Supplementary Information

Quantifying uncertainties influencing the long-term impacts of oil prices on energy markets and carbon emissions

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Supplementary Tables

Supplementary Table 1. Summary of scenario results for all supply-side sensitivity cases; multiple indicators shown. All climate policy cases assume a globally-harmonized carbon price that begins in 2020 and grows with an interest rate of 5%/yr throughout the century. The constrained biomass case assumes that global primary bio-energy supply (excluding traditional biomass) is limited to 100 EJ/yr at all points in time (see refs. [1,2] for further details); this is consistent with the lower end of sustainable bioenergy potential assessed by the IPCC[3]. Low (high) biofuel/synfuel production cost cases were run by assuming that the fully learned-out investment and O&M costs of the respective technologies are 33% lower (higher) than in the central case; in combination, more optimistic (pessimistic) assumptions for the overall market potential of these technologies were made by assuming maximum allowable (annual) diffusion rates that are two %-points higher (lower) than in the central case. 'FF&I': Fossil fuel and industrial process CO_2 emissions. One gigatonne (Gt) is equal to one billion (10^9) metric tonnes. One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules.

				<< Cumulative values (2010-2050) >>				
Oil price case	Sensitivity case	Carbon price [$/tCO$_2$eq, in 2030]	CO_2 (FF&I) [GtCO$_2$]	Crude Oil [ZJ]	Natural Gas [ZJ]	Low-carbon [ZJ]	Coal [ZJ]	Final Energy [ZJ]
Low	Central	0	1999	9.3	6.4	3.5	9.4	20.6
	Climate Policy	6.7	1809	9.0	6.3	4.2	8.0	20.1
		13.5	1659	8.8	6.1	4.7	7.2	19.7
		27	1424	8.4	5.7	5.6	6.1	19.1
		40	1287	8.0	5.5	6.1	5.3	18.6
		61	1183	7.7	5.3	6.4	4.8	18.0
	Constrained biomass	0	2005	9.3	6.4	3.4	9.5	20.6
		13.5	1697	8.9	6.2	4.2	7.4	19.6
	No oil-to-gas price-coupling	0	2011	9.5	3.7	4.1	11.0	20.3
		13.5	1649	9.1	3.7	5.4	8.5	19.5
	Low biofuel production costs, high availability	0	1995	9.2	6.4	3.6	9.4	20.6
		13.5	1659	8.8	6.1	4.8	7.3	19.7
	Low fossil synfuel production costs, high availability	0	2002	9.2	6.4	3.5	9.5	20.6
		13.5	1657	8.8	6.1	4.7	7.3	19.7
	Low biofuel & fossil synfuel production costs, high availability	0	1998	9.2	6.4	3.6	9.5	20.6
		13.5	1657	8.7	6.1	4.8	7.3	19.7
	High biofuel production costs, low availability	0	2001	9.3	6.4	3.5	9.5	20.6
		13.5	1659	8.8	6.1	4.7	7.2	19.7
	High fossil synfuel production costs, low availability	0	2001	9.2	6.4	3.5	9.5	20.6
		13.5	1659	8.8	6.1	4.8	7.2	19.7
	High biofuel & fossil synfuel production costs, low availability	0	2002	9.3	6.4	3.5	9.5	20.6
		13.5	1658	8.8	6.1	4.8	7.2	19.7
High	Central	0	1860	6.1	2.8	5.6	12.6	18.6
	Climate Policy	6.7	1679	6.0	2.8	5.9	11.5	18.3
		13.5	1521	5.9	2.9	6.3	10.5	18.0
		27	1307	5.8	2.8	6.8	9.1	17.4
		40	1177	5.7	2.9	7.2	8.0	17.1
		61	1070	5.5	2.9	7.5	7.3	16.7
	Constrained biomass	0	1893	6.4	2.8	4.7	12.7	18.5
		13.5	1572	6.2	2.9	5.3	10.6	17.9
	No oil-to-gas price-coupling	0	1882	5.9	4.6	5.3	11.9	19.0
		13.5	1533	5.7	4.7	6.0	9.7	18.2
	Low biofuel production costs, high availability	0	1853	6.0	2.8	5.7	12.6	18.6
		13.5	1518	5.8	2.9	6.4	10.5	18.0
	Low fossil synfuel production costs, high availability	0	1869	5.9	2.8	5.6	12.8	18.6
		13.5	1517	5.8	2.9	6.3	10.7	18.0
	Low biofuel & fossil synfuel production costs, high availability	0	1866	5.9	2.8	5.7	12.8	18.6
		13.5	1518	5.7	2.9	6.4	10.8	18.0
	High biofuel production costs, low availability	0	1863	6.2	2.8	5.4	12.6	18.6
		13.5	1520	6.0	2.9	6.3	10.4	18.0
	High fossil synfuel production costs, low availability	0	1856	6.2	2.8	5.6	12.5	18.6
		13.5	1524	6.0	2.9	6.3	10.3	17.9
	High biofuel & fossil synfuel production costs, low availability	0	1864	6.3	2.7	5.4	12.5	18.6
		13.5	1521	6.1	2.8	6.3	10.2	17.9

Supplementary Table 2. Numerical differences between scenario results for all supply-side sensitivity cases. All changes are calculated relative to the low oil price central case (without climate policy).

Oil price case	Sensitivity case	Carbon price [$/tCO$_2$eq, in 2030]	CO_2 (FF&I) [$GtCO_2$]	Crude Oil [ZJ]	Natural Gas [ZJ]	Low-carbon [ZJ]	Coal [ZJ]	Final Energy [ZJ]
				<< Cumulative values (2010-2050) >>				
Low	Central	0	0	0.00	0.00	0.00	0.00	0.00
	Climate Policy	6.7	-190	-0.21	-0.06	0.64	-1.40	-0.51
		13.5	-340	-0.44	-0.29	1.22	-2.20	-0.87
		27	-575	-0.88	-0.69	2.08	-3.37	-1.52
		40	-711	-1.25	-0.83	2.53	-4.11	-2.02
		61	-816	-1.60	-1.11	2.84	-4.62	-2.60
	Constrained biomass	0	6	0.03	0.00	-0.13	0.05	-0.01
		13.5	-302	-0.40	-0.13	0.69	-2.03	-0.94
	No oil-to-gas price-coupling	0	13	0.23	-2.70	0.56	1.57	-0.32
		13.5	-350	-0.20	-2.68	1.83	-0.97	-1.09
	Low biofuel production costs, high availability	0	-4	-0.02	0.00	0.12	-0.03	0.00
		13.5	-340	-0.48	-0.25	1.26	-2.20	-0.88
	Low fossil synfuel production costs, high availability	0	3	-0.03	-0.01	-0.03	0.06	-0.01
		13.5	-341	-0.49	-0.31	1.22	-2.11	-0.86
	Low biofuel & fossil synfuel production costs, high availability	0	0	-0.04	-0.01	0.09	0.03	-0.01
		13.5	-342	-0.53	-0.26	1.26	-2.11	-0.88
	High biofuel production costs, low availability	0	3	0.02	0.01	-0.05	0.01	0.01
		13.5	-339	-0.42	-0.31	1.21	-2.20	-0.85
	High fossil synfuel production costs, low availability	0	2	0.00	0.01	0.02	0.02	0.01
		13.5	-339	-0.42	-0.27	1.23	-2.26	-0.87
	High biofuel & fossil synfuel production costs, low availability	0	4	0.03	0.01	-0.04	0.01	0.01
		13.5	-341	-0.41	-0.31	1.23	-2.25	-0.87
High	Central	0	-139	-3.14	-3.58	2.05	3.14	-1.97
	Climate Policy	6.7	-320	-3.24	-3.55	2.40	2.09	-2.31
		13.5	-478	-3.32	-3.47	2.78	1.01	-2.60
		27	-691	-3.42	-3.54	3.32	-0.39	-3.13
		40	-822	-3.59	-3.43	3.69	-1.42	-3.49
		61	-929	-3.72	-3.49	3.97	-2.19	-3.88
	Constrained biomass	0	-106	-2.83	-3.56	1.17	3.23	-2.05
		13.5	-427	-3.05	-3.43	1.77	1.18	-2.69
	No oil-to-gas price-coupling	0	-117	-3.37	-1.74	1.72	2.44	-1.58
		13.5	-466	-3.56	-1.68	2.47	0.26	-2.33
	Low biofuel production costs, high availability	0	-146	-3.21	-3.58	2.17	3.12	-1.99
		13.5	-480	-3.40	-3.44	2.87	1.03	-2.61
	Low fossil synfuel production costs, high availability	0	-130	-3.31	-3.57	2.07	3.36	-1.97
		13.5	-482	-3.47	-3.47	2.82	1.28	-2.57
	Low biofuel & fossil synfuel production costs, high availability	0	-132	-3.39	-3.55	2.18	3.38	-1.97
		13.5	-481	-3.56	-3.45	2.88	1.36	-2.58
	High biofuel production costs, low availability	0	-135	-3.04	-3.62	1.91	3.12	-1.97
		13.5	-478	-3.21	-3.50	2.73	0.92	-2.59
	High fossil synfuel production costs, low availability	0	-143	-3.04	-3.61	2.04	3.04	-1.98
		13.5	-475	-3.24	-3.49	2.76	0.87	-2.63
	High biofuel & fossil synfuel production costs, low availability	0	-135	-2.90	-3.65	1.87	3.03	-1.97
		13.5	-477	-3.13	-3.53	2.72	0.75	-2.63

Supplementary Table 3. Summary of scenario results for all demand-side sensitivity cases; multiple indicators shown. Optimistic cases for electric, natural gas, and hydrogen vehicles assume that 'behavioral barriers' to vehicle adoption are largely overcome for the bulk of the population (with respect to, for instance, range anxiety, extent of refueling/recharging infrastructure, and risk aversion). For light-duty vehicles in particular, this amounts to an effective cost reduction of US$3,000-15,000 (depending on the year between 2030 and 2050) off the central case vehicle purchase price for electric vehicles; US$3,500-16,500 for natural gas vehicles; and US$9,000-63,000 for hydrogen vehicles. In addition, assumed upper limits on the maximum contribution of electricity/gas/hydrogen to total transport service demands were relaxed in each of these cases: from 35-50% (depending on the region; in any year to 2100) to 70% (across all regions) for electric vehicles; from 10-30% to 70% for natural gas vehicles; and from 60% to 70% for hydrogen vehicles. Pessimistic cases were only run for electric vehicles, since only this class of technologies experiences any significant deployment by 2050 in the corresponding central cases, including under climate policy. (Put another way, making pessimistic assumptions for natural gas and hydrogen technologies would not have a noticeable effect compared to the central cases.) The pessimistic cases assume electric vehicle costs that are higher and maximum contributions that are lower than in the central cases (e.g., US$6,000-8,000 cost increase for light-duty vehicles, and a decrease in the total transport contribution from electricity of 35-50% down to 25%). For more details about the modeling of the transport sector in MESSAGE, see ref. [1] (the constrained availability cases discussed here were the same as a subset of those used in that study for electric vehicles).

				<< *Cumulative values (2010-2050)* >>				
Oil price case	**Sensitivity case**	**Carbon price [$/tCO$_2$eq, in 2030]**	**CO$_2$ (FF&I) [GtCO$_2$]**	**Crude Oil [ZJ]**	**Natural Gas [ZJ]**	**Low-carbon [ZJ]**	**Coal [ZJ]**	**Final Energy [ZJ]**
Low	Central	0	1999	9.3	6.4	3.5	9.4	20.6
	Low electric vehicle costs, high availability	0	1990	8.7	6.4	3.6	9.7	20.3
		13.5	1626	8.3	6.2	4.9	7.3	19.4
	High electric vehicle costs, low availability	0	2006	9.5	6.4	3.5	9.3	20.7
		13.5	1671	9.0	6.0	4.7	7.2	19.8
	Low natural gas vehicle costs, high availability	0	1999	9.3	6.4	3.5	9.4	20.6
		13.5	1658	8.8	6.1	4.8	7.2	19.7
	Low hydrogen vehicle costs, high availability	0	1999	9.3	6.4	3.5	9.4	20.6
		13.5	1659	8.8	6.1	4.7	7.3	19.7
High	Central	0	1860	6.1	2.8	5.6	12.6	18.6
	Low electric vehicle costs, high availability	0	1855	5.8	2.7	5.6	12.8	18.4
		13.5	1503	5.5	2.9	6.4	10.6	17.8
	High electric vehicle costs, low availability	0	1877	6.7	2.8	5.5	12.3	18.9
		13.5	1540	6.3	2.9	6.2	10.4	18.2
	Low natural gas vehicle costs, high availability	0	1856	5.9	2.9	5.6	12.6	18.6
		13.5	1524	5.8	3.0	6.3	10.6	18.0
	Low hydrogen vehicle costs, high availability	0	1859	6.1	2.8	5.6	12.6	18.6
		13.5	1520	5.9	2.9	6.3	10.5	18.0

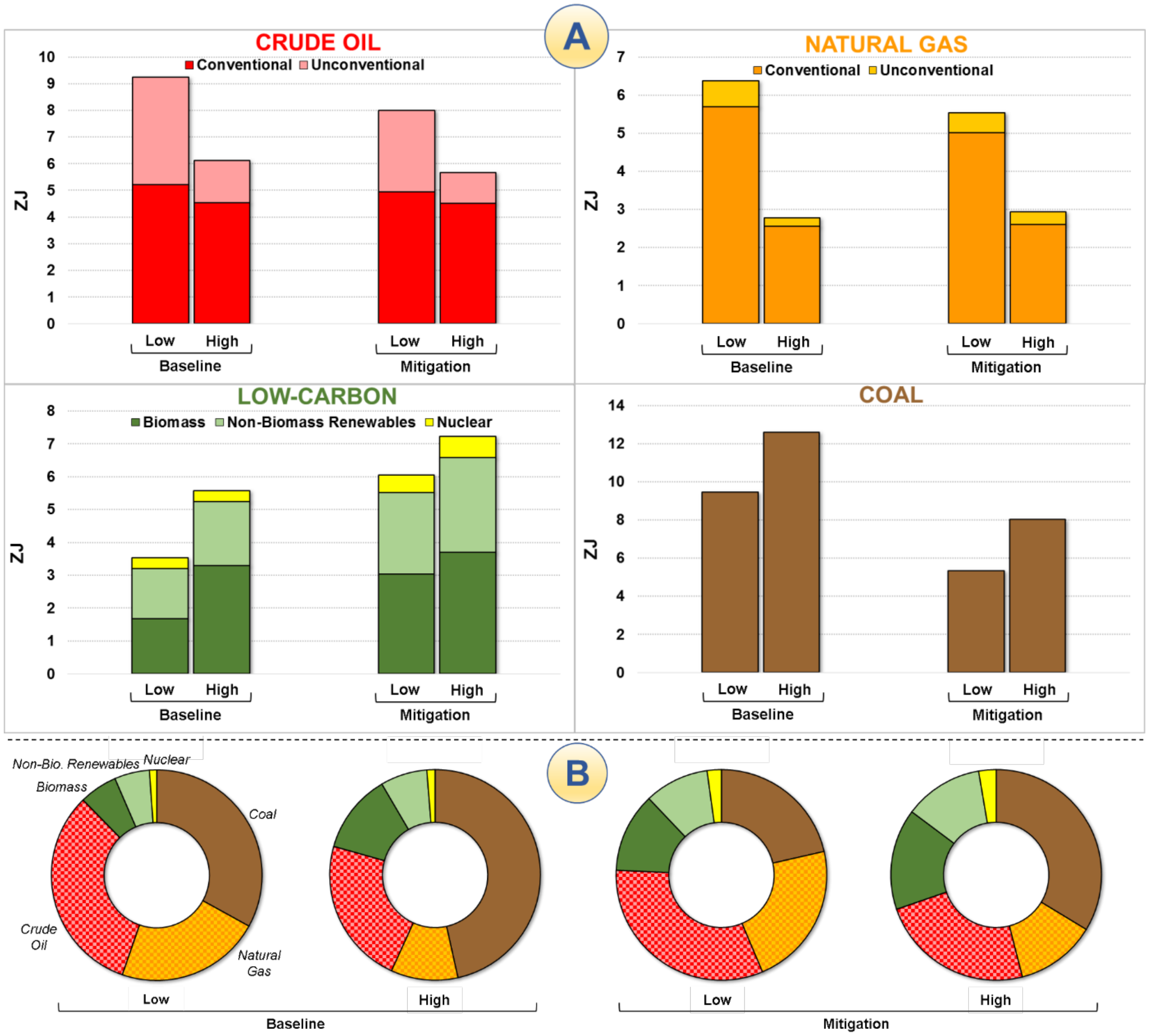
Supplementary Table 4. Numerical differences between scenario results for all demand-side sensitivity cases. All changes are calculated relative to the low oil price central case (without climate policy).

				<< Cumulative values (2010-2050) >>				
Oil price case	**Sensitivity case**	**Carbon price [$/tCO_2$eq, in 2030]**	**CO_2 (FF&I) [$GtCO_2$]**	**Crude Oil [ZJ]**	**Natural Gas [ZJ]**	**Low-carbon [ZJ]**	**Coal [ZJ]**	**Final Energy [ZJ]**
Low	Central	0	0	0.00	0.00	0.00	0.00	0.00
	Low electric vehicle costs, high availability	0	-9	-0.52	0.07	0.03	0.27	-0.32
		13.5	-372	-0.96	-0.20	1.35	-2.18	-1.18
	High electric vehicle costs, low availability	0	7	0.25	0.00	-0.03	-0.12	0.16
		13.5	-327	-0.21	-0.36	1.19	-2.23	-0.73
	Low natural gas vehicle costs, high availability	0	1	0.00	0.01	0.00	0.00	0.01
		13.5	-341	-0.44	-0.32	1.23	-2.20	-0.87
	Low hydrogen vehicle costs, high availability	0	0	0.00	0.00	0.00	0.00	0.00
		13.5	-340	-0.44	-0.29	1.22	-2.19	-0.86
High	Central	0	-139	-3.14	-3.58	2.05	3.14	-1.97
	Low electric vehicle costs, high availability	0	-144	-3.50	-3.65	2.07	3.40	-2.19
		13.5	-495	-3.71	-3.46	2.86	1.17	-2.83
	High electric vehicle costs, low availability	0	-121	-2.57	-3.60	2.00	2.89	-1.66
		13.5	-458	-2.91	-3.50	2.70	0.92	-2.37
	Low natural gas vehicle costs, high availability	0	-143	-3.31	-3.45	2.05	3.16	-1.98
		13.5	-475	-3.46	-3.39	2.76	1.12	-2.59
	Low hydrogen vehicle costs, high availability	0	-140	-3.17	-3.59	2.06	3.16	-1.99
		13.5	-478	-3.40	-3.47	2.78	1.10	-2.62

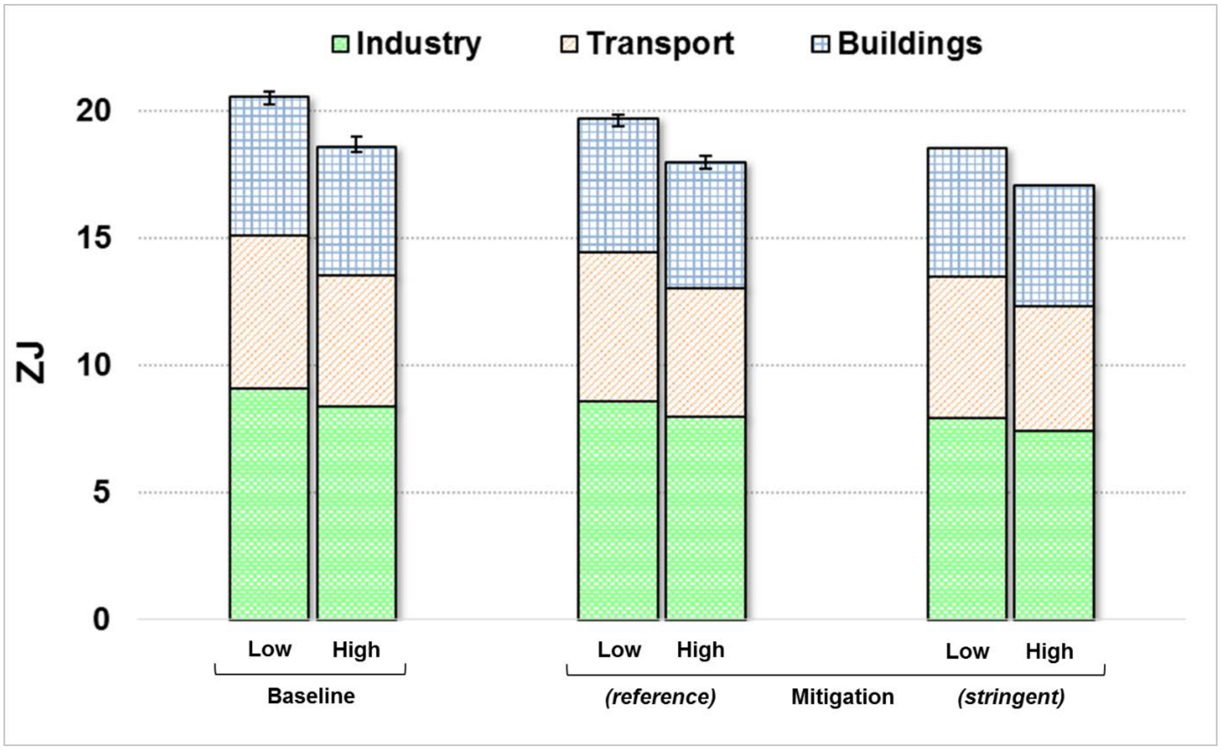
Supplementary Table 5. Summary of scenario results for the intermediate oil price case, along with a comparison to the core low and high oil price cases. The intermediate case is the model's default oil price projection and is meant to portray a continuation of the multi-year average trend between 2006 and 2012.

			<< Cumulative values (2010-2050) >>					
Oil price case	**Sensitivity case**	**Carbon price [$/tCO$_2$eq, in 2030]**	**CO_2 (FF&I) [$GtCO_2$]**	**Crude Oil [ZJ]**	**Natural Gas [ZJ]**	**Low-carbon [ZJ]**	**Coal [ZJ]**	**Final Energy [ZJ]**
Low	Central	0	1999	9.3	6.4	3.5	9.4	20.6
	Climate Policy	13.5	1659	8.8	6.1	4.7	7.2	19.7
Intermediate	Central	0	1939	7.2	4.4	4.8	11.6	19.7
	Climate Policy	13.5	1575	6.9	4.4	5.7	9.2	18.8
High	Central	0	1860	6.1	2.8	5.6	12.6	18.6
	Climate Policy	13.5	1521	5.9	2.9	6.3	10.5	18.0

Supplementary Figures



Supplementary Figure 1. Cumulative energy demand from 2010 to 2050 by primary resource type in the no climate policy ('Baseline') and stringent climate policy ('Mitigation') scenarios, under either low or high oil prices. The climate policy scenario shown here assumed higher carbon prices than the one focused upon in the main text, namely 25 $/t$CO_2$eq in 2020, 40 $/t$CO_2$eq in 2030 and 107 $/t$CO_2$eq in 2050, before continuing into the hundreds of dollars later in the century, in all cases growing with an interest rate of 5%/yr. Such carbon pricing in the MESSAGE framework leads to roughly 2.2 °C warming (median likelihood) above pre-industrial levels by 2100 (with temperatures peaking at roughly that time) and atmospheric GHG concentrations of approximately 525-535 ppm CO_2eq in the same year. In Panel 'A', crude oil and natural gas are sub-divided into conventional and unconventional resources (e.g., oil sands, shale oil and gas, and tight gas), following the definitions of ref. [4,5]; low-carbon energy is sub-divided into nuclear, biomass, and non-biomass renewables. Panel 'B' doughnuts (percentage shares) consolidate cumulative energy demand by resource type for each scenario; conventional and unconventional oil/gas are combined here. Note that in the mitigation cases, a minority share of the coal- and gas-based energy is equipped with carbon capture and storage (coal: 14-22%, gas: 6-10%). For reference, annual global primary energy production in 2010 was approximately 0.5 ZJ.



Supplementary Figure 2. Cumulative energy demand from 2010 to 2050 by end-use sector (final energy) in the no climate policy ('Baseline') and reference and stringent climate policy ('Mitigation') scenarios, under either low or high oil prices. Descriptions of the two climate policy scenarios (13.5 and 40 $/t$CO_2$eq, respectively, in 2030) are given elsewhere in the text – in terms of carbon price schedule and climate impact. Uncertainty ranges reflect values obtained across the sensitivity cases; these cases were not run for the stringent climate policy scenario. For reference, annual global final energy consumption in 2010 was approximately 0.35 ZJ.

Supplementary Discussion

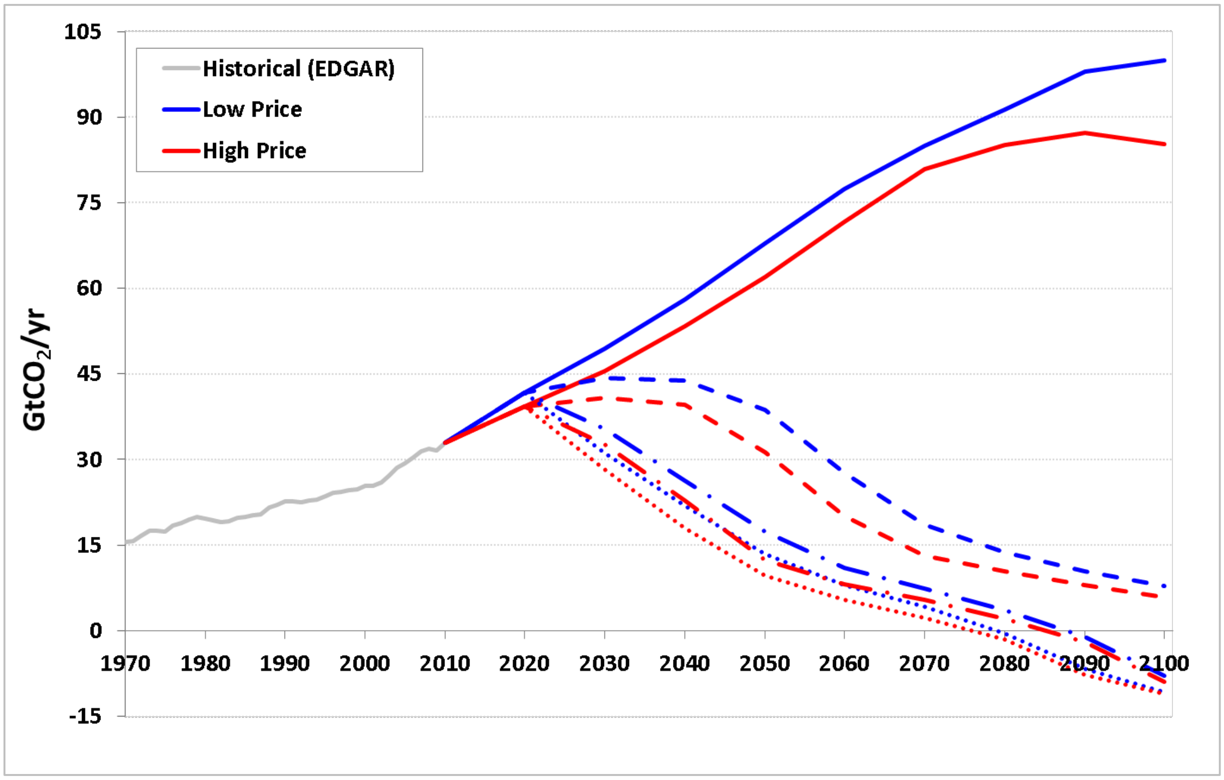
Extended discussion comparing this study's main energy and emissions insights to those of other studies

Previous studies[6-11] – some global, others not – have analyzed the impacts of different oil price levels, resource availabilities, and/or extraction cost potentials on future energy supply/demand and associated emissions, but none have quantitatively assessed how the broader, energy system-wide impacts of diverging oil price futures depend on a suite of critical drivers and uncertainties, such as those previously described. One recent analysis by the IEA[6], for instance, looked at scenarios where oil prices slowly return to either high (128 $/bbl) or mid (85 $/bbl) levels by 2040 (thus, the mid price case reaches considerably greater price levels than our low case, while the high price case only reaches our high case levels by 2030). That analysis arrives at findings similar, in the directional sense, to our reference scenarios: lower oil prices lead to greater cumulative oil and gas demand and lesser renewables and coal demand. In terms of magnitudes, however, the energy demand shifts we estimate (moving from high to low prices) are substantially larger (by one to two orders of magnitude) for each of the various energy sources: from +1.2 to +2.0 ZJ for oil, -0.6 to +2.3 ZJ for gas, -0.4 to -1.9 ZJ for coal, and -0.1 to -1.2 ZJ for renewables and nuclear (to 2040; values spanning all sensitivity cases), compared to +0.13 ZJ for oil, +0.01 ZJ for gas, -0.10 ZJ for coal, and -0.03 ZJ for biomass and non-hydro renewables according to the IEA's assessment (approximate calculations based on numbers shown in Table 4.1 of ref[6]). Such trivial shifts in the energy mix in the latter likely explain why cumulative CO_2 emissions are estimated to be a mere 3 $GtCO_2$ greater in the IEA's mid oil price case, whereas we calculate the increase to be in the range of 50 to 98 $GtCO_2$ (to 2040). An earlier study by van Ruijven and van Vuuren[7] also calculates considerably greater energy and emissions impacts than the recent IEA analysis, though still smaller than ours. Inter-study discrepancies so immense point to deep uncertainties in how critical factors will drive energy system development, and by extension climate change mitigation, over the twenty-first century.

Results for climate policy scenarios more stringent than those discussed in the main text

The following figures depict the CO_2 emissions and temperature change trajectories for a baseline and several pairs of climate policy scenarios, under either low or high oil prices. Descriptions of the reference and stringent climate policy scenarios (13.5 and 40 $/$tCO_2$eq, respectively, in 2030) are given elsewhere in the text. The most stringent climate policy scenario shown here assumed the highest carbon prices of all the policy cases, namely 37 $/$tCO_2$eq in 2020, 61 $/$tCO_2$eq in 2030 and 161 $/$tCO_2$eq in 2050. Such carbon pricing in the MESSAGE framework leads to a temperature peak of 2.0-2.1 °C (median likelihood) above pre-industrial levels around 2080-2090 (with temperatures gradually declining afterward) and atmospheric GHG concentrations of approximately 494-508 ppm CO_2eq in 2100.

One important observation from these figures is that both emissions and temperature change trajectories differ for a given oil price case (say, for the baseline without climate policy). This is a result of the way mitigation is incentivized in these scenarios – namely through carbon pricing, as opposed to a cumulative, century-long GHG budget or a radiative forcing or temperature target for the year 2100. For the same carbon price schedule, less mitigation is incentivized under low oil prices, meaning that both emissions and temperatures are higher than under high oil prices.



Supplementary Figure 3. Fossil fuel and industrial process CO_2 emissions in the no climate policy baseline (solid lines) and reference (dashed lines; 13.5 $/t$CO_2$eq in 2030), stringent (dashed-dotted lines; 40 $/t$CO_2$eq in 2030), and most stringent (dotted lines; 61 $/t$CO_2$eq in 2030) climate policy scenarios, under either low or high oil prices.

Supplementary Figure 4. Global average temperature change (median likelihood) relative to pre-industrial levels in the no climate policy baseline (solid lines) and reference (dashed lines; 13.5 \$/tCO_2eq in 2030), stringent (dashed-dotted lines; 40 \$/tCO_2eq in 2030), and most stringent (dotted lines; 61 \$/tCO_2eq in 2030) climate policy scenarios, under either low or high oil prices.

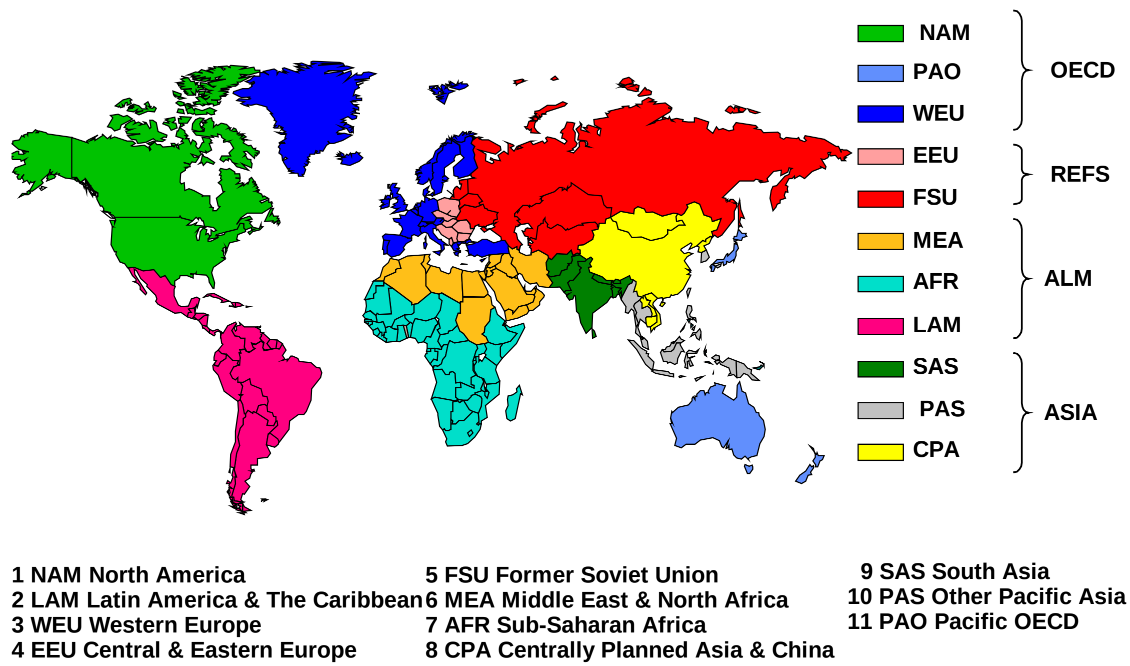
Supplementary Methods

Brief description of the MESSAGE integrated assessment modeling framework

This section provides additional information about MESSAGE on top of what is mentioned in the 'Methods' section of the main text. For even more detailed information, the reader is referred to the IAM model documentation Wiki that has been developed within the context of the EU-FP7 ADVANCE project: https://wiki.ucl.ac.uk/display/ADVIAM/MESSAGE.

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment model (IAM) is a global systems engineering optimization model used for medium-to-long-term energy system planning, energy policy analysis, and scenario development[12-14]. Developed at the International Institute for Applied Systems Analysis (IIASA) for more than two decades, MESSAGE is an evolving framework that, like other global IAMs in its class (e.g., MERGE, ReMIND, IMAGE, WITCH, GCAM, etc.), has gained wide recognition over time through its repeated utilization in developing global energy and emissions scenarios[13,15]).

MESSAGE divides the world up into eleven (11) regions (Supplementary Figure 5, Supplementary Table 6) in an attempt to represent the global energy system in a simplified way, yet with many of its complex interdependencies, from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Trade flows (imports and exports) between regions are monitored, capital investments and retirements are made, fuels are consumed, and emissions are generated. In addition to the energy system, the model includes also the other main greenhouse-gas emitting sectors, agriculture and forestry. MESSAGE tracks a full basket of greenhouse gases and other radiatively active gases – CO_2 , CH_4 , N_2O , NO_x , volatile organic compounds (VOCs), CO, SO_2, PM, BC, OC, NH_3, CF_4, C_2F_6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF_6 – from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning). In other words, all Kyoto gases plus several others are accounted for.



Supplementary Figure 5. Map of 11 regions in MESSAGE model

Supplementary Table 6. Listing of 11 MESSAGE regions by country

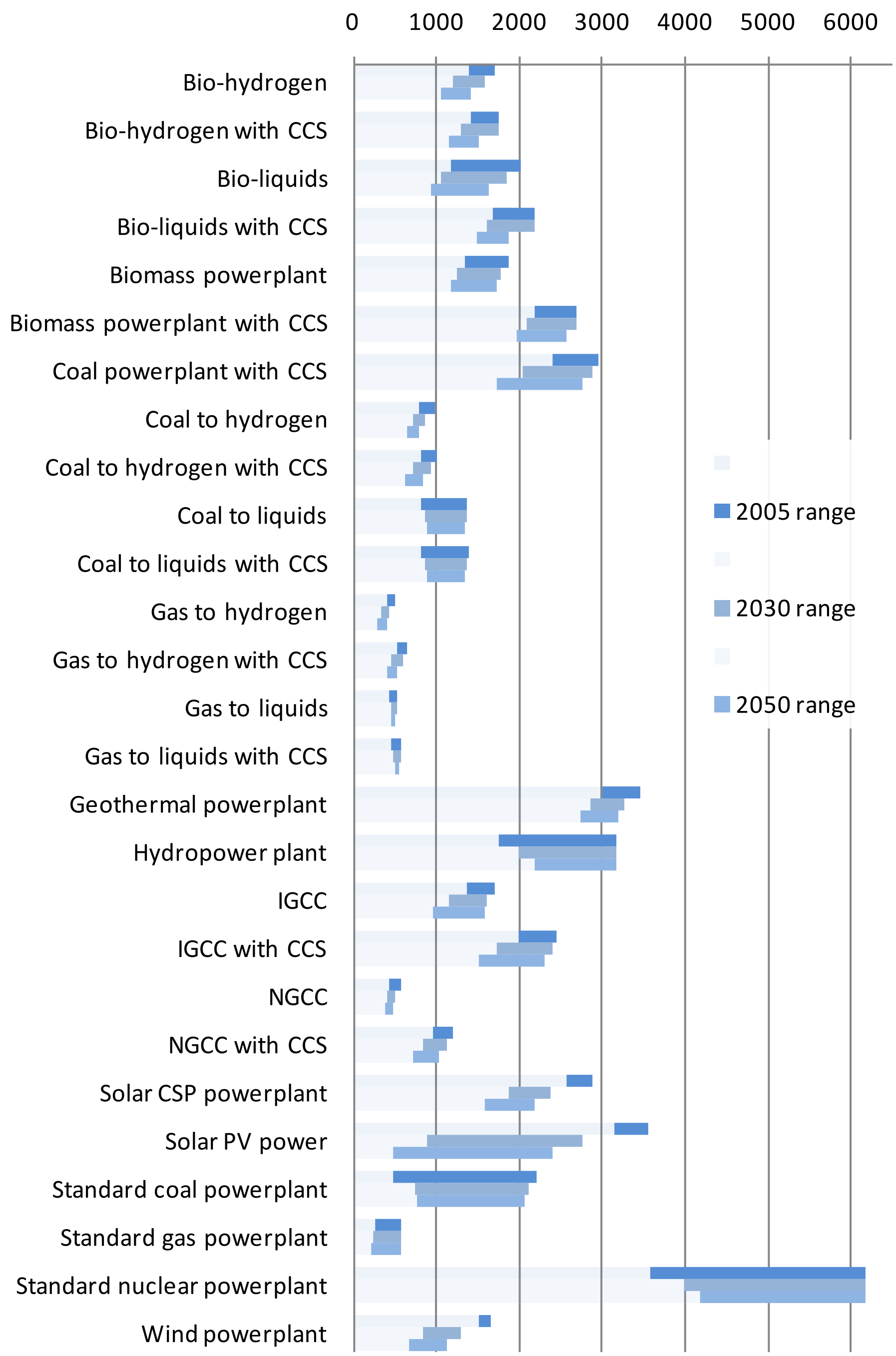
11 MESSAGE regions	Definition (list of countries)
NAM	**North America** (Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
WEU	**Western Europe** (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	**Pacific OECD** (Australia, Japan, New Zealand)
EEU	**Central and Eastern Europe** (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Estonia, Latvia, Lithuania)
FSU	**Former Soviet Union** (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA	**Centrally Planned Asia and China** (Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	**South Asia** (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	**Other Pacific Asia** (American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea,

	Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa)
MEA	**Middle East and North Africa** (Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)
LAC	**Latin America and the Caribbean** (Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)
AFR	**Sub-Saharan Africa** (Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can make use of. In the course of a model run, MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (1990-2110). It does this based on a linear programming, optimization solution algorithm, typically utilizing perfect foresight (though limited/myopic foresight is also possible[16-18]). The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and – in certain versions of the model – the phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, these factors can lead to "lock-in" effects[19,20] and path dependency (change occurs in a persistent direction based on an accumulation of past decisions). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to alter its course.

Important inputs for MESSAGE are technology costs and technology performance parameters (e.g., efficiencies and investment, variable, and O&M costs). For the scenarios included in this paper, technical, economic and environmental parameters for over 100 energy technologies are specified explicitly in the model. Costs of technologies are exogenously assumed to decrease over time as experience (measured as a function of cumulative output) is gained. For assumptions concerning the main energy conversion technologies see refs. [13-15,21]. (Supplementary Figure 6 shows the ranges of investment costs per kW that are assumed in MESSAGE across the different regions and over time.) For information on carbon capture and storage technologies specifically, see ref. [22]. While endogenous technological learning is possible with MESSAGE (see ref. [23]), this functionality was not utilized in the current study.

MESSAGE is able to choose between both conventional and non-conventional technologies and fuels (e.g., advanced fossil, nuclear fission, biomass, and renewables), and in this respect the portfolio of technologies/fuels available to the model obviously has an important effect on the model result. In the version of the model used in this study, we consider a portfolio of technologies whose components are either in the early demonstration or commercialization phase (e.g., coal, natural gas, oil, nuclear, biomass, solar, wind, hydro, geothermal, carbon capture and storage, hydrogen, biofuels, and electrified transport, to name just a subset). Notably, this portfolio includes bio-CCS, a technology that can potentially lead to negative emissions (i.e., permanent underground storage of CO_2 which was originally pulled out of the atmosphere by photosynthesis). Exceedingly futuristic technological options, such as nuclear fusion and geo-engineering, are, however, not considered.



Supplementary Figure 6. Assumed investment costs per unit of energy production capacity, in kW (excluding load factor), across the different MESSAGE regions and over time

Other important input parameters for our modeling include fossil fuel resource estimates and potentials for renewable energy. The resource estimates are brought into the model as cumulative supply curves (specific to each region), which in the case of fossil energy are combined with extraction technologies that must be invested into for production to occur. Despite the cumulative supply curves being fixed, technological learning exists in the form of gradually declining costs of resource extraction; there are also limits to how quickly these extraction technologies can scale up (e.g., representing capital and labor constraints). Note that for fossil fuel availability, the model distinguishes between conventional and unconventional resources for eight different categories of (oil, gas, coal) occurrences[5,13]. For biomass potentials, we rely on spatially explicit analysis of biomass availability and adopt the assumptions discussed in ref. [13].

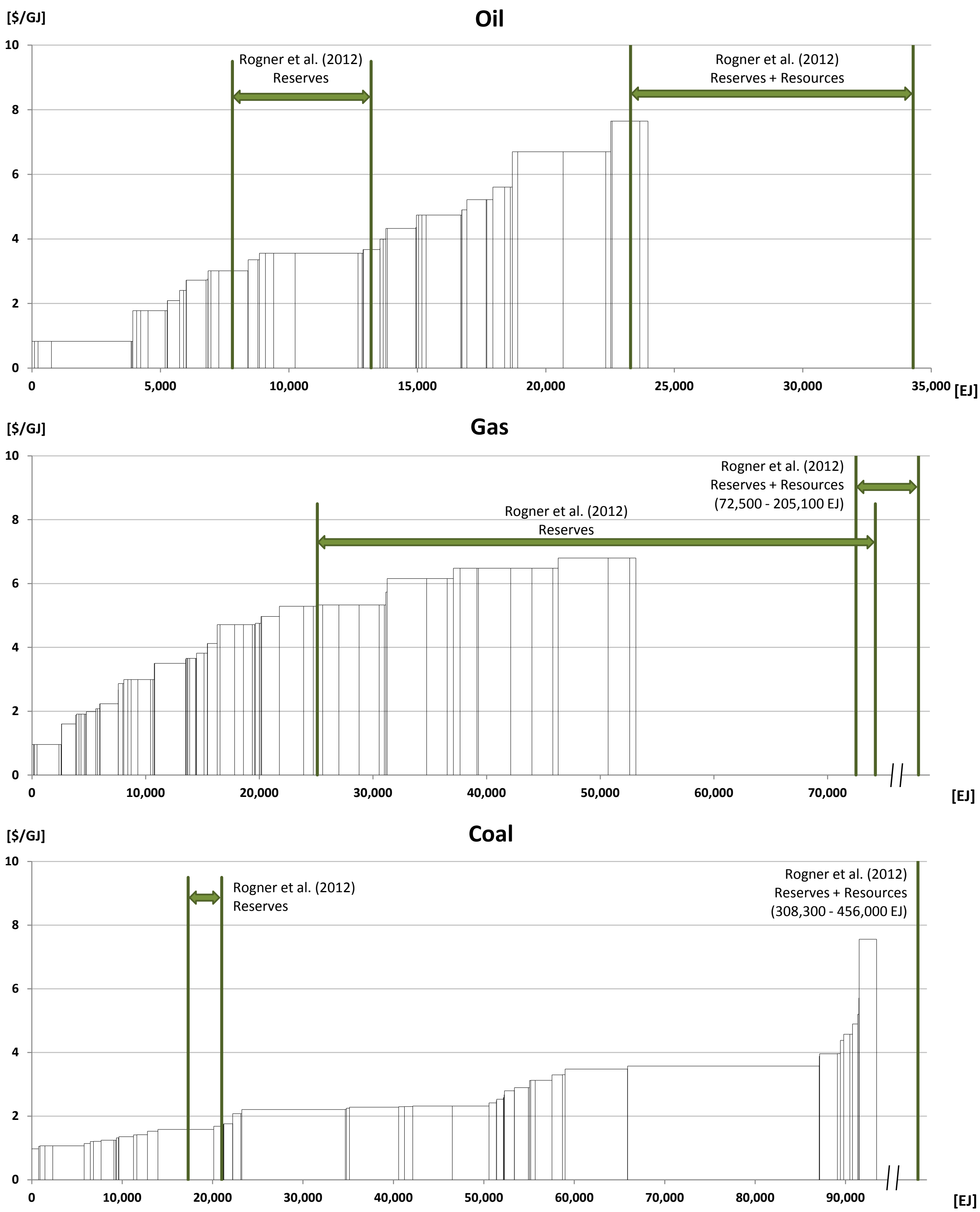
Supplementary Table 7 shows the assumed total quantities of fossil fuel resources in the MESSAGE model for the base year 2005 (global sums). The assumptions are compared with estimates from the Global Energy Assessment [4] as of the year 2009 (see also Supplementary Figure 7, which gives the resource estimates as global supply curves; note that these supply curves do not include the effect of the "price adjustment factors" for the different oil/gas price cases, which we apply in the current study). Estimating fossil fuel reserves is built on both economic and technological assumptions. With an improvement in technology or a change in purchasing power, the amount that may be considered a "reserve" vs. a "resource" (generically referred to here as resources) can actually vary quite widely. The low oil price case developed in the current study reflects this, with the regional supply curves for cumulative crude oil availability assumed to be different from those of the high oil price case (i.e., the standard assumptions in MESSAGE, which are consistent with ref. [5]). More specifically, we lower the regionally-specifically production costs for oil in Categories V to VIII, which, according to the original ref. [5] definitions, correspond specifically to unconventional resources of the following types: oil shales, tar sands/bitumen, heavy and extra-heavy crude oils, and deep-sea oil occurrences. Within the MESSAGE framework, this translates to a flattening out of the regional crude oil supply curves in the horizontal (quantity) dimension, meaning that a greater quantity of unconventional resources are available at a given cost of production (i.e., the supply curve plateaus at its mid-to-upper end, instead of continuously rising). As described in the main text, this storyline is meant to reflect a future of strong technological change in unconventional oil extraction, leading to lower costs of production.

Supplementary Table 7. Assumed global fossil fuel reserves and resources in the MESSAGE model, according to ref. [5]. Estimates from the Global Energy Assessment [4] also added for comparison.

Source	**MESSAGE**	**Rogner et al. (2012)**		
	Reserves + Resources [ZJ]	**Reserves [ZJ]**	**Resources [ZJ]**	**Additional occurrences [ZJ]**
Coal	259	17.3 – 21.0	291 – 435	
Conventional Oil	9.8	4.9 – 7.6	4.2 – 6.2	
Unconventional Oil	30.0$^{\alpha}$	3.8 – 5.6	11.3 – 14.9	>40
Conventional Gas	16.8	5.0 – 7.1	7.2 – 8.9	
Unconventional Gas	23.0	20.1 – 67.1	40.2 – 122	>1,000

$^{\alpha}$ The quantity of unconventional oil resources ultimately exploited depends on the underlying production cost assumptions, which vary by low/high oil price case.

Coal is the largest resource among fossil fuels with more than 100 ZJ; it accounts for more than 50% of total fossil reserve+resource estimates even at the higher end of the assumptions, which includes considerable amounts of unconventional hydrocarbons. Oil is the most vulnerable fossil fuel at less than 10 ZJ of conventional oil and possibly less than 10 ZJ of unconventional oil. Natural gas is more abundant in both the conventional and unconventional categories. When “additional occurrences” of unconventional oil and gas are considered, the potential resource base increases considerably.



Supplementary Figure 7. Cumulative global resource supply curves for oil, gas, and coal in the MESSAGE model. The double-headed arrows show the central reserve and resource estimates from Rogner et al. [24]. Note that these supply curves do not include the effect of the "price adjustment factors" for the different oil/gas price cases.

In the overall MESSAGE framework, price-induced demand responses for energy carriers at the final energy level result from a combination of three different factors: (i) adopting more efficient technologies, (ii) fuel switching and the resulting relative efficiency changes (e.g., differences between solids, gases and electricity), and (iii) demand response at the useful energy level. The latter changes in useful energy demand are modeled in MESSAGE via an iterative link to MACRO, an aggregated macro-economic model of the global economy[25]. Through an iterative solution process, MESSAGE and MACRO exchange information on energy prices, energy demands, and energy system costs until the demand responses are such (for each of the six end-use demand categories in the model: electric and thermal heat demands in the industrial and residential/commercial sectors (1-4), non-energy feedstock demands for industrial applications (5), and mobility demands in the transportation sector (6)) that the two models have reached equilibrium. This process is parameterized off of a baseline scenario (which assumes some autonomous rate of energy efficiency improvement, AEEI) and is conducted for all eleven MESSAGE regions simultaneously. Therefore, the demand responses motivated by MACRO are meant to represent the additional (compared to the baseline) energy efficiency improvements and conservation that would occur in each region as a result of higher prices for energy services. The macro-economic response captures both technological and behavioral measures (at a high level of aggregation), while considering the substitutability of capital, labor, and energy as inputs to the production function at the macro level.

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), version 6.8, has been used in this study to estimate the climate system impacts of the varying greenhouse gas emission trajectories of the scenarios. MAGICC is a reduced-complexity coupled global climate-carbon cycle model, in the form of a user-friendly software package that runs on a personal computer[26,27]. In its standard form, MAGICC calculates internally consistent projections for atmospheric concentrations, radiative forcing, global annual-mean surface air temperature, ice melt, and sea level rise, given emissions trajectories of a range of gases (CO_2, CH_4, N_2O, CO, NO_x, VOCs, SO_2, and various halocarbons, including HCFCs, HFCs, PFCs, and SF_6), all of which are outputs from MESSAGE. The time horizon of the model extends as far back as 1750 and can make projections as far forward as 2400. The climate model in MAGICC is an upwelling-diffusion, energy-balance model, which produces output for global- and hemispheric-mean temperature and for oceanic thermal expansion. Climate feedbacks on the global carbon cycle are accounted for through the interactive coupling of the climate model and a range of gas-cycle models. MAGICC has been used in all IPCC Assessment reports, dating back to 1990, and its strength lies in its ability to replicate the more complex global climate models that run on supercomputers. The CO_2-eq concentrations that we report in the main text are calculated from total radiative forcing estimates from MAGICC, using the standard approximation formula: $C_0 \exp(RF/\alpha)$, where C_0 = 278 ppm and α=5.35.

Further, more detailed information on the MESSAGE modeling framework is available, including documentation of model set-up and mathematical formulation[12,13] and the model's representation of technological change and learning[22,28,29].

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