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Climate policies can help resolve energy security and air pollution challenges

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Abstract This paper assesses three key energy sustainability objectives: energy security improvement, climate change mitigation, and the reduction of air pollution and its human health impacts. We explain how the common practice of narrowly focusing on singular issues ignores potentially enormous synergies, highlighting the need for a paradigm shift toward more holistic policy approaches. Our analysis of a large ensemble of alternate energy-climate futures, developed using MESSAGE, an integrated assessment model, shows that stringent climate change policy offers a strategic entry point along the path to energy sustainability in several dimensions. Concerted decarbonization efforts can lead to improved air quality, thereby reducing energy-related health impacts worldwide: upwards of 2–32 million fewer disability-adjusted life years in 2030, depending on the aggressiveness of the air pollution policies foreseen in the baseline. At the same time, low-carbon technologies and energy-efficiency improvements can help to further the energy security goals of individual countries and regions by promoting a more dependable, resilient, and diversified energy portfolio. The cost savings of these climate policy synergies are potentially enormous: \$100–600 billion annually by 2030 in reduced pollution control and energy security expenditures (0.1–0.7 % of GDP). Novel aspects of this paper include an explicit quantification of the health-related co-benefits of present and

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future air pollution control policies; an analysis of how future constraints on regional trade could influence energy security; a detailed assessment of energy expenditures showing where financing needs to flow in order to achieve the multiple energy sustainability objectives; and a quantification of the relationships between different fulfillment levels for energy security and air pollution goals and the probability of reaching the 2 °C climate target.

1 Introduction and motivation

Steering the global energy system in a more sustainable direction will necessitate transformative changes aimed at delivering simultaneous improvements across a number of dimensions (Goldemberg and Johansson 2004; Riahi et al. 2012), including, but not limited to, energy security enhancement, climate change mitigation, and the reduction of air pollution and its human health impacts. While satisfying all of these objectives will ultimately be important, recent history has shown quite uneven progress along the different fronts. More specifically, previous climate negotiations have failed to yield a globally binding agreement on greenhouse gas emission levels consistent with a 2 °C global warming target, whereas at both local and national levels, the issues of energy security and air pollution have gained a considerable amount of traction. The United States, for instance, has implemented biofuels mandates and stricter fuel economy standards for vehicles in order to reduce its dependence on foreign oil, which President Obama pledges to cut by one-third by 2025 (The White House 2011). Similarly, China, in an effort to keep pace with surging demand, has formulated ambitious energy efficiency targets for its economy, while at the same time continuing its scramble for access to energy resources worldwide (Sovacool and Brown 2010). And in resource-scarce Japan, following the nuclear incident in Fukushima, a dialogue on energy supply diversification has begun anew (Landau 2011). Similarly, in the air pollution and health dimension, emissions regulations (for vehicles, power plants and industrial facilities) in both industrialized and developing countries have become increasingly stringent in recent years, with correspondingly large improvements in energy-related health impacts in many parts of the world (Rao et al. 2012; Smith et al. 2011; WHO 2006).

This paper elaborates upon and substantiates the assertions made in McCollum et al. (2011), explaining how the common practice of narrowly focusing on singular energy policy issues ignores potentially enormous synergies, quite often leading to the implementation of short-sighted solutions that may have unnecessarily costly, long-term consequences. Informing the policy process in a more integrated, holistic way can be aided through new tools and approaches now being developed. Our own analysis finds enormous synergies between the multiple objectives for energy sustainability. More specifically, the combined costs of climate mitigation, energy security improvement and air pollution reduction come at a significantly reduced total energy bill when viewed from an integrated perspective. Climate change policy offers a strategic entry point along this path, whereas the other two objectives considered in this analysis do not.

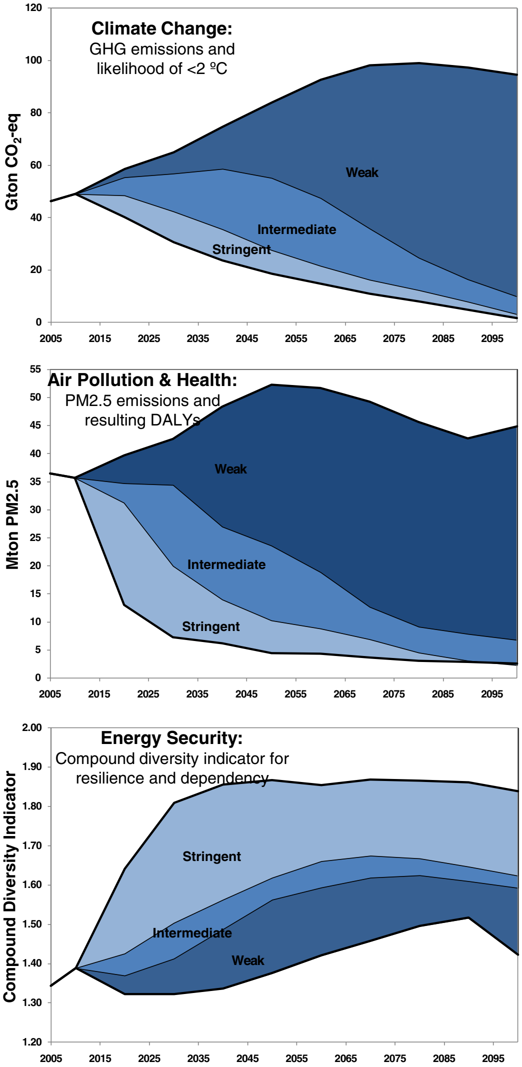
2 Spanning the scenario space

To better understand the synergies and trade-offs between multiple objectives, we conducted a large-scale experiment using MESSAGE-MACRO, an integrated assessment model with considerable technological detail of the global energy system (Riahi et al. 2007) [see the electronic supplementary material (SM)]. Starting from a baseline scenario of development to 2100, we developed an ensemble of several hundred alternate energy futures, each of which assumes a unique combination of policy priorities with respect to climate, energy security and air pollution. Hence, the scenarios stretch the potential development of the energy system in several dimensions by fulfilling the individual objectives to varying degrees of satisfaction (i.e., the sustainability targets are achieved at different levels). Importantly, within a given scenario, the fulfillment of each objective is independent from that of another, except for some important synergies, as discussed later. The ultimate goal of the analysis was to cover the entirety of the feasible scenario space under a common storyline for future population, economic development and resulting energy demand growth, using statistically corroborated "middle-of-the-road" assumptions from the scenario literature (Nakicenovic et al. 2006). Our focus was thus on the uncertainties surrounding future policy priorities rather than on, as is traditionally practiced, exogenous technological and socio-economic uncertainties.

Exploring these alternative pathways required linking MESSAGE to the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) air quality model (Amann et al. 2009). This permitted the estimation of regionally-aggregated, sector-based (outdoor) air pollutant emissions and pollution control costs for each scenario in the ensemble. More specifically, at each level of end-of-pipe air pollution control policy stringency and for each pollutant and region, emission factors for each technology in GAINS were applied to the corresponding energy technology in MESSAGE (Rafaj et al. 2010). Similarly, GAINS was used to estimate the costs of installing all necessary pollution control equipment by energy technology; these costs varied by policy regime. As a final step, health impacts from air pollution were calculated by drawing on the methodology described in Rao et al. (2012), in which regionally-aggregated air pollutant emissions from MESSAGE are down-scaled to the local level; concentrations are estimated using TM5, a global, 3-dimensional atmospheric chemistry-transport model (Dentener et al. 2006; Krol et al. 2005); and World Health Organization (WHO) Comparative Risk Assessment (CRA) methodologies are used to quantify the impacts. See the SM for more details.

Different indicators are used to measure the fulfillment of each energy objective along a normative scale: climate change in terms of the probability of limiting global temperature rise to 2 °C above pre-industrial levels, air pollution and health impacts in terms of disability-adjusted life years (DALY), and energy security in terms of a compound diversity indicator. The use of such different metrics, although necessary given the far-ranging impacts of the energy system, tends to complicate the comparison of scenarios that meet certain objectives but not others. For this reason, this paper adopts a simple framework to describe the scenario space across the three objectives. The framework, summarized in Fig. 1, defines three levels of satisfaction—Weak, Intermediate, and Stringent—for each of the three energy objectives.

Figure 1 illustrates the full scenario space across all three dimensions: climate, air pollution and health, and energy security. The degree to which each scenario (or rather, class of scenarios) fulfills the individual objectives is indicated in the figure by the shaded Weak, Intermediate, and Stringent regions. For instance, the uppermost panel illustrates ranges of GHG emissions trajectories for all scenarios in the large ensemble that correspond to varying probabilities of reaching the 2 °C target. (Note that the radiative forcing effects of pollutant emissions and other non-Kyoto gases are also considered, and that the uniform prior climate sensitivity probability density function from Forest et al. (2002) is used; see SM for more information.) The baseline scenario, which assumes no new climate, air pollution, or energy security policies, sees the largest growth in emissions throughout the century and is therefore at the upper bound of the Weak region. All other scenarios achieve emissions reductions compared with the baseline, and hence have comparatively higher probabilities of meeting the 2 °C target.



Degree of fulfillment of policy objective	**Climate change** (probability of staying within 2ºC warming limit)
Weak	**<20%**
Intermediate	**20-50%**
Stringent	**>50%**

Degree of fulfillment of policy objective	**Air pollution and health** (million DALYs, 2030)
Weak	**>33**
Intermediate	**15-33**
Stringent	**<15**

Degree of fulfillment of policy objective	**Energy security** (compound diversity indicator, 2030)
Weak	**<1.40**
Intermediate	**1.40-1.50**
Stringent	**>1.50**

Fig. 1 Trajectories for global greenhouse gas emissions, PM2.5 emissions, and the compound energy diversity indicator for the full scenario ensemble. Corresponding indicators for sustainability objective fulfillment within the Weak-Intermediate-Stringent framework are shown to the right

Consistent with Rogelj et al. (2011), we find that reaching the 2 °C target with greater than 50 % probability (Stringent region) requires that emissions peak in 2020 at levels only marginally higher than today and then be reduced significantly in the decades that follow. If, however, the climate objective is of lower priority, the permissible peak in emissions could certainly be greater and could even be delayed far beyond 2020.

The middle panel of Fig. 1 illustrates the full space of the scenario ensemble in the combined air pollution and health dimension by showing global PM2.5 emissions trajectories and resulting DALYs. Particulate matter is chosen as a representative pollutant for this discussion because of all types of air pollutant emissions, PM2.5 causes some of the most serious impacts on human health.[1] The emissions trajectories shown in the figure correspond to multiple pathways for energy system development under different portfolios of air pollution control legislation (see SM). Note that in Fig. 1, the shaded Weak, Intermediate, and Stringent regions correspond to DALYs at the global level (the aggregate of all world regions) that would be expected in 2030 under the air quality levels shown. By design, the lower end of Stringent region is consistent with the attainment of WHO Tier I Levels (35 $\mu g/m^3$) throughout the world by 2030 (WHO 2006). Whether the improvements are driven by either air quality or climate measures, or both, substantial reductions in PM2.5 emissions are possible in the near term.

Of particular note, our analysis focuses explicitly on presently legislated and planned pollution policies to 2030 and the implications of making those policies more stringent going forward. This is an important qualification because our conclusions for synergies and trade-offs between air pollution (and thus health) and the other objectives are conditional on this approach. Other prominent studies (e.g., Bollen et al. 2010) have approached the problem in a different way, aggegating all objectives into a single welfare function and then performing a joint optimization. The advantage of the latter approach is that it allows for an exploration of pollution legislation beyond that which is currently foreseen and expected. However, such an approach also has its disadvantages, for example, with respect to the difficulty of valuing human life. This is one of the reasons why we opted for a multi-criteria approach in our study: while it is more limited in scope, it avoids value judgments within the modeling framework and instead allows decision makers to explore solutions that correspond to their subjective weighting of different objectives. Box 1 highlights the development of a new type of integrated decision making and scenario communication tool that can be utilized for such a purpose.

Box 1 The IIASA Energy—Multi Criteria Analysis (ENE-MCA) Policy Tool

URL: http://www.iiasa.ac.at/web-apps/ene/GeaMCA

A feature of the current study is the development of the ENE-MCA tool (see SM), which provides an interactive overview of the various synergies and trade-offs involved in attaching priorities to four of the main energy sustainability objectives—climate change, energy security, air pollution and health, and affordability. Building upon the ensemble of scenarios presented in this paper, the ENE-MCA tool allows policymakers and the public to assign differing priorities to the diverse set of objectives, thus helping decision makers to envision how alternative worldviews can lead to qualitatively different energy system futures.

Lastly, the scenarios cover a broad space in the energy security dimension. Energy security is a difficult concept to define, and therefore to measure (Kruyt et al. 2009; Sovacool and Brown 2010). The portfolio approach—i.e., diversity of supply—offers one strategy for achieving system resilience, whereas supplying an increasing quantity of energy from domestic sources (i.e., reducing imports) leads to improved sovereignty. This analysis measures energy security using a compound diversity indicator (Eq. 1), aggregated at the global level (Jansen et al. 2004). The indicator takes into account the diversity of primary energy resources, as well as where those resources are sourced—that is, whether imported into geographically and socio-economically similar regions or produced internally. The diversity indicator rises with increasing diversity of the energy system but falls at higher levels of import dependency. In sum, the

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[1] Note that in addition to PM2.5, each scenario of the large ensemble possesses unique emissions trajectories for sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO), black carbon (BC), organic carbon (OC), and ammonia (NH_3).

higher the compound diversity indicator, the more secure the energy system. (For a more elaborated discussed on the security indicators, and in particular the influence of both resilience and sovereignty on the indicator's value, see the SM.)

$$I = -\sum_j \left\{ \left(1 - m_j\right) \cdot \left(p_j \cdot \ln p_j\right) \right\} \tag{1}$$

where:

- I: compound energy diversity indicator (resources + imports)
- p_j: share of primary energy resource j in total primary energy consumption
- m_j: share of primary energy resource j that is supplied by (net) imports (at the global level, imports are replaced by the traded quantities)[2]

Figure 1 shows how global energy system diversity develops over time in all of the scenarios of the large ensemble, with the Weak, Intermediate, and Stringent regions grouping together scenarios that fulfill the security objective to a similar degree by 2030. Notably, the lower bound of the Weak region is represented by the baseline scenario, meaning it is one of the least desirable in terms of diversity and, by extension, security. Compared with the baseline, virtually every other scenario, whether motivated by security or by climate policy, achieves a greater diversification of the global energy mix, particularly in the near term. In other words, both security- and climate-constrained scenarios respond by increasing the supply of domestic energy and by pushing energy efficiency and conservation. Similar trends are evident at the regional level, as shown in the SM.

Because the individual scenarios in the ensemble vary so greatly along the dimensions of climate change, air pollution and health, and energy security, total energy system costs naturally span a fairly wide range (see SM). The least costly scenario in the ensemble is the baseline, since it assumes no climate, air quality, or security policies other than what is already in place. Fulfillment of the various energy objectives (to any level of satisfaction) then adds to energy system costs to a certain degree. If one thinks of these multiple objectives as societal targets that the energy system should attempt to satisfy in the future (i.e., as scenario inputs), then total costs are an embodiment of the system-wide transformations that must take place (i.e., scenario outputs) in order to meet those objectives (e.g., conservation and increased utilization of advanced technologies and alternative fuels). The resulting total cost of a given scenario thus depends entirely on how far it goes toward satisfying each individual objective. In the ensemble, total costs stretch from 3.0 to 3.8 % of GDP for the class of scenarios that achieves Stringent fulfillment of all three objectives simultaneously. By comparison, energy system costs in the baseline are about 2.1 % of GDP over the same time period—hence, policy costs of some 0.9 to 1.7 percentage points at the maximum.

3 Synergies between multiple energy objectives

The discussions above have already begun to show the inherent synergies, and to a lesser extent the trade-offs, among the various energy objectives and how these complex interdependencies can be illuminated through analysis of a large ensemble of possible energy-climate-air pollution futures. This section explores these relationships further, focusing in

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[2] m_j is constrained to be between 0 and 1 to ignore the contribution of resources that are net exported (i.e., with negative m_j's); otherwise, the diversity indicator of exporting regions would be artificially improved.

particular on the air pollution and health and energy security synergies that derive from climate mitigation. Such work builds on a small, but growing, body of literature (e.g., Bollen et al. 2010; Cofala et al. 2010; McCollum et al. 2011; van Vuuren et al. 2006).

3.1 Climate change mitigation and air pollution and health

Climate change mitigation can be an important entry point for achieving society's pollution- and health-related goals. This is illustrated in the upper panel of Fig. 2, which relates global PM2.5 emissions in the near term (2030) to the probability of staying below 2 °C maximum temperature rise in the long term. Each data point in the figure represents a single scenario in the ensemble. The specific combination of air pollution and climate policy stringency is what distinguishes the scenarios from each other. In particular, different levels of pollution control legislation are indicated by the shapes of the data points (FLE, CLE, SLE, MFR; see SM and Rao et al. (2012) for further explanation), with the grey shaded areas representing the spread between the policy levels. The figure clearly shows that under less stringent pollution control frameworks (e.g., FLE and CLE), as the energy system is decarbonized and increasing shares of low-carbon, air pollution-free technologies are utilized, the probability of meeting the 2 °C target increases, and pollutant emissions are significantly reduced. In contrast, the co-benefits are less pronounced under more stringent frameworks (e.g., SLE and MFR), because in these scenarios even fossil energy technologies become extremely clean from a pollutant emissions perspective. As a result of these dual trends, the spread between the pollution control levels—quite wide in a baseline scenario (left side of the panels)—narrows as climate change mitigation becomes more of a priority, highlighting how the effects of pollution control legislation are much less variable as low-carbon technologies penetrate the market and fossil energy technologies are forced out. Simply put, the need for pollution control measures (e.g., improved combustion processes, flue gas desulfurization, selective catalytic reduction, electrostatic precipitators, and particulate filters) is dramatically reduced when there are fewer fossil energy technologies in the system (Cooper and Alley 2010). Non-combustible renewables, for example, require essentially no pollution control equipment.

Figure 2 (upper panel) also illustrates the extent to which each scenario in the ensemble fulfills the climate change and air pollution and health objectives, utilizing the Weak-Intermediate-Stringent framework discussed previously. Because of the major cuts in PM2.5 that decarbonization brings about, energy-related health impacts worldwide are reduced by up to 23 million DALYs in 2030, compared to our baseline scenario, which assumes that no new climate policies are implemented and that only currently legislated and planned air pollution policies are enacted (the CLE case). To be sure, the health co-benefits of climate mitigation depend strongly on the pollution policies assumed in the baseline; for instance, in the absence of a further strengthening of pollution legislation beyond today's levels (the FLE case), DALYs could be reduced by as much as 32 million. If, on the other hand, society treats air pollution reduction with the utmost importance over the next decades (the SLE and MFR cases), then the synergies of decarbonization would become exceedingly small: a reduction of 2 million DALYs compared to either an SLE or MFR baseline. Interestingly, the upper-right corner of the figure (corresponding to scenarios that would be Stringent on climate but Weak on air pollution and health) contains not a single scenario. In other words, strong climate change mitigation measures alone can yield pollutant emissions reductions that are as great as, or even greater than, currently planned pollution control legislation would likely yield in the absence of climate policy, thereby allowing the air pollution and health objective to be satisfied at the Intermediate level at a minimum. The opposite case (i.e., Weak on climate, Stringent on air pollution and health), in contrast, does not necessarily lead to the same conclusion, showing that stringent air quality legislation on its own is not likely to motivate dramatic reductions in greenhouse gas emissions. It should be noted, importantly, that this conclusion is conditional on our chosen methodological approach, namely our focus on presently legislated and planned air pollution controls. Hence, it is possible that we underestimate, for instance, structural changes or dedicated energy savings as a response to air pollution measures.

There is of course an important trade-off with reducing air pollutant emissions. Because certain types of pollutants, namely aerosols, have a cooling effect on the climate (Solomon et al. 2007), releasing fewer of them to the atmosphere leads to increased warming, all else being equal. For this reason, some have suggested that planners might consider pollution control strategies that reduce some pollutants proportionally more than others—for instance warming components (BC and the ozone precursors: CH_4, NO_x, CO, and VOCs) more than cooling components (SO_2 and OC)—in an effort to preserve the overall cooling effect of aerosols and, thus, to produce a net gain for the climate, or to at least remain radiant energy-neutral (Ramanathan and Xu 2010; UNEP 2011). The scenarios developed in this study are simpler, in that they assume across-the-board reductions for all types of air pollutants (see SM); for this reason the effect of more stringent pollution control leads to a net increase in global temperatures. While the effect is almost indistinguishable in Fig. 2, our calculations show that under the most stringent pollution policy packages, the increase in maximum transient temperatures is as much as 0.4 °C in the baseline scenario, the most extreme case. This assumes the IPCC's best estimate climate sensitivity value of 3 °C.[3]

Another important trade-off with reducing air pollutant emissions, whether through pollution control or climate policy, or both, is that such policies will necessarily lead to additional energy system costs. Yet, given the enormous synergies between pollution and climate policy, achieving society's air pollution and health objectives using climate change mitigation as an entry point has the potential to significantly reduce the added costs of pollution control. This is illustrated in the lower panel of Fig. 2, which plots pollution control costs (relative to all other energy system costs) for each scenario in the ensemble. The data points toward the right side of the panel, particularly in the middle-right portion, are some of the most interesting, as these represent scenarios that fulfill both the climate change and the air pollution and health objective simultaneously at the Stringent level (see upper panel of Fig. 2), though the added costs of pollution control in these scenarios are not much higher than in the baseline (lower-left corner of the lower panel). This indicates that while stringent climate policies will themselves necessitate increased energy system expenditures, a significant portion of these mitigation costs can be compensated for by reduced pollution control requirements (see also Fig. 4). Our scenarios indicate cost savings of up to US$500 billion per year by 2030, almost half the level of today's investments into the global energy system. This estimate depends strongly on the stringency of policies assumed in the baseline, however, and could thus be as low as US$100 billion.

3.2 Climate change mitigation and energy security

The previous discussion has shown that early deployment of low-carbon technologies can help to achieve both near-term pollution and long-term climate targets. We similarly find

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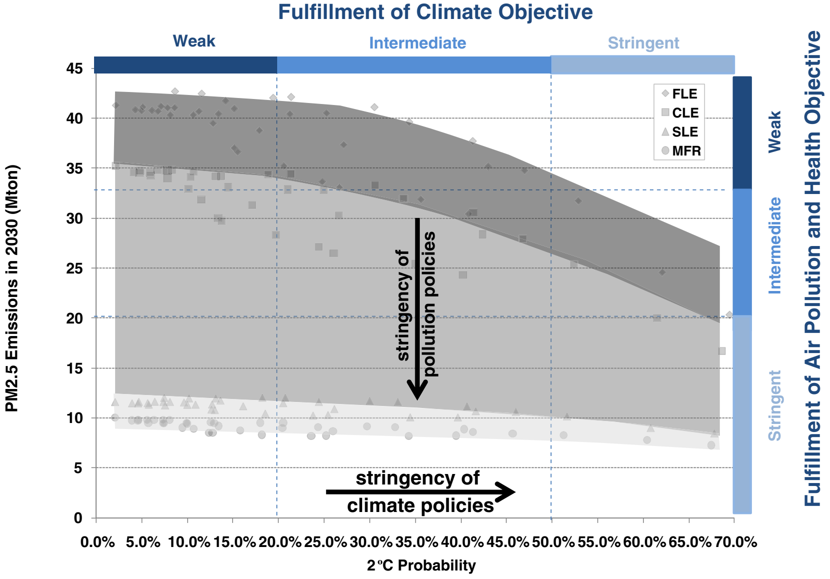
[3] The term climate sensitivity (CS) refers to the equilibrium global average warming expected if CO_2 concentrations were to be sustained at double their pre-industrial values. A CS of 3 °C has a (cumulative) likelihood of 53.9 % using the uniform prior climate sensitivity probability density function from Forest et al. (2002), which is in the middle of the range found in the literature. See SM.



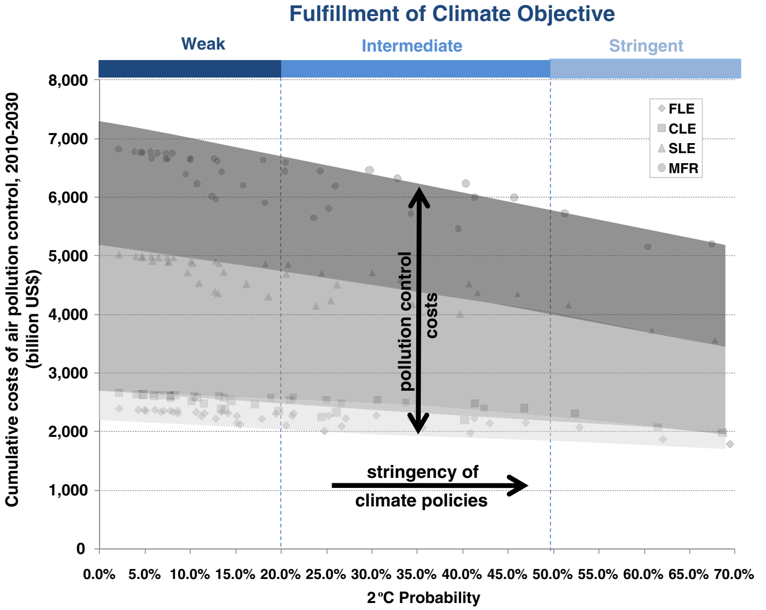


Fig. 2 Synergies between climate change mitigation and near-term pollution controls. The *upper panel* shows the relationship between climate change mitigation (expressed in terms of the likelihood of staying below 2 °C) and the reduction of PM2.5 emissions. The *lower panel* shows the corresponding relationship between climate change mitigation and resulting costs for pollution abatement technologies. Each *dot* in the panels represents a single scenario, and the style of each *dot* indicates the assumed stringency for air pollution control legislation (FLE = Frozen Legislation; CLE = Current and planned Legislation; SLE = Stringent Legislation; MFR = Maximum Feasible Reduction; see SM for details). *Grey-shaded areas* indicate the relative placement of scenarios with different pollution legislation. Vertical and horizontal blue bars indicate the range of outcomes for pollutant emissions (PM2.5) and climate (2 °C probability) that correspond to the Weak, Intermediate, or Stringent Fulfillment levels (see also Fig. 1)

important synergies between decarbonization and energy security, yet another key near-term objective. In short, as countries and regions invest more heavily in energy efficiency and renewables in an effort to decarbonize their economies, they will by extension reduce their need to import globally-traded fossil energy commodities such as coal, oil, and natural gas. Because renewables (biomass, hydro, wind, solar, and geothermal) are, in most cases, available domestically or regionally, they are from a dependency perspective inherently secure resources. Moreover, increased utilization of renewables and nuclear energy tends to diversify the energy resource mix away from one that relies so heavily on fossil energy. Thus, decarbonization of the energy system can simultaneously reduce import dependence (improved sovereignty) and increase energy diversity (improved resilience), two key indicators of a more secure energy supply.

Figure 3 (upper panel) illustrates the relationship between the climate and security objectives by showing global primary energy diversity and dependence in 2030 (measured in terms of the compound diversity indicator, see Section 2) as a function of the probability of staying below the 2 °C warming target. The third dimension captures several alternative policy levels representing the varying stringency of efforts to limit import dependency by individual world regions (see SM); these levels are grouped together by the grey shaded areas. The lower panel of Fig. 3 focuses on costs, plotting the probability of meeting the 2 °C target against cumulative total global policy costs as a share of global GDP between 2010 and 2030. In particular, the panel shows the subset of all scenarios in the large ensemble that have the same assumed level of pollution control legislation stringency (in this case the baseline CLE level; see SM). Even though there are differences in the deployment of pollution control equipment amongst the scenarios, the trends evidenced in the figures primarily serve to highlight the impact of climate mitigation on the costs of energy security policies.

The double effects of decarbonization and reduced import dependence are quite clear from the two panels of Fig. 3. As regions pursue strategies to mitigate climate change or enact policies and procurement strategies that prioritize domestic supplies over imports, the diversity of their energy resource mix is likely to increase (upper panel). And even though pushing both the climate and security objectives will necessitate increased energy system expenditures, at higher levels of decarbonization the costs of achieving security goals are significantly reduced (lower panel). When climate change is of relatively low priority (the Weak climate region), for instance, security-related expenditures add to total energy system costs by as much as 0.2 percentage points; under Stringent climate policies, on the other hand, the added costs of security approach zero. This translates to an investment cost savings of up to US$130 billion per year by 2030. As with pollution control, a significant portion of the climate mitigation costs can be compensated for by the reduced need for extra security expenditures, since climate policy promotes both energy efficiency and conservation and the increased utilization of domestically available, low-carbon energy sources (see also Fig. 4).

3.3 Broadening the perspective

The way in which decision makers prioritize the multiple objectives discussed here will have profound implications for the size and shape of the future energy investment portfolio. Under almost any policy framework, it appears that investments into energy efficiency and low-carbon energy supply will need to rise, whereas fossil energy investments are likely to fall (Fig. 4, lower panel). The exception is the air pollution and health objective, as expanding the most stringent suite of presently legislated and planned policies to all parts

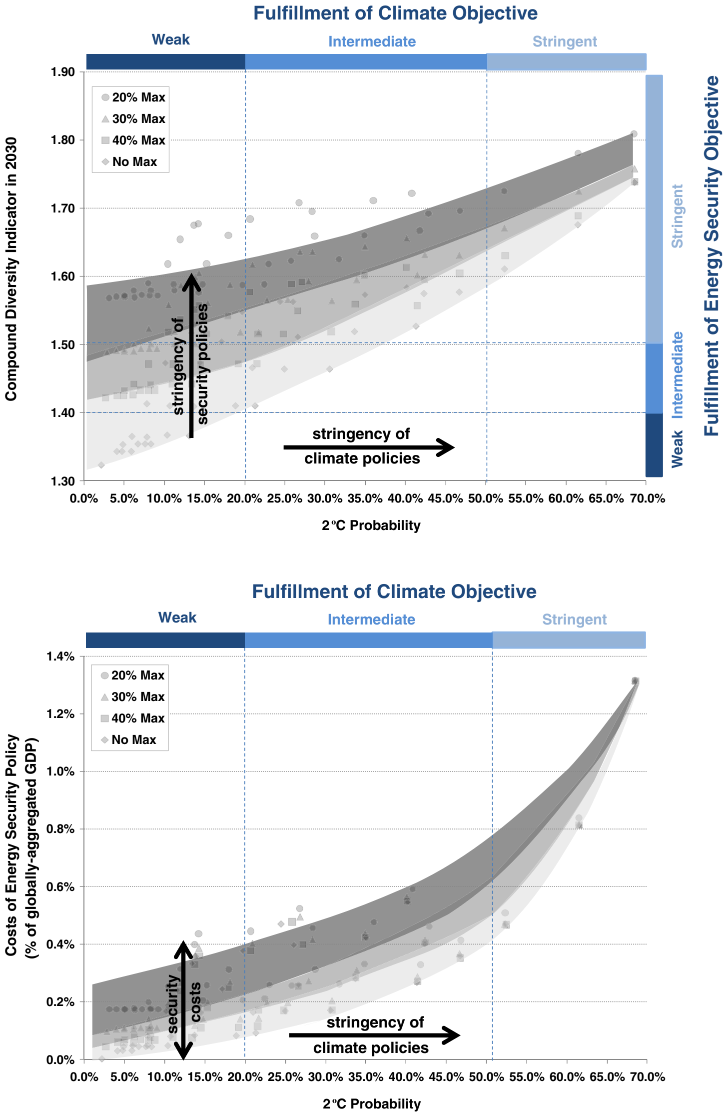


Fig. 3 Synergies between climate change mitigation and near-term improvement of energy security. The *upper panel* shows the relationship between climate change mitigation (expressed in terms of the likelihood of staying below 2 °C) and improvements in energy security with respect to both energy system resilience and sovereignty (expressed in terms of a compound diversity indicator, see Section 2 and the SM). The *lower panel* shows the corresponding relationship between climate change mitigation and the reduced costs for energy security expenditures. Each *dot* in the panels represents a single scenario, and the style of each dot indicates the assumed stringency for the energy security constraint used in the model (formulated as an upper limit on the share of total primary energy that can be supplied by imports in a given region and year). *Grey-shaded areas* indicate the relative placement of scenarios with different energy security legislation. *Vertical and horizontal blue bars* indicate the range of outcomes for energy security (diversity indicator) and climate (2 °C probability) that correspond to the Weak, Intermediate, or Stringent Fulfillment levels (see also Fig. 1). Energy security policy costs are global, cumulative (2010–2030), discounted, and relative to a baseline scenario which contains no explicit energy security policies. The costs of end-of-pipe air pollution policies are also included here; they do vary somewhat even though the scenarios assume the same level of stringency for air pollution control legislation

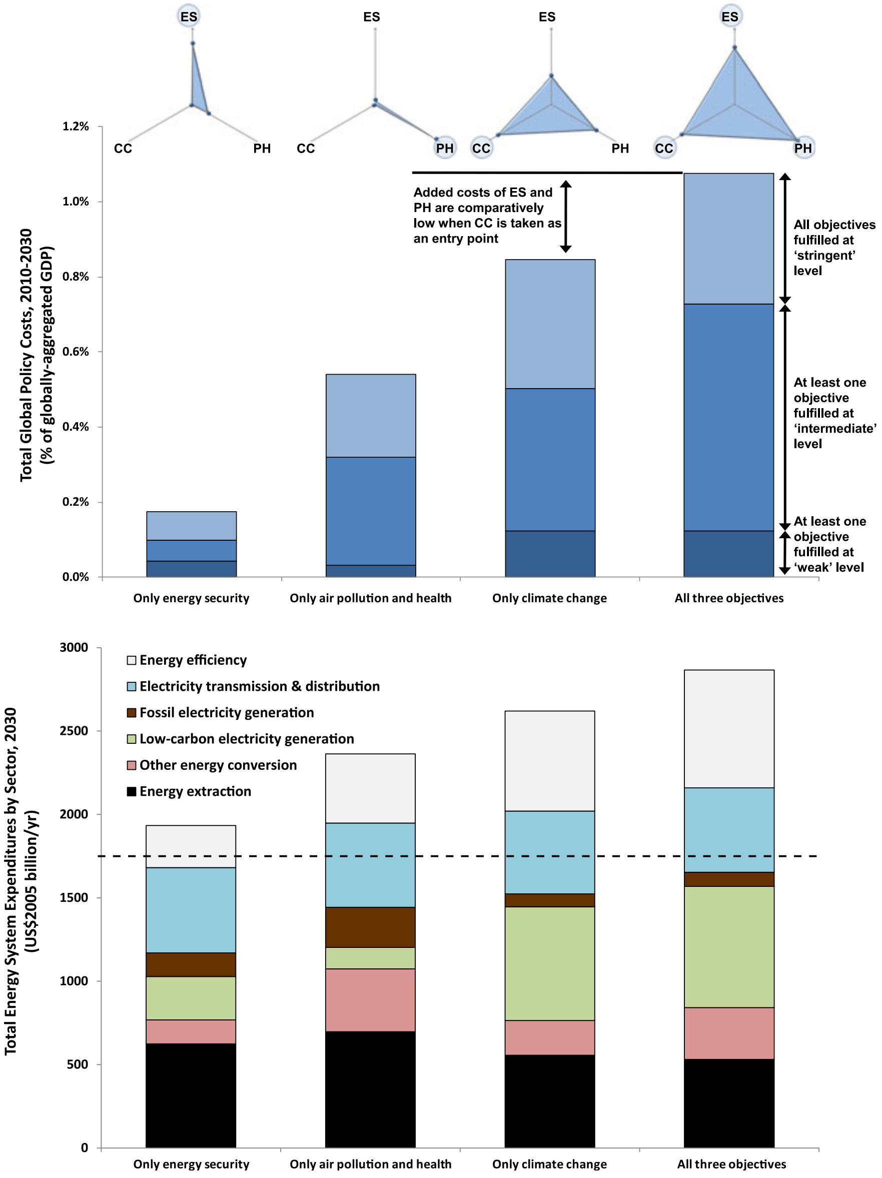


Fig. 4 Costs of achieving societal objectives for energy sustainability under different policy prioritization frameworks. The *upper panel* shows global policy costs between 2010 and 2030. This represents the net financial requirements (energy-system and pollution-control investments, variable, and operations and maintenance costs) over and above baseline energy-system development, which is itself estimated at 2.1 % of globally-aggregated GDP. Triangular schematics above the bars summarize the performance of scenarios that achieve 'stringent' fulfillment only for the objective(s) targeted under the corresponding policy frameworks (axis values normalized from 0 to 1 based on the full range of scenario ensemble outcomes; CC = Climate Change, ES = Energy Security, PH = Air Pollution and Health). [Adapted from Fig. 1 in McCollum et al. (2011)]. The *lower panel* shows the portfolio of expenditures (= investments + O&M; global, by sector) required to achieve the objectives at their most stringent fulfillment levels under each policy prioritization framework. Energy efficiency refers to efficiency and conservation measures beyond those in a no-policy baseline scenario. *Dashed line* indicates expenditures in the baseline

of the world can more or less solve the pollution problem without the need for structural shifts in the energy system. Such structural shifts will be necessary, in constrast, if pursuing ambitious climate policies. As the previous sections illustrate, an often overlooked advantage of these policies is that, in general, many of the mitigation strategies they will motivate will generate positive synergies in the energy security and air pollution and health dimensions simultaneously. In fact, once Stringent climate policies are in place, our calculations show the synergistic relationships to be so strong that the added costs of any supplementary policies needed to ensure fulfillment of the other objectives at their Stringent levels are significantly reduced. A simple way of visualizing these synergies in Fig. 4 (upper panel) is to note how the sum of the three leftmost cost bars (single-minded policy approaches) is much larger than the rightmost bar (integrated policy approach). Simply put, climate mitigation offers a strategic entry point for society to achieve an array of its energy-related goals. And when viewed from an integrated perspective (i.e., properly accounting for the synergies of greenhouse gas abatement strategies on both energy security and air pollution and health), the combined costs of all policies come at a significantly reduced total energy bill.

The synergies might be even greater still, considering that this analysis only performs a partial economic accounting. We have only attempted to capture multiple benefits in terms of avoided or reduced costs for climate change mitigation, energy security, and pollution control; however, we make no attempt to economically value many of the other benefits, including things like reduced health expenditures (Nemet et al. 2010) and the avoided costs of climate-related adaptation measures (IPCC 2007).

4 Conclusions

In this paper we aim to make several contributions to the literature. First, by explicitly quantifying the impact of presently legislated and planned air pollution control policies, we quantify the health-related co-benefits from reducing energy-related air pollution. Second, we describe scenarios through the use of energy security indicators and analyze how future constraints on regional trade could influence energy security. Third, we conduct a detailed assessment of future energy expenditures by sector, showing where financing needs to flow in order to achieve the multiple objectives. Finally, and perhaps most importantly, we quantify the relationships between different fulfillment levels for energy security and air pollution goals and the probability of reaching a 2 °C climate target; we then use this framing to explore synergies and trade-offs between the objectives.

We find that the energy system of the future could potentially develop along a number of different directions, depending on how society and its decision makers prioritize various worthwhile energy objectives, including, but not limited to, climate change mitigation, energy security, and air pollution and human health. These objectives are generally discussed in the context of different time frames (security and pollution/health in the near term, climate in the medium to long term). For this reason, they frequently compete for attention in the policy world. An added challenge is that in many countries, separate policy institutions are responsible for dealing with each of the multiple objectives. As a result, the important synergies between them are not well enough understood, or are simply overlooked, and the costs of reaching each objective individually are often overstated.

By adopting a holistic and integrated perspective that addresses all of the objectives simultaneously, the analysis described in this paper clearly indicates that cost-effective climate-pollution-security policies are likely to lead to substantial co-benefits, in terms of costs avoided and the achievement of societal objectives for sustainability. First, fulfillment of near-term air pollution and health goals is greatly furthered by climate change mitigation. Under stringent climate policy scenarios, for instance, globally-aggregated DALYs can be reduced by as much as 23 million by 2030 relative to a baseline scenario that assumes currently legislated and planned air pollution policies are enacted, or by as much as 32 million relative to a baseline without any further tightening of regulations. However, if such policies turn out to be more stringent than now foreseen—irrespective of climate goals—then the synergies from concerted decarbonization efforts would become exceedingly small (maximum reductions of 2 million DALYs). At the same time, stringent climate policies can help to further the energy security goals of individual countries and regions by promoting energy efficiency, the diversification of the energy supply mix, and the increased utilization of domestically available renewable energy sources. The result would be energy systems that are on the one hand more resilient and simultaneously have a higher degree of sovereignty, especially compared to those that rely to a large extent on imports of fossil energy commodities, as is common practice today, for example in North America, Europe, and Japan, and increasingly in China. These findings illustrate how climate change mitigation can be an important entry point for achieving society's other objectives for energy sustainability.

Our analysis further shows that the aforementioned synergies will only be realized if there is a significant upscaling of investments into energy efficiency and low-carbon energy supply. While such a path is not without cost, we show that the combined costs of climate change mitigation, energy security, and air pollution control come at a significantly reduced total energy bill when the multiple benefits of each are properly accounted for in the calculation of total energy system costs. For instance, the total added costs of pollution control at the global level are cut significantly (between US$100 and US$500 billion annually in 2030, depending on the stringency of policy assumed in the baseline scenario) as the stringency of climate policy increases and the utilization of low-carbon, pollution-free (thus, pollution control-free) technologies rises. Similarly, security costs also decrease substantially under increasingly aggressive levels of decarbonization: in scenarios with stringent climate policies, the added costs of security actually approach zero (translating to an annual cost savings of more than US$130 billion by 2030). Total cost savings are therefore quite significant: between 0.1 % and 0.7 % of globally-aggregated GDP in 2030 in the baseline scenario. And although steps taken to mitigate climate change will themselves add to total energy system expenditures (up to 1.5 % of GDP in 2030, depending on the stringency of policy), what this analysis shows is that these climate costs will be substantially compensated for by the corresponding reductions for air pollution control and energy security expenditures.

An important caveat to these conclusions is that our estimates are based on the results of a single integrated assessment model, MESSAGE-MACRO, and are thus conditional on the particular methodological approach we have employed. Previous inter-comparison studies have shown that the spread across models can be quite significant, owing to key structural differences and varied assumptions (Clarke et al. 2009). There is, hence, a clear need for model comparisons and systematic analyses of multiple objectives utilizing diverse methodologies.

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