3180	5561
USA	174	177	138	327	156	2031	3552
LAM	442	373	649	791	109	3831	6703
CHN	91	197	343	310	96	1767	3090
OAS	83	71	113	153	26	205	354
AFR	367	134	194	213	55	202	352
EUR	50	96	176	243	54	339	599
IND	32	9	17	23	3	9	14
JPN	0	1	1	1	7	49	86
WORLD	**6289**	**2541**	**3534**	**5774**	**1892**	**14051**	**24581**
Availability	100%	100%	100%	100%	100%	15%	15%
Extraction Costs $US05/GJ	2-3	3-5	5-7	7-9	9-10	10-14	14-16

Tab. S3: Assumptions for the availability of natural gas in EJ.

	Conventional Gas				Unconventional gas		
	Recoverable amounts					Original gas in place	
	Proved recoverable	Estimated additional	Additional Speculative	Enhanced recovery	Recoverable reserve	Resources	Additional Occurrence
RUS	1797	1462	2112	656	845	1462	2210
MEA	3645	1312	1631	680	746	1564	2370
ROW	295	410	489	237	1357	2785	4179
USA	254	294	321	173	719	1439	2158
LAM	300	335	578	163	544	1256	1842
CHN	106	193	297	67	879	1005	1507
OAS	280	183	244	90	139	362	500
AFR	238	209	332	87	158	356	553
EUR	121	234	352	147	209	461	670
IND	41	51	74	23	29	57	86
JPN	1	1	2	1	27	57	85
Global	**7077**	**4685**	**6431**	**2324**	**5652**	**10802**	**16161**
Availability	100%	100%	100%	100%	100%	20%	20%
Extraction Costs $US05/GJ	1-2.6	2.6-4.2	4.2-6.5	6.5-7.6	7.6-8.9	8.9-11	11-13.1

Tab. S4: Assumptions for the availability of oil in EJ.

	Proven recoverable reserves	Estimated additional resources in place	Remaining occurences	Additional occurences
RUS	3635	4960	16442	65800
MEA	766	121	4055	16229
ROW	3082	3028	4797	19170
USA	5266	17830	1994	7955
LAM	432	401	293	1172
CHN	2378	2101	6908	27633
OAS	115	859	93	415
AFR	38	91	632	2529
EUR	288	1317	2303	9211
IND	1296	3904	200	800
JPN	9	303	89	357
WORLD	**17304**	**34915**	**37807**	**151269**
Availability	100%	50%	30%	30%
Extraction Costs $US05/GJ	1-2.4	2.4-4.2	4.2-6.3	6.3-9.4

The potentials for solar PV and CSP are based on [12]. To account for the competition of PV and CSP for certain sites, an additional constraint for the combined deployment of PV and CSP [13]. The total solar potential is as high as 10 000 EJ/yr, with almost half of it located in Africa.

Global potentials for onshore wind are assumed to be 120 EJ/yr. This value is twice the potential estimated by [14], and about half that given by [15]. Regional disaggregation is based on [16]. An additional resource potential of 40 EJ was assumed for offshore wind.

Since offshore wind is not represented explicitly in the present version of ReMIND-R, the offshore wind potential was added to the potential for conventional wind energy, albeit at an investment cost penalty of 50%.

Global potentials of hydro-power are based on [14] and disaggregated into regional potentials based on [16].

1.3.2. Secondary energy carriers and energy conversion matrices

Secondary energy carriers considered in ReMIND-R include:

- Electricity
- Heat
- Hydrogen
- Other liquids
- Solid fuels
- Gases
- Transport fuel petrol
- Transport fuel diesel

In the present version of ReMIND-R, electricity is only demanded for stationary use. An implementation of electrification of the transport sector is under way.

The most notable part of the energy system is the conversion of primary energy into secondary energy carriers via specific energy conversion technologies. In total, some 50 different energy conversion technologies are represented in ReMIND-R. The energy conversion matrix in Tab. S2 provides an overview of the primary energy types, secondary energy types and relevant conversion technologies between them.

Tab. S2: The energy conversion matrix - overview on primary and secondary energy carriers and the available conversion technologies. Yellow colors indicate that technologies can be combined with CCS.

		PRIMARY ENERGY CARRIERS						
		Exhaustible				**Renewable**		
		Coal	**Oil**	**Gas**	**Uranium**	**Solar, Wind, Hydro**	**Geothermal**	**Bio-mass**
SECONDARY ENERGY CARRIERS	**Electricity**	PC, IGCC	DOT	NGCC	LWR, *Gen IV Fast Reactors*	SPV, WT, Hydro, *CSP*	HDR	BIGCC
	H2	C2H2		SMR				B2H2
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid fuels	C2L	Refin.					B2L Bioethanol
	Other Liquids		Refin.					
	Solids	CoalTR						BioTR

Abbreviations: PC = conventional coal power plant, IGCC = integrated coal gasification combined cycle, CoalCHP = coal combined hat power, C2H2 = coal to H2, C2G = coal to gas, CoalHP = coal heating plant, C2L = coal to liquids, CoalTR = coal transformation, DOT = diesel oil turbine, Refin. = Refinery, GT = gas turbine, NGCC = natural gas combined cycle, GasCHP = Gas combined heat power, SMR = steam methane reforming, GasTR = gas transformation, GasHP= gas heating plant, LWR = light water reactor, SPV = solar photo voltaic, WT = wind turbine, Hydro = hydro power, HDR = hot-dry-rock, GeoHP = heating pump, BioCHP = biomass combined heat and power, BIGCC = Biomass IGCC, B2H2 = biomass to H2, B2G = biogas, BioHP = biomass heating plant, B2L = biomass to liquids, BioEthanol = biomass to ethanol, BioTR = biomass transformation

Coal and biomass are highly flexible primary energy carriers since generally all types of secondary energy can be produced from them. Crude oil and natural gas are mainly used to produce liquids and gases. Renewable energy carriers other than biomass are well suited for the production of electricity, but they are less suited to produce other secondary energy carriers. Renewable energy sources including biomass are assumed to be non-tradable.

In the default setting, all secondary energy carriers are assumed to be non-tradable across regions, while statistical data indicates that liquid fuels are traded globally. However, the scale of trade in refined fuels is relatively small compared to trade in crude oil. Since the ReMIND-R model considers crude oil to be tradable the bias is limited. Secondary energy carriers are converted into final energy carriers by considering cost mark-ups as well as technical losses for transmission and distribution. Final energy is demanded by the macro-economic sector and rewarded with equilibrium prices. Note that in the present ReMIND-R version, the end use sectors household and industry are aggregated to the stationary sector. Hence, we distinguish the stationary and the transport sector as final energy demanding sectors.

All technologies are represented in the model as capacity stocks following the putty-clay approach. Since there are no constraints on the rate of change in investments, the possibility of investing in different capital stocks provides high flexibility of the technological evolution. Nevertheless, every additional energy production (either based on existing or new technologies) needs investments in capacities in advance. Moreover, the model does not allow for idle capacities. The lifetime of capacities differs between various types of technologies. Depreciation rates are quite low in the first two decades, and increase afterwards.

Each region is initialized with a vintage capital stock calibrated to meet the input-output relations given by IEA energy statistics [17,18]. The technical transformation coefficients for new vintages are the same for all regions and assumed to be constant. However, the following modifications apply: the transformation efficiency is improved over time for fossil power generation technologies and different technology grades are considered when renewable energy sources are used. The by-production coefficients of the combined power-heat technologies (CHP) have been region-specifically adjusted to the empirical conditions of the base year.

Ambitious mitigation targets typically result in substantial expansion of renewables, mostly solar and wind. Techno-economic parameters for electricity generation from renewable energy sources are given in Tab. S3. Wind, solar PV and CSP feature learning by doing, i.e. specific investment costs decrease by 12, 20, 9%, respectively, for each doubling of capacity.

Tab. S3: Techno-economic characteristics of technologies based on non-biomass renewable energy sources [19,20,21,22].

	Lifetime [Years]	**Investment costs** [$US/kW]	**Floor costs** [$US/kW]	**Learning Rate** [%]	**Cumulative capacity 2005** [GW]	**O&M costs** [$US/GJ]
Hydro	95	3000	-	-	-	4.23
Geo HDR	35	3000	-	-	-	4.2
Wind	40	1200	883	12	60	0.89
SPV	40	4900	650	20	5	2.33
CSP	40	9000	2000	9	0.4	

Tab. S4: Techno-economic parameters of storage technologies; based on [23].

	Units	Daily variation	Weekly variation	Seasonal variation
Technology		Redox-Flow-batteries	H2 electrolysis + combined cycle gas turbine	Capacity penalty to secure supply
Efficiency	[%]	80	40	
Storage capacity	[Hours]	12	160	
Investment costs	[$US/kW]	4000	6000	
Floor costs	[$US/kW]	1000	3000	
Learning rate	[%]	10	10	
Cumulative capacity in 2005	[TW]	0.7	0.7	
Life time	[Years]	15	15	
Cheaper technologies but not included due to limited potential		Pump-storage hydro & compressed air storage	Pump-storage hydro & compressed air storage	

The fluctuating renewable electricity sources wind and solar PV require storage to guarantee stable supply of electricity [13]. Since the techno-economic parameters applied for CSP include the costs for thermal storage to continue electricity production at night-time, CSP is assumed not to require any further storage for balancing fluctuations.

The approach implemented into the ReMIND model distinguishes between variations on the daily, weekly and seasonal time scale. The general idea of storage is that increasing market shares of fluctuating energy sources increase the need for storage because balancing the fluctuations becomes ever more important to guarantee stable electricity supply. The superposition of variations on the three time scales is completely represented. Daily and weekly variations are compensated by explicit installation of storage plants; the techno-economic parameters are provided in Tab. S4. Seasonal variations demand a penalty on the capacity factors; i.e. a certain fraction of the capacity remains unused due to over-supply. By 2050, the storage requirement results in a markup in investment cost of typically about 20% for wind and 30% for solar PV.

Techno-economic parameters for technologies based on exhaustible resources and biomass are listed in Tab. S5. A relevant mitigation option for the power sector, albeit typically somewhat less dominant than renewables, is the expansion of nuclear energy. Investment costs for nuclear power plants are set to 3000 $US/kW. In the present version, only thermal nuclear reactors are considered. The use of nuclear is largely constrained by limited competitiveness vis-à-vis renewable electricity sources as well as limited resource potentials for uranium. No external effects such as the risk of nuclear accidents or risks arising from nuclear waste are considered.

In ReMIND-R no hard limits are applied on the expansion of technologies. However, expansion in the deployment of technologies is subject to adjustment costs that scale with the square of the relative change in capacity additions between time steps.

Emissions from fossil fuel combustion can be curbed by deploying carbon capture and storage (CCS). In ReMIND-R CCS technologies exist both for generating electricity as well as for the production of liquid fuels, gases and hydrogen from coal. Moreover, biomass can be combined with CCS to generate net negative emissions. Such bio-energy CCS (BECCS) technologies are available for electricity generation (biomass integrated gasification combined cycle power plant), biofuels (biomass liquefaction), hydrogen, and syngas production. The sequestration of captured CO_2 is represented explicitly in ReMIND-R with costs for transportation and storage [24]. While the overall global CO_2 storage potential is estimated to be as high as 1000 GtC, the regional potentials for the EU (50 GtC), Japan (20 GtC) and India (50GtC) constrain the deployment of CCS technologies significantly in these regions.

The only technology represented in ReMIND-R for conversion from secondary energy to secondary energy is the production of hydrogen from electricity via electrolysis (Tab. S6).

Tab. S5: Techno-economic characteristics of technologies based on exhaustible energy sources and biomass [24-36].

		Life-time	Investment costs		O&M costs		Conversion efficiency		Capture Rate
		[Years]	[$US/kW]		[$US/GJ]		[%]		[%]
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1400	2400	2.57	5.04	45	36	90
	Oxyfuel	55		2150		4.32		37	99
	IGCC	45	1650	2050	3.09	4.20	43	38	90
	C2H2*	45	1264	1430	1.65	1.87	59	57	90
	C2L*	45	1000	1040	1.99	2.27	40	40	70
	C2G	45	900		0.95		60		
Gas	NGCC	40	650	1100	0.95	1.62	56	48	90
	SMR	40	498	552	0.58	0.67	73	70	90
Biomass	BIGCC *	40	1860	2560	3.95	5.66	42	31	90
	BioCHP	40	1700		5.06		43.3		
	B2H2*	40	1400	1700	5.27	6.32	61	55	90
	B2L*	40	2500	3000	3.48	4.51	40	41	50
	B2G	40	1000		1.56		55		
Nuclear	TNR	40	3000		5.04		33~		

*Abbreviations analogous to Tab. S2. Technologies marked with * represent joint production processes. For these processes, investment cost and efficiency penalties for capturing can be rather small. A thermal efficiency of 33% is assumed for thermal nuclear reactors.*

Tab. S6: Matrix for energy conversion from secondary to secondary energy carrier.

		SECONDARY ENERGY CARRIERS						
		Electricity	**H2**	**Gases**	**Heat**	**Liquid fuels**	**Other liquids**	**Solids**
SECONDARY ENERGY CARRIERS	**Electricity**	-						
	H2	Electrolysis	-					
	Gases			-				
	Heat				-			
	Liquid fuels					-		
	Other liquids						-	
	Solids							-

1.3.3. From secondary energy to final energy

The distribution of energy carriers to end use sectors forms the interface between the macro-economic module and the energy system module. ReMIND-R distinguishes between the stationary end-use sector (aggregating industry and residential/buildings) and end use in the transport sector. Secondary energy carriers available for supply in the stationary sector are electricity, heat, solids, gases, liquids, and hydrogen. The transport sector consumes diesel, petrol, and hydrogen. An implementation of electricity use in the transport sector is under way. Transport and distribution of secondary energy carriers is represented via capacities that require investments and incur costs for operation and maintenance.

In the present version of ReMIND-R, no energy services (such as transportation service in passenger km) are represented.

Tab. S7: Matrix representing distribution of secondary energy to end-use sectors.

		END-USE SECTORS	
		Stationary	**Transport**
SECONDARY ENERGY CARRIERS	**Electricity**	Transport and distribution	
	H2	Transport and distribution	Transport and distribution
	Gases	Transport and distribution	
	Heat	Transport and distribution	
	Diesel		Transport and distribution
	Petrol		Transport and distribution
	Other Liquids	Transport and distribution	
	Solids	Transport and distribution	

1.4. Climate module

The present version of REMIND-R includes a rather simple reduced-form climate model similar to the DICE model. The model includes an impulse-response function with three time scales for the carbon-cycle, and an energy balance temperature model with a fast mixed layer and a slow deep ocean temperature box. The carbon cycle – temperature model is amended by equations describing the concentration and radiative forcing resulting from CH_4 and N_2O as well as sulphate aerosols and black carbon [4]. The emission of sulphates is directly linked to the combustion of fossil fuels in the energy sector. CO_2 emissions from land-use changes as well as emissions of CH_4 and N_2O are calculated based on marginal abatement costs curves [37]. The climate module determines the atmospheric CO_2 concentration and considers the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature. The climate sensitivity - as the most important parameter of the climate module – is set to 3.0°C. The integration of the more complex climate module ACC2 [4] is under way, but its deployment is subject to computational constraints.

Tab. S8: Overview of the treatment of radiative forcing components in the climate module.

	REMIND
CO_2 fuel combustion	By source
other CO_2 industry	Exog.
CO_2 LUC	MAC
CH_4	MAC
N_2O	MAC
CFCs	Exog.
PFCs	Exog.
SF_6	Exog.
Montreal gases	Exog.
CO	Exog.
NO_x	Exog.
VOC	Exog.
SO_2	Coupled to CO_2
Fossil fuel burning BC	Exog. / Coupled to CO_2 depending on climate module
Fossil fuel burning OC	
Biomass burning BC	Exog.
Biomass burning OC	Exog.
Nitrate	Exog.
Mineral dust	Exog.
Albedo	Exog.

1.5. Key strengths and caveats

Since ReMIND-R is a hard-linked coupled multi-regional energy-economy model it can fully capture the interactions between economic development, trade, and climate mitigation policy. The full macro-economic integration is particularly valuable for the assessment of the regional distribution of mitigation costs.

The central strength of ReMIND-R is its ability to calculate first-best mitigation strategies that provide benchmark development pathways against which mitigation scenarios under sub-optimal settings can be compared. In particular, in its default setting ReMIND-R features

- full *where-flexibility* due to interregional trade of goods and emission permits;
- full *when-flexibility* due to the intertemporal optimization and the endogenous choice of a welfare-optimizing emission reduction trajectory;
- *What-flexibility* within the energy system due to a fully integrated perspective on primary energy endowments and end-use demand. An improved representation of non- CO_2 greenhouse gases is under development.

The fully integrated, hard-linked formulation of ReMIND-R along with the intertemporal optimization makes the model numerically very heavy. This computational complexity puts a hard limit to the amount of detail that can be represented in the model. In particular, the following caveats exist:

- The spatial resolution of the model is limited to 11 world regions. Many relevant sub-scale processes, particularly in terms of infrastructure for power grids, transportation, pipelines etc. are not resolved explicitly.

- Electricity from renewables such as wind and solar is characterized by strong fluctuations of supply. The challenge of integrating these intermittent power sources into the grid is represented rather crudely (cf. Section 1.3.2).

- The demand for final energy is represented via the macro-economic production function. This approach lacks detail on the level of energy consuming activities. Demand side efficiency is therefore exogenously prescribed (via efficiency parameters that change over time) or parameterized as substitution within the production system. This approach can only to a limited extent capture the real-world efficiency potentials (e.g. [38]).

- Technological change in the macro-economic module is exogenously driven. Consequently, climate policy relevant feedbacks from knowledge accumulation and technological spillovers are missing.

- In particular for ambitious climate policy scenarios, the availability of substantial amounts of bio-energy is critical. Such massive up-scaling of bio-energy production may have strong implication for conservation and food security. An effort is underway to soft-couple ReMIND to the land-use model MAgPIE [39], in order to explore constraints and side-effects to bio-energy production.

2. Detailed results

2.1. The use of fossil fuels

The following analysis adds to the main paper by providing a detailed analysis of the near term reactions of the fossil fuel market due to policy signals.

The imposition of a carbon budget and the phase-out of nuclear power production are considered as severe policy interventions. The impact on global fossil fuel consumption in 2020 in the four relevant scenarios is depicted in Fig. S5. The reference case without and additional policy is given at the top. The next scenario shown below is that with an additional nuclear phase-out. Since nuclear power is not expanded in the near term in the absence of a carbon budget, fossil fuel use in 2020 is hardly affected (<1%) and a phase-out of nuclear power is not expected to change the development of the global energy system until 2020. The picture changes dramatically if a carbon budget is imposed. The use of all fossil energy carriers decreases (third from top), coal by 40%, gas by 18% and oil by 13%. Hence, climate policies have the most significant impact on the fossil fuel markets, which is agreement with many studies dealing climate change mitigation and the impact on fossil fuel markets.

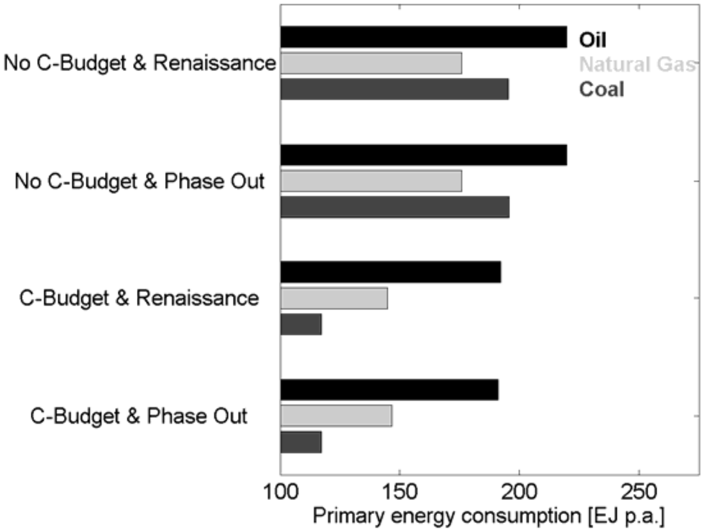

Fig. S5: Consumption of fossil primary energy consumption in 2020 for different scenarios.

2.2. Electricity generation in the various scenarios

The following analysis adds to the main body of the paper by providing a more detailed analysis of the future development of the global electricity generation mix in various policy scenarios. In particular, the figures add to Fig. 4 of the main text.

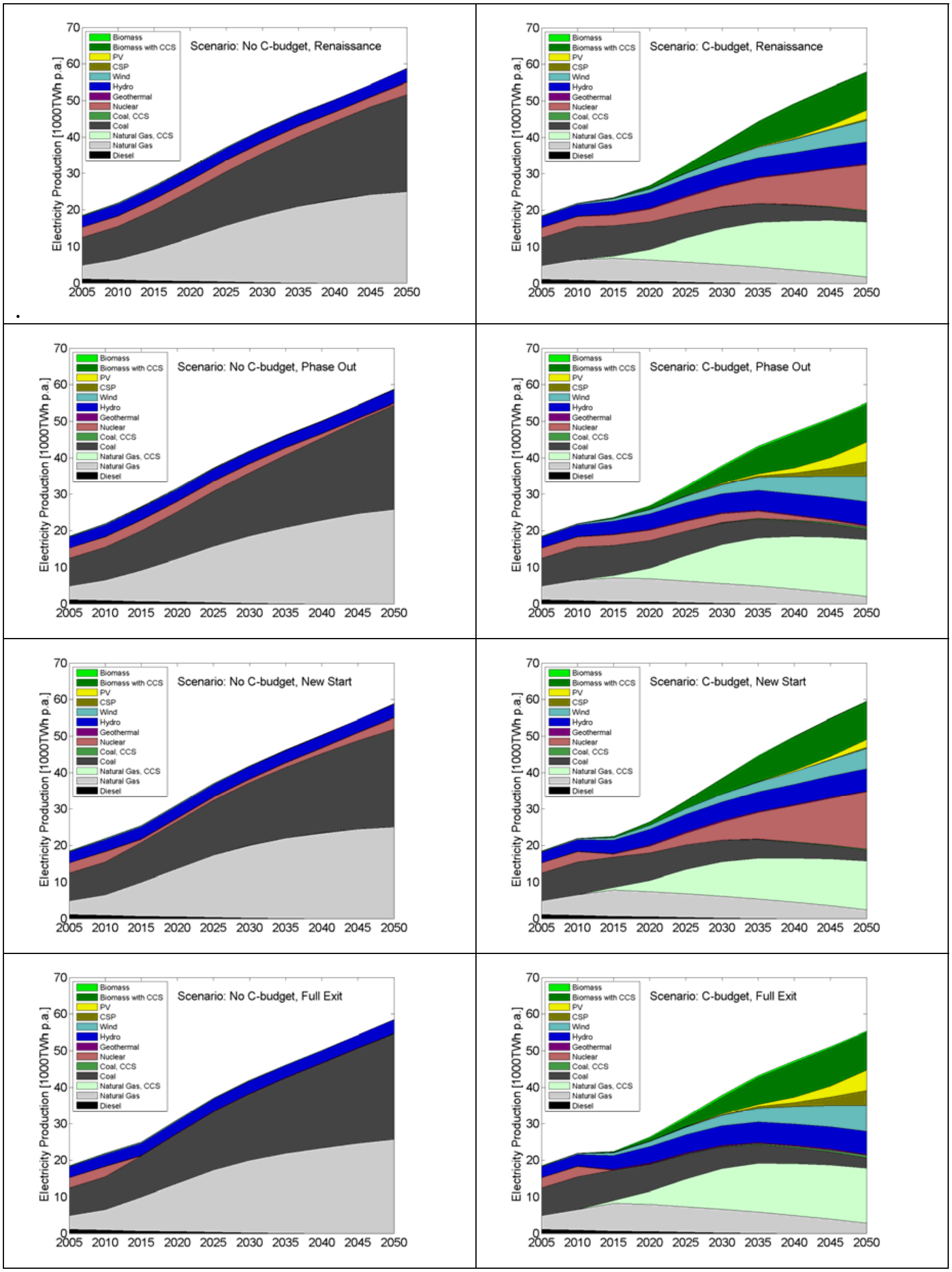

Fig. S6: Global electricity generation mix for eight scenarios 2005-50. The scenario names are provided in the figures.

Fig. S6 presents the electricity generation mixes in various scenarios providing the temporal dimension of changes in the power sector. Adding the carbon budget (right column) implies the most notable consequences: in the near term the electricity supply is reduced – though still growing – and in the medium to longer term coal fired power plants are replaced by low-carbon alternatives. The existing coal fired power plants are used until the end of their technical life-time, but at the global level coal fired power generation would not be growing any more.

The four scenarios with decommissioning of existing nuclear power plants are provided in the lower two rows. Compared with the corresponding renaissance scenario (top row of both columns) electricity production is reduced in both scenarios with decommissioning (see also Fig. 4 in the main paper).

The imposition of the carbon budget leads to a strong deployment of CCS technologies in combination with bioenergy and natural gas for generating electricity. Coal with CCS does not play a significant role because the residual emissions are relatively high.

2.3. Gas prices

The following analysis adds to the arguments for explaining the differences of GDP losses that were presented in Fig. 6 of the main paper.

Fig. S7 shows the gas prices in the various scenarios with different policies implemented in the fields of nuclear power and climate change mitigation. The graph shows that the imposition of the climate policy is the main factor that leads to lower prices. The reason is that the immediate effect of relaxing demand and the lower future demand of natural gas decrease the price in the near term; see also Fig. S5.

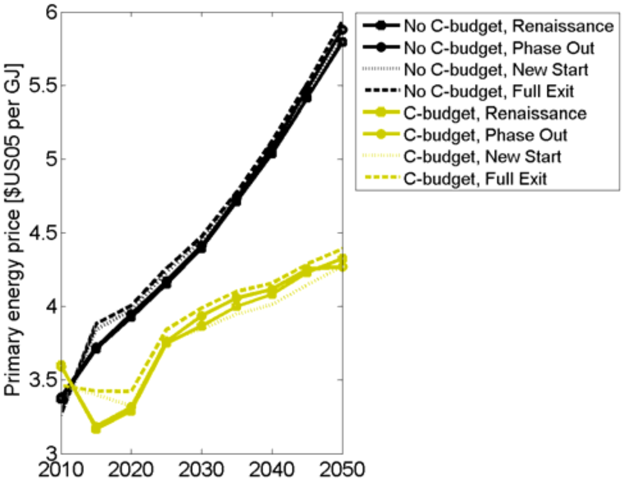

Fig. S7: Global average gas prices in 2005 $US values for various scenarios 2010-50. The global prices are regionally weighted averages.

The introduction of nuclear power policies has a much smaller effect driving the prices consistently upwards. For the combined effect it is important to note that less natural gas is traded at a lower price. Hence the additional demand induced by the restrictive nuclear power policy comes on top of much more relaxed global gas market in case the climate policy is imposed.

2.4. Detailed analysis of policy costs

The following analysis is a more detailed treatment of the results that were presented in Fig. 6 of the main paper.

There are four main macro-economic impacts of the various scenarios over the period 2010-20, as shown in Fig. S8 Firstly, the major effect is related to the imposition of the carbon budget (difference between black and yellow lines). Secondly, the negative impact on GDP of decommissioning is increased if new nuclear capacity is not allowed (differences between dashed and solid lines increase when moving from bottom to top). This shows that the strength of the cost escalation between the two dimensions of nuclear power policies – highlighted in the main paper – depends on the strength of the decommissioning policy. To put it differently, the alternative to built new nuclear power plants gets more important with the capacity that decommissioned. Third, the addition of climate policies does not lead to further escalation of GDP losses that need to be considered for the choice between the alternatives "Renaissance" and "Full Exit" as well as between the alternatives "Renaissance" and "Restart". Finally, the GDP impact depends non-linearly (S-shaped slope) on the vintages that are decommissioned.

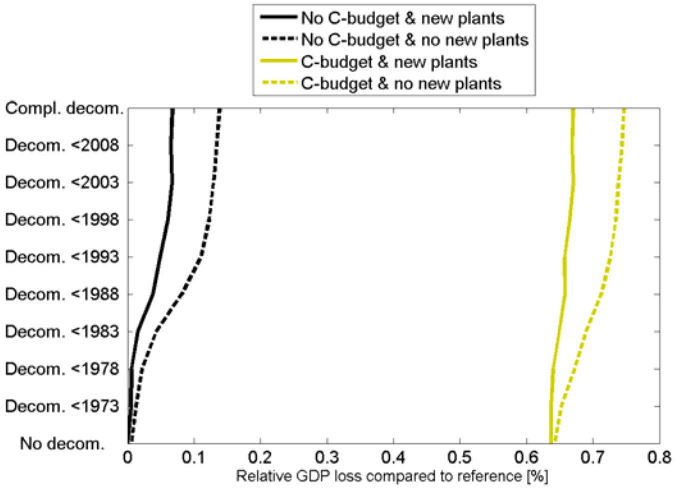

Fig. S8: Cumulative GDP loses compared to the reference case without any policy intervention in relative terms over the time horizon 2010-20 using a discount rate of 5%.

The graph mainly highlights the issue that decommissioning and its impacts are both gradual. For example, scrapping the oldest plants does not make a large difference, but including plants built in the 1980s will lead to growing GDP impacts. If plants built in the 1990s and later are considered for decommissioning, costs do not increase significantly because capacity additions were declining at that time. Therefore, the costs of decommissioning existing nuclear power plants depend on the vintages that are addressed. Since the bulk of nuclear power capacity has been built in the 1980ies, these vintages are the most sensitive ones.

The slope of the curves also highlights that decommissioning existing power plants is a gradual issue. The slope of the curve indicates where the sensitive parameter ranges are located. It should be kept in mind that the present study assumed 60 years of technical life-time. The observed reactor life times are much lower. For instance currently no reactor is in operation that has been running for more than 45 years.

2.5. Sensitivity of investment costs of nuclear power generation

The following analysis adds to the main paper by exploring on of the key parameters that is highly uncertain. Part of the uncertainty is due to future regulations and safety requirements.

Investment costs significantly affect the deployment of nuclear power; see Fig. S9. Increasing the overnight investment costs from the default value of 3000$US/kW to 5000$US/kW reduces the investments in the case without C-budget down to zero. In this case the Phase Out scenario would be realized for economic reasons.

In case with a C-budget this is not the case, though the results' sensitivity is strong. Nuclear power generation increases slightly in the case with 5000$US per kW specific investment costs. If the investment costs are further increased to 6000$US per kW the electricity output even falls below the most optimistic cost assumption in the no carbon budget setting. The nuclear power generation is then only slightly higher than in the phase-out scenario.

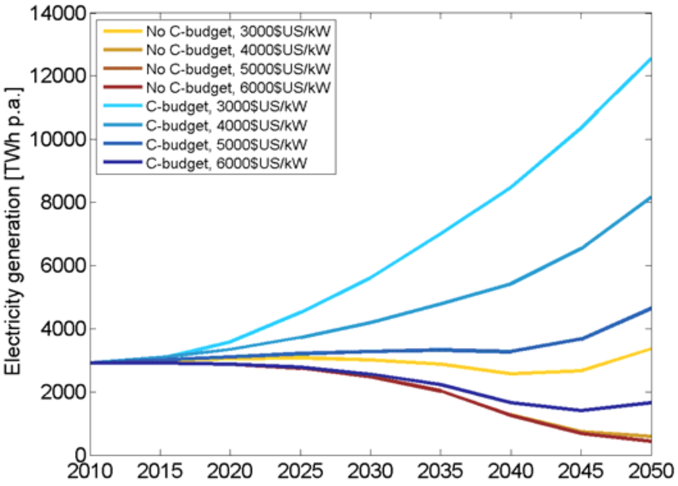

Fig. S9: Sensitivity of nuclear power generation in Nuclear Renaissance scenarios with respect to nuclear power investment costs and the imposition of a carbon budget.

2.6. Sensitivity of the carbon budget

The following analysis adds to the main body of the text by providing an in-depth analysis of the strength of the climate policy expressed in the size of the intertemporal carbon budget.

Fig. S10 shows sensitivity of the carbon budget on for the deployment of nuclear power. The tighter the emission budget is that can be used over the 21st century the earlier nuclear power is deployed. However, the policy regarding decommissioning is more important in the near term.

Fig. S11 shows the impact on the total policy costs for the four nuclear power policy options. The graph shows the expected slope that with increasing stringency of the carbon budget the policy costs increase gets stronger. It also shows how the differences between the nuclear policy scenarios depend on strength of the carbon budget. The difference between the policy cost curve for the Renaissance and the Full Exit nuclear policy shows for relaxing the carbon budget the difference becomes larger. This reflects the finding in shown in Fig. 6 of the main paper that the extra costs of restrictive nuclear policies are smaller in case of the carbon budget. Fig. S9 shows that the finding extends to the continuous case: the extra costs of restrictive policies decrease with the strength of the carbon budget.

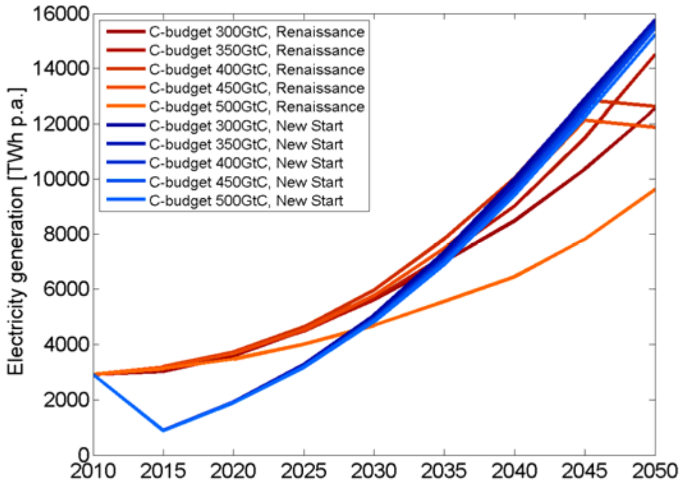

Fig. S10: Sensitivity of nuclear power generation with respect to nuclear power investment costs and the imposition of a carbon budget.

The sensitivity of the costs also highlights that the choice of the carbon budget is a gradual issue that is trading off with the nuclear power policy. For example, the 300GtC with nuclear renaissance leads to the same costs like the Full Exit nuclear power policy combined with a relaxed carbon budget of 350GtC.

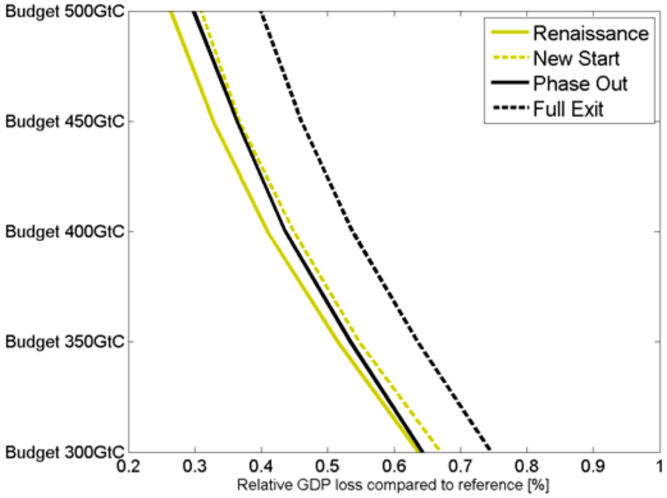

Fig. S11: Policy costs for the four nuclear power policy scenarios and varying carbon budgets. The x-axis measures cumulative GDP losses in relative terms compared to the reference case without any policy intervention over the time horizon 2010-20 using a discount rate of 5%.

2.7. The Role of CCS

The following analysis focuses on the role of CCS and how important the costs of CCS installations are for achieving the mitigation target und the various constraints on nuclear power.

For the case with Full Exit Fig. S12 shows the CCS activity that optimally starts early and is applied in all regions as shown in the left hand panel. This requires sufficient underground storage space. The geological storage limitations considered in this study are optimistic [40] and are not constraining the CCS option throughout the 21st century. Compared with more pessimistic assessment of CCS potentials the most sensitive regions are Latin America, Africa, Japan and Other Asia.

The CCS option is first applied in combination with natural gas and latter with bio-energy. The option of coal is not used at large. Hence, nuclear power is not substituted with coal and CCS in the present study. The use of natural gas with CCS is relatively more attractive than coal with CCS, because of the ratio of natural gas and coal prices as well as the smaller residual CO_2 emissions. The importance of CCS comes from the combination with bioenergy because the negative emissions allow for the prolonged use of oil and gas derived products in small and decentralized applications. This is best achieved, if bio-energy is used in capture plants with high capture rates, which suggests the production of electricity and hydrogen rather than liquid fuels. The availability of bio-energy technologies with CCS is essential for meeting the carbon budget. The deployment of CCS is insensitive to changes in nuclear power policies in the present scenarios because the interaction with the electricity sector is relatively weak.

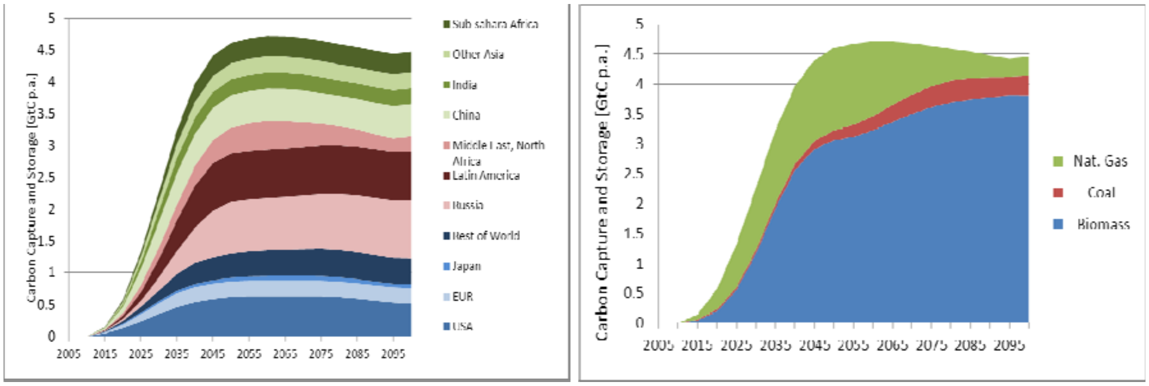

Fig. S12: CCS activity in the case of Full exit and the carbon budget over the 21st century.

Finally, we tested the sensitivity of the mitigation costs with respect to costs of CCS technologies. For this purpose we increased the investment and the fixed operation and maintenance by 50% for those CCS technologies using coal and bio-energy and by 33% for natural gas using CCS technologies. These changes have been applied to the four cases of nuclear power policies and the imposition of the carbon budget. The cumulative discounted GDP differences are insensitive in the short run for all scenarios (less than 1.5% increase). Only if the time horizon is extended beyond 2020 the GDP development gets more sensitive. The cumulative discounted GDP differences until 2050 increase by about 10%, but (like the deployment level of CCS) the costs are not sensitive to the choice of the nuclear power policy.

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