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Feasible mitigation actions in developing countries

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Energy use is not only crucial for economic development, but is also the main driver of greenhouse-gas emissions. Developing countries can reduce emissions and thrive only if economic growth is disentangled from energy-related emissions. Although possible in theory, the required energy-system transformation would impose considerable costs on developing nations. Developed countries could bear those costs fully, but policy design should avoid a possible 'climate rent curse', that is, a negative impact of financial inflows on recipients' economies. Mitigation measures could meet further resistance because of adverse distributional impacts as well as political economy reasons. Hence, drastically re-orienting development paths towards low-carbon growth in developing countries is not very realistic. Efforts should rather focus on 'feasible mitigation actions' such as fossil-fuel subsidy reform, decentralized modern energy and fuel switching in the power sector.

Today's developed countries account for the largest share of global greenhouse-gas (GHG) emissions accumulated in the atmosphere. However, recent years have witnessed a rapid increase in developing countries' emissions, most prominently in China, which became the world's largest emitter in 2006. China's energy-related CO_2 emissions per capita (7.1 t), even though still below the Organisation for Economic Co-operation and Development (OECD) average, almost reached the European Union (EU-27) average of 7.4 t in 2012[1]. If other developing countries follow China's carbon-intensive growth pattern, ambitious climate stabilization targets — such as the target to limit warming to 2°C above pre-industrial levels, agreed by the world community — are likely to become infeasible, even if industrialized countries were to drastically reduce their emissions[2].

Analyses with large-scale integrated assessment models often conclude that mitigation costs for developing countries are relatively moderate[3]. Some recent studies have highlighted the potential positive effects of climate measures on economic growth[4–6] and the associated promise to create new economic dynamism by means of a 'green industrial revolution'[7]. Despite these optimistic assessments of the possibility to re-orient growth paths towards 'low-carbon development'[8], this Perspective argues that — although possible in theory — it is fraught with considerable obstacles in practice due to the central role that fossil fuels have played and continue to play for economic development.

The remainder of this Perspective is organized as follows. First, we discuss the historic relationship between economic growth, energy use and CO_2 emissions in detail. The second part highlights major challenges to low-carbon transitions in developing countries, concluding that we need to be cautious in what can be expected with regard to low-carbon development there. Third, we discuss feasible mitigation actions, focusing on subsidy reform, decentralized modern energy access for rural areas and fuel switching in the power sector.

Economic growth, energy use and emissions

Socioeconomic development in the past has been closely correlated to energy use[9,10]. As fossil fuels have traditionally constituted the major source of energy, there is also a close correlation between human development and GHG emissions[11]. No country has managed to achieve high levels of economic development without having crossed a threshold in final energy consumption of approximately 40 GJ per capita[12,13]. Only one-quarter of these energy needs can be explained by subsistence needs such as cooking or heating[14]; an important part of the threshold can be explained by the energy needed to build up physical capital stocks, for example, infrastructure[13,15].

Even though per capita emissions in developing countries generally remain below the OECD average, they have been catching up fast, in particular in China. Not only for China, but also for other newly industrializing countries, economic growth is clearly identified as the main driver of rising CO_2 emissions, especially for the 2000s[16]. A significant share of these emissions is released for the production of goods and services that are finally consumed in developed countries[17,18]. However, observed flows of emissions embodied in trade cannot be interpreted as a sign of 'outsourcing' of emissions, and it seems likely that developing countries' emissions would have experienced a sharp increase even without trade with industrialized countries[19]. This trend of rising emissions in developing countries is reinforced by a global 'renaissance of coal' that has led to an increasing carbonization of the global energy system[16]. This implies that the historical relationship between economic growth and energy use, which is dominated by fossil fuels, also seems to apply to countries that have only recently started to industrialize and which seem to replicate the patterns of energy use and emissions observed in the past in today's developed countries — albeit at an accelerated pace[20]. This is illustrated in Fig. 1, which shows per capita CO_2 emissions against the log of per capita gross domestic product (GDP) (the log is chosen to make dynamics at low-income levels visible). It is remarkable that this relationship is very similar for most countries. For instance, China's income–emissions trajectory very closely tracks the historical emissions of Korea, Japan and France at the same income levels. The heavy reliance on fossil fuels is, of course, related to their low cost (if we ignore their negative climate and environmental externalities, such as emissions and air pollution), wide availability and versatility to supply different energy needs in different sectors[21,22].

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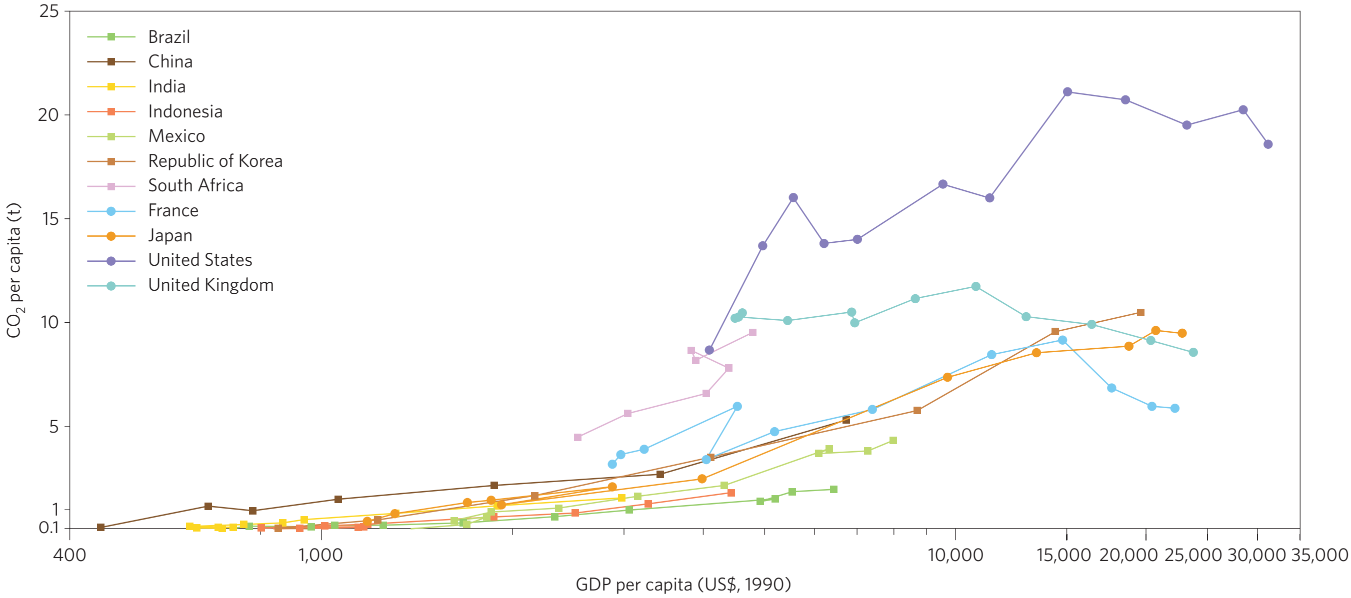

Figure 1 | CO_2 emissions and gross domestic product (GDP) per capita. CO_2 emissions per capita[97] against GDP per capita (in US$, 1990)[98] for selected developed countries (circles) and selected newly industrializing countries (squares) from 1900 to 2008 for 10-year intervals (when available). See Supplementary Information for a more detailed description of the data.

Interestingly, similar patterns can also be found in studies investigating the carbon footprint of households at the micro-level for selected developing countries. An Indonesian household with the same level of income of the average European household exhibits a carbon footprint similar to that of the average European. Specifically, analyses for India, Indonesia and the Philippines show that richer households in these countries have considerably higher carbon footprints than poorer ones[23–25]. Figure 2 shows that for these three countries the relationship between (the log of) per capita income and CO_2 emissions in a cross-section of households rather closely matches the macroeconomic relationship between GDP and emissions over time. This suggests that income is the most important driver of variations in emissions over time and between households in developing countries (as it has been the case in developed countries in the past). It also implies that an emerging middle class, at least in middle-income countries, will further drive substantial emissions growth if energy systems are not significantly decarbonized, and that such a decarbonization should not be expected to happen automatically, but will very likely involve additional economic as well as political effort and associated costs.

However, empirical studies also suggest that at even higher levels of income, per capita emissions increase less than proportionally with per capita income[24,25]. That is, threshold effects, for example, ownership of energy-intensive consumption goods including refrigerators, air conditioners or cars at some income threshold, are likely to be present. Thus, high-inequality countries are not necessarily high per capita emitters. As shown by Grunewald *et al.*[26], income inequality is negatively correlated with per capita emissions, particularly in low- and most middle-income countries, suggesting a trade-off between inequality reduction and mitigation; in high-income countries, however, the correlation is positive, suggesting that reductions in inequality can lower per capita emissions there (Supplementary Fig. 2).

Challenges of energy-system transformation

The evidence presented above suggests that developing and emerging countries can be expected to increase their emissions in the future. These observations have three immediate implications. First, a drastic transformation of energy systems towards low-emissions energy sources (such as renewable energy, carbon capture and sequestration, or nuclear) would be necessary. Second, poor and emerging economies would need substantial financial support to cover the incremental costs of low-carbon development paths, estimated to exceed US$100 billion yr^{-1} for a 450 ppm CO_2-only target[27,28]. Third, the within-country differences in incomes, consumption patterns and carbon footprints have an important bearing on the emissions intensity of economic growth and, hence, on policies that may be able to reconcile social and GHG reduction objectives. In this section we will discuss (1) the feasibility of large-scale energy-system transformations and thus emissions reductions, (2) potential financial transfers towards developing countries in the context of finance for climate change mitigation and (3) political economy issues.

Emissions reduction scenarios in developing countries. Given the strong link between energy consumption and economic development in the past, future growth of today's poor countries will require a large amount of additional energy. Steckel *et al.*[13] have shown that climate change mitigation scenarios implicitly assume that developing countries will not significantly increase their current levels of energy use. In the light of the results described above, keeping energy consumption constant does not seem possible, as energy will be required for basic needs, infrastructure and other consumption goods demanded by a growing middle class in today's developing countries[29]. At the same time, developing countries are expected to shoulder a large and rising share of global mitigation. In ambitious mitigation scenarios (IPCC category I + II; ref. 30), the median share of emissions reductions (compared with the business-as-usual scenario) taking place in developing (non-Annex I) countries is approximately 60% in the near term increasing to 70% at the end of the century, as shown in Fig. 3.

Large-scale adoption of low-carbon energy sources could allow increasing energy use without increasing emissions at the same time. Renewable energy is seen to be key in energy-system transformations and it is shown to have the highest technological option value of low-carbon energy technologies — that is, emissions abatement costs would increase more in the case of not expanding renewable energy than in the case of not expanding nuclear energy and carbon capture and storage[3]. Carbon capture and sequestration, however, in combination with biomass, is crucial for low-stabilization scenarios, as it provides the possibility to generate negative emissions[31]. At present, renewable energy accounts for only about 11% of energy use in developing countries, of which the largest share is traditional biomass and hydro power[32]. Although the potential for renewable energy is usually seen to be large, it is often still more expensive than fossil fuels[33,34], particularly when taking into account the costs of integrating variable renewable energy sources into the electricity grid[35,36]. Low institutional capacities and credit constraints also hinder the transformation of the energy system on a larger scale[22,37].

On the micro-energy level, renewable energy using off-grid systems are often competitive today[38] and can contribute to fulfilling basic needs. However, such decarbonization of energy systems is linked to relatively high incomes, as highlighted by extensive cross-country and time-series research on 'energy ladders' examining how fuel choices are related to levels of socioeconomic development[39]. For example, an analysis of Kenyan households' lighting fuel choices suggests that there is a cross-sectional energy ladder, with a very high income threshold for modern fuel use — including solar energy use[40]. Furthermore, scaling up low-carbon energy supply to a level needed beyond fulfilling basic needs would probably impose additional costs on developing countries[21] and seems unlikely to result in deep structural economic transformations that could trigger massive productivity increases, as has been the case for railroad or information technologies[41]. All this implies that much more action and support (including finances, technologies and capacity building) will be required to promote renewable energies in developing countries. Owing to persistent energy shortages, legitimate energy access targets and high economic growth, the cost of waiting until such support materializes is high[22], necessitating fast, concerted action to avoid lock-in effects that would make a re-orientation of energy systems more difficult and costly in the future[42,43].

A possible climate finance curse. It is widely acknowledged that developing countries should not be negatively affected by climate change mitigation, as for example, reflected in the United Nations Framework Convention on Climate Change principle of "common but differentiated responsibilities"[44]. As a consequence, scenarios frequently assume that mitigation costs are shared globally according to an equitable burden-sharing scheme (for example, emissions certificates being allocated according to an equal per capita scheme) that results in transfers from developed regions and relatively low mitigation costs or even net gains for developing countries[3]. Propositions to establish a global carbon budget similarly imply considerable financial transfers, mostly for countries at an early stage of development[45]. Jakob *et al.*[27] estimated that financial transfers could — at least for those allocation schemes that are usually perceived to be the most equitable — largely exceed recipients' mitigation costs and could reach almost US$400 billion in 2020. For some regions, they would be of a comparable order of magnitude as revenues from natural resource exports in the past.

Even if such sizeable transfers to developing countries were politically feasible from the perspective of developed countries, their effect on recipient countries may well be less beneficial than expected, as they might negatively affect long-term growth prospects, comparable to adverse effects observed for natural resource revenues[46,47]. The literature has identified several channels that drive this so-called resource curse, of which Dutch disease (that is, crowding out of the manufacturing sector as a result of increased revenues from natural resources and an associated appreciation of the currency), volatility and rent seeking in combination with the quality of the institutional environment are most important[48]. Kornek *et al.*[49] analysed the similarities between these channels and concluded that financial transfers for climate change mitigation could, in general, be comparable to resource revenues and hence have the potential to result in a 'climate rent curse'. Although in theory these adverse effects could be alleviated by specific measures (such as sovereign wealth funds or appropriate fiscal and monetary policies), recipients often may not have the required institutions in place. Figure 4 shows indicators for 'rule of law' and 'control of corruption', exemplary for institutional quality, ranging from −2.5 to 2.5 with higher values indicating a better quality of governance[50,51] for countries that would have received transfers if an 'equal per capita' allocation scheme had been in place in 2008, assuming per capita emissions rights of 2 t (ref. 7) (note that we only consider energy-related emissions). Countries are ranked according to the share of the inflows in GDP. Countries that receive the highest transfers generally also score relatively badly (that is, below 0) on

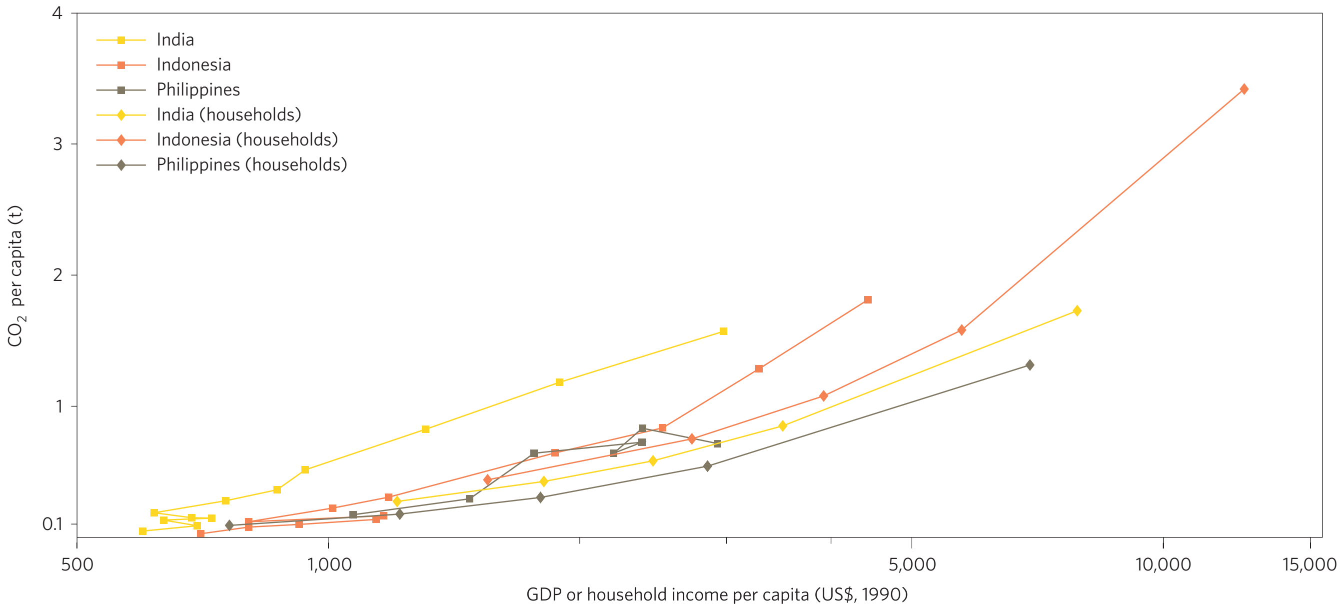

Figure 2 | Relationship between CO_2 emissions per capita and gross domestic product (GDP) or household income in India, Indonesia and the Philippines. For household data, income quintiles (with per capita emissions as the mean of households in the respective quintile) are shown. Data from ref. 23 for India, ref. 25 for Indonesia and ref. 24 for the Philippines. Macroeconomic data are taken from ref. 97 for CO_2 per capita and ref. 98 for GDP per capita data. Data points for every 10 years from 1900 to 2008 (Philippines 1950–2008) are shown. See Supplementary Information for a more detailed description of the data.

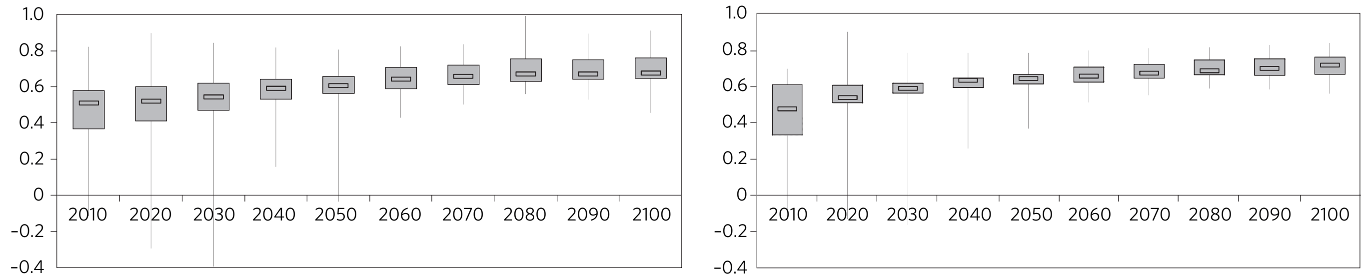

Figure 3 | Mitigation in different emissions reduction scenarios. a,**b**, Percentage of global mitigation carried out by non-Annex I countries in medium ambitious (**a**; IPCC category III + IV) and ambitious (**b**; IPCC category I + II) climate change mitigation scenarios as part of the scenarios considered for the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation*[33,99]. In total, 131 different mitigation scenarios have been considered including second-best (for example, delayed participation or constrained technology) scenarios. Boxes show the 25–75 percentile ranges, whiskers the maxima and minima, and the bold lines the median. See Supplementary Information for a more detailed description of scenario data.

institutional quality. With very few exceptions, countries that receive more than median financial inflows display institutional quality below zero (that is, the upper right quadrant of Fig. 4 is practically empty); hence, most of the countries receiving high inflows might indeed be at risk of suffering from a 'climate finance curse'. Furthermore, even though financial transfers are usually seen to facilitate participation of poorer countries in international climate agreements[52], potential recipients of climate finance could find it less attractive to participate in an international agreement when they take into account potential negative effects of financial inflows[49].

One obvious solution to address the possibility of a climate finance curse would be restricting the transfer of rents, for example, by financial mechanisms that only transfer (the considerably lower) incremental investment costs for low-carbon technologies[27,53]. While attractive in principle, such schemes would be hard to implement due to the difficulty of establishing baselines and providing appropriate incentives for cost-effective emissions reductions. Moreover, limiting the amount of rent that can be collected could also undermine developing countries' willingness to participate in these arrangements.

Income distribution and political economy issues. The relationship between household incomes and emissions discussed above suggests that countries in certain stages of economic development may face a trade-off. Although income growth for lower- and middle-income classes is desirable for many reasons[54], such an income-growth pattern may lead to higher per capita emissions, mainly because of increased modern carbon-intensive energy use. As a consequence, the high carbon footprint of rich(er) households in developing countries would offer pathways to reduce emissions while simultaneously addressing income inequality through well-designed price and tax policies. However, such policies, which have the potential to increase aggregate well being, can easily fall victim to power struggles that have a wide-ranging impact on economic performance and social stability. For instance, Rodrik[55] specified how changes in the terms of trade (that is, the prices of imports relative to those of exports) can result in a costly 'war of attrition', leaving everyone worse off, and Acemoglu and Robinson[56] showed how technological advances that would be beneficial for society can be blocked by 'political losers' whose power base would be eroded by the change. It seems likely that these considerations also apply for distributional as well as political economy effects of policies to reduce emissions.

Feasible mitigation actions

As energy use is fundamental for economic development, and fossil fuels can arguably be expected to constitute the least-cost source of energy in most cases, it is not surprising that developing countries have so far refrained from entering internationally binding commitments to reduce their GHG emissions. Yet, several non-Annex I countries, including China, Mexico, South Korea and Vietnam, have recently announced unilateral emissions targets and the creation of emissions trading systems[57]. According to Ostrom[58], a plausible explanation can be found in policy objectives that are not related to climate change, but that still contribute to mitigating GHG emissions as a co-benefit. For instance, in India, energy security considerations rather than climate concerns are likely to drive energy-system transformation[59], and in Vietnam, energy efficiency and economic restructuring are regarded as the central aim of recently adopted Green Growth policies[60].

For this reason, we argue that in the short term, mitigation in developing countries should be targeted at areas that promote important development objectives, such as improving energy access and energy security, reducing local air pollution and increasing economic efficiency. Furthermore, mitigation actions in developing countries need to be feasible along three dimensions. First, politically, as most mitigation options create winners and losers and may require potential losers to be compensated and public opinion mobilized. Second, institutionally, as many mitigation measures require fairly sophisticated institutional and administrative capacities (for example, feed-in-tariffs, cap-and-trade systems or participation in international mechanisms such as Reducing Emissions from Deforestation and Forest Degradation (REDD+)). Third, financially, as resource needs for mitigation efforts can be substantial, for example, when thinking of upfront investments of some energy technologies. From this set of feasible measures, those that have the largest potential to avoid or mitigate lock-ins into carbon-intensive development paths should be prioritized.

In the following, we discuss fossil-fuel subsidy reform, decentralized modern energy for rural areas and fuel switch in the power sector as examples of feasible mitigation options. A full assessment of their political, institutional and financial feasibility is not only beyond the scope of this Perspective, but also subject to a multitude of country-specific factors. However, previous assessments of mitigation options have highlighted the potential of these options to promote human development while at the same time reducing emissions. Although focusing on large emitters such as China, India, South Africa and Indonesia could be the most straightforward way to achieve emissions reductions, feasible mitigation actions could also contribute to limiting increases in countries such as Vietnam or Nigeria, which are at an earlier state of economic development, but whose emissions are expected to rise sharply in the near future.

Fossil-fuel subsidy reform. Low fuel prices cause important external effects, such as high local air pollution and related health effects. In the transport sector, which accounts for the second largest share of emissions in developing countries and is growing fast[61], the costs of congestion add to these effects[62]. For the case of Beijing, Creutzig and He[63] estimated that, at present, the social costs of congestion

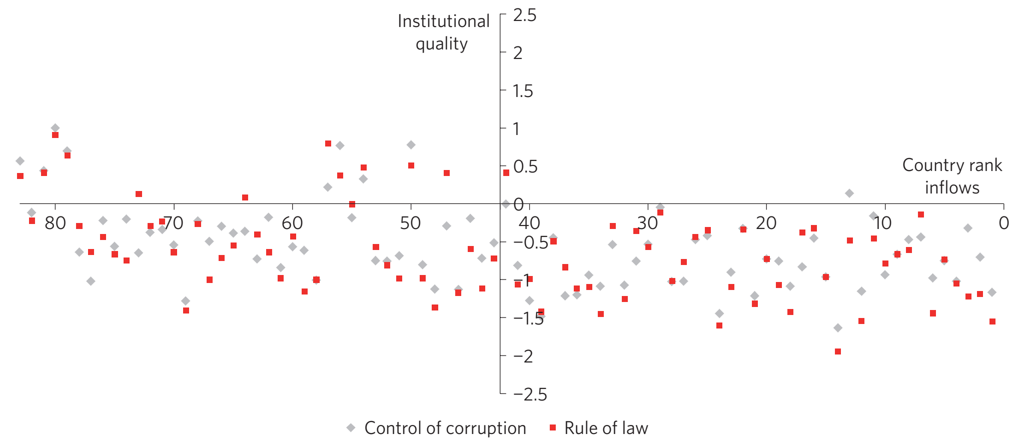

Figure 4 | Financial inflows and institutional quality. Indicators for 'control of corruption' and 'rule of law' (exemplary for institutional quality) ranging from −2.5 to 2.5, with higher values indicating a better level of governance (data taken from ref. 51; see ref. 50 for a detailed description of how governance indicators are calculated) against countries with per capita emissions of <2 t in 2008; that is, those that would have received net revenues from selling emission permits on the international carbon market if permits were allocated on an 'equal per capita' basis (based on data from ref. 100). Countries are ranked based on the share of financial inflows arising from climate finance in gross domestic product (independent of a potential carbon price). See Supplementary Information for a more detailed description of the data.

as well as health impacts each amount to more than 3% of regional GDP. Yet, not only do governments fail to internalize these effects, but fuel subsidies are still commonplace and impose high costs on state budgets. For instance, in 2011, Iran spent roughly US$65 billion on subsidizing energy consumption, India about US$34 billion and China about US$20 billion (ref. 64). The economic distortion (that is, the deadweight loss) related to subsidies for transport fuels (gasoline and diesel) have been estimated to amount to US$44 billion yr^{-1} in the ten countries with the highest subsidies[65]. Furthermore, fossil-fuel subsidies have been found to be regressive in the sense that the largest benefits often accrue to rich households[66]. However, distributional effects strongly depend on the underlying energy type and existing tariff structure. If increasing block-tariff systems are designed as a pro-poor pricing instrument in the electricity sector, removing subsidies could lead to substantial income losses for the poor[67]. Phasing-out fuel subsidies — or even starting to tax fossil fuels — would be highly effective in reducing fuel consumption and associated emissions. In a meta-review of studies from developed as well as developing countries, Brons *et al.*[68] estimated a price elasticity of −0.84 for transport fuels. That is, a 20% price increase resulting from lower subsidies or a tax would decrease fuel consumption (and hence associated emissions) by about 17%. By considerably decreasing fuel consumption, fuel-tax reform would hence improve air quality as well as energy security, provide direct economic benefits and also alleviate pressure from tight government budgets. In terms of climate benefits, the International Energy Agency[2] estimates that a complete phase-out of subsidies for oil products would reduce global GHG emissions by about 4.4% yr^{-1} by 2020.

Despite these significant benefits of subsidy reform, fuel subsidies of different kinds are still a common policy instrument throughout the developing world, with powerful interest groups blocking reforms[69]. This implies that there is scope for increasing support for fuel-subsidy reforms by better communicating the abovementioned benefits and lobbying against such vested interest[70] (with a stronger role for the civil society, possibly supported by the international community). Furthermore, even if the effects of reforms were progressive (and more so if they are actually regressive), removing subsidies without providing appropriate compensation would actually leave the poorest part of the population worse off[71]. For this reason, it is crucial to establish appropriate compensation schemes that avoid adverse development outcomes and ensure buy-in of affected stakeholders. Good examples of successful compensation mechanisms include lump-sum cash transfers (Iran and Georgia), increasing public expenditures that benefit low-income households (Indonesia, Niger and Ghana) and strengthening social safety nets (Indonesia, Jordan and Moldova)[72,73].

Administering well-targeted compensation programmes may be the most challenging component of a policy package of fuel-subsidy cuts and compensatory policies, as the subsidy reform itself — or the introduction of fuel taxes — does not require highly developed institutional capacity.

Decentralized modern energy for rural areas. Globally, about 1.4 billion people lack access to electricity, and almost 2.7 billion rely on traditional sources of fuel[2], in particular biomass, for heating and cooking. This creates substantial health impacts, estimated to amount to more than 1.6 million deaths and over 38.5 million disability-adjusted life years in 2000[33]. In poorer countries or remote rural areas, off-grid low-carbon energy sources, for example, solar home systems and pico-hydro power stations, can be economically viable solutions to provide modern energy access[38]. Although measures to ensure access to clean cooking fuels, such as increased provision of liquefied petroleum gas stoves, may under some circumstances raise emissions, this increase seems to be negligible[74], in particular bearing in mind that energy demand in developing countries has been largely met by increased coal use in recent years[13]. It seems likely that grid-based electrification would mostly imply expansion of carbon-intensive fossil technologies. Fostering decentralized energy access might be primarily motivated from a development perspective, but may nevertheless offer significant emissions reduction potential[75].

Achieving total rural electrification and universal access to clean-combusting cooking fuels and stoves will require substantial additional energy-system investments, estimated to amount to about US$65–86 billion yr^{-1} (ref. 74). Arguably, most developing nations will not be able to meet these financing needs from their budgets, regardless of the associated development benefits. Rather, at least some part of it will have to be provided by climate finance. In view of the fact that energy access is increasingly acknowledged as a fundamental cornerstone of the Millennium Development Goals[76] and initiatives such as the United Nation's Sustainable Energy for All[77], some progress on this account seems to be within reach. Furthermore, recent research has made advances in identifying 'best practices' with regard to business models for off-grid electricity supply and their relationship to public policies[78].

Fuel switch in the power sector. Local air pollution is a widespread concern in many developing countries, in particular in regions that to a large extent derive their energy consumption from coal, which is associated with emissions of SO_2 and particulate matter (PM). In 2005, 89% of the world's population (especially in East Asia) lived in areas where the World Health Organization Air Quality Guideline for PM2.5 was exceeded[79]. In 2013, PM2.5 levels were more than five times the World Health Organization annual maximum level in 58 Chinese cities[80].

These emissions, and the related health concerns, could be mitigated by a switch to either renewable energy, nuclear or natural gas, which at the same time are either carbon free or less carbon intensive than coal. Some authors point out that the co-benefits of air-quality improvements resulting from measures to reduce GHG emissions would be of comparable magnitude or even above their associated climate benefits. In a meta-analysis of co-benefits of air-quality improvements resulting from climate change mitigation scenarios for 13 studies on developing countries, Nemet *et al.*[81] reported a range of US$27–196 per ton of CO_2, with a mean of US$81 per ton of CO_2. In a similar vein, West *et al.*[82] pointed out that in their model calculations, health co-benefits in East Asia are 10–70 times the marginal abatement costs for the representative concentration pathway RCP4.5 stabilization scenario in 2030.

Even though it is conceivable that these health benefits could also be achieved by less costly technical solutions — such as installing scrubbers in existing coal power plants — they have to be evaluated in combination with other benefits (for example, increased energy security) to provide a full picture[83]. In any case, reducing coal consumption can be expected to have an important part to play for reaping these co-benefits, due to its significant mitigation potential and its high intensity of emissions of SO_2 and PM per unit of final energy generated. This is in line with the currently introduced Action Plan for Air Pollution Prevention and Control in China. Although mainly aimed at improving ambient air quality, if properly implemented it could result in declining CO_2 emissions from 2020 onwards[80].

Other measures. The examples above are not intended to provide a comprehensive list of options. In different contexts, other mitigation options might either provide higher benefits or enjoy a higher degree of political or institutional feasibility. To illustrate the heterogeneity and complexity of possible combinations of feasible mitigation actions, we briefly discuss three additional policy areas and instruments, namely, agriculture, public transport and international 'non-climate' agreements.

For some countries, important mitigation options can be found in the agricultural sector, which accounts for about 10–12% of global GHG emissions, predominantly in the form of nitrous oxide and methane[84], and is thought to be responsible for 80% of deforestation and forest degradation, which is an important source of CO_2 emissions[85]. The largest share of the emissions reduction potential in agriculture — which according to the United Nations Environment Programme[86] lies between 1.1 and 4.3 Gt CO_2 equivalent yr^{-1} — could be reaped by means of conservation tillage, combined organic and inorganic fertilizer application, adding biochar to the soil, improved water management and reducing flooding, and fertilizer use in rice paddies[87]. These measures could be attractive for numerous reasons other than reducing GHG emissions, including increased agricultural productivity, reduced costs for fertilizer input[86], alleviated soil erosion[87] and improved water management[88].

The introduction or expansion of more public transport can also provide considerable benefits in terms of less congestion, reduced local air pollution and increased safety. In contrast to fuel-subsidy reform, public transport infrastructure can put considerable pressure on government budgets; moreover, the political economy of expanding urban public transport can be challenging[61]. Although financially, politically and institutionally more demanding, the benefits of improved public transport can be substantial (see ref. 89 for the case of Taipei). Importantly, such policies can avoid lock-ins by preventing urban sprawl and achieving a more compact urban form[90], which in turn would result in substantial emissions reductions as an ancillary benefit in the long run. Seeking low-cost context-adapted solutions, such as enforced fast lanes for buses and including private operators into planning, would certainly increase the feasibility of mitigation actions for urban transport.

Finally, regional trade and integration agreements could become a vehicle to further promote a mitigation agenda. Regional trade agreements that go beyond trade liberalization and include environmental provisions have been found to reduce absolute emissions levels in signatory countries[91]. Implementing these agreements is not primarily motivated by mitigation, but environmental provisions are often included to prevent a race to the bottom in environmental standards between trading partners[92]. Regional trade agreements have been the most popular form of trade liberalization in recent years[93]. Combining them with strong environmental provisions, measures to spur technology transfer and capacity building could lower mitigation costs and alleviate concerns of emissions leakage for all participants[94]. Hence, such agreements could provide another entry point for furthering an ambitious global mitigation agenda.

Steps towards low-carbon development

Our analysis points to a major dilemma for global climate policy. While mitigation of GHG emissions in developing countries will be essential in any effort to limit global warming, economic growth is closely related to the use of fossil fuels, and spontaneous leapfrogging to less carbon-intensive development paths seems highly unlikely. Yet, requiring developing countries to forego economic growth and put their development goals at risk is clearly neither defensible nor feasible. However, measures that address poor countries' development priorities and at the same time reduce GHG emissions could constitute feasible mitigation actions. We hence stress the importance of development benefits and propose to prioritize options that avoid lock-ins into carbon-intensive development paths, while explicitly considering each option's political, institutional and financial feasibility.

This Perspective has discussed a number of issue areas — with a focus on fossil-fuel subsidy reform, decentralized modern energy for rural areas and fuel switching in the power sector — that could meet the above requirement of achieving emissions reductions as a co-benefit. Such measures alone are probably not sufficient to achieve the globally cost-optimal emissions trajectory and might even render the most ambitious stabilization targets — such as the 2 °C target — difficult to achieve. However, they could form the building blocks of a future system of loosely coordinated climate agreements, which could promote technological innovation and change the political landscape to pave the way towards a gradual expansion of such initiatives, eventually resulting in an ambitious global mitigation agenda[95].

The systematic identification of feasible mitigation options, whose mix will obviously differ considerably between countries, should be closely aligned with the process of formulating 'nationally appropriate mitigation actions'[96], which could be supported by the Green Climate Fund and bi- and multilateral donors, such as the World Bank or the Global Environment Facility. Furthermore, donors have already begun to mainstream climate change into their aid portfolios, which should give some impetus to reducing emissions in areas not primarily targeted at climate change mitigation.

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References

1. Olivier, J. G. J., Janssens-Maenhout, G. & Peters, J. A. H. W. *Trends in Global CO_2 Emissions: 2013 Report* (PBL Netherlands Environmental Assessment Agency, 2013); www.pbl.nl/en
2. International Energy Agency *World Energy Outlook 2011* (IEA, 2011).
3. Luderer, G. *et al.* The economics of decarbonizing the energy system — results and insights from the RECIPE model intercomparison. *Climatic Change* **14,** 9–37 (2011).
4. Organisation for Economic Co-operation and Development *Towards Green Growth* (OECD, 2011); www.oecd.org/dataoecd/37/34/48224539.pdf
5. United Nations Environment Programme *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication* (OECD, 2011); www.unep.org/greeneconomy/greeneconomyreport/tabid/29846/default.aspx
6. World Bank *Inclusive Green Growth: The Pathway to Sustainable Development* (World Bank, 2012); https://openknowledge.worldbank.org/bitstream/handle/10986/6058/9780821395516.pdf?sequence=1
7. Stern, N. *A Blueprint for a Safer Planet: How to Manage Climate Change and Create a New Era of Progress and Prosperity* (Bodley Head, 2009).
8. World Bank *World Development Report* (World Bank, 2010).
9. Grübler, A. *Transitions in Energy Use* (International Institute for Applied Systems Analysis, 2004).
10. Schäfer, A. Structural change in energy use. *Energ. Policy* **33,** 429–437 (2005).
11. Costa, L., Rybski, D. & Kropp, J. P. A human development framework for CO_2 reductions. *PLoS ONE* **6,** e29262 (2011).
12. Steinberger, J. K. & Roberts, J. T. From constraint to sufficiency: the decoupling of energy and carbon from human needs, 1975–2005. *Ecol. Econ.* **70,** 425–433 (2010).
13. Steckel, J. C., Brecha, R. J., Jakob, M., Strefler, J. & Luderer, G. Development without energy? Assessing future scenarios of energy consumption in developing countries. *Ecol. Econ.* **90,** 53–67 (2013).
14. Pereira, M. G., Sena, J. A., Freitas, M. A. V. & da Silva, N. F. Evaluation of the impact of access to electricity: a comparative analysis of South Africa, China, India and Brazil. *Renew. Sust. Energ. Rev.* **15,** 1427–1441 (2011).
15. Minx, J. C. *et al.* A 'carbonizing dragon': China's fast growing CO_2 emissions revisited. *Environ. Sci. Technol.* **45,** 9144–9153 (2011).
16. Steckel, J. C., Jakob, M., Marschinski, R. & Luderer, G. From carbonization to decarbonization? Past trends and future scenarios for China's CO_2 emissions. *Energ. Policy* **39,** 3443–3455 (2011).
17. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO_2 emissions. *Proc. Natl Acad. Sci. USA* **107,** 5687–5692 (2010).
18. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl Acad. Sci. USA* **108,** 8903–8908 (2011).
19. Jakob, M. & Marschinski, R. Interpreting trade-related CO_2 emission transfers. *Nature Clim. Change* **3,** 19–23 (2012).
20. Jakob, M., Haller, M. & Marschinski, R. Will history repeat itself? Economic convergence and convergence in energy use patterns. *Energ. Econ.* **34,** 95–104 (2012).
21. Jakob, M. & Steckel, J. C. How climate change mitigation could harm development in poor countries. *WIREs Clim. Change* **5,** 161–168 (2014).
22. Collier, P. & Venables, A. J. Greening Africa? Technologies, endowments and the latecomer effect. *Energ. Econ.* **34,** S75–S84 (2012).
23. Grunewald, N., Harteisen, M., Lay, J., Minx, J. & Renner, S. *The Carbon Footprint of Indian Households* (International Association for Research in Income and Wealth, 2012); www.iariw.org/papers/2012/GrunewaldPaper.pdf
24. Irfany, I. *Affluence and Emission Trade-offs: Evidence from Indonesian Household Carbon Footprint* (Courant Research Centre: Poverty, Equity and Growth - Discussion Papers, No. 161, Univ. of Göttingen, 2014); https://www.econstor.eu/dspace/bitstream/10419/100103/1/791342972.pdf
25. Seriño, M. N. V. *Do Philippine Households Lead a Carbon Intensive Lifestyle?* (Courant Research Centre: Poverty, Equity and Growth-Discussion Papers No. 158; 2014); http://www.econstor.eu/handle/10419/100100
26. Grunewald, N., Klasen, S., Martínez-Zarzoso, I. & Muris, C. *Income Inequality and Carbon Emissions* (Courant Research Centre PEG, 2011); http://ideas.repec.org/p/got/gotcrc/092.html
27. Jakob, M., Steckel, J. C., Flachsland, C. & Baumstark, L. Climate finance for developing country mitigation: Blessing or curse? *Clim. Dev.* http://dx.doi.org/10.1080/17565529.2014.934768
28. Olbrisch, S., Haites, E., Savage, M., Dadhich, P. & Shrivastava, M. K. Estimates of incremental investment for and cost of mitigation measures in developing countries. *Clim. Policy* **11,** 970–986 (2011).
29. Ekholm, T., Krey, V., Pachauri, S. & Riahi, K. Determinants of household energy consumption in India. *Energ. Policy* **38,** 5696–5707 (2010).
30. IPCC *Climate Change 2007 Mitigation of Climate Change* (eds Metz, B. *et al.*) (Cambridge Univ. Press, 2007).
31. Klein, D. *et al.* The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE. *Climatic Change* **123,** 705–718 (2014).
32. Pfeiffer, B. & Mulder, P. Explaining the diffusion of renewable energy technology in developing countries. *Energ. Econ.* **40,** 285–296 (2013).
33. IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2011).
34. Edenhofer, O., Seyboth, K., Creutzig, F. & Schlömer, S. On the sustainability of renewable energy sources. *Annu. Rev. Environ. Resourc.* **38,** 169–200 (2013).
35. Joskow, P. L. Comparing the costs of intermittent and dispatchable electricity generating technologies. *Am. Econ. Rev.* **101,** 238–41 (2011).
36. Ueckerdt, F., Hirth, L., Luderer, G. & Edenhofer, O. System LCOE: What are the costs of variable renewables? *Energy* **63,** 61–75 (2013);
37. Staub-Kaminski, I., Zimmer, A., Jakob, M. & Marschinski, R. Climate policy in practice: a typology of obstacles and implications for integrated assessment modeling. *Clim. Change Econ.* **5,** 1440004 (2014).
38. Casillas, C. E. & Kammen, D. M. The energy–poverty–climate nexus. *Science* **330,** 1181–1182 (2010).
39. Barnes, D. F. & Floor, W. M. Rural energy in developing countries: a challenge for economic development. *Annu. Rev. Energ. Environ.* **21,** 497–530 (1996).
40. Lay, J., Ondraczek, J. & Stoever, J. Renewables in the energy transition: evidence on solar home systems and lighting fuel choice in Kenya. *Energ. Econ.* **40,** 350–359 (2013).
41. Demailly, D. & Verley, P. *The Aspirations of the Green Industrial Revolution: A Historical Perspective* (IDDRI, 2013); www.iddri.org/Publications/Les-espoirs-de-la-revolution-industrielle-verte-une-perspective-historique
42. Jakob, M., Luderer, G., Steckel, J., Tavoni, M. & Monjon, S. Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Climatic Change* **114,** 79–99 (2011).
43. Kalkuhl, M., Edenhofer, O. & Lessmann, K. Learning or lock-in: optimal technology policies to support mitigation. *Resourc. Energ. Econ.* **34,** 1–23 (2012).
44. Mattoo, A. & Subramanian, A. Equity in climate change: an analytical review. *World Dev.* **40,** 1083–1097 (2012).
45. German Advisory Council on Global Change *Solving the Climate Dilemma: The Budget Approach* (WBGU, 2009).
46. Nordhaus, W. To tax or not to tax: alternative approaches to slowing global warming. *Rev. Environ. Econ. Policy* **1,** 26–42 (2007).
47. Sachs, J. D. & Warner, A. M. *Natural Resource Abundance and Economic Growth* (National Bureau of Economic Research, 1995); http://ideas.repec.org/p/nbr/nberwo/5398.html
48. van der Ploeg, F. Natural resources: Curse or blessing? *J. Econ. Lit.* **49,** 366–420 (2011).
49. Kornek, U., Steckel, J. C. & Edenhofer, O. *The Climate Rent Curse: New Challenges for Burden Sharing* (Working Paper, Potsdam Institute for Climate Impact Research, 2013); https://www.pik-potsdam.de/members/steckel/publications/kornek-etal-wp.pdf
50. Kaufmann, D., Kraay, A. & Mastruzzi, M. *The Worldwide Governance Indicators : Methodology and Analytical Issues* (World Bank, 2010); http://ideas.repec.org/p/wbk/wbrwps/5430.html
51. Worldwide Governance Indicators *Worldwide Governance Indicators* (WGI, 2012); govindicators.org
52. Weikard, H-P. Cartel stability under optimal sharing rules. *Manch. Sch.* **77,** 575–593 (2009).
53. Bowen, A., Campiglio, E. & Tavoni, M. *A Macroeconomic Perspective on Climate Change Mitigation: Meeting the Financing Challenge* (Grantham Research Institute on Climate Change and the Environment, 2013); http://ideas.repec.org/p/lsg/lsgwps/wp122.html
54. Klasen, S. The efficiency of equity. *Rev. Polit. Econ.* **20,** 257–274 (2008).
55. Rodrik, D. Where did all the growth go? External shocks, social conflict, and growth collapses. *J. Econ. Growth* **4,** 385–412 (1999).
56. Robinson, J. A. & Acemoglu, D. Political losers as a barrier to economic development. *Am. Econ. Rev.* **90,** 126–130 (2000).
57. Townshend, T. *et al.* How national legislation can help to solve climate change. *Nature Clim. Change* **3,** 430–432 (2013).
58. Ostrom, E. Polycentric systems for coping with collective action and global environmental change. *Glob. Environ. Change* **20,** 550–557 (2010).
59. Dubash, N. K. The politics of climate change in India: narratives of equity and cobenefits. *WIREs Clim. Change* **4,** 191–201 (2013).
60. Zimmer, A., Jakob, M. & Steckel, J. *What Motivates Vietnam to Strive for a Low Carbon Economy? An Explorative Case Study on the Drivers of Climate Policy in a Developing Country* (International Conference on Public Policy, 2013); www.icpublicpolicy.org/IMG/pdf/panel_46_s2_zimmer.pdf
61. Kahn Ribeiro, S. *et al.* in *Global Energy Assessment — Toward a Sustainable Future* (eds Johansson, T. B. *et al.*) 575–648 (Cambridge Univ. Press, 2012); www.globalenergyassessment.org

62. Parry, I. W. H. & Small, K. A. Does Britain or the United States have the right gasoline tax? *Am. Econ. Rev.* **95,** 1276–1289 (2005).
63. Creutzig, F. & He, D. Climate change mitigation and co-benefits of feasible transport demand policies in Beijing. *Transport. Res. D* **14,** 120–131 (2009).
64. Organisation for Economic Co-operation and Development & International Energy Agency *OECD-IEA Fossil Fuel Subsidies and Other Support* (OECD, 2014); www.oecd.org/site/tadffss
65. Davis, L. W. *The Economic Cost of Global Fuel Subsidies* (National Bureau of Economic Research, 2013); http://ideas.repec.org/p/nbr/nberwo/19736.html.
66. Sterner, T. *Fuel Taxes and the Poor: The Distributional Effects of Gasoline Taxation and Their Implications for Climate Policy* (Johns Hopkins Univ. Press, 2011).
67. Lay, J., Renner, S. & Schleicher, M. *Distributional Implications of Energy Subsidy Reform in Indonesia* (GIGA, 2014).
68. Brons, M., Nijkamp, P., Pels, E. & Rietveld, P. A meta-analysis of the price elasticity of gasoline demand. A SUR approach. *Energ. Econ.* **30,** 2105–2122 (2008).
69. Strand, J. *Political Economy Aspects of Fuel Subsidies : A Conceptual Framework* (World Bank, 2013); http://ideas.repec.org/p/wbk/wbrwps/6392.html
70. Clements, B., Coady, D., Fabrizio, S., Gupta, S. & Shang, B. Energy subsidies: How large are they and how can they be reformed? *Econ. Energ. Environ. Policy* **3,** http://dx.doi.org/10.5547/2160-5890.3.1.bcle (2014).
71. Rao, N. D. Kerosene subsidies in India: when energy policy fails as social policy. *Energ. Sust. Dev.* **16,** 35–43 (2012).
72. International Monetary Fund *Energy Subsidy Reform: Lessons and Implications* (IMF, 2013); www.imf.org/external/np/pp/eng/2013/012813.pdf
73. World Bank *Implementing Energy Subsidy Reforms: Evidence from Developing Countries* (World Bank, 2012); http://dx.doi.org/10.1596/978-0-8213-9561-5
74. Pachauri, S. *et al.* Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* **8,** 024015 (2013).
75. Detchon, R. & Van Leeuwen, R. Bring sustainable energy to the developing world. *Nature* **508,** 309–311 (2014).
76. Modi, V., McDade, S., Lallement, D. & Saghir, J. *Energy Services for the Millennium Development Goals* (Energy Sector Management Assistance Programme, United Nations Development Programme, 2005).
77. Rogelj, J., McCollum, D. L. & Riahi, K. The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2 °C. *Nature Clim. Change* **3,** 545–551 (2013).
78. Schnitzer, D. *et al. Microgrids for Rural Electrification: A Critical Review of Best Practices Based on Seven Case Studies* (United Nations Foundation, 2014).
79. Brauer, M. *et al.* Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. *Environ. Sci. Technol.* **46,** 652–660 (2011).
80. Sheehan, P., Cheng, E., English, A. & Sun, F. China's response to the air pollution shock. *Nature Clim. Change* **4,** 306–309 (2014).
81. Nemet, G. F., Holloway, T. & Meier, P. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environ. Res. Lett.* **5,** 014007 (2010).
82. West, J. J. *et al.* Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Clim. Change* **3,** 885–889 (2013).
83. McCollum, D. L., Krey, V. & Riahi, K. An integrated approach to energy sustainability. *Nature Clim. Change* **1,** 428–429 (2011).
84. Tubiello, F. N. *et al.* The FAOSTAT 19 database of greenhouse gas emissions from agriculture. *Environ. Res. Lett.* **8,** 035019 (2013).
85. Kissinger, G., Herold, M. & de Sy, V. *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers* (Lexeme Consulting, 2012).
86. United Nations Environment Programme *The Emissions Gap Report 2013* (UNEP, 2013); www.unep.org/pdf/UNEPEmissionsGapReport2013.pdf
87. Smith, P. *et al.* Greenhouse gas mitigation in agriculture. *Phil. Trans. R. Soc. B* **363,** 789–813 (2008).
88. International Rice Research Institute *Smart Water Technique for Rice* (IRRI, 2013).
89. Chen, Y. & Whalley, A. Green infrastructure: the effects of urban rail transit on air quality. *AEJ Econ. Policy* **4,** 58–97 (2012).
90. Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P-P. & Seto, K. A global typology of urban energy use and potentials for an urbanization mitigation wedge. *Urban Climate* (in the press).
91. Baghdadi, L., Martinez-Zarzoso, I. & Zitouna, H. Are RTA agreements with environmental provisions reducing emissions? *J. Int. Econ.* **90,** 378–390 (2013).
92. Prakash, A. & Potoski, M. Racing to the bottom? Trade, environmental governance, and ISO 14001. *Am. J. Polit. Sci.* **50,** 350–364 (2006).
93. Freund, C. & Ornelas, E. Regional trade agreements. *Annu. Rev. Econ.* **2,** 139–166 (2010).
94. Jakob, M., Steckel, J. C. & Edenhofer, O. Consumption- versus production-based emission policies. *Annu. Rev. Resourc. Econ.* http://dx.doi.org/10.1146/annurev-resource-100913-012342 (2014).
95. Urpelainen, J. A model of dynamic climate governance: dream big, win small. *Int. Environ. Agreem.* **13,** 107–125 (2013).
96. United Nations Framework Convention on Climate Change *Decision 2/CP.15* (UNFCCC, 2009); https://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php
97. Carbon Dioxide Information Analysis Centre *Fossil-Fuel CO_2 Emissions by Nation* (CDIAC, 2013); http://cdiac.ornl.gov
98. Maddison, A. *Statistics on World Population, GDP and Per Capita GDP, 1–2008 AD* (Univ. of Groningen, 2010); http://www.ggdc.net/maddison/oriindex.htm
99. Krey, V. & Clarke, L. Role of renewable energy in climate mitigation: a synthesis of recent scenarios. *Clim. Policy* **11,** 1131–1158 (2011).
100. World Bank *World Development Indicators* (World Bank, 2014); http://data.worldbank.org/data-catalog/world-development-indicators

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Author contributions

M.J., J.C.S., S.K., J.L. and O.E. were involved in conceptualizing the paper. J.C.S. and M.J. analysed data, conceptualized and produced graphs. N.G. and I.M-Z. performed analyses on inequality issues and S.R. provided household-level analyses. M.J., J.C.S., J.L., S.K., I.M-Z. and S.R. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.J. or J.C.S.

Competing financial interests

The authors declare no competing financial interests.