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Comparison and interactions between the long-term pursuit of energy independence and climate policies

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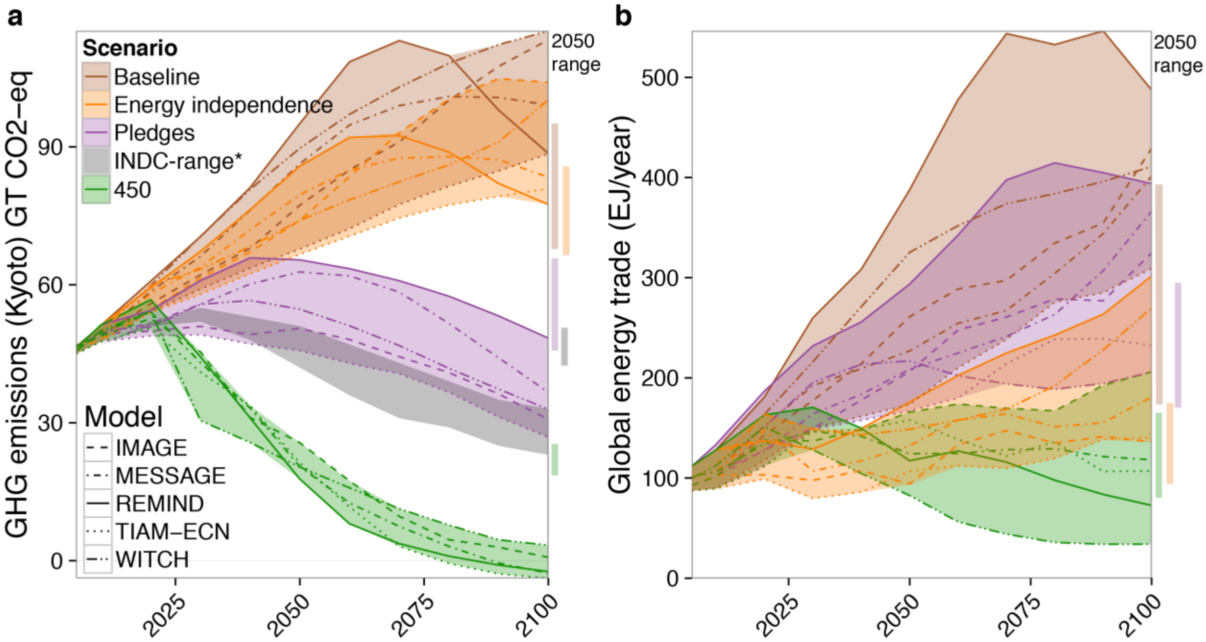
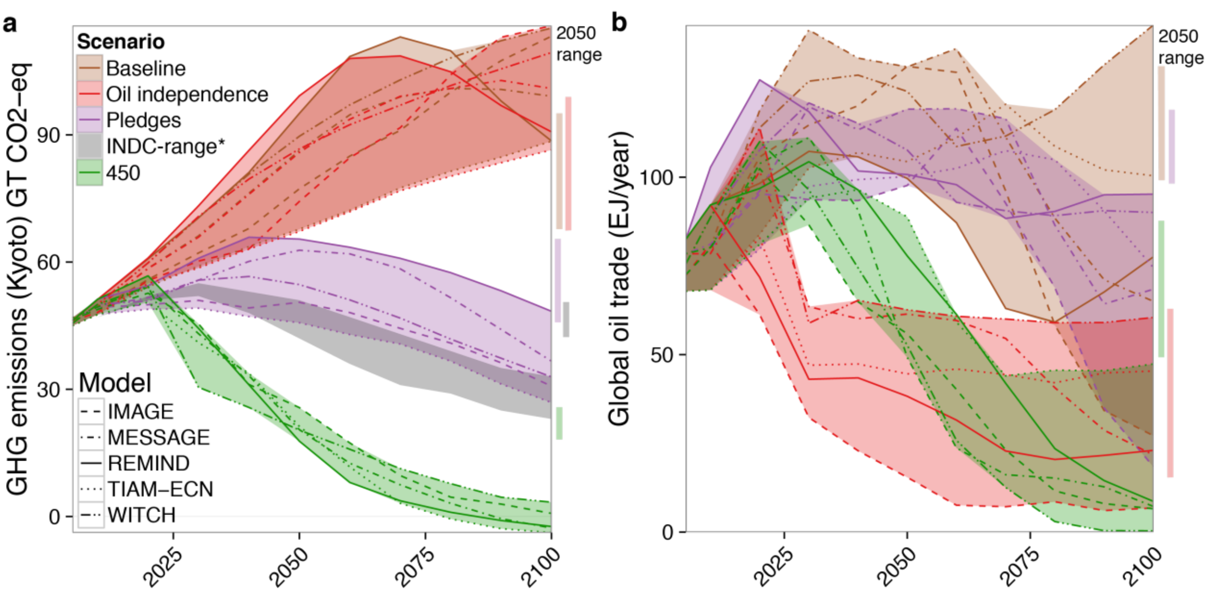
Supplementary Figures

Supplementary Figure 1. Comparing energy and emission effects of Energy independence and climate policy scenarios



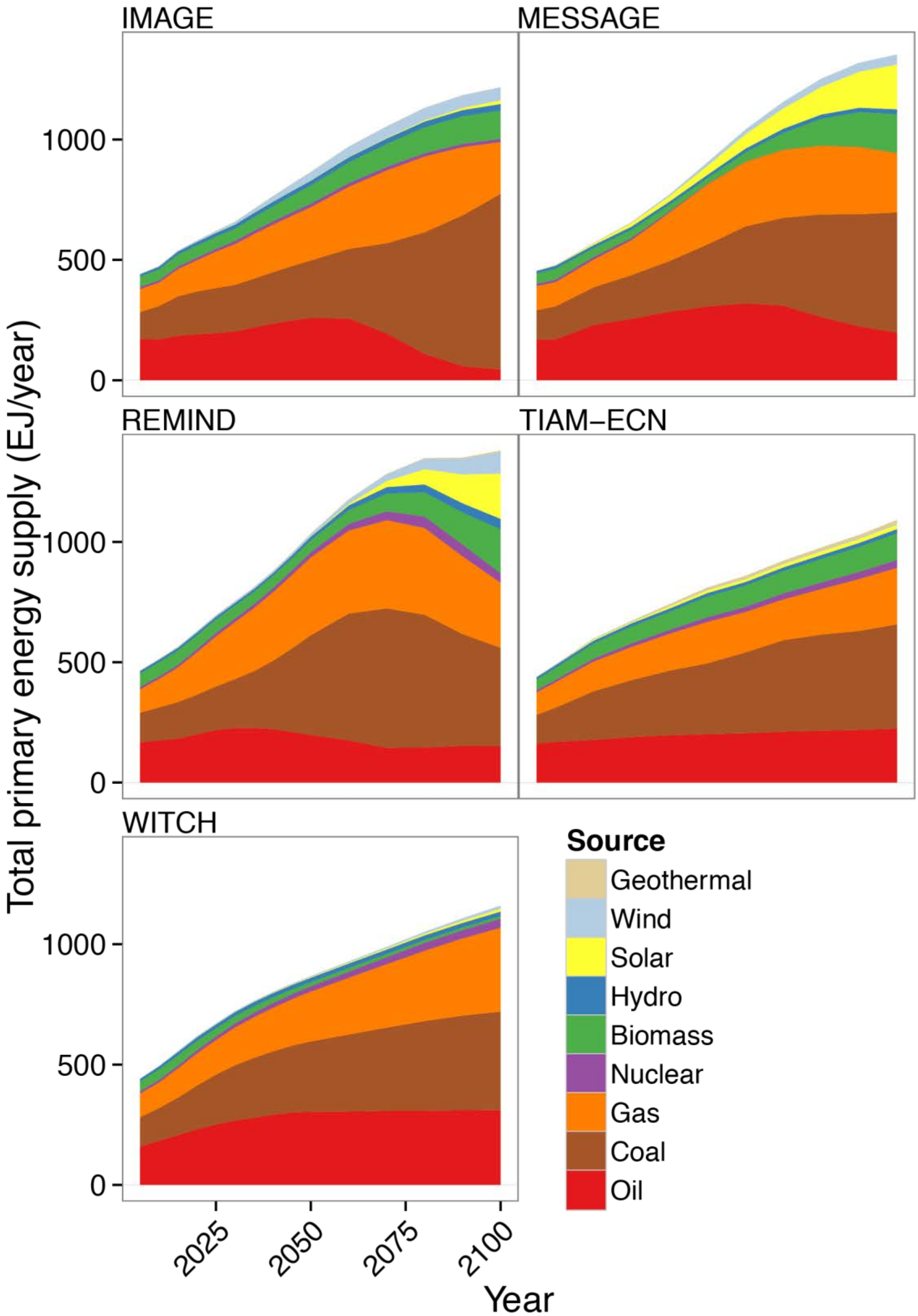
(**a**) Emission impacts of the scenarios, (**b**) energy trade impacts of the scenarios. *The INDC range is from the Climate Action Tracker[1].

Supplementary Figure 2. Comparing energy and emission effects of Oil independence and climate policy scenarios



(**a**) Emission impacts of the scenarios, (**b**) energy trade impacts of the scenarios. *The INDC range is from the Climate Action Tracker[1]

Supplementary Figure 3. Baseline energy mixes



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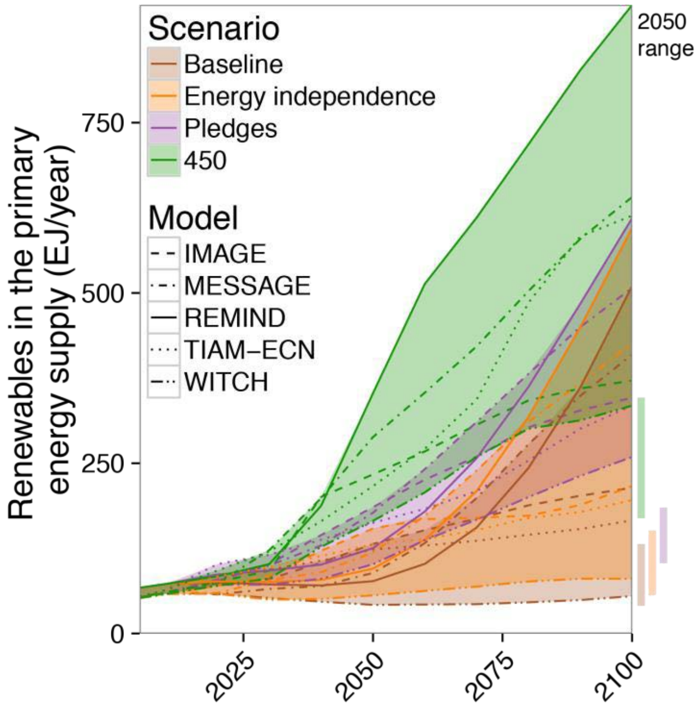
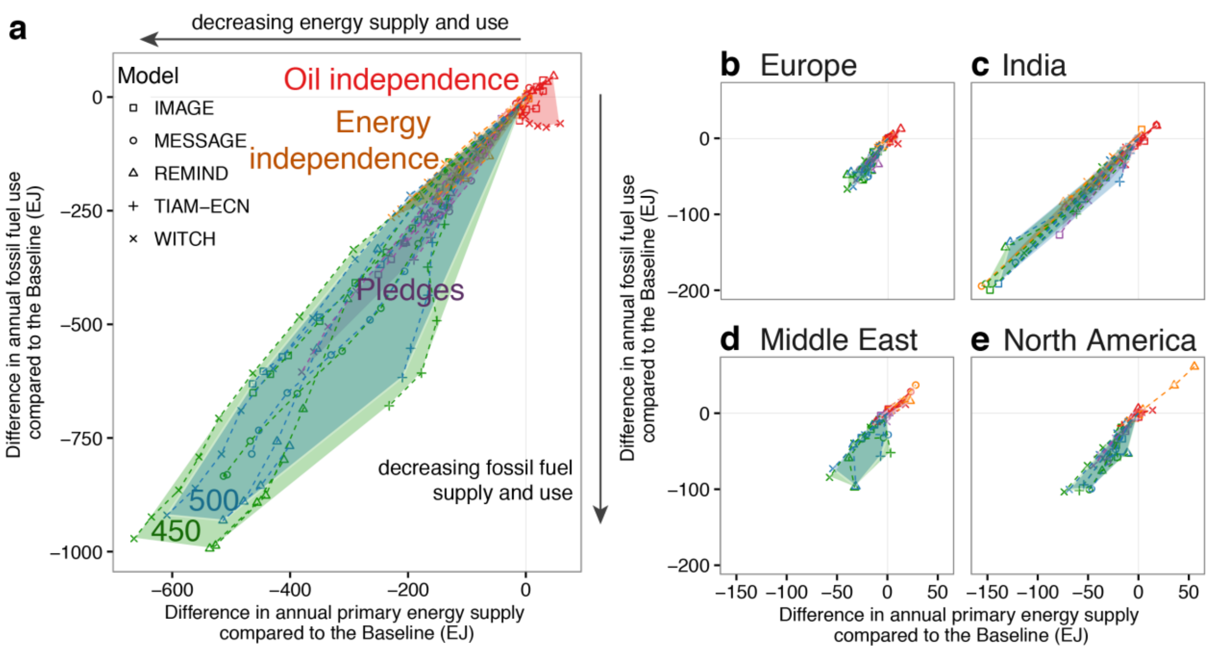
Supplementary Figure 4. The development of renewables under the Baseline and Energy independence and climate policy scenarios

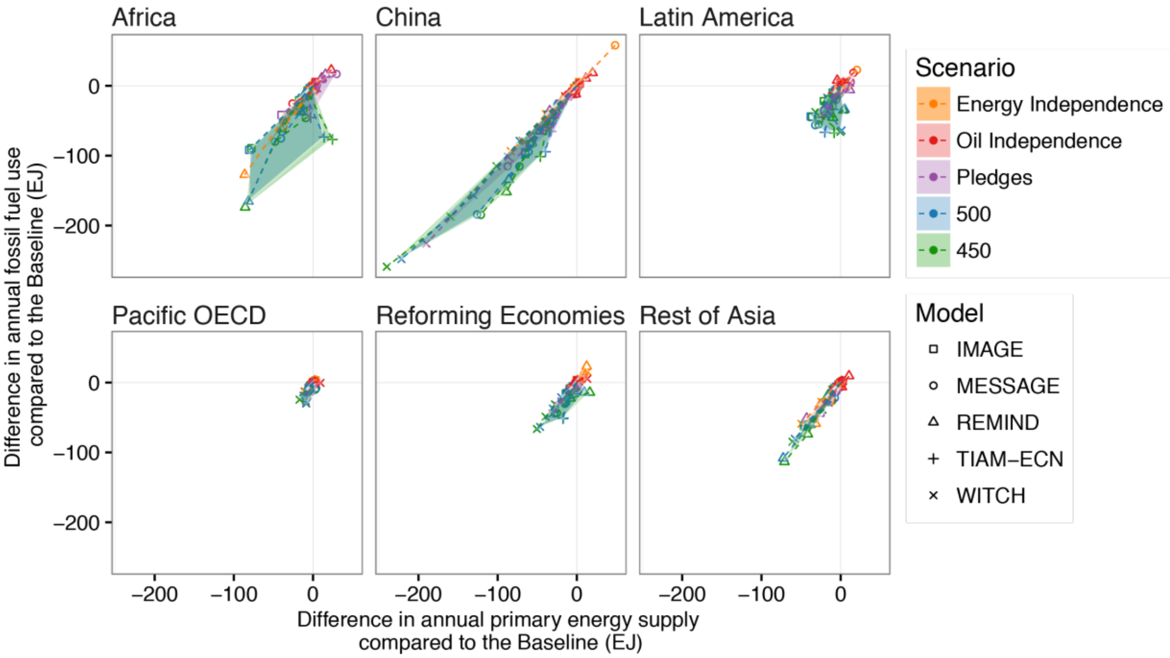


Supplementary Figure 5. The main energy system changes from energy independence compared to climate policy scenarios



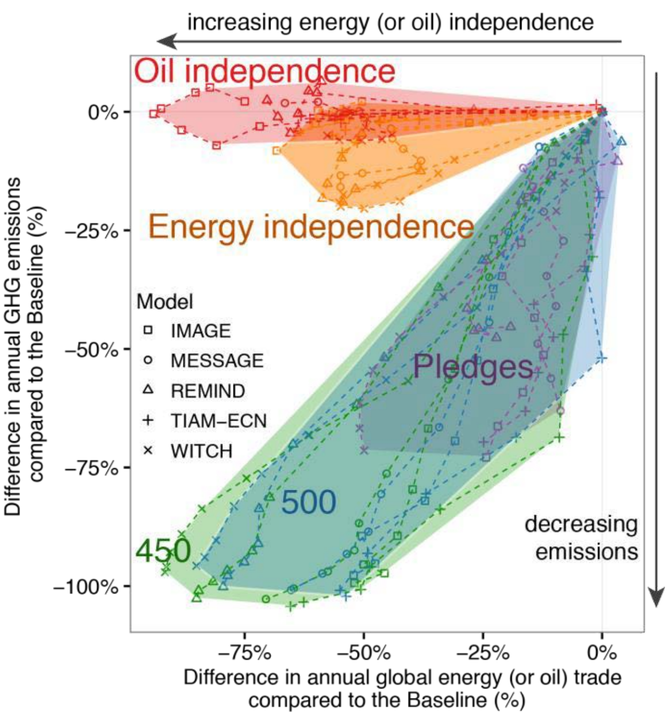
Panel **a** shows the changes at the global level while panels **b-e** show representative regions. The regions represent industrialized economies (Europe–**b**), emerging energy-importing economies (India–**c**), and traditional and emerging exporters (Middle East and North America–**d** and **e**). See Supplementary Note 1 and Supplementary Table 9 for regional definitions. All changes are calculated compared to the Baseline energy mix (shown in Supplementary Figure 3). In panel **a**, each model's results are depicted for each decadal year between 2010 and 2100. In panels **b-e**, each model's results are depicted for the years 2030, 2050 and 2100.

Supplementary Figure 6. The main energy system changes in the remaining six regions not represented in Figure 2



Each model's results are depicted for the years 2030, 2050 and 2100.

Supplementary Figure 7. GHG emission and energy trade impacts of energy independence and climate policy scenarios



For the Energy independence, 450 and Pledges scenario, the decrease is relative to total energy trade whereas for the Oil independence scenario, the difference is relative to global oil trade. Each line represents a model's results for each decadal year between 2010 and 2100. GHG emissions represent Kyoto gases except in TIAM-ECN where they represent CO_2, CH_4 and N_2O.

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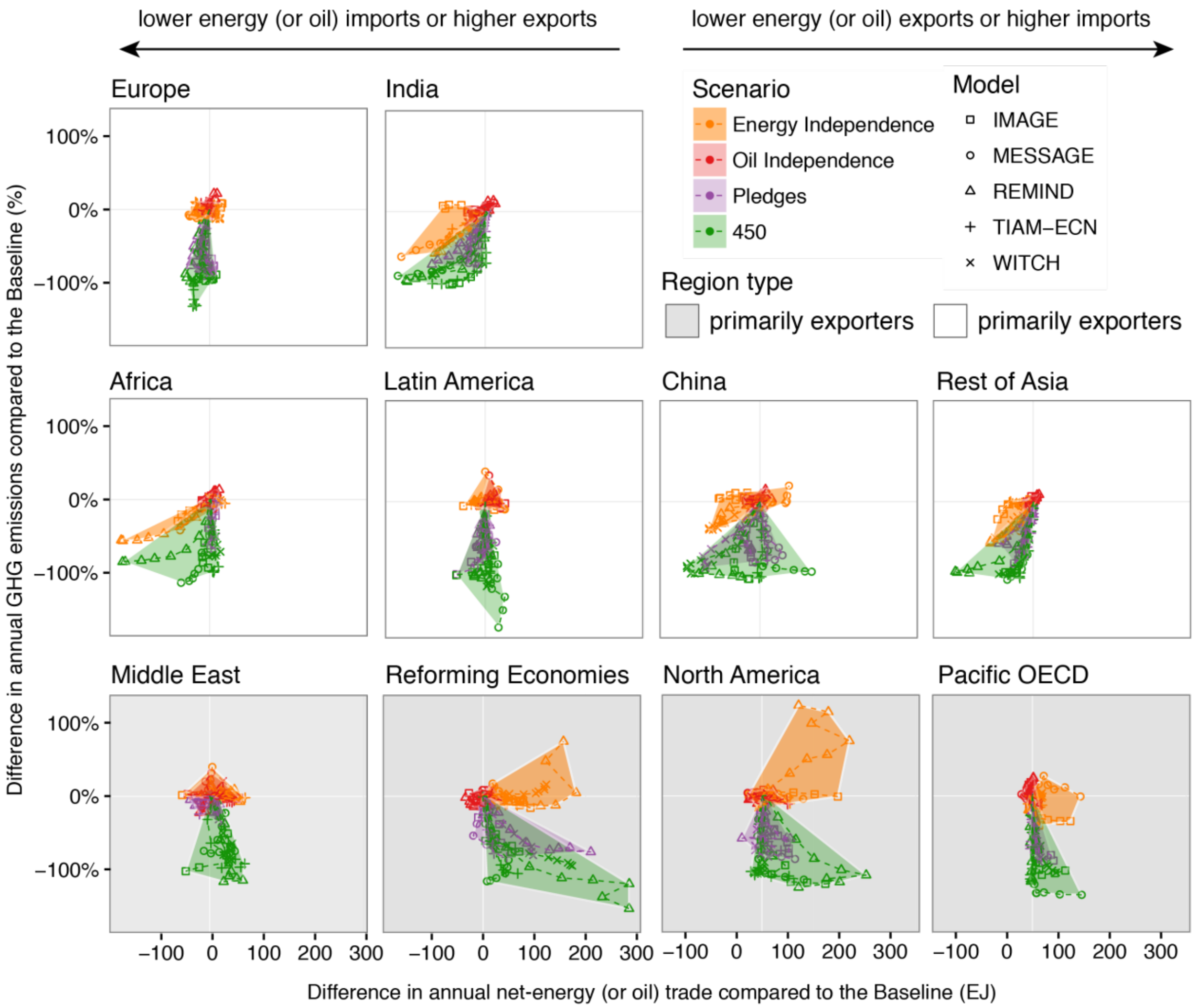
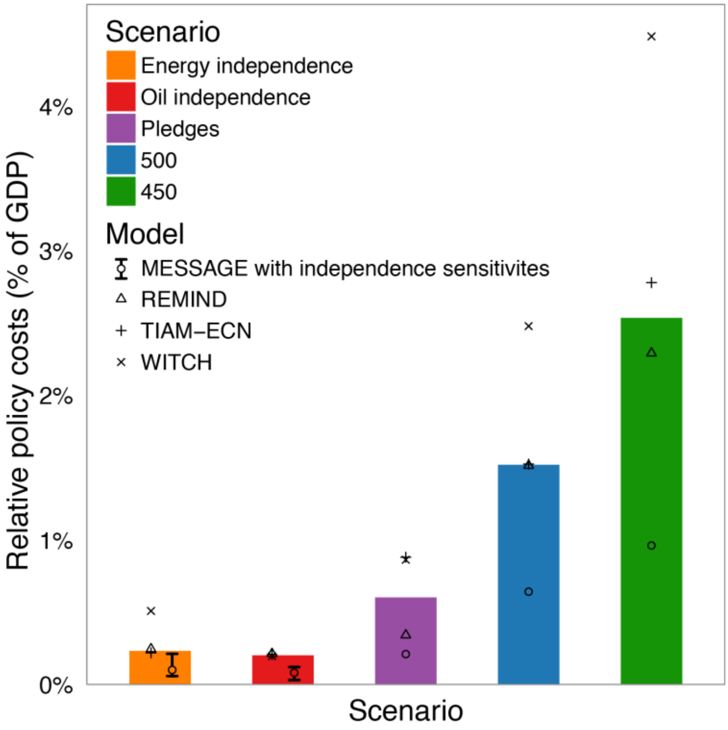
Supplementary Figure 8. GHG emission and net-energy trade impacts of energy independence and climate policy scenarios for all regions



For the Energy independence, 450 and Pledges scenario, the decrease is relative to total net-energy trade whereas for the Oil independence scenario, the difference is relative to net-oil trade. Each line represents a model's results for each decadal year between 2010 and 2100. GHG emissions represent Kyoto gases in all models except TIAM-ECN where they represent CO_2, CH_4 and N_2O. As discussed in the main text, the regional patterns vary greatly depending on whether a region is depicted as a net-exporter or net-importer in the Baseline scenario. For example, India is depicted as a major energy importer throughout the 21st century thus, energy independence and climate policies lead to a drop in energy imports and a drop in emissions. In contrast, the U.S. is depicted as a net-exporter in most models under the Baseline for most of the century; energy import restrictions decrease the global demand for the U.S.' fossil exports and as a result they are used domestically, thus increasing the region's GHG emissions. The same phenomenon is observed in the Middle East and Reforming Economies.

Supplementary Figure 9. Global policy costs for energy independence and climate policy scenarios through 2050



See Methods for calculation of policy costs. Bars show medians, markers show individual models. Costs are expressed in relative differences of Net Present Value from 2010 to 2050 using a 5% discount rate compared with the Baseline scenario. In MESSAGE the full range of sensitivity cases for the independence scenarios is shown.

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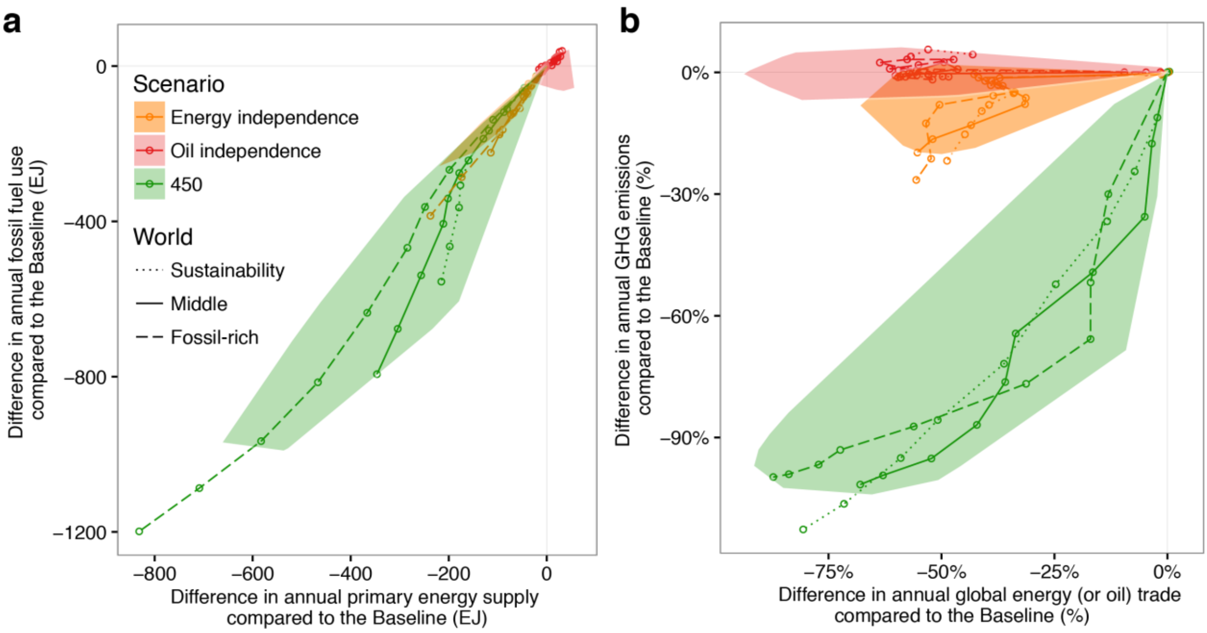
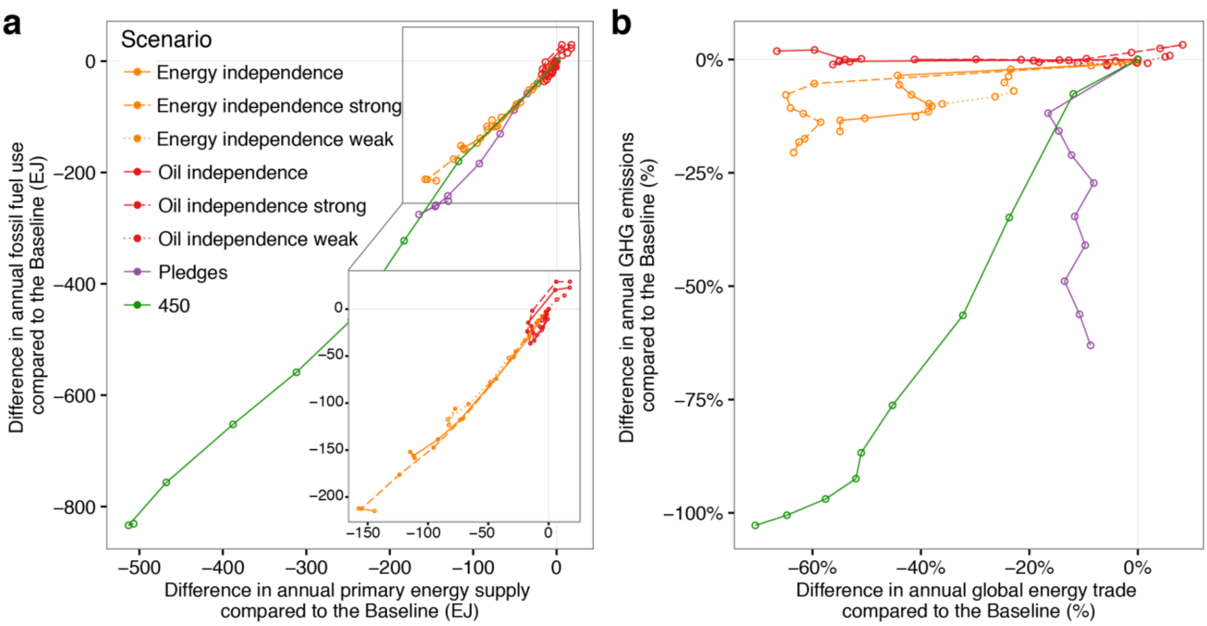
Supplementary Figure 10. Energy and emissions impacts of energy and oil independence targets in different SSP worlds



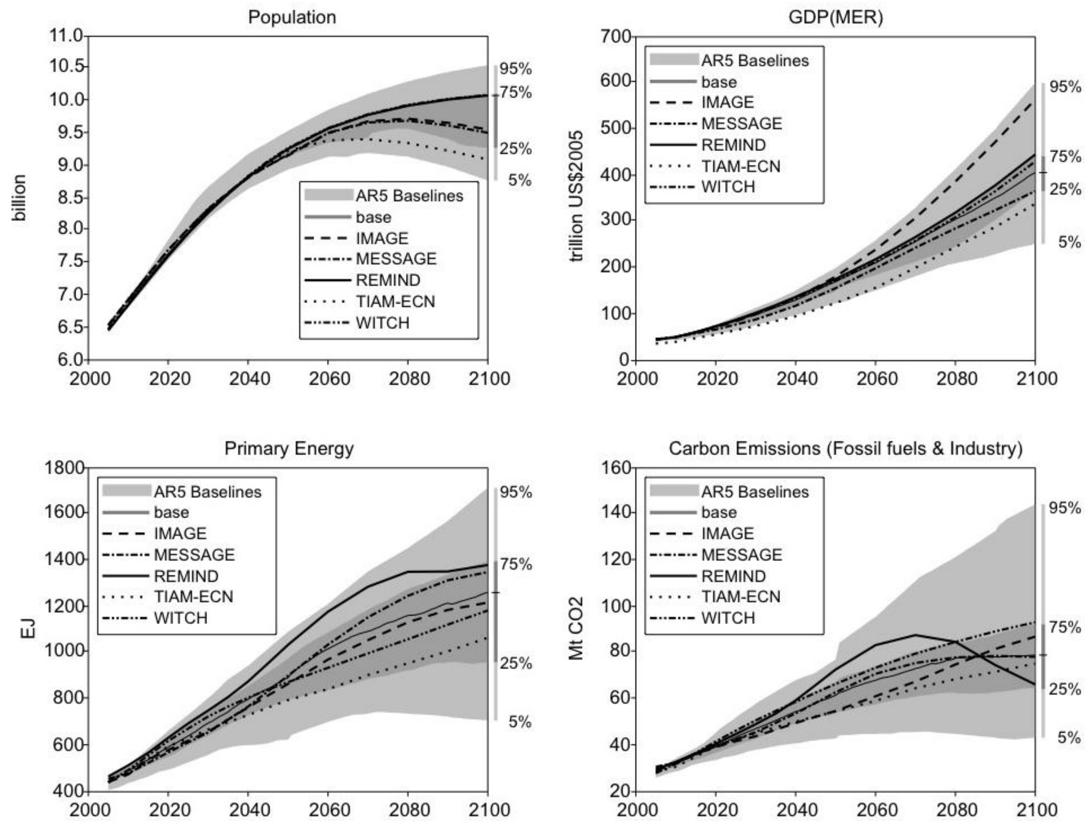
(a) energy impacts of different SSP scenarios, **(b)** emission and trade impacts of different SSP scenarios. The SSP scenarios are from the MESSAGE model[2]. For the Energy independence and 450 scenario, trade is total energy trade; for the Oil independence scenario, we only use oil trade. The scenario ranges from Figure 2 and 3 are shown in the shaded regions.

Supplementary Figure 11. Energy and emissions impacts of energy and oil independence impacts of different energy and oil independence targets



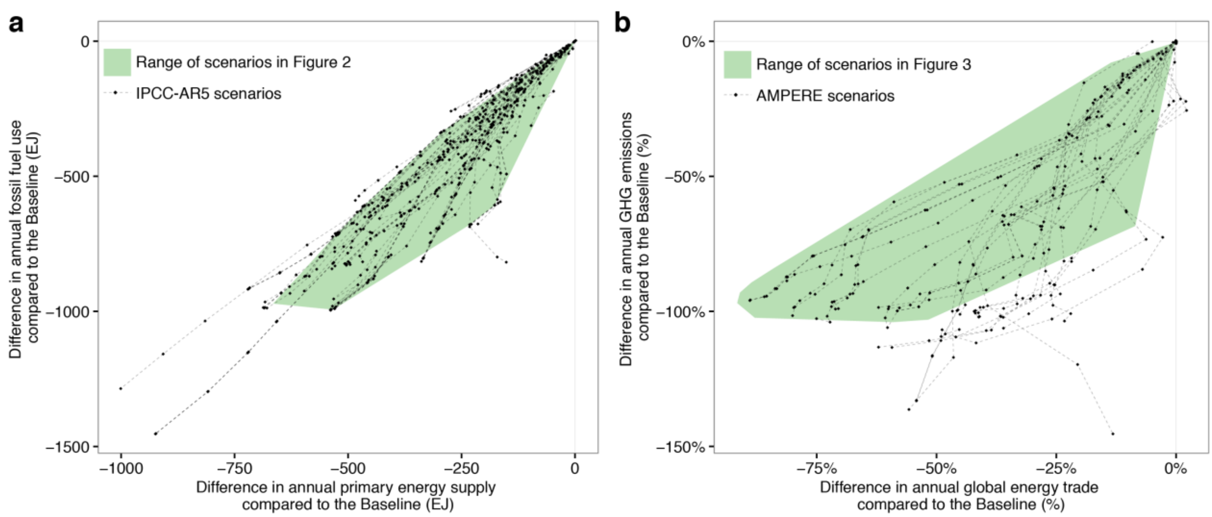
(a) energy impacts of different levels of import restrictions, **(b)** emission and trade impacts of different levels of import restrictions. For the Energy independence and 450 scenario, trade is total energy trade; for the Oil independence scenario, we only use oil trade.

Supplementary Figure 12. Comparison of our Baselines to the Baselines in the IPCC 5th Assessment report database (AR5)



The IPCC scenarios are from the IPCC scenario database[3-5]

Supplementary Figure 13. Comparison of our results for the 450 scenario to comparable scenarios from the IPCC and AMPERE databases



(**a**) compares our results to the IPCC scenario database[3-5] (**b**) compares our results to the AMPERE database[6,7]. For (a) we include T0, P1 and P2 scenarios. In b, global energy trade in b is calculated based on the 5 IPCC-RCP regions rather than the regions we use in our paper for all models which comprehensively report energy trade in the AMPERE database; this is because the AMPERE database does not include the ten regions we use in our study.

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Supplementary Tables

Supplementary Table 1. Technology and emission targets in the Pledges scenario including the GHG emission intensity reduction rate post 2020

Region	GHG emissions reduction in 2020[1]	GHG intensity reduction in 2020[2]	Modern Renewable share in electricity[3]	Installed renewable capacity in 2020[4] (Wind, solar)	Installed nuclear power capacity [5]	Average GHG emissions intensity reduction after 2020[6]
EU27	-25% (2005)	N/A	20% (2020)	-	N/A	3.6%
China	N/A	- 45%	25% (2020)	300 GW; 80GW	80 GW (2020)	3.9%
India	N/A	- 25%	-	40 GW; 20GW	20 GW (2020)	3.5%
Japan	-12% (2005)	N/A	-	5 GW; 28GW	N/A	2.5%
USA	-17% (2005)	N/A	25% (2020)	-	N/A	3.0%
Russia	+12% (2005)	N/A	4.5% (2020)	-	44 GW (2030)	3.4%
AUNZ	-22% (2005)	N/A	20% (2020)	-	N/A	3.6%
Brazil	-36% (BAU)	N/A	-	-	N/A	3.7%
Mexico	-30% (BAU)	N/A	35% (2020)	-	N/A	4.0%
LAM	-30% (BAU)	N/A	35% (2020)	-	N/A	3.3%
CAS	N/A	N/A	N/A	N/A	N/A	3.4%
KOR	-30% (BAU)	N/A	N/A	16 GW; -	N/A	3.9%
IDN	-26% (BAU)	N/A	15% (2025)	-	N/A	3.3%
SSA	N/A	N/A	N/A	-	N/A	2.7%
CAN	-17% (2005)	N/A	25% (2020)	-	N/A	3.3%
EEU	N/A	N/A	N/A	N/A	N/A	3.4%
EFTA	N/A	N/A	N/A	N/A	N/A	3.6%
MEA	N/A	N/A	N/A	-	N/A	2.0%
NAF	N/A	N/A	20% (2020)	-	N/A	2.0%
PAK	N/A	N/A	N/A	N/A	N/A	2.9%
SAF	-34% (BAU)	N/A	N/A	N/A	N/A	3.6%
SAS	N/A	N/A	N/A	-	N/A	3.3%
SEA	N/A	N/A	15% (2020)	-	N/A	3.3%
TUR	N/A	N/A	-	20 GW;-	N/A	3.3%
TWN	N/A	N/A	N/A	N/A	N/A	3.6%

Abbreviations:

AUNZ = Australia and New Zealand
LAM = Latin America
CAS = Central Asia
KOR = South Korea
IDN = Indonesia
SSA = Sub-saharan Africa
CAN = Canada
EEU = Eastern Europe
EFTA = European Free Trade Association (Lichtenstein, Iceland, Norway, and Switzerland)
MEA = Middle East
NAF = North Africa
PAK = Pakistan
SAF= South Africa
SAS = South Asia
SEA = South-east Asia
TUR = Turkey
TWN = Taiwan
N/A = Not Applicable

(1) Including Land-use Change, Land-use Change and Forestry (LULUCF) and relative to 2005 or business as usual (BAU) as specified in brackets. (If GHG emissions in baseline is lower, baseline trajectory is adopted for the region concerned.)
(2) Including LULUCF and relative to 2005 (If GHG intensity reduction in baseline is higher, baseline trajectory is adopted for the region concerned.)
(3) Reference quantity is always electricity production except for EU27 where it is final energy.
(4),(5) Capacity targets are minimum targets; target year is specified in brackets.
(6) %/year; GHG intensity improvement rates calculated based on Kyoto GHG equivalent emissions including LULUCF relative to GDP. (If GHG emissions (intensity) reduction in baseline is higher, baseline trajectory is adopted for the region and period concerned.)

Supplementary Table 2. Overview of energy import restrictions for the Energy independence scenario

Native model region *and region type* (defined in Table 2)	Models	NID 2010 (IEA)(1)	Target NID 2030-2100
1. Developed regions with high import dependence and low energy demand growth halve their energy imports			
Western Europe	I, M, T, W	51-53%	26-27%
European Union 27	R	62%	31%
Central and Eastern Europe	I, M, T, W	38-39%	19-20%
Ukraine	I	47%	23%
Turkey	I	71%	36%
Japan	I, R, T	92%	46%
Japan, Canada & New Zealand	W	38%	19%
Pacific OECD	M	39%	20%
South Korea	I, T	90-99%	45-50%
2. Developing regions with low import dependence and high energy demand growth maintain their energy import level			
China	R, T, W	18-20%	18-20%
Centrally-planned Asia	I, M	14-18%	14-18%
India	I, R, T, W	26%	26%
Other Asia/Southeast Asia	I, M, R, W	14-33%	14-33%
Brazil	I	9%	9%
Rest of Central America	I	23%	23%
3. Energy exporters never become energy importers			
Other Developing Asia	T	Exporter	0%
Indonesia	I	Exporter	0%
Sub-saharan Africa	M, R, T, W	Exporter	0%
East Africa	I	Exporter	0%
North Africa	I	Exporter	0%
West Africa	I	Exporter	0%
South Africa	I	Exporter	0%
Rest of Sub-saharan Africa	I	Exporter	0%
Middle East	All	Exporter	0%
Oceana and Australia	I, T	Exporter	0%
Canada	I, T	Exporter	0%
Latin America	M, R, T, W	Exporter	0%
Mexico	I	Exporter	0%
Rest of South America	I	Exporter	0%
Reforming Economies	All	Exporter	0%
Kazakhstan	I	Exporter	0%
Rest of the World	R, W	Exporter	0%
4. The U.S./North America becomes energy independent by 2030			
USA	I, R, T, W	26%	0%
North America	M	17%	0%

(1) Calculated from the IEA database[8] according to the regional definition of each model. Since different models have slightly different country mappings for a given region, there is a small range. For model-specific regional constraints see Supplementary Table 4, Supplementary Table 5, Supplementary Table 6, Supplementary Table 7 and Supplementary Table 8.

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Supplementary Table 3. Overview of oil import restrictions for the Oil independence scenario

Native model region *and region type*	Models	NID 2010[(1)]	Target NID 2030-2100
1. Oil importers			
Western Europe	I, M, T, W	81-82%	20-21%
European Union 27	R	99%	50%
Central and Eastern Europe	I, M, T, W	92-93%	46%-47%
Ukraine	I	75%	38%
Turkey	I	97%	24%
Pacific OECD	M	95%	48%
Japan	I, R, T	104%	50%
Japan, Canada & New Zealand	W	48%	24%
South Korea	I, T	114%	50%
Brazil	I	0%	0%
Rest of Central America	I	86%	43%
China	R, T, W	63%	32%
Centrally-planned Asia	I, M	65-67%	33-34%
India	I, R, T, W	76%	38%
Other Asia/Southeast Asia	I, M, R, W	62-88%	31-44%
Other Developing Asia	T	73%	37%
Indonesia	I	29%	15%
South Africa	I	156%	50%
Oceana and Australia	I, T	54%	27%
Korea, South Africa, & Australia	W	102%	50%
USA	I, R, T, W	63%	0%
North America	M	49%	0%
2. Oil exporters			
Sub-saharan Africa	M, R, T, W	Exporter	0%
East Africa	I	Exporter	0%
North Africa	I	Exporter	0%
West Africa	I	Exporter	0%
Rest of Sub-Saharan Africa	I	Exporter	0%
Middle East	All	Exporter	0%
Canada	I, T	Exporter	0%
Latin America	M, R, T, W	Exporter	0%
Mexico	I	Exporter	0%
Rest of South America	I	Exporter	0%
Reforming Economies	All	Exporter	0%
Kazakhstan	I	Exporter	0%
ROW	R	Exporter	0%

(1) Calculated from the IEA database[8] according to the regional definition of each model. Since different models have slightly different country mappings for a given region, there is a small range. For model-specific regional constraints see Supplementary Table 4, Supplementary Table 5, Supplementary Table 6, Supplementary Table 7 and Supplementary Table 8.

Supplementary Table 4. Energy and oil import constraints for the independence scenarios in IMAGE

Region	Region Type for Energy independence	Energy independence		Oil independence	
		NID 2010[(1)]	Target NID	oilNID 2010[(1)]	Target oilNID
BRA	2	9%	9%	0%	0%
CAN	3	-63%	0%	-87%	0%
CEU	1	39%	20%	93%	47%
CHN	2	18%	18%	67%	34%
EAF	3	-20%	0%	-129%	37%
INDIA	2	26%	26%	76%	38%
INDO	3	-90%	0%	29%	15%
JAP	1	92%	45%	104%	50%
KOR	1	90%	45%	114%	50%
ME	3	-160%	0%	-304%	0%
MEX	3	-25%	0%	-61%	0%
NAF	3	-109%	0%	-144%	0%
OCE	3	-111%	0%	54%	27%
RCAM	2	23%	23%	86%	43%
RSAF	3	-121%	0%	-739%	0%
RSAM	3	-74%	0%	-113%	0%
RSAS	2	19%	19%	80%	40%
RUS	3	-91%	0%	-279%	0%
SAF	3	-13%	0%	156%	50%
SEAS	2	32%	32%	81%	41%
STAN	3	-78%	0%	-249%	0%
TUR	1	71%	36%	97%	49%
UKR	1	47%	47%	75%	38%
USA	3	26%	0%	63%	0%
WAF	3	-96%	0%	-685%	0%
WEU	1	52%	26%	81%	41%

[(1)] Calculated from the IEA database[8].

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Supplementary Table 5. Energy and oil import constraints for the independence scenarios in MESSAGE

Region	Region Type for Energy independence	Energy independence		Oil independence	
		NID 2010[1]	Target NID	oilNID 2010[1]	Target oilNID
AFR	3	-55%	0%	-343%	0%
CPA	2	14%	14%	65%	33%
EEU	1	39%	20%	92%	46%
FSU	3	-69%	0%	-236%	0%
LAC	3	-25%	0%	-46%	0%
MEA	3	-149%	0%	-272%	0%
NAM	3	17%	0%	49%	0%[2]
PAO	1	39%	20%	95%	48%
PAS	2	33%	33%	88%	44%
SAS	2	25%	25%	77%	39%
WEU	1	53%	26%	82%	41%

(1) Calculated from the IEA database[8].

(2) The target was delayed till 2040 because the region was unable to build up enough infrastructure in the model by 2030 to be fully oil import independent.

Supplementary Table 6. Energy and oil import constraints for the independence scenarios in REMIND

Region	Region Type for Energy independence	Energy independence		Oil independence	
		NID 2010[1]	Target NID	oilNID 2010[1]	Target oilNID
AFR	3	-72%	0%	-491%	0%
CHN	2	20%	20%	63%	32%
EUR	1	62%	31%	99%	50%
IND	2	26%	26%	76%	38%
JPN	1	92%	46%	104%	50%
LAM	3	-25%	0%	-47%	0%
MEA	3	-141%	0%	-278%	0%
OAS	2	26%	26%	83%	42%
ROW	3	-44%	0%	-26%	0%
RUS	3	-86%	0%	-256%	0%
USA	3	26%	0%	63%	0%

(1) Calculated from the IEA database[8].

Supplementary Table 7 Energy and oil import constraints for the independence scenarios in TIAM-ECN

Region	Region Type for Energy independence	Energy independence		Oil independence	
		NID 2010[1]	Target NID	oilNID 2010[1]	Target oilNID
AFR	3	-69%	0%	-236%	0%
AUS	3	-131%	0%	54%	27%
CAN	3	-63%	0%	-87%	0%
CHI	2	15%	20%	63%	32%
CSA	3	-25%	0%	-40%	0%
EEU	1	38%	19%[2]	92%	46%
FSU	3	-67%	0%	-229%	0%
IND	2	26%	26%	76%	38%
JPN	1	92%	46%	104%	45%[3]
MEA	3	-127%	0%	-268%	0%
MEX	3	-25%	0%[4]	-61%	0%
ODA	3	6%	6%%	73%	37%
SKO	2	99%	45%	114%	50%
USA	3	26%	0%	63%	0%
WEU	1	52%	26%	81%	41%

[1] Calculated from the IEA database[8].
[2] Relaxed to 35% in the latter half of the century (see Methods).
[3] Relaxed to 60% in the latter half of the century (see Methods).
[4] Relaxed to 31% in the latter half of the century (see Methods).

Supplementary Table 8. Energy and oil import constraints for the independence scenarios in WITCH

Region	Region Type for Energy independence	Energy independence		Oil independence	
		NID 2010[1]	Target NID	oilNID 2010[1]	Target oilNID
CAJAZ	2	38%	19%	48%	24%
CHINA	2	20%	20%	67%	34%
EASIA	2	-15%	0%	62%	31%
INDIA	2	26%	26%	76%	38%
KOSAU	3	4%	0%	102%	50%
LACA	3	-25%	0%	-46%	0%
MENA	3	-149%	0%	-270%	0%
NEWEURO	1	39%	20%	95%	48%
OLDEURO	1	51%	26%	81%	41%
SASIA	2	23%	23%	89%	45%
SSA	3	-72%	0%	-491%	0%

[1] Calculated from the IEA database[8].

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Supplementary Table 9. Regional definitions

Region	Description
Africa	Includes countries in Sub-Saharan Africa. Some models also include North African countries but others do not. For REMIND and WITCH, South Africa is included in the Rest of the World region.
China	Primarily composed of China but in some models includes additional Asian countries such as Cambodia, Vietnam, North Korea, and Mongolia.
Europe	Eastern and Western European countries (i.e. EU27) but REMIND and WITCH also include Turkey.
India	Primarily India but in some models also includes other South Asian countries such as Nepal, Pakistan, Bangladesh, and Afghanistan.
Latin America	Latin American and Caribbean countries.
Middle East	Middle Eastern countries such as Iran, Iraq, Israel, Saudi Arabia and Qatar. For some models this also includes North African countries such as Algeria, Egypt, Morocco, Tunisia) and for REMIND it also includes the Central Asian former Soviet states.
Pacific OECD	OECD (Organisation for Economic Co-operation and Development) countries which are in the Eastern Hemisphere and abut the Pacific Ocean. For most models this region is dominated by Japan, Australia and New Zealand. For REMIND, only Japan is included, Australia and New Zealand are included in the Rest of the World region. WITCH also does not include Australia, which is instead part of the Rest of the World region. WITCH also includes Canada in the Pacific OECD.
Reforming Economies	This region is dominated by Russia. For all models except REMIND, it also includes Reforming Economies which were part of the Soviet Union such as Ukraine, Kazakhstan and Azerbaijan. WITCH also includes Turkey in this region.
Rest of Asia	Includes other Asian countries which are not in the India or China regions such as South Korea, Malaysia, Philippines, Singapore, Thailand and Indonesia. For WITCH, South Korea is included in the Rest of the World region.
U.S./North America	For most models this includes the United States of America and Canada but in REMIND, Canada is included in the Rest of the World region and for WITCH, Canada is included in the Pacific OECD region.
Rest of the World	This region is only present in REMIND and WITCH and includes countries which are not included elsewhere for these two models. For REMIND, this includes Australia, Canada, Iceland, Norway, New Zealand, Moldova, Serbia, South Africa, Switzerland, Turkey, Ukraine, and some other smaller countries. For WITCH this includes Australia, South Africa, and South Korea

This table includes a full list of the super regions along with a non-exhaustive sample of countries included in each.

Supplementary Table 10. Regional distribution of policy costs in different scenarios

Region	Energy independence	Oil independence	Pledges	450
Middle East	31% – 73%	25% – 77%	0% – 22%	6% – 31%
Reforming Economies	9% – 38%	1% – 19%	0% – 40%	4% – 14%
Africa	2% – 35%	1% – 7%	-1% – 4%	3% – 8%
India	-8% – 0%	-2% – 36%	-4% – 3%	6% – 12%
China	-8% – 4%%	-11% – 12%	-4% – 15%	2% – 24%
Rest of Asia	-11% – 11%	-6% – 9%	-15% – 10%	-2% – 11%
Latin America	0% – 14%	4% – 11%	9% – 50%	7% – 10%
North America	-4% – 36%	-4% – 36%	10% – 13%	10% – 15%
Pacific OECD	-1% – 3%	-5% – 7%	-7% – 5%	2% – 4%
Europe	-11% – 8%	-12% – 14%	13% – 30%	5% – 12%

Costs are calculated using Net Present Value from 2010 to 2050 using a 5% discount rate.

Supplementary Table 11. Summary of key model characteristics

Model	Equilibrium type	Modeling approach	Energy trade depiction(1)	Energy trade constraint	TI-p(2)	CoEI(3)
IMAGE	Partial equilibrium	Recursive dynamic	All fuels bi-lateral	Tax on imported fuels	Mixed	Low
MESSAGE	General equilibrium	Intertemporal optimization	Most fuels and carriers global pool; natural gas bi-lateral between certain regions(4)	Binding constraint	High	Low
REMIND	General equilibrium	Intertemporal optimization	All fuels global pool	Binding constraint	High	Low
TIAM-ECN	Partial equilibrium	Intertemporal optimization	All fuels bi-lateral	Binding constraint	High(5)	Low(5)
WITCH	General equilibrium	Intertemporal optimization	All fuels global pool	Binding constraint	Low	High

(1) See Methods for discussion of which fuels are depicted in which model.
(2) The TI-p or the Transformation Index (primary energy) classification of model behavior under carbon taxes from Kriegler et al.[9]. "Low" indicates a relatively smaller transformation of primary energy supply compared to other models whereas "High" indicates a relatively larger transformation of the primary energy system compared to other models.
(3) CoEI or the carbon intensity over energy intensity indicator characterizes model behavior under carbon taxes from Kriegler et al.[9]. "Low" indicates models which have a stronger reduction in carbon intensity relative to energy intensity compared to other models whereas "High" indicates models which have a stronger demand response compared to growth in low carbon energy sources.
(4) See Methods.
(5) From TIAM-ECN team.

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Supplementary Table 12. Global policy costs for meeting energy independence targets and the 450 target in different SSP worlds

	SSP World	Energy independence	Oil independence	450
2050	Sustainability	0.03%	0.05%	0.1%
	Middle-of-the-road	0.04%	0.05%	0.2%
	Fossil-rich	0.07%	0.07%	1%
2100	Sustainability	0.03%	0.04%	0.2%
	Middle-of-the-road	0.02%	0.03%	0.4%
	Fossil-rich	0.1%	0.07%	2%

Costs represent consumption losses and are expressed in Net Present Value from 2010 to 2050 and 2010 to 2100, respectively, using a 5% discount rate. The SSP scenarios are from the MESSAGE model[2].

Supplementary Table 13 Energy independence sensitivities (MESSAGE)

Regions	Region Type (Table 2)	NID 2010 (IEA)	Energy independence strong	Main Energy independence	Energy independence weak
AFR	3	-55%	0%	0%	0%
CPA	2	14%	7%	14%	21%
EEU	1	39%	10%	20%	30%
FSU	3	-69%	0%	0%	0%
LAM	3	-25%	0%	0%	0%
MEA	3	-149%	0%	0%	0%
NAM	3	17%	0%	0%	17%
PAO	1	39%	10%	20%	30%
PAS	2	33%	17%	33%	50%
SAS	2	25%	13%	25%	38%
WEU	1	53%	13%	26%	39%

Supplementary Table 14. Oil independence sensitivities (MESSAGE)

Regions	oilNID 2010 (IEA)	Oil independence strong	Main Oil independence	Oil independence weak
AFR	-343%	0%	0%	0%
CPA	65%	16%	33%	49%
EEU	92%	23%	46%	69%
FSU	-236%	0%	0%	0%
LAM	-46%	0%	0%	0%
MEA	-272%	0%	0%	0%
NAM	49%	0%[(1)]	0%[(1)]	25%
PAO	95%	24%	48%	71%
PAS	88%	22%	44%	66%
SAS	77%	19%	39%	58%
WEU	82%	21%	41%	62%

[(1)] The target was delayed till 2040 because the region was unable to build up enough infrastructure in the model by 2030 to be fully oil import independent.

Supplementary Table 15. The impact of the different target-sensitivity cases on our key energy and emission findings

Finding	2030	2050	2100
Reduction of total primary energy supply from the Baseline (annual)			
Energy independence weak	-1%	-4%	-6%
Energy independence	-2%	-5%	-8%
Energy independence strong	-4%	-8%	-11%
Reduction of fossil fuel use from the Baseline (annual)			
Energy independence weak	-3%	-6%	-13%
Energy independence	-5%	-10%	-17%
Energy independence strong	-8%	-14%	-23%
Reduction of GHG emissions from the Baseline (cumulative)			
Energy independence weak	-0.1%	-5%	-13%
Energy independence	-1%	-8%	-16%
Energy independence strong	-2%	-11%	-21%

Supplementary Table 16. The impact of the level of import target on the policy costs

Scenario	2050	2100
Energy independence weak	0.04%	0.04%
Energy independence	0.1%	0.1%
Energy independence strong	0.2%	0.2%
Oil independence weak	0.04%	0.04%
Oil independence	0.1%	0.08%
Oil independence strong	0.2%	0.1%
Pledges	0.2%	0.2%
450	0.6%	1%

Costs represent consumption losses and are expressed in Net Present Value from 2010 to 2050 and 2010 to 2100, respectively, using a 5% discount rate.

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Supplementary Notes

Supplementary Note 1. Regional definitions

In this paper, regional analysis is based on ten "super regions" which represent countries with similar geographies and/or levels of development and thus with relatively similar energy system structures and requirements (Supplementary Table 9). However, since native regions in these models differ, the energy and oil independence constraints are imposed on native model regions (Supplementary Table 4 - Supplementary Table 8).

Supplementary Note 2. Model uncertainty

Model uncertainty arises due to different methods of representing energy-economy systems. For example, are investment decisions based only on present information or are they based on expectations about future development? While both processes are present in the real world, the structure and approach of a particular model emphasizes one of these over the other. A widely accepted approach to address the uncertainties that arise from these structural and conceptual differences embedded in different models is a model inter-comparison project (MIP). The first MIP was developed by the Energy Modeling Forum in the late 1970s following the oil crises[10] and MIPs have since become the standard in policy-relevant energy modeling[5]. Following this approach, we use a model inter-comparison in this study. By including models with fundamentally different characteristics, we address the model uncertainty, caused by different model characteristics.

Our study includes both optimization models with perfect foresight (e.g. REMIND) and simulation models with limited foresight (e.g. IMAGE). Optimization models model the response of energy systems to import restrictions by finding an optimal solution to meeting given physical constraints. Simulation models model responses of energy systems to an energy import tax adjusted so as to achieve the energy import target level. Another model variation, particularly relevant to our study, is the different representation of energy trade – either as bilateral between two regions or to-and-from a global pool (for more discussion see 'Methods'). Since the models in our study include two purely bi-lateral trade models (TIAM-ECN and IMAGE), two global pool models (REMIND and WITCH) and one which is a mix of the two (MESSAGE), we have been able to test that our results are robust under different assumptions about energy trade mechanisms.

Supplementary Table 11 summarizes key characteristics of the models in this study. The models differ in their representation of the economy (equilibrium type), modeling approach and representation of energy trade. In addition, this table includes two diagnostic indicators which have been recently developed for IAMs to capture two aspects of a model's response to a given carbon price[9]. The first is its relative response in transforming primary energy supply (TI-p) compared to other models. That is, at a given carbon price, how much does the primary energy mix of a model change. A model with a "High" TI-p shows a relatively high degree of changes in the primary energy mix compared to a model with a "Low" TI-p. A related indicator is the CoEI, or Carbon Intensity over Energy Intensity indicator. This indicator is an expression of how much the carbon intensity of an energy system changes (as a proportion of Baseline carbon intensity) compared to the overall energy intensity changes (also as a proportion of Baseline energy intensity) under a given carbon price. A model with a "High" CoEI value shows a relatively higher energy intensity (and therefore demand) response than a model with a "Low" CoEI. The CoEI and TI-p indicate how the model balances demand-side changes with structural changes in energy supply not only in response to a climate policy but also in response to other constraints, such as import restrictions as investigated in in our study.

All models assume a portfolio approach to changes necessary to achieve the energy independence targets through a combination of decreasing energy intensity and thus the overall demand and increasing the share of domestic supply. Whether or not the decrease in energy imports is achieved by primarily decreasing energy demand from energy efficiency improvements or by incresing domestic energy supply is determined by the relative flexibility of demand (expressed in the CoEI indicator) and supply (expressed in the TI-p indicator) in a particular model. For example, WITCH has the highest CoEI and thus the strongest demand response to constraints imposed on energy systems. This explains why in Figure 2, WITCH is the model on the far left of the graph, i.e. the model with the largest reduction in the overall energy demand and supply. In contrast, REMIND has a relatively lower CoEI and thus a smaller demand response.

The relative balance between these two responses also affects the modeled penetration of renewables due to energy import restrictions. The models with a stiffer energy supply system (and a low TI-p), such as WITCH and to some extent IMAGE, depict lower penetration of renewables than other models such as REMIND, which has a relatively more flexible energy supply. The rate of expansion of renewables in response to import constraints is also affected by the representation of renewable energy integration and the regional renewable capacity factors (for the latter two see Luderer et al.[11]). This can explain different penetration of renewables not only under policy constraints but also in the Baseline, particularly at the regional level.

The net result of energy import restrictions on emissions can also be interpreted in light of the balance between these energy system responses. For example, as shown in Figure 3, the decrease of emissions under the same import constraints is higher in WITCH than in MESSAGE. This is because WITCH responds to energy import restrictions by decreasing energy intensity and thus lowering the demand which also leads to a drop in fossil fuel supply and emissions, whereas in MESSAGE similar restrictions lead to smaller reductions in energy demand and larger increases in

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domestic energy production. Since domestic energy also includes domestic fossils, the drop in the fossil energy supply and consequently GHG emissions is smaller in MESSAGE than in WITCH (Figure 2).

Supplementary Note 3. Parametric uncertainty

In terms of parametric uncertainty, the question is would our results hold up under various socioeconomic and technological assumptions. In part, this uncertainty overlaps with the model uncertainty discussed in the previous section. The models in our study already span a wide range of socioeconomic assumptions under the Baseline scenario: the 50th percentile for population, primary energy and emission and the 70th percentile for GDP compared to the AR5 database (Supplementary Figure 12). Another key variation which is depicted in the models are different resource supply curves. Previous research has shown that resource availability assumptions impact future energy trade, more than GDP or other socioeconomic assumptions[12] and the models in this study span a wide range of resource cost-curve assumptions[13].

Additionally, we have compared the key results from the 450 scenarios in our study to the AR5 range of scenarios with similar attributes[3-5] and the AMPERE database[6,7]. Our model results span most of the range of uncertainty represented in the IPCC database (Supplementary Figure 13). The two main outliers in the left pane are from the MERGE-ETL model, which depicts a fossil-intensive Baseline scenario (much like the 'Fossil-rich World' – discussed below) and was found to have the largest decrease in coal use from emission caps[13].

In addition to using models which span a wide range of assumptions, we test the sensitivity of our results to technological, resource, energy demand and socioeconomic uncertainties using the MESSAGE model. We do this by building on the 'shared-socioeconomic pathways' (SSPs) which have been developed by the IAM community to systematically explore a wide range of parameter uncertainties in under internally-consistent scenarios and assumptions[14-16]. "Internally-consistent" means that variables are changed in a way that makes sense with how other variables change[17]; for example, a scenario with low fossil-fuel availability will have higher rates of technological development.

To test for parametric uncertainties, we apply the energy and oil import constraints to the three of these scenarios which span the widest range of assumptions and represent the most optimistic developments for climate change mitigation (SSP1), the most pessimistic (SSP3), and an intermediate path (SSP2). All the SSPs we test are from the MESSAGE-model implementation[2]. In 'SSP1' or the 'Sustainability World', the costs of new technologies fall along with economic growth and the use of fossil resources, all of which leads to low mitigation challenges. In the 'SSP2' or 'Middle-of-the-road World', technology, the economy and population develop in a way which is consistent with historical patterns, and mitigation challenges are moderate. Finally, in the 'SSP3' or regional 'Fossil-rich World' world, technological development is slow and energy systems remain fossil-rich leading to a particularly high challenge for climate change mitigation.

In a 'Fossil-rich World', coal becomes king, not only by dominating the primary energy system but also as the most widely traded energy commodity by mid-century. In contrast, in the 'Sustainability World', while coal trade still grows, it is about five times less by the end of the century. In spite of this divergence, energy import restrictions have similar effects, decreasing emissions by 6-10% (Supplementary Figure 10a). Under different SSP worlds, oil import restrictions still have no net impact on emissions. All in all we find that the uncertainty in our results generated as a result of differences between the three baseline worlds is comparable to the uncertainty arising due to the differences between the models (Supplementary Figure 10b).

However, this uncertainty analysis also shows that the absolute energy system changes (in terms of overall fossil use and overall size) are biggest in the 'Fossil-rich World' and smallest in the 'Sustainability World' both in the Climate stabilization and in Energy independence scenarios (Supplementary Figure 10). In the 'Fossil-rich World', with the emergence of massive coal use and trade, the changes to the energy system to meet energy independence and the climate stabilization targets are bigger than they are in the other two worlds. Nevertheless, the *relationship* between the changes under the Energy independence and 450 scenarios are comparable under all baseline assumptions: the energy system changes required to meet 450 are more than four times larger those required to meet energy independence targets.

We also find that the cost of meeting energy independence targets can be achieved at a fraction of the cost in all three worlds, though meeting the energy import restrictions is relatively easier in a 'Sustainability World' where there is rapid technological development and a shift away from fossil fuel use even without climate or energy independence policies (Supplementary Table 12. Global policy costs for meeting energy independence targets and the 450 target in different SSP world). Thus, a world which is better suited for climate change mitigation, is also more suited for increasing energy independence. However, the levels of fossil fuel use and technological development affect the costs of climate policies more than the costs to import restrictions.

Supplementary Note 4. Import policy uncertainty

The final sensitivity we explore relates to the specific level of the import constraints. In our Energy and Oil independence scenarios, we set import constraints at least as ambitious as empirically observed policies (see Methods). This reinforces our conclusion that realistically ambitious energy independence policies would lead to smaller emission reductions and energy system changes and also cost less than climate stabilization policies. To further test the robustness of this conclusion, we

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conduct a sensitivity test varying energy and oil independence targets by both increasing and decreasing it by 50% of the main Independence scenarios in the MESSAGE model (Supplementary Table 13 and Supplementary Table 14).

Varying the level of import restrictions changes the numbers but our basic conclusions related to energy system changes and the respective emissions still hold (Supplementary Figure 11, Supplementary Table 15). Doubling the level of energy import reductions slightly increases the overall reduction in fossil use, primary energy supply and greenhouse gas emissions but it still pales in comparison to the changes needed to meet a 450 target. This is because even very strong energy independence targets (with all regions importing less than 20%) can be met by much smaller energy system changes than those required to meet climate stabilization targets. The energy system changes for the Strong Energy independence case are comparable to those under the Pledges scenario but under cost-effective assumptions, even these strong import restrictions do not lead to significant emissions reductions, except over the very long-term (Supplementary Figure 12). This is because, over the short-term, imported oil and gas are substituted for more emission-intensive domestic coal.

Similarly, the stringency of the energy import restrictions affects the cost results with stronger import targets costing more (Supplementary Table 16). However the nature of our main finding, that energy import restrictions costs a fraction of what a climate stabilization do, holds up even under even under very strong energy independence restrictions with all regions importing less than 20% of primary energy supply.

Supplementary Note 5. Model descriptions

IMAGE: The IMAGE modeling framework focuses on the chain of global environmental change for both climate and land use. Important inputs into the system are assumptions on population and economic development. Next, two models describe the trends in the demand for key environmental services: energy and food demand. The global energy system model TIMER[18] has been developed to simulate long-term energy baseline and climate change mitigation scenarios. The model describes the investments in and use of different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. For food and agriculture, the IMAGE system uses projections made by the computable-general-equilibrium MAGNET model. This model describes, in interaction with the main IMAGE framework, changes in food production and trade for a broad set of crops and animal products. The Terrestrial Environment System (TES) of IMAGE[19,20] computes land-use changes based on regional production of food, animal feed, fodder, grass, bio-energy and timber, with consideration of local climatic and terrain properties. Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated. Through the linkage to IMAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. The Atmospheric Ocean System (AOS) part of IMAGE calculates changes in atmospheric composition using the emissions from the TIMER model and TES, and by taking oceanic carbon dioxide uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic parameters by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport. The energy import restrictions are achieved in IMAGE through a tax on all imported energy.

MESSAGE: The MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is an energy-economic model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis[21-23]. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. To estimate regionally-aggregated, sector-based air pollutant emissions and related pollution control costs, MESSAGE has been linked to the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model[24,25]. or the estimation of price-induced changes of energy demand, iterations between the MESSAGE model and the macro-economic model MACRO[26] are relied upon. In MACRO, capital stock, available labor, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6[27] for calculating internally consistent scenarios for climatic indicators such as atmospheric concentrations, radiative forcing, annual-mean global surface air temperature and global-mean sea level implications. The energy import restrictions are achieved in MESSAGE through constraining absolute levels of energy imports by region.

TIAM-ECN: The global TIMES Integrated Assessment Model (TIAM) of the Energy research Centre of the Netherlands (ECN) is a linear optimization model, based on energy system cost minimization with perfect foresight until 2100. TIMES is an acronym for The Integrated MARKAL-EFOM System, a model generator inspired by two bottom-up energy system models: The MARket Allocation model (MARKAL) and Energy Flow Optimization Model (EFOM). Depicting 15 world regions, TIAM-ECN simulates the development of the global energy economy over time from

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resource extraction to the consumption of final energy to satisfy demand for useful energy. The objective function is represented by the total discounted aggregate energy system costs summed over all time periods and across all regions. The main cost components included in the objective function are the investment costs and fixed plus variable operation and maintenance costs for energy conversion technologies and emission reduction measures. Since TIAM-ECN is based on a partial equilibrium approach with demands for energy services that respond to changes in their respective prices through end-use price elasticities, savings of energy demand and corresponding cost variations are accounted for in the objective function as well. TIAM-ECN is operated with a comprehensive technology database that includes many possible fuel transformation and energy supply pathways and encompasses technologies based on fossil, nuclear and renewable energy resources. Both currently applied technologies and future advanced technologies, such as ultra-supercritical fossil-fuelled power plants, hydrogen technologies and options for carbon dioxide capture and storage (CCS) in power plants and industrial applications, are available in the model's technology portfolio. With regard to climate change mitigation measures, the model covers reduction options for the three main greenhouse gas emissions, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), for both energy and non-energy related emission sources. More detailed model descriptions and further examples of the application of TIAM-ECN can be found in[28-31], as well as the references therein. As an energy system model, TIAM-ECN allows analysis of greenhouse gas reduction pathways over the whole energy supply chain up to end-use energy demand. The region and sector-specific demands for end-use energy or industrial products are driven by socio-economic parameters, such as GDP, population and number of households. The energy import restrictions are achieved in TIAM-ECN through constraining absolute levels of energy imports by region.

REMIND: The REMIND model is a multi-regional, inter-temporal energy-economy-environment model composed of three components: (i) the macro-economic growth module that describes socio-economic developments and determines the economy's demand for final energy, (ii) a detailed energy system module describing conversion pathways from various types of primary energy via secondary energy to final energy, and (iii) a climate module that simulates the response of the climate system to anthropogenic emissions of greenhouse gases and other forcing agents[32-34]. It is composed of three components. A key feature of the model is that all three components are solved in an integrated, intertemporal optimization framework, thus fully accounting for feedbacks between all components of the system. By embedding a detailed description of the energy sector into a representation of the macroeconomic environment, REMIND combines the major strengths of bottom-up and top-down models. Economic dynamics are calculated through inter-temporal optimization, assuming perfect foresight by economic actors. This implies that technological options requiring large up-front investments that have long pay-back times (e.g. via technological learning) are taken into account in determining the optimal solution. For tasks requiring a detailed representation of land-use, REMIND is coupled to the land-use model MAgPIE[35]. The energy import restrictions are achieved in REMIND through constraining absolute levels of energy imports by region.

WITCH: The WITCH (World Induced Technical Change Hybrid) model is a global integrated assessment model with two main distinguishing features: a regional game-theoretic setup, and an endogenous treatment of technological innovation for energy conservation and decarbonization[36,37]. A top-down inter-temporal optimal growth model is hard linked with a compact representation of the energy sector described in a bottom-up fashion, hence the hybrid denomination. The regional and intertemporal dimensions of the model make it possible to differentiate and assess the optimal response to several climate and energy policies across regions and over time. The non-cooperative nature of international relationships is explicitly accounted for via an iterative algorithm which yields the open-loop Nash equilibrium between the simultaneous activity of a set of representative regions. Regional strategic actions interrelate through GHG emissions, dependence on exhaustible natural resources, trade of fossil fuels and carbon permits, and technological R&D spillovers. These can be useful for analyzing second-best worlds such as those evaluated in this project. Externalities can be internalized in a fully cooperative setting to yield also first-best solutions. R&D investments are directed towards either energy efficiency improvements or development of carbon-free breakthrough technologies. Such innovation cumulates over time and spills across countries in the form of knowledge stocks and flows. The competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors, is described through a soft link with a land use and forestry model (GLOBIOM, Global Biosphere Management Model)[38]. A climate model (MAGICC) is used to compute climate variables from GHG emission levels. While for this exercise WITCH is used for cost-effective mitigation analysis, the model supports climate feedback on the economy to determine the optimal adaptation strategy, accounting for both proactive and reactive adaptation expenditures. The energy import restrictions are achieved in WITCH through constraining absolute levels of energy imports by region.

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