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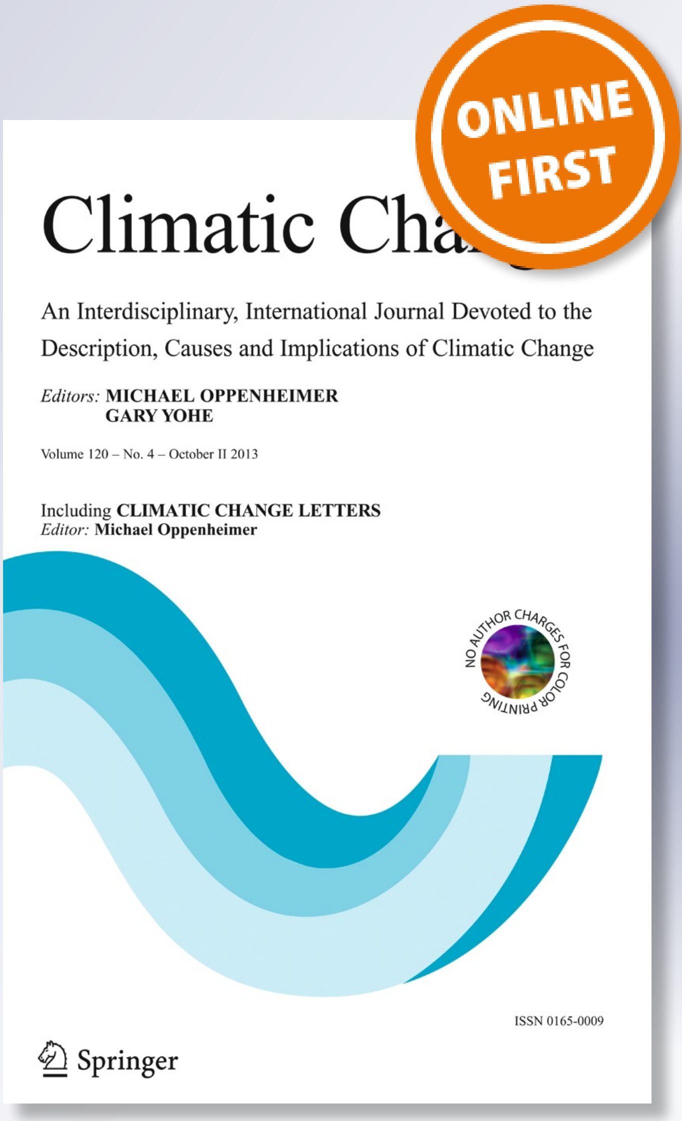

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Fossil resource and energy security dynamics in conventional and carbon-constrained worlds

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Abstract Fossil resource endowments and the future development of fossil fuel prices are important factors that will critically influence the nature and direction of the global energy system. In this paper we analyze a multi-model ensemble of long-term energy and emissions scenarios that were developed within the framework of the EMF27 integrated assessment model inter-comparison exercise. The diverse nature of these models highlights large uncertainties in the likely development of fossil resource (coal, oil, and natural gas) consumption, trade, and prices over the course of the twenty-first century and under different climate policy frameworks. We explore and explain some of the differences across scenarios and models and compare the scenario results with fossil resource estimates from the literature. A robust finding across the suite of IAMs is that the cumulative fossil fuel consumption foreseen by the models is well within the bounds of estimated recoverable reserves and resources. Hence, fossil resource constraints are, in and of themselves, unlikely to limit future GHG emissions this century. Our analysis also shows that climate mitigation policies could lead to a major reallocation of financial flows between regions, in terms of expenditures on fossil fuels and carbon, and can help to alleviate

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near-term energy security concerns via the reductions in oil imports and increases in energy system diversity they will help to motivate. Aggressive efforts to promote energy efficiency are, on their own, not likely to lead to markedly greater energy independence, however, contrary to the stated objectives of certain industrialized countries.

1 Introduction and motivation

Fossil resource endowments and the future development of fossil fuel prices are important factors that will critically influence the nature and direction of the global energy system. On the one hand, the availability and geographic distribution of fossil fuels will largely dictate energy trade patterns. On the other hand, changes in fossil fuel prices will have important implications for the affordability of energy in the near-to-midterm, and perhaps equally important, impact the potential of alternative energy options to diffuse into the market. The availability and price of fossil fuels are therefore not only important drivers of the carbon intensity of the future energy system, they are also critical determinants of the costs of climate change mitigation.

In this paper we analyze a multi-model ensemble of long-term energy and emissions scenarios that were developed within the framework of the Energy Modeling Forum 27 (EMF27) model inter-comparison exercise. The diverse nature of these integrated assessment models (IAM), including their underlying assumptions, highlights large uncertainties in the likely development of fossil resource (coal, oil, and natural gas) consumption and prices over the course of the twenty-first century. We explore and explain some of the differences across scenarios and models and compare the scenario results with fossil resource estimates from studies in the literature. In particular, we address the question of whether or not physical resource availability is likely to be a limiting factor for future greenhouse gas (GHG) emissions and, thus, climate change. Previous reviews (e.g., Höök and Tang (2013)) have found that the literature remains sparse on this issue. Similarly, we survey the literature that assesses the world's capacity for geological storage of carbon dioxide (CO_2) and put these estimates into the context of what is shown by the EMF27 models, again in an attempt to identify potential constraints on this "resource" base.

Moreover, because the deployment of fossil fuels differs markedly in scenarios that assume stringent climate policies compared to those without, we also compare resource consumption and price trends in both of these types of scenarios. Implications of climate policies for regional expenditures on fossil fuels are explicitly analyzed, and the results are put into a future perspective by relating them to potential expenditures for carbon mitigation. Finally, we introduce simple indicators for exploring the regional energy security implications of climate policy, with a particular emphasis on import dependency and energy system diversity–proxies for the sovereignty and resilience of the future energy system–as proposed in Jewell et al. (2013b).

In carrying out the analyses described above, we focus on only a subset of the EMF27 scenarios. These scenarios, which are referred to throughout the paper, are briefly described below. A more detailed overview of the study design can be found in the EMF27 overview by Kriegler et al. (this issue).

- Base FullTech

  Baseline scenario with intermediate energy demand growth (final energy intensity improvements compatible with historically observed improvements of about 1.2 % per year globally). All technologies are assumed to be available; no restrictions.

- Base LowEI

  Low energy demand growth scenario (final energy intensity improvements are more rapid, leading to 20–30 % lower final energy demand in 2050 and 35–45 % in 2100 compared to the Base FullTech reference case). All technologies available.

- 550 FullTech

  Climate policy scenario with intermediate energy demand growth. All technologies available. 550 parts-per-million ppm CO_2-equivalent (CO_2-eq) climate target, not to be exceeded throughout the twenty-first century.

- 450 FullTech

  Climate policy scenario with intermediate energy demand growth. All technologies available. 450 ppm CO_2-eq climate target; overshoot of target is allowed as long as concentrations return to this level by 2100.

2 The impact of climate mitigation on fossil resource markets

Future coal, oil, and gas consumption depends strongly on the cost and availability of these resources relative to other energy supply options. In most cases, this information is input into a given IAM as a set of assumptions in the form of supply curves. Such information was collected for this paper for a subset of the IAMs participating in the EMF27 exercise. These global fossil fuel supply curves are given in the "Supplementary Material" (SM). Because estimates of available fossil fuel resources (Table 1) vary significantly in the literature (BGR 2009, 2010, 2012; BP 2010; Rogner et al. 2012; USGS 2000; WEC 2007), the supply curve assumptions in the models also differ significantly. Total available resources of oil (at all cost steps) range from 19 zettajoules (MERGE) to levels several times higher (GRAPE), depending on whether unconventional oil resources and reserves are included, whether additional occurrences of oil that are not economically or technically viable today are considered, and how exactly the oil supply curves are incorporated into the models. At $100 per barrel, for example, ReMIND assumes the least amount of oil available (15 ZJ) while GCAM has the most (91 ZJ). Similar comparisons are possible for other resources at varying price thresholds.

Table 1 Ranges of fossil fuel reserve and resource estimates in the literature (source: Global Energy Assessment (Rogner et al. 2012)). The distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves. Additional occurrences of unconventional oil and gas–on the order of >40 and >1000 ZJ, respectively–are excluded here due to large uncertainties regarding volumes and economic potential

	Type	**Reserves (ZJ)**	**Resources (ZJ)**	**Total Reserves + Resources (ZJ)**		
Oil	Conventional	4.9 – 7.6	4.2 – 6.2	9.1 – 13.8	24.1 – 34.2	404.9 – 695.3
	Unconventional	3.8 – 5.6	11.3 – 14.8	15.0 – 20.4		
Natural Gas	Conventional	5.0 – 7.1	7.2 – 8.9	12.2 – 16.0	72.5 – 205.0	
	Unconventional	20.1 – 67.1	40.2 – 121.9	60.3 – 189.0		
Coal	-	17.3 – 21.0	291.0 – 435.0	-	308.3 – 456.1	

The term "resources" is used generically in this paper to refer to fossil energy commodities of all types, whether technically classified as conventional/unconventional or reserves/resources

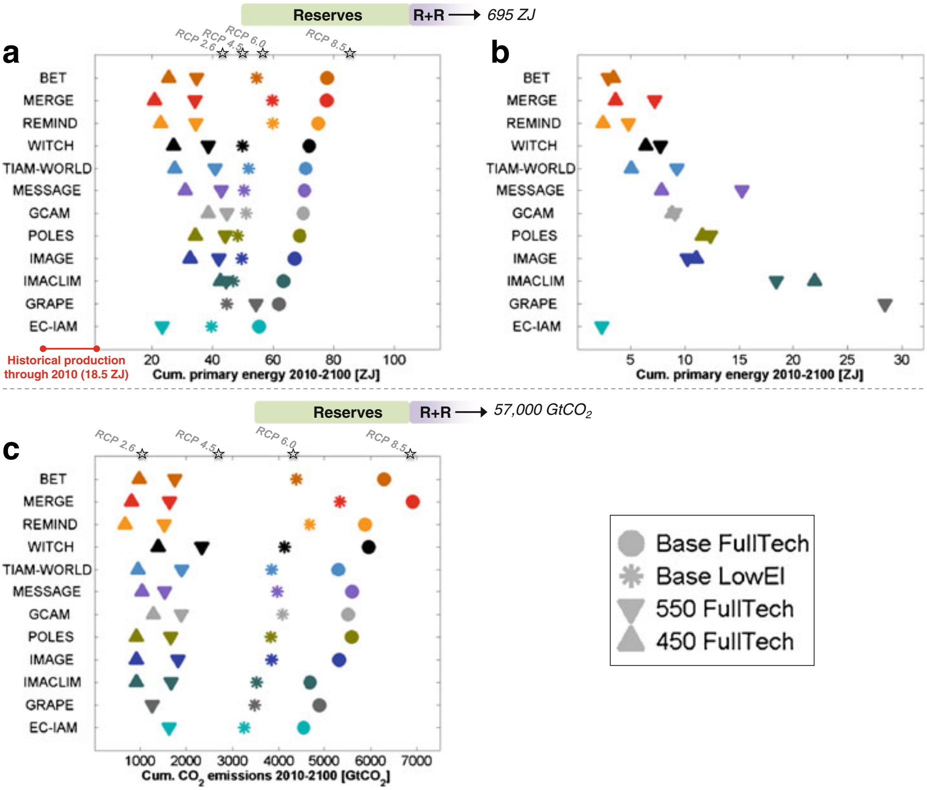


Fig. 1 Cumulative global primary energy consumption of fossil fuels and cumulative global emissions of CO_2 across the EMF27 models (full-century models only). Panel (a) shows all fossil fuels (coal, oil, and natural gas combined) for different EMF27 scenarios; Panel (b) only those fossil fuels used in combination with CCS in the climate policy scenarios (450 FullTech, 550 FullTech). Panel (c) focuses on CO_2 emissions from fossil fuels and industry. Not all scenarios were run by all models. EMF27 model results are compared to the four RCP scenarios (van Vuuren et al. 2011), and to the lower/upper fossil reserves and resources estimates of Table 1 ("R + R" = reserves + resources). In the case of Panel (c), the reserves and resource estimates represent the total quantity of CO_2 emissions that would result if the fossil fuels in these two categories were fully combusted

Differences in these cost-availability mappings, combined with the cost-availability of other energy supply options, result in significant differences in the cumulative consumption of fossil resources over the 21st century. Figure 1 illustrates these differences by showing, for a given scenario, the large range of total fossil fuel consumption that is calculated by the various models. (Note that coal, oil, and gas consumption is broken out separately in Fig. 1 of the SM.) Despite the uncertainty, however, a fairly robust trend across the models is that in the baseline scenario (Base FullTech), which is built on reference energy demand growth projections, fossil fuels are likely to continue to dominate the energy mix for the foreseeable future (55–80 ZJ from 2010 to 2100). Yet, even in the highest scenarios in our set, cumulative consumption is well below the estimated amount of total fossil resource available (405–695 ZJ; see Table 1). On a fuel-by-fuel basis, this is also the case (see "Supplementary Material"), especially for coal, a fuel that is massively deployed in the baseline scenarios of several models (e.g., MERGE), though one for which the resource base is extremely large. For oil and gas, this would mean eventually tapping into more costly, unconventional resources and reserves. As an example, no more than 25 ZJ of oil is consumed between 2010 and 2100 across the models in any scenario (see "Supplementary Material"); and while this level is well within the range of total oil estimated to be available globally (24 ZJ to 74 ZJ),[1] it is considerably larger than the amount of conventional oil (9 ZJ to 14 ZJ).[2]

An important conclusion deriving from the comparison of EMF27 model results to the resource estimates of the literature is that fossil resource constraints are, in and of themselves, unlikely to limit future GHG emissions and, thus, global climate change during the twenty-first century. This is shown clearly in Fig. 1 (Panel (a)) by noting how the size of the global fossil resource base (based on values in Table 1) far exceeds the levels of fossil consumption that are expected by 2100 according to the models. Interestingly, this also seems to be the case in even higher energy demand futures, such as the Representative Concentration Pathways (RCP) 8.5 scenario (Riahi et al. 2011), which has also been added to the figure for comparison.[3] Panel (c) further makes the point by showing the cumulative emissions of CO_2 in both the EMF27 and RCP scenarios and comparing them to the emissions that would hypothetically be realized if the world's reserves and resources of coal, oil, and gas were each combusted in their entirety. Clearly, none of the scenarios come anywhere close to this potentially high quantity, an amount that is off the chart shown here but could easily reach into the tens of thousands of gigatonnes (Gt) of CO_2. (Note that in some scenarios cumulative emissions do approach those strictly from reserves. This is because the models consume a mixture of reserves and resources for coal and oil; see SM.) These results across a suite of IAMs appear to contradict those of other recent studies (e.g., Ward et al. (2012) and Höök and Tang (2013)), which argue that fossil resource scarcity will ultimately be a limiting factor in GHG emissions growth. Such studies assert that IAM scenario estimates for future fossil fuel production are too optimistic.

Aggressive energy efficiency and decarbonization efforts will naturally lead to major reductions in fossil resource consumption compared to the baseline scenarios. This is illustrated by the 550 FullTech and 450 FullTech scenarios in Fig. 1. Interestingly, the reductions exhibited in these scenarios are, for nearly all models, larger than those observed in the Base LowEI (low energy demand) scenario. That is, as a stand-alone climate mitigation strategy, energy efficiency and conservation cannot on its own provide the required large reductions in fossil fuel use that are needed to stabilize the global climate at either 550 or 450 ppm CO_2-eq.[4] What the models do show, in contrast, is that in order to

[1] This range includes additional occurrences of unconventional oil (see Rogner et al. (2012)).

[2] The extent of ultimately recoverable oil, gas, and coal is the subject of numerous reviews; yet, still the range of values in the literature is large (Table 1). Uncertainties stem from varying boundaries of what is included in the analysis of a finite stock of an exhaustible resource, e.g., conventional oil only or conventional oil plus unconventional occurrences, such as oil shale, oil sands, and extra-heavy oils (Rogner et al. 2012). Past studies that have indicated stricter resource limitations (e.g., Rutledge (2011) for coal) generally assume narrower boundary conditions, excluding some portion of reserves and/or resources. Such a perspective is useful to explain short-term trends of proven reserves but is less applicable for long-term analysis of full-century scenarios, which must consider future technological improvements and other factors that have historically contributed to increases in fossil reserves extractable at market conditions.

[3] The RCP scenarios were developed by four different IAMs and were meant to serve as inputs for climate and atmospheric chemistry modeling as part of the preparatory phase for the development of new scenarios for the IPCC's Fifth Assessment Report and beyond. Each RCP is named according to the radiative forcing level (W/m^2) attained in 2100.

[4] Energy efficiency and conservation, as discussed here, refers to the combined, additional set of technological and structural changes that take place throughout the economy leading to marked increases in the autonomous rates of energy efficiency improvement (AEEI) for individual regions and sectors. Such developments represent an alternative scenario worldview and are not envisioned to be motivated by climate-related concerns.

achieve stabilization, the ultimately permissible amount of fossil consumption depends to a large extent on the utilization of carbon capture and storage (CCS) (Panel b of Fig. 1), for which a number of technical and socio-political challenges still remain to be overcome (IPCC 2005). The climate targets can in most cases be met without CCS (not shown here, instead see Krey et al. (2013)), but then other issues and concerns could arise, with respect to renewable resource availability, reliance on nuclear power, and so on. To be sure, there is a large spread in fossil CCS deployment across models for a given scenario.[5] In the 450 FullTech, for example, 20-85 % of cumulative coal consumption is in combination with CCS, while the range is 15-50 % for gas. These differences lead to varying estimates for the total volume of CO_2 that must be geologically stored (see Box 1). Note that models deploy fossil CCS technologies in varying quantities because of the heterogeneous suites of mitigation measures represented within them, including renewables (Luderer and Krey 2013), bio-energy (Rose et al. 2013a), afforestation (Popp et al. 2013), and non-GHG emissions (Rose et al. 2013b). Furthermore, differences in model structure and solution framework affect the flexibility of models to reduce energy demand and to substitute other fuels in the energy supply (see "Supplementary Material" for further explanation).

Box 1. CO_2 storage requirements to meet climate stabilization targets

One can think of the world's geological storage capacity for CO_2 as a kind of "resource" whose utilization depends on the amount of fossil fuel consumed over the next decades, or perhaps centuries. The availability and geographic distribution of such reservoirs will become increasingly important in a carbon-constrained world, and concerns could eventually surface regarding the potential of this resource to permanently sequester the large flows of CO_2 that may ultimately be required. Estimates of global storage capacity vary quite widely in the current literature, from 1,680 $GtCO_2$ (IEA 2010) to 24,000 $GtCO_2$ (Benson et al. 2012), depending on how much of the capacity is deemed viable. Figure 2 of the SM compares these literature estimates to the model-estimated cumulative volumes of CO_2 stored (both regionally and globally) in the 450 FullTech climate stabilization scenario. In sum, by the end of the century, EMF27 model results point to global CO_2 storage requirements of around 1,300 $GtCO_2$ (median across models), with a range of 650 to 2,400 $GtCO_2$. Thus, except in the most pessimistic case, enough storage capacity appears to exist to meet demand over the twenty-first century. This conclusion also generally holds at the regional level; though if there are any concerns, this is where they could potentially surface. For instance, whereas countries of the OECD90 appear to have plenty of excess storage capacity, other regions (especially Asian countries) could eventually approach their capacity limits, depending on what those limits turn out to be. Whether or not surplus capacity could be shared across regions is still an open question, as this would necessitate the transport of CO_2 over long distances via pipelines or ocean-going vessels; the existence of such trade links is model-dependent.

As mentioned previously, a major factor influencing fossil resource consumption, and thus the challenge of mitigation, relates to fossil fuel prices. Figure 2 shows for several EMF27 models the evolution of oil and gas prices (globally–averaged) as a function of cumulative extraction in the Base FullTech and 450 FullTech scenarios. Because of the lower demand for fossil fuels that climate policies will motivate, fossil prices are, in general, lower in the 450 FullTech scenario. There are marked differences in price developments across models, however, as well as between fuels. For instance, TIAM-WORLD exhibits higher natural gas prices in the 450 FullTech scenario, even when its oil prices remain roughly the same. Such differences depend to a large extent on model structure and assumptions (see "Supplementary Material").

[5] The GRAPE model is unique among the models in that it sees more rapid uptake, as well as much greater cumulative deployment throughout the century, of fossil technologies with CCS. Bioenergy with CCS also penetrates the market more quickly. Hence, GRAPE's cumulative fossil resource use in the 550 FullTech scenario is only slightly less than in the Base FullTech.

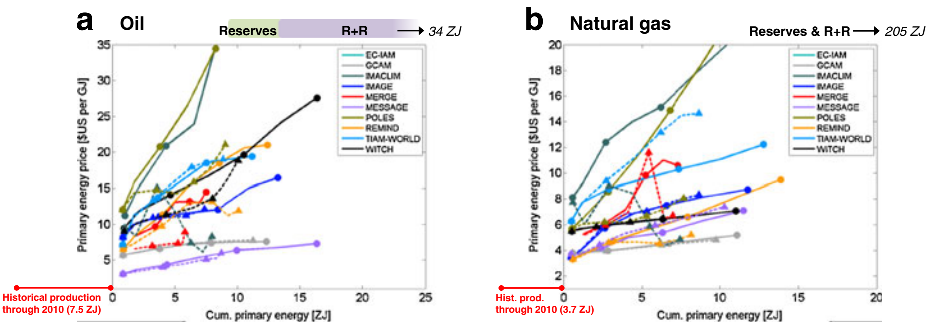


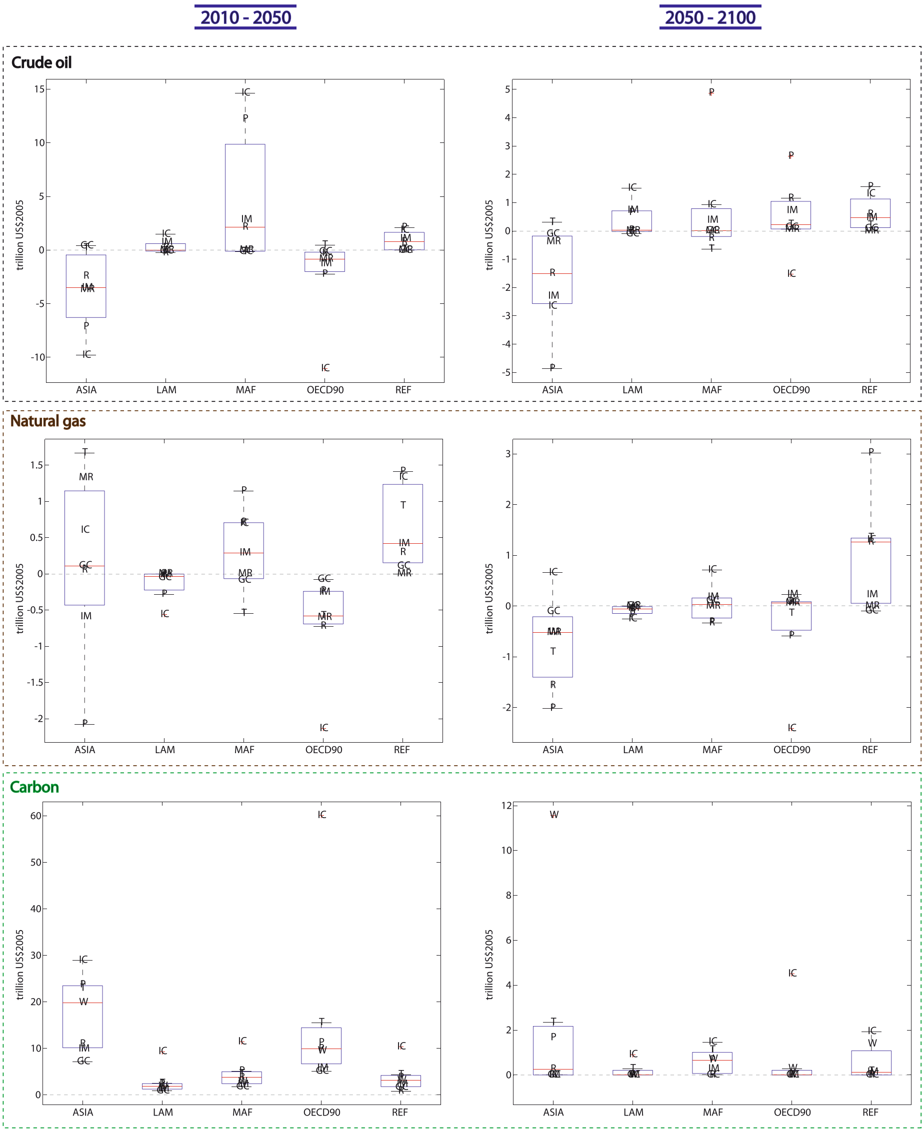
Fig. 2 Oil and natural gas prices as a function of cumulative global primary energy consumption (2010–2070) across the EMF27 models (full-century models only). Two scenarios are shown: Base FullTech (solid lines with circles) and 450 FullTech (*dashed lines with triangles*). The *markers* indicate the years 2010, 2030, 2050, and 2070. EMF27 model results are compared to the lower/upper fossil reserves and resources estimates of Table 1 ("R + R" = reserves + resources). For natural gas, these estimates are off the chart; therefore, no boxes are shown

3 Effect of climate policy on carbon and fossil fuel expenditures

The varying fossil resource consumption and price dynamics discussed in the previous section naturally lead to large differences across models with respect to fossil fuel expenditures. In the event of a global regime to mitigate climate change, fossil resource trade will be especially affected, while simultaneously the market for CO_2 as a commodity will grow by several orders of magnitude. This section compares the evolution of regional carbon expenditures (calculated as the product of CO_2 emissions from fossil fuels and industry and carbon price) with total fossil fuel expenditures and with expenditures/revenues for oil and gas imports/exports in the 450 FullTech and Base FullTech scenarios. We focus upon these specific metrics because for energy-importing regions carbon pricing policies will, depending on implementation, redirect financial flows back into the local economy.[6] Pursuant to the EMF27 study design, the carbon price in the 450 FullTech climate stabilization scenario is globally harmonized (i.e., no regional differentiation and no carbon trade). Burden-sharing is outside the scope of this paper, though other IAM inter-comparison exercises have looked into these important issues (Tavoni et al. 2013). Note that due to varying regional definitions across the EMF27 models, the analysis described here is applied at the level of the five RCP aggregation regions (van Vuuren et al. 2011)[7]: ASIA, LAM (Latin America), MAF (Middle East and Africa), OECD90, REF (Reforming Economies).

The graphical panels of Fig. 3 compare regional expenditures (on a cumulative basis) across models for the two scenarios. All expenditures are shown as differences between the climate policy scenario (450 FullTech) and the baseline (Base FullTech), which assumes no climate policy and thus carbon expenditures of zero. By expressing net oil and gas import expenditures in monetary terms, both price and consumption effects are accounted for. A negative value indicates that import expenditures are lower in the 450 FullTech scenario than in the Base FullTech; this would represent, *ceteris paribus*, a gain compared to the baseline

[6] We assume here that the price put on CO_2 emissions is implemented as a tax. Hence, the expenditures deriving from the carbon tax represent fiscal revenues accruing to the region where the emissions are generated. These revenues could then be redistributed throughout the rest of the economy.
[7] A full listing of countries by RCP region can also be found at the following URL: www.iiasa.ac.at/web-apps/tnt/RcpDb/.



Abbreviations used for labeling: 'R' (ReMIND), 'IC' (IMACLIM), 'IM' (IMAGE), 'T' (TIAM-WORLD), 'P' (POLES), 'W' (WITCH), 'MR' (MERGE), 'GC' (GCAM).

Cost of consumption (primary fossil / GDP)		Coal			Gas			Oil			Total		
		Min	*Median*	*Max*	*Min*	*Median*	*Max*	*Min*	*Median*	*Max*	*Min*	*Median*	*Max*
2010-2050	Base FullTech	0.40%	0.55%	1.52%	0.60%	0.93%	1.81%	1.09%	2.52%	4.41%	2.24%	4.08%	7.75%
	450 FullTech	0.18%	0.31%	0.64%	0.63%	0.77%	1.45%	0.66%	2.12%	2.83%	1.53%	3.01%	4.40%
	%-point difference	-0.11%	-0.25%	-1.10%	0.04%	-0.14%	-0.51%	-0.01%	-0.43%	-1.89%	-0.19%	-0.74%	-3.40%
2050-2100	Base FullTech	0.28%	0.52%	2.24%	0.35%	0.78%	2.13%	0.21%	1.59%	4.23%	1.30%	3.53%	7.55%
	450 FullTech	0.00%	0.06%	0.27%	0.12%	0.35%	0.64%	0.04%	0.39%	1.04%	0.19%	0.86%	1.69%
	%-point difference	-0.21%	-0.43%	-1.96%	-0.15%	-0.45%	-1.89%	-0.18%	-0.78%	-3.19%	-0.81%	-1.84%	-6.64%

◀ **Fig. 3** Comparison of cumulative crude oil, natural gas, and carbon trade expenditures by region (*upper panels*) and global fossil resource expenditures relative to GDP (*lower panel*) in the Base FullTech and 450 FullTech scenarios. In the upper panels (note differing scales), trade expenditures are shown as differences between the two scenarios; thus, for example, a negative value indicates that import costs are lower in the latter. Boxes indicate the 25–75 percentile ranges across the EMF27 models; lines within boxes denote medians; red crosses are outliers. All future costs are discounted to 2010 with a 5 % real interest rate before being cumulated. Values in bottom panel do not necessarily sum to totals or %-point differences because the Min, Median, and Max estimates are calculated independently in each case

for the importing region. On the other hand, a positive value indicates that export revenues are lower as a result of climate policy; this would represent a loss compared to the baseline for the exporting region. In addition, the tabular panel of Fig. 3 presents cumulative global fossil expenditures (not only trade) as a share of globally-aggregated gross domestic product (GDP) for the same two scenarios. Note that these expenditures are calculated based on international fuel prices and therefore exclude national fiscal policies (including carbon prices) and other mark-ups (distribution costs, profits, etc.). For reference, fossil fuel expenditures over the past several years have amounted to roughly 5 % of global GDP.

3.1 Carbon expenditures vs. oil and gas trade expenditures

To some extent, carbon taxation policy represents a reallocation of financial flows between importing regions and exporters: some of the money that was previously used to purchase energy resources from outside the region can instead be kept within the local economy. This is why Fig. 3 explicitly compares the magnitude of expenditures on carbon to those of oil and gas imports–or to the corresponding loss of export revenues in the case of fossil fuel producing regions.

ASIA and the OECD90 together account for the bulk of carbon expenditures between now and 2050, with around $30 trillion cumulative of fiscal revenues (median across models; range: $12–100 trillion). At the same time, these regions—being net energy importers in all models in the first half of the century—are also the two that benefit the most from climate policy, in terms of the reductions in oil trade that decarbonization promotes (see also Section 4). Yet, the gain from a decrease in oil import expenditures is still lower than the amount spent on carbon expenditures. The main exporters over the first half of the century (LAM, MAF, REF) all see decreasing oil exports by value. Natural gas, on the other hand, displays a different trend than for oil. Expenditures on gas imports increase for ASIA under stringent climate policy (median result; some models anticipate a decrease), primarily due to the substitution of gas (with CCS) for coal in power generation. Although not obvious in the figure, the REF region seems to benefit the most from this situation, exporting more to ASIA.

3.2 Total fossil fuel expenditures

Figure 3 (bottom panel) also shows that in a no-climate policy baseline scenario cumulative global expenditures on oil, relative to GDP, decrease over time (comparing Base FullTech results across the 2010–2050 and 2050–2100 periods). Meanwhile, the reductions in coal and gas expenditures are more minor. The force behind these dynamics is a gradual shift away from oil in the middle of the century, as and then gas later in the century, in favor of lower-priced coal supplies. Coal is used in great quantities for power production, particularly in ASIA, and in some models for liquid transportation fuels, thus replacing oil. Climate policy has a pronounced impact on this situation, especially for coal. The impact on oil is more pronounced in the second period. This is due to the relative inelasticity of oil demand (compared to other fuels) in most models and is indicative of the inertia of the global transport system, which is almost completely dependent on oil at present, in response to constraints on carbon. Finally, expenditures on gas are not greatly affected by climate policy in the first half of the century, which is explained by the fact that gas tends be a short- to mid-term transitional solution for mitigating emissions. The fuel's carbon content eventually becomes a handicap, however, when deeper emission reductions must be made; thus, gas expenditures decrease more significantly after 2050.

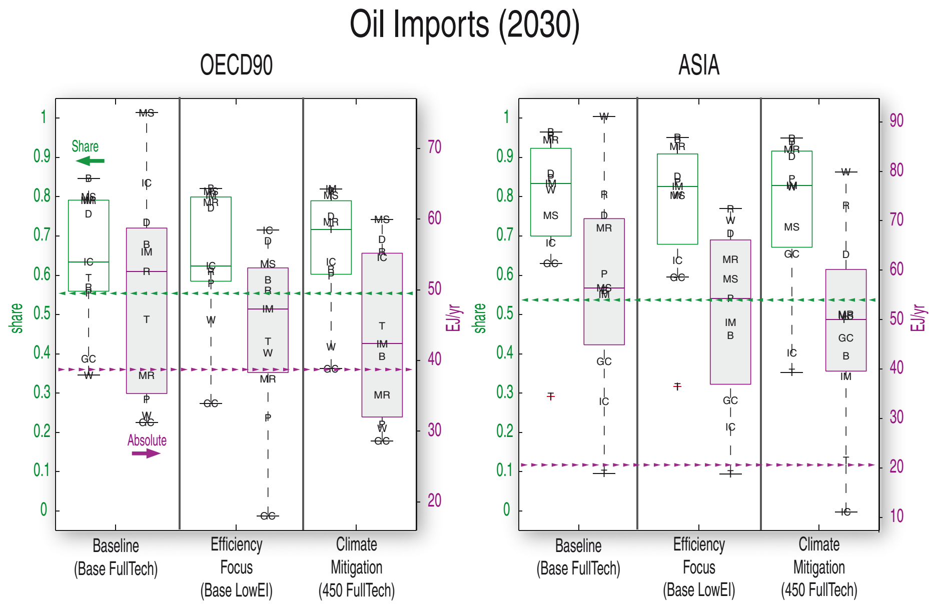
4 Implications of energy efficiency and decarbonization for energy security

The discussions thus far in the paper have shown that climate mitigation policies could have significant impacts on fossil fuel consumption, trade, and prices over the twenty-first century. Yet, not all regions will be affected the same by these developments. As discussed in Section 3, some will fare better than others, depending on their resource endowments. This could potentially lead to concerns over energy security in certain regions. This section complements the earlier discussions of this paper by linking the fossil resource and energy security dynamics displayed by the models. To be sure, none of the EMF27 scenarios are explicitly driven by normative targets for security (e.g., import dependence); rather, we illustrate here the security implications of policies promoting energy efficiency and decarbonization. Unlike other discussions in this paper, the focus is shifted to the near term (2030), since this is the timeframe in which energy security is typically discussed in policy circles.

Energy security concerns can be categorized along three dimensions: sovereignty, resilience, and robustness (Cherp et al. 2012; Cherp and Jewell 2011). We only focus on the first two in this paper, concentrating specifically on oil and gas. Sovereignty relates to the degree of control national governments have over their energy systems; resilience describes the ability of energy systems to respond to disruptions. Recent years have seen growing dependence of the OECD, and increasingly Asian countries, on imported oil and gas (sovereignty) from a limited number of suppliers (resilience). And while renewables and gas have made major inroads in energy systems across the world over the past decades, there is still a marked lack of diversity in energy supply in most regions and/or sectors, such as transport, where readily available substitutes are lacking in the short term (resilience).

Use of oil, especially imported oil, tends to be the most oft-cited energy security concern of today's (and tomorrow's) major importing regions, the OECD90 and ASIA.[8] As a group, OECD90 countries imported approximately 39 EJ of their oil from other regions in 2010 – roughly 55 % of all oil consumption (see Fig. 4). The share of oil imports in ASIA is currently about the same, albeit out of a much smaller total level of oil consumption (20 EJ). Economic and energy demand growth in the latter group is projected to be considerably more rapid over the next decades; in a baseline scenario (Base FullTech) this is likely to translate to a multi-fold increase in oil consumption by 2030. According to the EMF27 models, most of that demand will be met by imports: Fig. 4 shows that across the models the share of oil imports in ASIA could grow to more than 80 % (median value; interquartile range: 70–90 %) within only two decades. Although the increases are less dramatic for

[8] RCP aggregation; see previous footnote.



Abbreviations used for labeling: 'D' (DNE21+), 'MS' (MESSAGE), 'R' (ReMIND), 'IC' (IMACLIM), 'IM' (IMAGE), 'T' (TIAM-WORLD), 'P' (POLES), 'W' (WITCH), 'B' (BET), 'MR' (MERGE), 'GC' (GCAM).

		Baseline trends (Base FullTech)	Efficiency Focus (Base LowEI)	Climate Mitigation (450 FullTech)
Impacts of policies and measures	*Sovereignty*	• Growing dependence on imported oil and gas, both in absolute terms and as share of total oil/gas consumption; situation considerably more alarming in ASIA than in the OECD90.	• Marginal impact on oil and gas dependence in both ASIA and the OECD90.	• Reduced dependence on oil imports. • Marginal impact on gas imports in the OECD90; greater dependence on imported gas in ASIA.
	Resilience	• International trade markets for oil and gas become even more concentrated (increasingly limited number of suppliers); gas market becomes far more concentrated than market for oil today. • Modest diversification of the primary energy mix in both ASIA and the OECD90.	• Marginal impact on the geographic supply diversity of oil exports; considerably less diversity of gas markets. • Marginal impact on the diversity of the primary energy mix.	• Marginal impact on the geographic supply diversity of oil and gas exports. • Considerably increased diversification of the primary energy mix.

Fig. 4 Energy security implications of stringent energy efficiency and climate mitigation efforts. Panels show oil imports as a share of total regional oil consumption (*white/green boxes*, *left axes*) and total oil imports in absolute terms (*grey/purple boxes*, *right axes*) for the OECD90 and ASIA regions in 2030. *Boxes* indicate the 25–75 percentile ranges across the EMF27 models; *lines within boxes* denote medians; *red crosses* are outliers. *Dashed arrows* refer to 2010 values (*color* and *direction* indicate relevant axis)

OECD90 countries, the region evidences similar trends, owing to sustained demand growth and diminishing supplies of conventional oil. These developments are likely to only exacerbate energy security concerns along the sovereignty dimension.

Energy and climate policies can play a role, however, in shifting the balance between imported vs. domestic (i.e., produced within the region) oil consumption. The suite of EMF27 models show that under scenarios of stringent climate mitigation (450 FullTech), wherein total oil demand in 2030 is generally lower, absolute oil imports into the OECD90 and ASIA in 2030 are likely to be lower as well (Fig. 4). This finding is broadly similar to those of Jewell et al. (2013b), who conduct a cross-model comparison and analyze four major economies. At the same time, the share of total oil consumption being met by imports remains at roughly the same level as in the baseline. This indicates that both domestic and imported oil (primarily from the countries of the Middle East and Africa, MAF, or the reformed countries of the former Soviet Union, REF, including Russia and the Caspian region) are cut in roughly equal quantities–an outcome with important economic and policy implications. The ability of stringent climate mitigation efforts to generate near-term synergies for energy security derives from *both* energy efficiency improvements (beyond those foreseen in the baseline) *and* shifts to non-fossil based energy forms (e.g., renewables, which in most cases are inherently sovereign and thus secure) (McCollum et al. 2011; Riahi et al. 2012). However, focusing on energy efficiency and conservation measures alone (Base LowEI) – in the absence of an overarching carbon policy framework – is not likely to bear security benefits of the same magnitude. As illustrated in Fig. 4, compared to baseline levels, oil imports (whether in absolute or relative terms) into the OECD90 and ASIA are only marginally reduced, if at all. Why? Primarily because efficiency measures are likely to drive out higher-cost supplies of both domestic and imported oil, assuming competitive markets are at play.[9] Such a robust finding across the models does not unequivocally support the stated objectives of certain industrialized countries, where energy efficiency (e.g., improved fuel economy standards for road vehicles) has often been touted as major step toward achieving energy independence.[10] In short, while efficiency measures are critical, they would need to be complemented by either security- or climate-focused policies to have maximal impact.

Exactly where all of this imported oil (and gas) originates will of course not be lost on the countries bringing it across their borders. Today's oil and gas export markets are dominated by the countries comprising the MAF and REF regions; together these energy producers account for more than 90 % of global trade. It is perhaps no wonder that oligopolistic markets this concentrated have some importers concerned (resilience dimension). According to the EMF27 models, these concerns show no signs of diminishing in the near-to-medium term. In fact, as measured by the Shannon-Wiener diversity index (SWDI; see "Supplementary Material"), global oil and gas export markets are likely to become even more concentrated over the next two decades (i.e., lower geographic supply diversity) in the baseline scenario. For gas in particular, the market in 2030 could even reach a diversification level that is far less than today's market for oil (see Fig. 5 in SM), a finding also noted by Jewell et al. (2013a). Policies promoting energy efficiency and decarbonization do not appear able to improve this situation to any measurable degree.[11] A recent study by Cherp et al. (2013) on this topic finds that climate policies could decrease the geographic diversity of oil- and coal- producing regions.

[9] The extent to which the global oil market is competitive is outside the scope of this paper. IAMs tend to represent this market in an admittedly abstract way, accounting very simply for the myriad intricacies therein (e.g., cartel behavior, long-term bilateral contracts, etc.); hence, certain market dynamics are not captured. Nevertheless, global markets will likely continue to favor lower-cost oil supplies, notwithstanding geopolitical impediments, and these supplies are generally found outside of the OECD90 and ASIA.

[10] Note that the EMF27 scenarios assume that climate and/or efficiency policies are pursued in all regions simultaneously, not just in the countries of the OECD90 and ASIA.

[11] While this discussion focuses on the diversity of *global* oil and gas markets, the trends shown here are indicative of *regional* and *national* markets as well. Individual countries of the OECD90 and ASIA would, generally speaking, also become more reliant on oil and gas from MAF and REF countries throughout the century. Lack of country-level data in the EMF27 exercise prevents a detailed exploration of this topic, however.

5 Conclusions

In this paper we analyze a multi-model ensemble of long-term energy and emissions scenarios that were developed within the framework of the EMF27 model inter-comparison exercise. The diverse nature of these integrated assessment models highlights large uncertainties in the likely development of fossil resource (coal, oil, and natural gas) consumption, trade, and prices over the course of the twenty-first century and under different climate policy frameworks. We explore and explain some of the differences across scenarios and models and compare the scenario results with fossil resource estimates from the literature. A robust finding across the suite of IAMs is that the cumulative fossil fuel consumption foreseen by the models is well within the bounds of estimated recoverable reserves and resources found in the literature. A corollary conclusion deriving from this finding is that fossil resource constraints are, in and of themselves, unlikely to limit future GHG emissions and, thus, global climate change this century.

Moreover, while the models show that fossil fuel consumption–especially of coal–must decrease strongly to achieve either a 550 or 450 ppm CO_2-eq climate stabilization target, there appears to be no agreement on the individual contributions from coal, oil, and gas, as this depends on a number of other factors simultaneously influencing climate mitigation, such as the cost and deployment of non-fossil technologies and the utilization of CCS, as well as non-CO_2 emissions and mitigation in the non-energy sectors (e.g., afforestation). Energy demand growth will also be an important determinant in future fossil use, though one point on which all models agree is that energy efficiency/conservation cannot on its own provide the required reductions in fossil fuel use that are needed to protect the global climate.

Our analysis of the implications of climate policies for regional expenditures on fossil fuels and carbon shows that such policies could lead to a major reallocation of financial flows between regions. Although the costs of carbon will be non-negligible in a low-carbon future, countries of ASIA and the OECD90 may be able to partially offset them through reduced oil and gas import expenditures. Major exporting regions (MAF, LAM, REF) regions, on the other hand, will lose out on key export revenue streams. The changing face of global energy trade will also have a marked impact on near-term energy security concerns. In baseline scenarios, these concerns are likely to rise over the next two decades in ASIA and the OECD90. Policy efforts focused on mitigating climate change can alleviate these concerns to some extent via the reductions in oil imports (sovereignty) and increases in energy system diversity (resilience) they will help to motivate. Contrary to the stated objectives of certain countries, however, aggressive efforts to promote energy efficiency are, on their own, not likely to lead to markedly greater energy independence. Moreover, an important, and growing, energy security concern (in both baseline and carbon-constrained futures) is likely to be the increasing concentration of oil and gas exports in just two producing regions – that is, unless policies in importing countries explicitly target the sources of their imports.

Given the uncertainties mentioned herein, further research is needed to improve our collective understanding of the full equilibrium effects of energy efficiency and climate policies on fossil energy markets.

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