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

Jewell, J.; Vinichenko, V. ; McCollum, D.; Bauer, N.; Riahi, K.; Aboumahboub, T.; Fricko, O.; Harmsen, M. ; Kober, T.; Krey, V. ; Marangoni, G.; Tavoni, M.; van Vuuren, D.P.; van der Zwaan, B.; Cherp, A.

DOI
10.1038/nenergy.2016.73

Publication date
2016

Document Version
Final published version

Published in
Nature Energy

nature energy

ANALYSIS

PUBLISHED: 6 JUNE 2016 | ARTICLE NUMBER: 16073 | DOI: 10.1038/NENERGY.2016.73

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

Jessica Jewell[1]*, Vadim Vinichenko[2], David McCollum[1], Nico Bauer[3], Keywan Riahi[1,4], Tino Aboumahboub[3], Oliver Fricko[1], Mathijs Harmsen[5,6], Tom Kober[7,8], Volker Krey[1], Giacomo Marangoni[9,10,11], Massimo Tavoni[9,10,11], Detlef P. van Vuuren[5,6], Bob van der Zwaan[7,12,13] and Aleh Cherp[2,14]

Ensuring energy security and mitigating climate change are key energy policy priorities. The recent Intergovernmental Panel on Climate Change Working Group III report emphasized that climate policies can deliver energy security as a co-benefit, in large part through reducing energy imports. Using five state-of-the-art global energy-economy models and eight long-term scenarios, we show that although deep cuts in greenhouse gas emissions would reduce energy imports, the reverse is not true: ambitious policies constraining energy imports would have an insignificant impact on climate change. Restricting imports of all fuels would lower twenty-first-century emissions by only 2–15% against the Baseline scenario as compared with a 70% reduction in a 450 stabilization scenario. Restricting only oil imports would have virtually no impact on emissions. The modelled energy independence targets could be achieved at policy costs comparable to those of existing climate pledges but a fraction of the cost of limiting global warming to 2 °C.

With increasing tensions between Russia and the West, the escalation of several crises in the Middle East, and the volatility of the oil market, energy security is at the top of the political agenda[1–3]. At the same time, world leaders have agreed to limit the increase in global mean temperature to below 2 °C (ref. 4) and there is a multitude of efforts to curb greenhouse gas (GHG) emissions[5].

Climate change mitigation policies are frequently considered to lead to significant energy security co-benefits, such as reduction in energy imports, slower depletion of non-renewable resources, and increasingly diverse energy sources[6–12]. Previous research has also explored the benefits of achieving climate and non-climate energy objectives simultaneously[13–15]. However, some of these non-climate objectives, such as reducing energy imports, can also be pursued on their own and achieved either by climate-friendly measures such as constraining energy demand and expanding domestic renewables or by high-carbon alternatives such as increasing domestic coal use.

In this study, we reverse the usual question and examine the effects of energy independence policies on GHG emissions. We conduct a multi-model comparison of these two policy objectives, using five leading global energy-economy models (IMAGE, MESSAGE, REMIND, WITCH and TIAM-ECN). We conduct a quantitative analysis of the interaction between strategies to reduce energy imports (both for oil and for all fuels together) and climate change mitigation. We address three questions related to this interaction. First, how would energy independence policies change energy systems as compared with climate policies? Second, what would be the impact of energy independence policies on GHG emissions? Finally, what would energy independence policies cost compared with climate policies? We find that although climate stabilization policies would result in lower energy trade, energy independence policies would decrease cumulative twenty-first-century GHG emissions by only 2–15% compared with a Baseline scenario. In this case, the global median temperature would be 3.5–4 °C above the pre-industrial level for 2100, far exceeding the 2 °C target agreed on by the international community. Oil import restrictions would have virtually no impact on emissions or global temperature increase. We also show that energy import constraints would lead to decreasing fossil fuel and overall energy use, but not necessarily to universal expansion of renewables. Finally, the policy costs of the modelled energy independence targets would be a fraction of those of climate change stabilization.

The concept of energy security

Energy security is a complex policy problem that can encompass everything from securing oil supplies to reducing the risks of blackouts and protecting critical infrastructure[16–19]. Historically, the focus of much of the energy security literature has been security

[1]International Institute for Applied Systems Analysis, Energy Program, 2361 Laxenburg, Austria. [2]Central European University, Department of Environmental Science and Policy, 1051 Budapest, Hungary. [3]Potsdam Institute for Climate Impact Research, Research Domain Sustainable Solutions, 14473 Potsdam, Germany. [4]Graz University of Technology, 8010 Graz, Austria. [5]University of Utrecht, Faculty of Geosciences, 3584 CS Utrecht, The Netherlands. [6]PBL Netherlands Environmental Assessment Agency, Department of Climate, Air and Energy, 3720 AH Bilthoven, The Netherlands. [7]Energy Research Centre of the Netherlands, Policy Studies, 1043 NT Amsterdam, The Netherlands. [8]Paul Scherrer Institut, Energy Economics Group, 5232 Villigen, Switzerland. [9]Fondazione Eni Enrico Mattei, Climate Change and Sustainable Development Programme, 20123 Milan, Italy. [10]Centro Euromediterraneo sui Cambiamenti Climatici, 73100 Lecce, Italy. [11]Politecnico di Milano, Department of Management, Economics and Industrial Engineering, 20156 Milan, Italy. [12]University of Amsterdam, Faculty of Science, 1098 Amsterdam, The Netherlands. [13]Johns Hopkins University, School of Advanced International Studies, 40126 Bologna, Italy. [14]International Institute for Industrial Environmental Economics, Lund University, 22100 Lund, Sweden. *e-mail: jewell@iiasa.ac.at

Table 1 | Overview of scenarios.

Scenario	Description
Baseline	A counterfactual development without climate policies or restrictions on energy imports[38,42] (Supplementary Fig. 3).
Energy independence	Restrictions on overall energy imports. Targets based on observed policies and trends (Table 2) are set for 2030 with the net energy import level maintained throughout the rest of the century. In rare instances when a model could not achieve the target for a particular region, it was systematically relaxed until a solution was found (see also Methods and Supplementary Tables 2 and 4–8).
Oil independence	All oil-importing regions cut their net oil import dependence in half by 2030 and maintain that level throughout the century. In rare instances when a model could not achieve the target for a particular region, it was systematically relaxed until a solution was found (see also Methods and Supplementary Tables 3 and 4–8).
Pledges	An ambitious interpretation of the Copenhagen climate pledges is met by 2020; between 2020 and 2100, comparable emission reduction efforts are extrapolated (see also Methods and Supplementary Table 1)[37,38].
500-climate stabilization	Climate policies beginning after 2020 to achieve GHG stabilization at 500 ppm_e by 2100 (see Supplementary Figs 5–7).
450-climate stabilization	Climate policies beginning after 2020 to achieve GHG stabilization at 450 ppm_e by 2100.

of supply and energy dependence[20,21] but recently the concept has expanded to also include security of energy-related infrastructure and resilience of energy systems[18,19,22]. In this paper we follow a general definition of energy security as 'low vulnerability of vital energy systems'[16] that served as the basis for energy security assessment frameworks used in the Global Energy Assessment[23], the IEA Model of Short-term Energy Security[24] and in evaluating energy security in long-term global scenario studies[7,8,10]. We delineate vital energy systems as primary energy supplies or specifically oil supplies for major economies.

The vulnerability of vital energy systems can be analysed from three distinct perspectives: robustness, resilience and sovereignty[17]. The robustness perspective (minimizing exposure to predictable threats such as resource scarcity[25]) and the resilience perspective (increasing the ability of vital energy systems to respond to disruptions[22,26,27]) have also been assessed in long-term scenarios[8,9], but modelling corresponding policies has not yet been performed and should be part of future research. We focus our analysis on the sovereignty perspective where the main vulnerabilities come from energy systems being controlled by foreign actors. This perspective prescribes energy independence as the main energy security strategy.

Pursuing energy independence has consistently been observed across a range of historic periods, configurations of energy systems, levels of economic development and political arrangements and continues to shape current policy discourses[2,3,28–32]. For example, in the 2012 US presidential race, President Obama pledged to cut oil imports by one-third by 2025[29] and the Republican candidate pledged to achieve energy independence by 2020[30]. In 2010, Japan's Basic Energy Plan aimed to double its energy 'self-sufficiency ratio' by 2030[33,34] and, more recently, India's Power and Coal Minister vowed to stop importing coal by 2019[31]. The level of energy imports has also been one of the most widely used indicators of energy security in the context of long-term scenarios[8,9,12,15].

Modelling energy independence and climate policies

We model achieving energy independence objectives in all world regions, both limited to oil and extending to the overall primary energy supply. Over the past several decades, oil has been the main energy security concern owing to its geographically concentrated production, perceived and real scarcity, and lack of substitutes, particularly in the transport, agriculture and defence sectors[23,32,35]. However, oil has not always dominated the energy security agenda, and may not in the future. For instance, in the 1950s and 1960s the US and many Western European countries switched a number of power plants from coal to oil to avoid coal's 'high prices and irregularities in supplies'[36]. In the European Union, the energy security strategy focuses on reducing and diversifying natural gas imports[2]. Many long-term scenarios indicate that future gas trade could significantly increase, and coal could become the most traded fuel by mid-century[8,10].

We compare energy system changes from pursuing energy independence to reduce either energy or oil imports to two different climate policy scenarios from the literature: projecting an ambitious interpretation of the Copenhagen climate pledges to 2100[6,37,38] and consistent with the Intended Nationally Determined Contributions (INDCs) to 2030 (Supplementary Fig. 1 and Supplementary Table 1); and ensuring climate stabilization with universal action beginning after 2020 and stabilizing GHG concentration at 450 ppm CO_2-equivalent (CO_2e) by 2100[38]. We also include a 500 ppm CO_2e scenario[38] to explore a more modest climate change stabilization target (Table 1). Additional scenario runs were used to test the robustness of the results.

Energy dependence is calculated as the net imports of all traded fuels divided by the total primary energy supply in a given region and year (equation (1)). For each region, we model energy independence targets that are at least as ambitious as empirically observed policies and trends: import-dependent developed regions with low energy-demand growth cut their energy imports in half by 2030 and rapidly growing emerging economies maintain their current relatively low level of imports for the rest of the century (Table 2 and Supplementary Table 2). Energy exporters, including North America after 2030, do not become importers. These restrictions are imposed on all fuels and carriers represented in models to ensure that overall energy imports including trade in 'new fuels' such as bioenergy remains within the established limits (Table 3).

Oil independence is calculated as net oil imports divided by the total oil supply (equation (2)). In the oil independence scenario, we model a world where all importing regions cut their net oil import dependence in half by 2030, except the US/North American region, which goes further and becomes oil independent by 2030. This reflects the fact that most emerging economies already have high oil import dependence (Supplementary Table 3).

Effect of energy independence policies on energy systems

We find that pursuing energy independence leads to lower energy intensity (measured as primary energy use over gross domestic product, GDP) resulting in lower energy demand and consequently in lower oil and gas use over the short term (to mid-century) and a drop in coal use over the long term (Figs 1 and 2). This contrasts with the strong growth in coal trade to up to four times today's oil trade volumes in the Baseline scenario[8,10]. Primary energy supply

Table 2 | Regional import reduction targets for the Energy independence scenario.

Region type	Includes	Target
Energy-importing developed regions with low energy-demand growth	Europe and OECD regions other than North America	Cut their 2010 net energy import dependence in half by 2030 and maintain that relative level throughout the twenty-first century
Energy-importing emerging economies with high energy-demand growth	China, India and other non-OECD Asian economies	Maintain their current level of net energy imports throughout the century
Energy exporters	Middle East, former Soviet Union, Africa, Latin America, and other regions that are net energy exporters	Never become energy importers
The US/North American region	US and North America	Becomes energy independent by 2030 and maintains energy independence, consistent with political debates[29,30] and recent modelling results[8,63–65]

See Supplementary Note 1 and Supplementary Table 9 for regional definitions and Supplementary Tables 2–8 for quantitative regional targets.

Table 3 | Energy products that are traded in each model.

Model	Energy products that are traded
IMAGE	Crude oil, natural gas, coal, biomass, biofuels, hydrogen
MESSAGE	Crude oil, natural gas, coal, oil products, electricity, biofuels, hydrogen, liquefied coal and natural gas
REMIND	Crude oil, natural gas, coal, biomass
TIAM-ECN	Crude oil, natural gas, coal, biomass, biofuels, oil products
WITCH	Crude oil, natural gas, coal

also drops to significantly lower levels in the Pledges and Climate stabilization scenarios. In the Energy independence scenario, an increase in renewable energy use varies from one model to another, although in no model does it reach the level observed under the 450 scenario (Fig. 1 and Supplementary Fig. 4).

The Energy independence scenario portrays three distinct regional trends for major twenty-first century importers, industrialized economies, and energy exporters (Fig. 2 and Supplementary Figs 5 and 6). These groups are typified in Fig. 2 by India, Europe, and North America and the Middle East respectively. The major importers (Africa, India, China, and the rest of Asia) experience a large reduction in energy intensity and fossil fuel supply that curtails the growth of energy imports expected under the rapidly growing demand in the Baseline. The reduction in fossil energy use and increase in renewables in some of these regions in the Energy independence scenario is comparable to the Pledges scenario and in certain models even to the Climate stabilization scenarios. This is because there is no other way to meet rapidly rising demand given scarce domestic fossils.

Industrialized importers (Europe and Pacific Organization for Economic Cooperation and Development (OECD)) experience a relatively modest reduction in the use of fossil fuels and decrease in energy demand under the Energy independence scenario. This is due to lower energy-demand growth in the Baseline; as a result, less change is required to meet the energy independence targets. Regionally, the difference between the Climate stabilization and Energy independence scenarios is most pronounced for the twenty-first-century energy exporters (Middle East, the former Soviet Union and North America) where there might actually be a slight increase in fossil fuel use under the Energy independence scenario as the global demand for oil, gas and coal drops. As a result, energy independence policies in importing countries may make it less attractive for energy exporters to decarbonize.

The Oil independence scenario shows less oil use, primarily in the transport sector but the energy demand and the overall fossil fuel use are almost the same as in the Baseline because gas and coal substitute oil (Fig. 2 and Supplementary Figs 5 and 6). Regionally, oil independence policies primarily affect energy systems in oil-importing regions; however, the Middle East experiences a small increase in domestic oil use as the global demand contracts (Fig. 2).

Mutual impact of independence and climate policies

The modest changes in fossil energy use in the Energy independence scenarios lead to a small decrease in cumulative GHG emissions: 2–15% lower than in the Baseline compared with over 70% reduction in the Climate stabilization scenarios and a 30–45% decrease under the Pledges (Fig. 3). These trends correspond to roughly a 3.5–4 °C temperature increase above pre-industrial levels in the Energy independence scenario, 2.5–3.2 °C in the Pledges scenario and to no more than 2 °C for the climate stabilization scenario (see Methods for details on warming estimates). Oil independence policies have almost no impact on GHG emissions (Fig. 3 and Supplementary Fig. 2).

On the other hand and consistent with other studies[7,8,10,39], we find that climate stabilization policies reduce energy trade and energy imports by up to 75% by 2050 (Fig. 3 and Supplementary Fig. 1). In fact, over the long term, climate stabilization policies lead to lower energy imports than in the Energy independence scenario due to a phase-out of tradable fossil fuels. Over the next couple of decades, however, the modelled Energy independence policies result in lower energy imports because the 450 scenario limits the use of domestic coal. These results are different at the regional level, particularly depending on whether a region is an energy importer or exporter (Supplementary Fig. 8).

In the Pledges scenario, there is some decrease in global energy trade compared with the Baseline; however, this decrease is much smaller than in the Energy independence scenario and would not be sufficient to curtail growing energy imports in rapidly growing regions. This is consistent with earlier findings[8] showing that under the Pledges scenario energy imports would decline in some regions (for example, the EU) but would continue to grow in China and India.

Policy costs of energy independence versus climate goals

We calculate policy costs as a proxy for the relative difficulty of implementing the modelled targets using a cost-effective strategy (see Methods). Although there is considerable uncertainty surrounding the policy costs of climate policies[6,40–43], we find that the relationship between the policy costs of independence targets and climate policies is robust between models. The policy costs of the Energy and Oil independence scenarios to 2050 are between

NATURE ENERGY DOI: 10.1038/NENERGY.2016.73

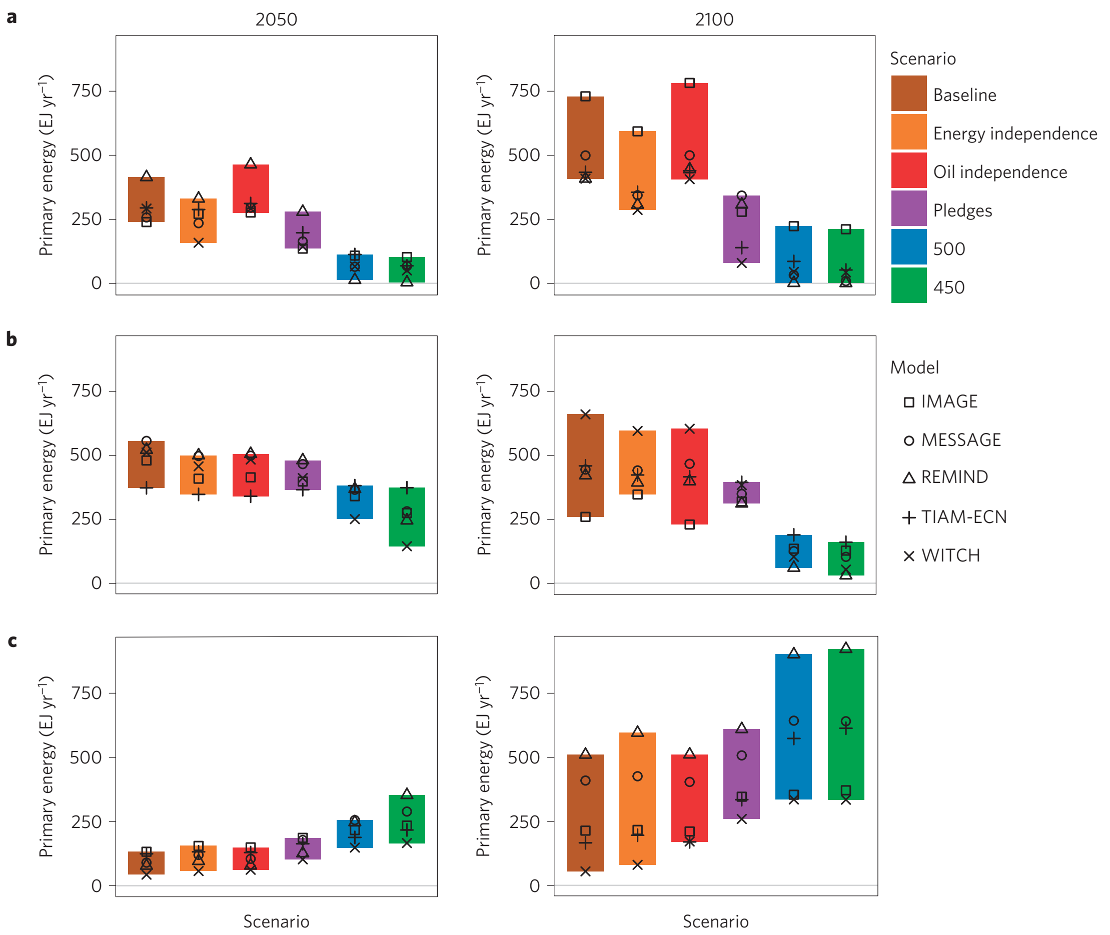

Figure 1 | Primary energy development under energy independence and climate policy scenarios. a–c, The development of coal (**a**), oil and gas (**b**) and renewables (**c**) in the Baseline, energy independence and climate policy scenarios. Colours represent each scenario; symbols distinguish the different models studied.

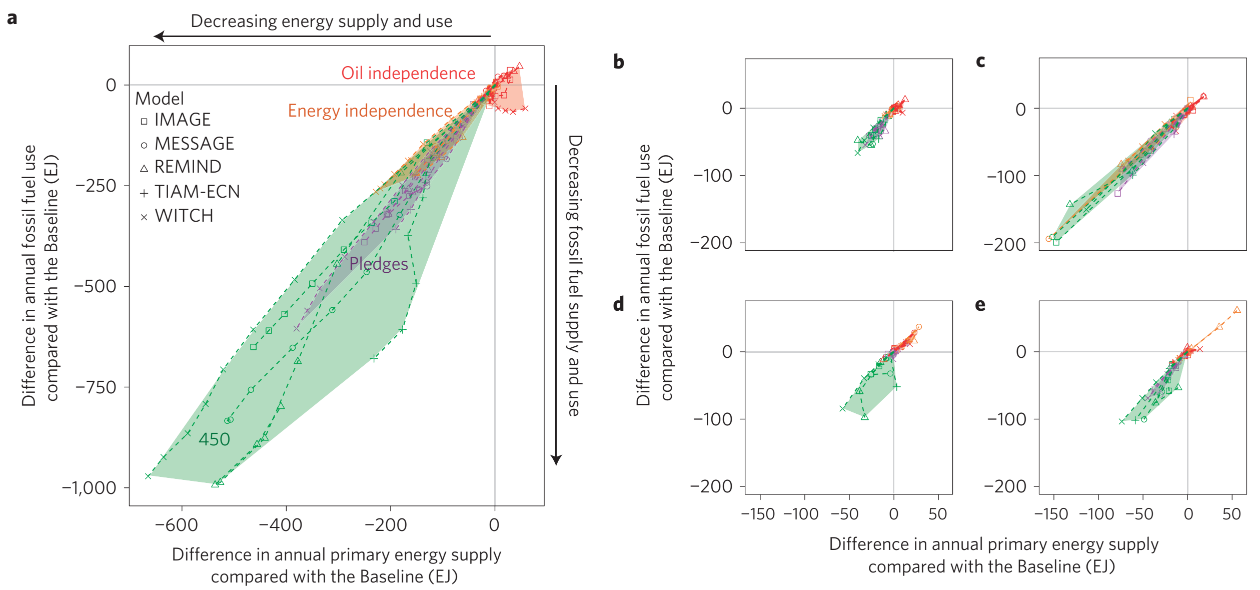

Figure 2 | Main energy system changes from energy independence compared with climate policies scenarios. a–e, Changes at the global level (**a**) and for representative regions (**b**–**e**): industrialized economies (Europe) (**b**); emerging energy-importing economies (India) (**c**); and traditional (**d**) and emerging (**e**) exporters (Middle East and North America, respectively). See Supplementary Note 1 and Supplementary Table 9 for regional definitions. See Supplementary Fig. 6 for regions not depicted in this figure. All changes are calculated compared with the Baseline energy mix (shown in Supplementary Fig. 3). In **a**, each model's results are depicted for each decadal year between 2010 and 2100. In **b**–**e**, each model's results are depicted for the years 2030, 2050 and 2100. Colours represent each scenario; symbols distinguish the different models studied.

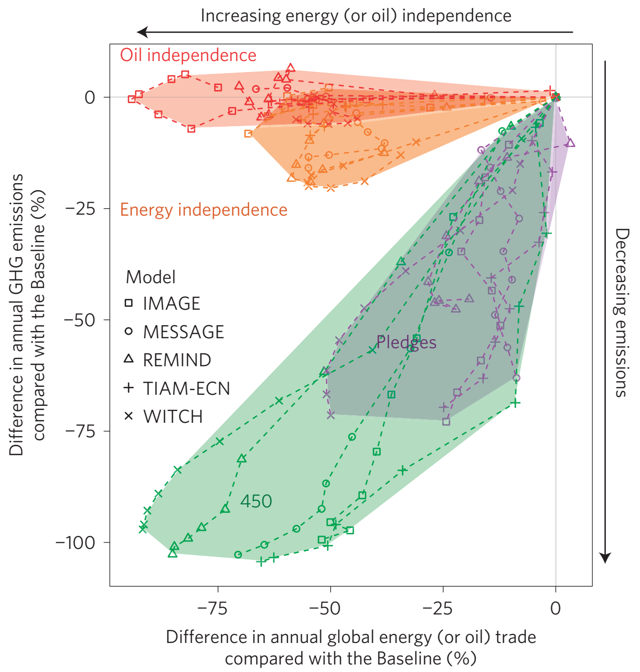

Figure 3 | Emission and energy trade impacts of energy independence and climate policy scenarios. For the Energy independence, 450 and Pledges scenarios, the decrease in energy trade is relative to total energy trade whereas for the Oil independence scenario, the difference is relative to global oil 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. Colours represent each scenario; symbols distinguish the different models studied.

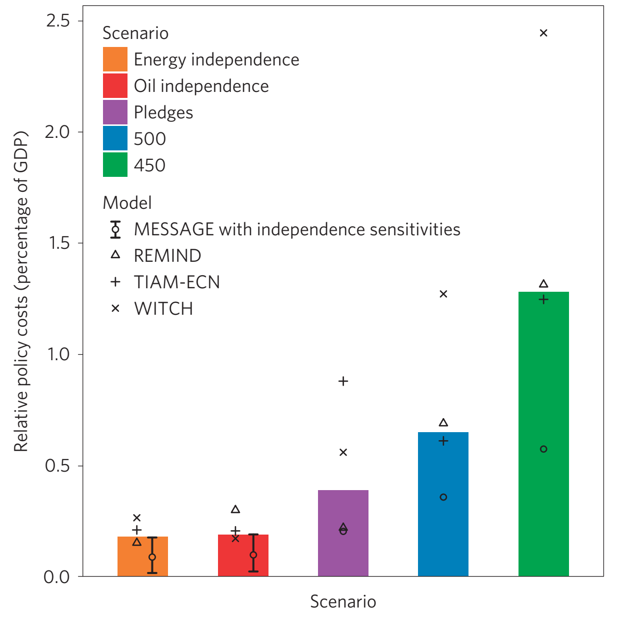

Figure 4 | Global policy costs for energy independence and climate policy scenarios to 2050. Bars show medians; markers show individual models. Costs are expressed in relative differences of net present value from 2010 to 2050 using a 5% discount rate compared with the Baseline scenario. In MESSAGE the full range of sensitivity cases for the independence scenarios is shown (see also Supplementary Tables 12 and 16). Colours represent each scenario; symbols distinguish the different models studied. See Methods for calculation of policy costs.

0.1 and 0.3% of global GDP, which is comparable to those of the Pledges scenario (0.1–0.8% of global GDP) but only between one-fifth and one-tenth of the cost of the 450 scenario (0.6–2.4% of global GDP) and between one-half and one-fifth the cost of a 500 scenario (0.4–1.2%) (Fig. 4). By 2100, the global policy costs of the Energy independence scenario in all models are one-tenth of the costs of the 450 scenario and one-fifth to one-seventh of the cost of the 500 scenario (Supplementary Fig. 9). Uncertainties in these costs both between models and with respect to specific assumptions are shown in Fig. 4 (see also 'Uncertainties and sensitivities' below).

The policy costs of energy independence are predominantly borne by energy exporters (Middle East, Africa, and the former Soviet Union) because they include lost export revenues due to other regions limiting fossil fuel imports, for either the sake of energy independence or climate policies. For example, the Middle East bears between a quarter and three-quarters of the global policy costs in the energy independence scenarios. The costs of climate change mitigation are more evenly distributed across regions; for example, the Middle East's cost burden is less than a third of the global policy costs in the 450 scenario (Fig. 5 and Supplementary Table 10).

Uncertainties and sensitivities

We have tested the sensitivity of our findings against three types of uncertainty: model uncertainty, parametric uncertainty, and import policy uncertainty. We address the model uncertainty by including results from five models with different representations of energy-economy systems (for example, how investment decisions are made and how energy demand and supply respond to policy constraints—Supplementary Note 2). We probed the parametric uncertainty by modelling import restrictions in the MESSAGE model under three baseline scenarios spanning a wide range of uncertainties. These scenarios are based on three distinct shared socio-economic pathways (SSPs), designed by the climate change research community to explore how socio-economic, technological, energy demand and resource uncertainties might impact climate change mitigation and adaptation challenges[44–46]. We use the three SSPs that represent the widest range of challenges for climate change mitigation: from the 'Sustainability World' where the cost of new technologies rapidly falls and fossil resource availability is constrained, to a fossil-rich world with slow uptake of new technologies and large fossil resource availability (Supplementary Note 3). Finally, we also used the MESSAGE model to test the sensitivity of our results against the import policy uncertainty by varying the level of energy import restrictions to 50% higher and lower than the targets used in our energy independence scenarios (Supplementary Note 4).

The sensitivity analysis shows that our main findings that energy import restrictions would result in smaller emission reductions, more modest energy systems changes and require a fraction of the effort of climate change mitigation are robust across five models and radically different Baselines. Consistent with diagnostic indicators for our models from ref. 47, we find that models with more flexible energy demand and 'stiffer' supply (for example, WITCH) show a stronger demand response and weaker structural response (that is, shift to renewables) to energy import constraints than other models (for example, REMIND) (Fig. 1 and Supplementary Fig. 4). In a fossil-rich world with slow uptake of new technologies, restricting energy imports would require more extensive energy system changes and lead to more emission reductions (Supplementary Fig. 10). However, the relative scale of changes compared with the Baseline and 450 scenarios would be similar to our findings (because emissions in the Baseline would be higher and climate stabilization would also require larger emission reductions). We also find that even under much stricter import constraints, with all regions importing less than 20% of their energy needs, the energy and emission changes as well as the costs are still significantly

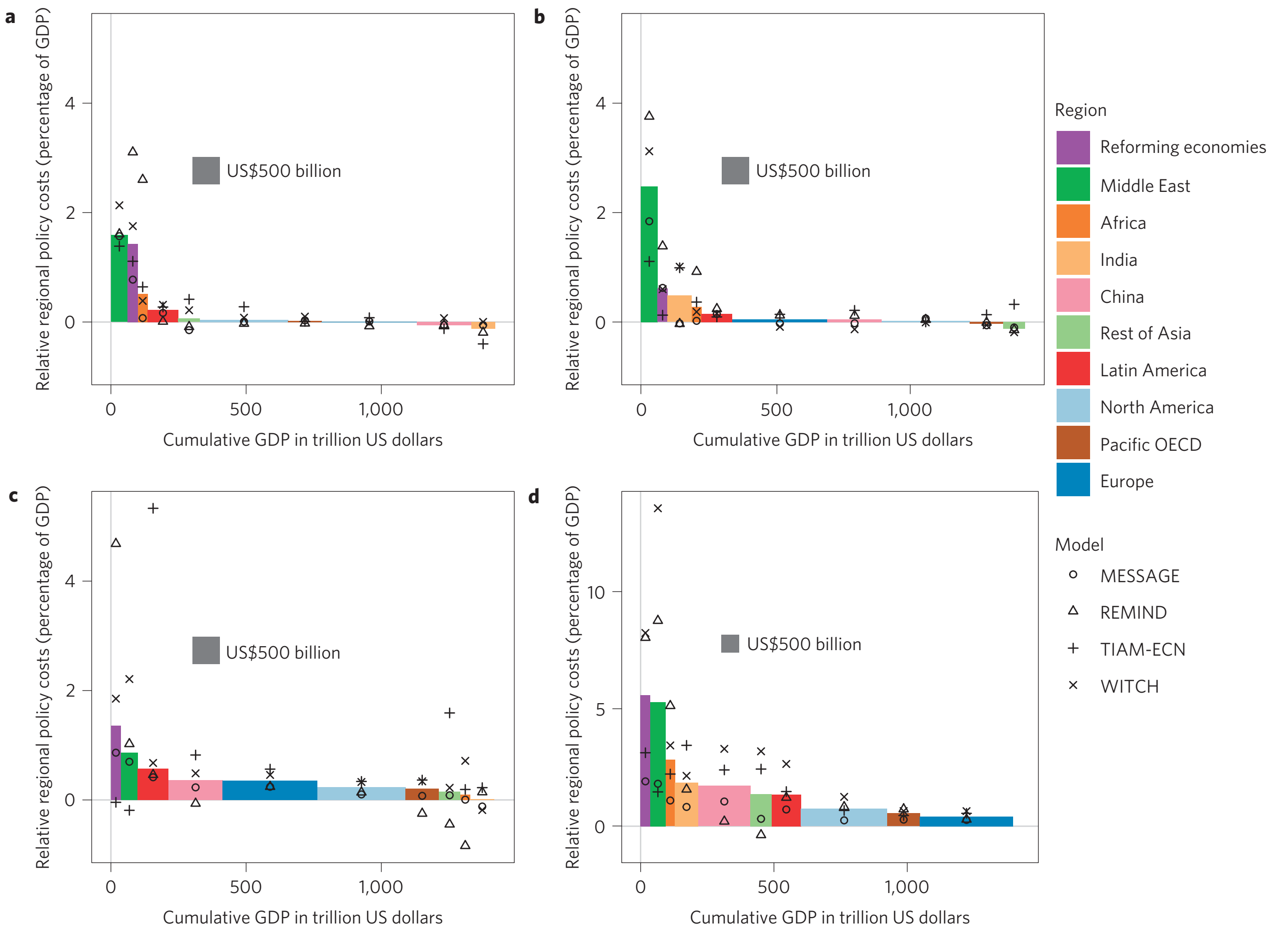

Figure 5 | Regional policy costs for energy independence compared with climate policy scenarios to 2050. a–d, Energy independence (**a**), Oil independence (**b**), Pledges (**c**) and 450 (**d**) scenarios. Note the *y* axis in the 450 panel (**d**) is a different scale from the other panels because the costs of climate stabilization are several times more than the costs of the other three scenarios. The height of the bars shows median policy costs as a percentage of the relevant regional GDP and the area of the bars shows total median policy costs of each region. Markers show the range of policy costs as percentage of GDP for individual models. Costs are expressed in net present value from 2010 to 2050 using a 5% discount rate. See Supplementary Note 1 and Supplementary Table 9 for regional definitions. See Methods for calculation of policy costs. Colours represent regions; symbols distinguish the different models studied.

smaller than those required for climate stabilization (Supplementary Fig. 11 and Supplementary Tables 15 and 16).

While the sensitivity analysis demonstrates the overall robustness of our results, it also points to several key caveats. First of all, although our findings are valid under a wide range of baseline assumptions, one could in principle imagine baselines where these findings may be less pronounced. In particular, technological limitations (for example, on unconventional fossils) could make achieving climate stabilization easier and achieving energy independence more difficult so that the differences between the effects of the two objectives would be less. Second, the cost difference between climate stabilization and energy independence policies declines in a 'Sustainability World' (Supplementary Table 12). Under even more limited fossils and even faster uptake of renewables the costs of climate stabilization and energy independence may both drop and further converge, especially for a more modest stabilization target. In addition, our exploration of model uncertainties shows that in the case of more flexible energy demand and renewable penetration, import restrictions result in larger emission reductions. Once again, it is possible to imagine a model with such high responsiveness of demand and share of renewables that import restrictions would lead to even higher emission reductions less different from those needed for climate stabilization.

Conclusions

Our analysis dispels two assumptions often present in energy and climate policy discourses. First, we find that the cost-effective pursuit of ambitious energy independence targets is not likely to result in significant reduction of GHG emissions nor would it universally increase renewable energy use and be sufficient for achieving even the climate Pledges. In other words, climate will not be saved as a 'side effect' of energy independence efforts. Second, our findings question the main (although not always explicit) assumption behind the efforts to quantify 'co-benefits' of climate policies. The assumption is that the knowledge of such co-benefits would automatically increase support for climate measures from advocates of non-climate energy policy objectives. We show that at least in the case of decreasing energy imports this argument should be more nuanced: although stringent climate policies may indeed bring a considerable reduction in energy imports, a similar reduction can be achieved at a fraction of the climate change mitigation cost if energy independence is pursued as a separate objective in its own right. This means that cost-sensitive political advocates of energy independence may have little reason to support climate stabilization policies. In other words, whether the presence of energy security or other 'co-benefits' is likely to significantly increase political support for climate policies should be subject to special analysis that takes into account both the relative costs of achieving various energy objectives and cost sensitivity of political preferences for these objectives.

Methods

Study design. This study is based on modelling long-term global energy scenarios using five integrated assessment models: IMAGE[48,49], MESSAGE[50,51], REMIND[52], TIAM-ECN[53,54] and WITCH[55,56] (see also Supplementary Note 5). In addition to the Baseline, we model two energy independence scenarios with restrictions on regional energy imports, and Climate stabilization scenarios that stabilize GHG concentration at 450 ppm CO_2e or 500 ppm CO_2e (by 2100) or depict regional emission pathways consistent with recent climate Pledges[37]. We follow a target-based policy approach by setting harmonized policy objectives and computing the corresponding policies and measures endogenously. The limitation of this study design is that it depicts stylized pathways to achieve policy objectives rather than the effects of specific policy instruments, which depend on the particular context of their application and interaction[57–59]. Investigating these dynamics requires more research including modelling at the national and sub-national level. Additional information on the scenarios is available in the online database https://tntcat.iiasa.ac.at/LIMITSPUBLICDB.

Setting energy and oil dependence targets. Among those model regions that are also political jurisdictions, very few have explicit energy independence targets. Japan is an exception; in its Basic Energy Plan from 2010[33,34], the country aimed to reduce its import dependence to 64% by 2030. This ambition was weakened in the INDC 2015[60] owing to contraction in nuclear power after the Fukushima accident. Ukraine, South Korea, the European Union and Turkey plan measures (for example, deployment of renewables and nuclear energy) that will affect their import dependence to a much smaller degree. The targets that we set for importing economies vary between 19 and 50% and thus are more ambitious than one of the countries with the strongest historical commitment to energy security[61,62]. This is by design. If we were to model weaker, and perhaps more realistic energy independence policies, the energy and emissions impacts that we find would be even smaller.

We set the energy independence targets based on the 2010 level and the trend in the development of the energy system over the century (Table 2 and Supplementary Table 2). Developed regions with high net energy import dependence today and low projected energy-demand growth cut their energy imports in half by 2030 and maintain this level throughout the century. Developing and emerging economies with relatively lower energy imports today maintain their current level of net energy import dependence throughout the century; this contrasts with rapidly rising energy imports in most of these regions under the Baseline. Finally, energy exporters never become importers. The US/North American region is projected to become energy independent within the next several decades even under the Baseline[8,63–65]; thus for this region, we model energy independence by 2030 and maintaining that level throughout the century.

Import restrictions for oil independence are set as the same for all importing regions because most developing and emerging economies already have high net oil import dependence (Supplementary Table 3). All oil-importing regions cut their 2010 oil imports in half by 2030 and maintain that level throughout the century. The US/North America region achieves oil independence by 2030.

Regional energy and oil import restrictions are set for native model regions (Supplementary Tables 4–8). The independence targets are met with a 10% tolerance interval. Under Energy independence, in TIAM-ECN, the South Korean target was relaxed to 60% (from 45%) and small deviations were made in Mexico and Eastern Europe in the latter half of the century: in Mexico, the target was relaxed from no imports to 31% import dependence and in Eastern Europe to 35% from a target net import dependence of 20%. In the Oil independence scenarios, in MESSAGE in the North America region, the target was delayed until 2040. On the global level, these relaxations represent less than 5% of global energy trade and on the regional level, the energy independence levels are still quite stringent compared with the Baseline development.

Calculating net energy import dependence. Net import dependence (NID) is calculated by summing the net energy trade (imports minus exports) of all primary energy sources and secondary energy carriers for a given region and year and then dividing by the respective total primary energy supply (equation (1)). We calculate the NID for each model for all fuels that it trades (Table 3).

$$\mathrm{NID}_{r,y} = \frac{\sum P\,\mathrm{imports}_{r,y} + S\,\mathrm{imports}_{r,y} - P\,\mathrm{exports}_{r,y} - S\,\mathrm{exports}_{r,y}}{\mathrm{Total\ primary\ energy\ supply}_{r,y}} \qquad (1)$$

where $\mathrm{NID}_{r,y}$ is the net energy import dependence in region r in year y, $P\,\mathrm{imports}_{r,y}$ is the total primary energy imports, $S\,\mathrm{imports}_{r,y}$ is the total secondary energy imports, $P\,\mathrm{exports}_{r,y}$ is the total primary energy exports, $S\,\mathrm{exports}_{r,y}$ is the total secondary energy exports, and $\mathrm{Total\ primary\ energy\ supply}_{r,y}$ is the total primary energy supply.

The oilNID is calculated as the difference between crude oil and oil product imports and crude oil and oil product exports over the total oil supply (equation (2)).

$$\mathrm{oilNID}_{r,y} = \frac{\sum C\,\mathrm{imports}_{r,y} + OP\,\mathrm{imports}_{r,y} - C\,\mathrm{exports}_{r,y} - OP\,\mathrm{exports}_{r,y}}{\mathrm{Total\ primary\ oil\ supply}_{r,y}} \qquad (2)$$

where $\mathrm{oilNID}_{r,y}$ is the net oil import dependence in region r in year y, $C\,\mathrm{imports}_{r,y}$ is the total crude oil imports, $OP\,\mathrm{imports}_{r,y}$ is the total oil products imports, $C\,\mathrm{exports}_{r,y}$ is the total crude oil exports and $OP\,\mathrm{exports}_{r,y}$ is the total oil products exports.

Representation of energy trade in the models. All of our models depict energy trade between regions. This approach excludes intra-regional trade (such as imports to Germany from Norway). This is however consistent with policy-driven energy security assessments that often treat energy imports from neighbouring suppliers differently than those from distant exporters[66,67].

Models differ on the types of energy trade they depict (Table 3). Energy import restrictions are imposed on all fuels that each model trades. As all models represent oil, gas and coal trade, which account for almost all energy trade today, the starting points for regional net energy import levels are similar. The scope of this paper is limited to trade in primary and secondary energy and excludes technological dependencies, which are also important for energy security[23] and could significantly change under different energy scenarios. More work is needed to understand these vulnerabilities and their evolution in the future.

It should be noted that net imports are not constrained by taxing fossil fuel technologies. Rather, models make energy imports (including ‘new fuels’ such as biofuels and hydrogen for those models that depict it—see Table 3) less attractive either by hard constraints on energy imports (in the optimization models) or by imposing a tax on imported fuels (in IMAGE, the simulation model).

Geographically, there are two main ways to represent energy trade in the models—bilateral trade and global pool trade. Under bilateral trade, one region sells energy directly to another region. In global pool trade, an energy exporter sells energy to a global pool that energy importers can buy from. For example, in a model with only bilateral trade, Middle Eastern oil exports would be sold directly to oil-importing regions such as Europe or India. In contrast, in a model with global pool trade, the Middle East would first sell its oil exports to a global pool, from which oil-importing regions could buy.

Neither mechanism is a perfect representation of reality. Bilateral trade best represents direct trade between two countries such as natural gas trade in Europe where Russia sells natural gas directly to European countries and transports it using pipelines whereas global pool trade best represents much of the oil market. In IMAGE and TIAM-ECN, all energy trade is bilateral. In WITCH all energy trade goes through a global pool. REMIND also assumes a global pool but enhances this with differentiated regional trade costs to and from the pool. In MESSAGE, piped natural gas trade is bilateral between several regions (for example, Europe and Russia) and all other energy trade goes through the global pool (including liquefied-natural gas and secondary fuels). The import restrictions are defined in the same way regardless of the energy trade mechanism and the results are robust regardless of which energy trade mechanism the model uses.

Implementing energy and oil independence targets. The optimization models (MESSAGE, REMIND, TIAM-ECN and WITCH) achieve the target energy import levels by imposing constraints on the net energy import volumes (in exajoules) and not on net energy import dependence level (in percentage terms). The net energy import level is determined by multiplying the targets in the Energy and Oil independence scenarios by the primary energy development in the Baseline (total primary energy supply for all import scenarios and total primary oil supply for the oil scenarios). The import restriction level is then imposed as a volume constraint rather than as a proportion constraint. This avoids the model artefact of increasing the total primary energy supply (the denominator) to decrease overall energy dependence. IMAGE limits energy imports by imposing a tax on all imported energy. As net import constraints include ‘new fuels’ such as biofuels and hydrogen for those models that depict it (Table 3), the neutrality of emissions of this target is an endogenous outcome.

Modelling climate pledges. The Pledges scenario depicts a world where all regions implement climate mitigation policies consistent with an ambitious interpretation of the Copenhagen pledges (Supplementary Table 1). This level of climate policy ambition is extrapolated beyond 2020 by projecting the GHG emission reduction rate that is achieved under the specified technology and GHG targets from 2020 to 2100. The Pledges scenario that we analyse is generally consistent with the INDC emission range from the Climate Action Tracker[68] over the short term, which is also consistent with INDC 2030 estimates from REMIND[69] and PBL[70]. See the last column of Supplementary Table 1 for the regional GHG emission reduction rate in each region from 2020 to 2100 and ref. 38 for model-specific implementation.

Estimating policy costs and warming. Policy costs represent consumption losses over GDP for MESSAGE, REMIND and WITCH, all of which have a macro-economic component. For TIAM-ECN, policy costs represent additional energy system costs over GDP. IMAGE costs are excluded because the model is not able to calculate energy independence costs in a comparable way to the model's calculation of climate policy costs. GDP is expressed in market exchange rates. The real-world economic costs would depend on the choice of policy instruments and other factors. Costs do not include benefits from reduced warming.

The estimate of warming under the Energy independence scenario is based on a non-probabilistic parameterization of MAGICC 6 (ref. 71); all temperature estimates represent the median temperature response, which carries a ±20% range of uncertainty with a 66% probability[72].

Uncertainty analysis. The multi-model study design ensures that our findings are robust across model uncertainties including different solution mechanisms, representations of energy trade and different methods for restricting energy imports (see Supplementary Note 2 and Supplementary Table 11). The model uncertainty covered in our study also spans a wide range of the literature, in both key inputs and outputs. Supplementary Fig. 12 shows the Baseline development of key input parameters in our models compared with the Baseline scenario space in the Intergovernmental Panel on Climate Change AR5 database; Supplementary Fig. 13 compares our key results for the 450 scenario to the 450 scenario space in the literature. We also test the robustness of our findings against parametric uncertainties by imposing the energy import restriction constraints in scenarios with three different Baselines based on SSPs[44–46,73] that span a wide range of uncertainties (see Supplementary Note 3 and Supplementary Fig. 10). To test the robustness of our findings against the level of the energy and oil import restriction targets, we perform a sensitivity analysis using the MESSAGE model and vary the import restrictions both 50% higher and 50% lower than the main Energy and Oil independence scenarios (see Supplementary Note 4 and Supplementary Tables 13 and 14 and Supplementary Fig. 11).

Received 29 September 2015; accepted 3 May 2016; published 6 June 2016

References

1. van Renssen, S. Energy security vs climate policy. *Nature Clim. Change* **4**, 756–757 (2014).
2. *European Energy Security Strategy* (European Commission, 2014); http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0330&from=EN
3. Rai, S. Narendra Modi roams the world in attempt to secure India's energy supply. *Forbes* (25 November 2014); http://www.forbes.com/sites/saritharai/2014/11/25/narendra-modi-roams-the-world-in-attempt-to-secure-indias-energy-supply
4. *Cancun Climate Change Conference* (UNFCCC, 2010); http://unfccc.int/meetings/cancun_nov_2010/meeting/6266.php
5. *Intended Nationally Determined Contributions* (*INDCs*) (UNFCCC, 2016); http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx
6. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) 413–510 (IPCC, Cambridge Univ. Press, 2014).
7. Jewell, J., Cherp, A. & Riahi, K. Energy security under de-carbonization scenarios: an assessment framework and evaluation under different technology and policy choices. *Energy Policy* **65**, 743–760 (2014).
8. Jewell, J. *et al.* Energy security of China, India, the E. U. and the U.S. under long-term scenarios. *Clim. Change Econ.* **4**, 1340011 (2013).
9. Kruyt, B., van Vuuren, D. P., de Vries, H. J. M. & Groenenberg, H. Indicators for energy security. *Energy Policy* **37**, 2166–2181 (2009).
10. Cherp, A., Jewell, J., Vinichenko, V., Bauer, N. & De Cian, E. Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. *Climatic Change* **136**, 83–94 (2016).
11. Grubb, M., Butler, L. & Twomey, P. Diversity and security in UK electricity generation: the influence of low-carbon objectives. *Energy Policy* **34**, 4050–4062 (2006).
12. Shukla, P. R. & Dhar, S. Climate agreements and India: aligning options and opportunities on a new track. *Int. Environ. Agreem.* **11**, 229–243 (2011).
13. McCollum, D. L., Krey, V. & Riahi, K. An integrated approach to energy sustainability. *Nature Clim. Change* **1**, 428–429 (2011).
14. Bollen, J., Hers, S. & van der Zwaan, B. An integrated assessment of climate change, air pollution, and energy security policy. *Energy Policy* **38**, 4021–4030 (2010).
15. McCollum, D. L. *et al.* Climate policies can help resolve energy security and air pollution challenges. *Climatic Change* **119**, 479–494 (2013).
16. Cherp, A. & Jewell, J. The concept of energy security: beyond the four As. *Energy Policy* **75**, 415–421 (2014).
17. Cherp, A. & Jewell, J. The three perspectives on energy security: intellectual history, disciplinary roots and the potential for integration. *Curr. Opin. Environ. Sustain.* **3**, 202–212 (2011).
18. Sovacool, B. K. & Brown, M. A. Competing dimensions of energy security: an international perspective. *Annu. Rev. Environ. Resour.* **35**, 77–108 (2010).
19. Farrell, A. E., Zerriffi, H. & Dowlatabadi, H. Energy infrastructure and security. *Annu. Rev. Environ. Resourc.* **29**, 421–469 (2006).
20. Colglazier, E. W. Jr & Deese, D. A. Energy and security in the 1980s. *Annu. Rev. Energy* **8**, 415–449 (1983).
21. Yergin, D. Energy security in the 1990s. *Foreign Aff.* **67**, 110–132 (1988).
22. Stirling, A. Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. *Energy Policy* **22**, 195–216 (1994).
23. Cherp, A. *et al. Global Energy Assessment: Toward a More Sustainable Future* 325–383 (Cambridge Univ. Press, 2012).
24. Jewell, J. *The IEA Model of Short-term Energy Security* (*MOSES*)*: Primary Energy Sources and Secondary Fuels* (OECD/IEA, 2011); http://www.oecd-ilibrary.org/energy/the-iea-model-of-short-term-energy-security-moses_5k9h0wd2ghlv-en
25. Turton, H. & Barreto, L. Long-term security of energy supply and climate change. *Energy Policy* **34**, 2232–2250 (2006).
26. Molyneaux, L., Wagner, L., Froome, C. & Foster, J. Resilience and electricity systems a comparative analysis. *Energy Policy* **47**, 188–201 (2012).
27. Gracceva, F. & Zeniewski, P. A systemic approach to assessing energy security in a low-carbon EU energy system. *Appl. Energy* **123**, 335–348 (2014).
28. Lubell, H. Security of supply and energy policy in western Europe. *World Politics* **13**, 400–422 (1961).
29. Calmes, J. & Broder, J. M. Obama sets goal of one-third cut in oil imports. *The New York Times* (30 March 2011); http://www.nytimes.com/2011/03/31/science/earth/31energy.html?_r=1
30. Hargreaves, S. Romney sets goal of energy independence by 2020. *CNN* (23 August 2012); http://money.cnn.com/2012/08/23/news/economy/romney-energy
31. Das, K. N. Goyal: may stop thermal coal imports in 2–3 years. *Reuters India* (13 November 2014).
32. Yergin, D. *The Prize: The Epic Quest for Oil, Money, and Power* (Simon & Schuster, 1991).
33. *Enerugii kihon keikaku* [*Basic Energy Plan*] (Ministry of Economy, Trade and Industry of Japan, 2010).
34. Duffield, J. S. & Woodall, B. Japan's new basic energy plan. *Energy Policy* **39**, 3741–3749 (2011).
35. Cheon, A. & Urpelainen, J. Escaping oil's stranglehold: when do states invest in energy security? *J. Confl. Resolut.* **59**, 953–983 (2015).
36. Industry Division of the Economic Commission for Europe *Relationship Between Coal and Black Oils in the West European Fuel Market* (United Nations, 1954).
37. Tavoni, M. Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Clim. Change* **5**, 119–126 (2015).
38. Kriegler, E. *et al.* What does the 2 C target imply for a global climate agreement in 2020? The LIMITS Study on Durban Platform Scenarios. *Clim. Change Econ.* **4**, 1340008 (2013).
39. McCollum, D., Bauer, N., Calvin, K., Kitous, A. & Riahi, K. Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Climatic Change* **123**, 413–426 (2014).
40. Riahi, K. *et al.* Locked into Copenhagen pledges—Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* **90**, 8–23 (2015).
41. Kriegler, E. *et al.* Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change* **90**, 24–44 (2015).
42. Tavoni, M. *et al.* The distribution of the major economies' effort in the Durban platform scenarios. *Clim. Change Econ.* **4**, 1340009 (2013).
43. Clarke, L. *et al.* International climate policy architectures: overview of the EMF 22 international scenarios. *Energy Econ.* **31**, S64–S81 (2009).
44. van Vuuren, D. P. & Carter, T. R. Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic Change* **122**, 415–429 (2014).
45. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400 (2013).
46. SSP Database (Shared Socioeconomic Pathways) - Version 1.0 (2015) https://secure.iiasa.ac.at/web-apps/ene/SspDb
47. Kriegler, E. *et al.* Diagnostic indicators for integrated assessment models of climate policy. *Technol. Forecast. Soc. Change* **90**, 45–61 (2014).

48. van Vuuren, D. P. *Energy Systems and Climate Policy-Long-Term Scenarios for an Uncertain Future* PhD thesis, Utrecht Univ. (2007).
49. *Integrated Modelling of Global Environmental Change* (Netherlands Environmental Assessment Agency (MNP), 2006).
50. Riahi, K., Grubler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change* **74**, 887–935 (2007).
51. Riahi, K. *et al. Global Energy Assessment: Toward a More Sustainable Future* 1203–1306 (Cambridge Univ. Press, 2012).
52. Bauer, N. *et al.* Global fossil energy markets and climate change mitigation—an analysis with REMIND. *Climatic Change* **136**, 69–82 (2016).
53. Keppo, I. J. & van der Zwaan, B. The impact of uncertainty in climate targets and CO_2 storage availability on long-term emissions abatement. *Environ. Model Assess.* **17**, 177–191 (2011).
54. Kober, T., van der Zwaan, B. & Rösler, H. Emission certificate trade and costs under regional burden-sharing regimes for a 2 °C climate change control target. *Clim. Change Econ.* **5**, 1440001 (2014).
55. Bosetti, V., De Cian, E., Sgobbi, A. & Tavoni, M. *The 2008 WITCH Model* FEEM Working Paper No. 85.2009 (Fondazione Eni Enrico Mattei, 2009).
56. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. WITCH: a world induced technical change hybrid model. *Energy J.* **27**, 13–37 (2006).
57. Pethig, R. & Wittlich, C. *Interaction of Carbon Reduction and Green Energy Promotion in a Small Fossil-fuel Importing Economy* (CESIFO, 2009).
58. Böhringer, C. & Rosendahl, K. E. Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *J. Regul. Econ.* **37**, 316–325 (2010).
59. Fankhauser, S., Hepburn, C. & Park, J. Combining multiple policy instruments. *Clim. Change Econ.* **1**, 209–225 (2010).
60. Government of Japan *Submission of Japan's Intended Nationally Determined Contribution (INDC)* (UNFCCC, 2015).
61. Toichi, T. Energy security in Asia and Japanese policy. *CAPR* **10**, 44–51 (2003).
62. Calder, K. E. Japan's energy angst: Asia's changing energy prospects and the view from Tokyo. *Strategic Anal.* **32**, 123–129 (2008).
63. *World Energy Outlook 2014* (OECD/IEA, 2014).
64. *BP Energy Outlook 2030* (British Petroleum, 2013).
65. Neff, S. & Coleman, M. EIA outlook: reversal in U.S. oil import dependency. *ESR* **5**, 6–13 (2014).
66. Scheepers, M., Seebregts, A. J., de Jong, J. & Maters, H. *EU Standards for Energy Security of Supply* 1–104 (ECN/Clingendael International Energy Programme, 2007).
67. *A Quest for Energy Security in the 21st Century: Resources and Constraints* 1–113 (Asia Pacific Energy Research Centre, 2007).
68. Climate Action Tracker *Effect of Current Pledges and Policies on Global Temperature* (Ecofys, Climate Analytics, PIK, New Climate Institute, 2015); climateactiontracker.org
69. Spencer, T. *et al. Beyond the Numbers* (Institut du développement durable et des relation internationales, 2015).
70. *PBL Climate Pledge INDC Tool* (PBL, 2015); http://infographics.pbl.nl/indc
71. Meinshausen, M. *et al.* The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**, 213–241 (2011).
72. Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim. Change* **2**, 248–253 (2012).
73. O'Neill, B. C. *et al.* The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004 (2015).

Acknowledgements
The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007–2013 under grant agreement no. 282846 (LIMITS). A.C. and V.V. also received support from CEU's Intellectual Themes Initiative. We would also like to thank P. Kolp for technical support.

Author contributions
J.J., A.C., K.R., D.M. and V.K. designed the experiments. J.J. and V.V. analysed the data. V.V., D.M., N.B., T.A., O.F., M.H., T.K., V.K., G.M., M.T., D.P.v.V. and B.v.d.Z. performed the experiments and contributed tools and analysis methods. J.J. and A.C. wrote the paper with input from all authors.

Additional information
Supplementary information is available online. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.J.

Competing interests
The authors declare no competing financial interests.