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PERSPECTIVE

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The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2 °C

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Progress towards climate protection has been modest over the past decades despite the ever-increasing urgency for concerted action against global warming. Partly as a response to this, but more directly as a means to promote sustainable development and poverty eradication, the United Nations has initiated a process to promote three global energy objectives: energy access, renewable energy and energy efficiency. Here we discuss the consistency of the proposed energy-related objectives with the overarching climate goal of limiting global temperature increase to below 2 °C. We find that achieving the three energy objectives could provide an important entry point to climate protection, and that sustainability and poverty eradication can go hand in hand with mitigating climate risks. Using energy indicators as the sole metrics for climate action may, however, ultimately fall short of the mark: eventually, only limits on cumulative greenhouse gas emissions will lead to stringent climate protection.

In the past few years, progress towards effective climate protection has been limited under the United Nations Framework Convention on Climate Change[1] (UNFCCC). Because of this impasse in limiting the growth of greenhouse-gas (GHG) emissions[2–4], alternative approaches are now being considered that could put the world on a path that protects the global climate. One of those focuses on the promotion of energy-related objectives.

Climate change is driven by the cumulative amount of GHGs emitted to the atmosphere[5–10], in particular of long-lived species such as carbon dioxide[11] (CO_2). Therefore, to halt anthropogenic climate change, global GHG emissions need to be reduced to virtually zero in the long term[12]. Achieving this will require massive transformations of all GHG-emitting sectors. Given that the global energy system (which supplies fuels and electricity to the residential/commercial, industrial and transportation end-use sectors) is currently responsible for about 80% of global CO_2 emissions[13–15], transformations in this sector will be essential for realizing a low-carbon future. Moreover, the need for transformational change in the energy system has also been advocated for other important reasons, for instance to spur sustainable development or to improve the well-being of the impoverished billions in our society who lack regular access to modern forms of energy to meet their basic needs. In this Perspective we look at how energy-related targets fostering the abovementioned objectives would, or would not, be consistent with global climate protection.

Energy at the core of development

Energy plays a critical role in enabling sustainable development, as highlighted at the Rio+20 Sustainable Development conference[16]. Furthermore, United Nations Secretary-General Ban Ki-moon declared 2012 the year of 'Sustainable Energy for All' (SE4ALL) and launched a new global initiative[17] that explicitly focuses on taking energy as a starting point to achieve several global sustainability objectives, including defeating poverty and ultimately halting anthropogenic climate change. The SE4ALL initiative is built on three core energy objectives, each of which should be reached by 2030.

Ensuring universal access to modern energy services. This implies that access to modern forms of energy is guaranteed for the world's poorest[18]. Three billion people currently lack access to either electricity or clean fuels for cooking, or both; this has severe, adverse implications for human health[19]. In practice, ensuring universal access means providing electricity to remote and poor rural areas, as well as the substitution of traditional biomass (for example fuel wood) by clean and modern energy carriers and appliances (for example natural gas, biogas or liquefied petroleum gas/LPG).

Doubling the share of renewable energy in the global energy mix. This requires increasing the share of renewables in final energy (the energy available to actual users) from 15% to 30% by 2030 (ref. 18). Renewable energy sources include, for example, wind power, solar power, hydropower, biomass (modern and traditional) and geothermal power.

Doubling the rate of improvement in energy efficiency. Interpreted as the energy efficiency of the global economy, this objective has been translated to an average improvement rate for global energy intensity (measured here in units of final energy per global gross domestic product, MJ per US dollar; ref. 18). More specifically, this means that global energy intensity improves by an average rate of 2.4% per year between 2010 and 2030 (compared with the historical rate of 1.2% per year).

Note that we rely on one specific interpretation of the SE4ALL targets[18], but the main initiative text[17] leaves room for ambiguity. To reduce this, targets would need to be more distinctly defined.

Energy system transformation and CO_2 emissions

The most important way for short-term energy objectives to contribute to climate stabilization is by effectively stimulating the phase-out of CO_2 emissions. Achieving this objective through transformational change in the energy system is possible through concerted action in two dimensions: improvements in energy intensity (EI) and in carbon intensity (CI). Energy intensity is defined in this context as the amount of final energy (FE) used

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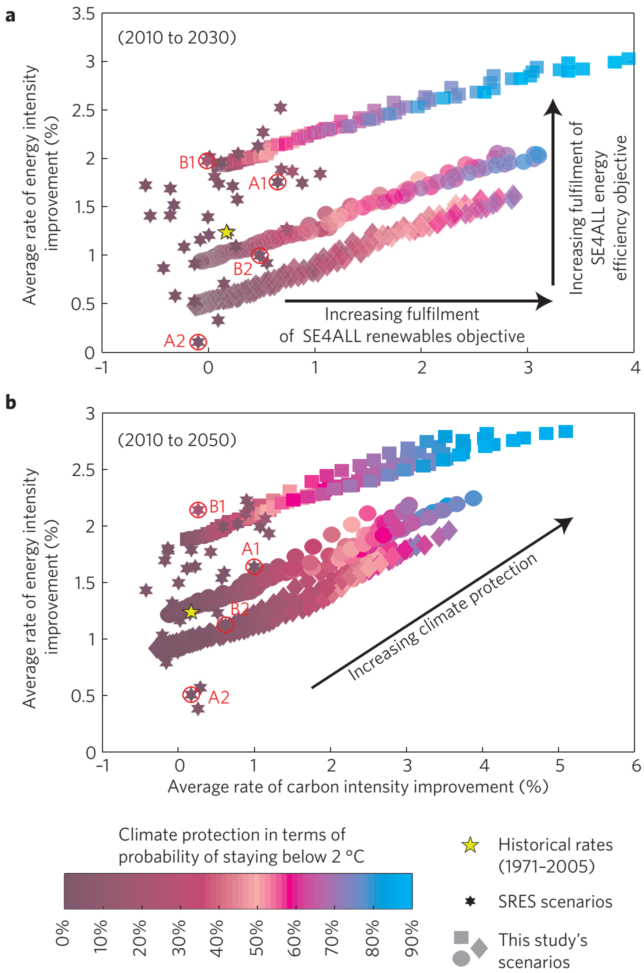

Figure 1 | Joint influence of carbon intensity and energy intensity improvements for limiting global temperature. The plots show the joint influence of these two factors on limiting the warming to below 2 °C during the twenty-first century, in a large illustrative set of scenarios ($n > 500$). Average global rates **a**, between 2010 and 2030; **b**, between 2010 and 2050. The yellow star indicates the historically observed rate between 1971 and 2005, six-pointed stars the values found in the SRES scenarios[31]. SRES marker scenarios are highlighted in red. The arrows in **a** indicate the direction along which scenarios will move when achieving two of the three SE4ALL objectives; in **b** the arrow illustrates the direction of increasing climate protection. Other symbols are colour-coded as a function of their probability of limiting warming to below 2 °C, and the shape of the symbols reflects the base level of future energy demand assumed in the scenarios (diamond: high; circle: intermediate; square: low). Note that whereas all scenarios of this study assume a consistent evolution of climate mitigation over the course of the full century, the SRES scenarios represent baseline scenarios without climate mitigation. The long-term development in the SRES scenarios might thus differ from their short-term trends.

per unit of global gross domestic product (GDP), carbon intensity as the amount of CO_2 emitted per unit of final energy. Ultimately, the amount of CO_2 emission resulting from the energy system is given by the relationship $CO_2 = CI \times EI \times$ global GDP (a variation of the well-known Kaya identity[20]). Achieving emission reductions in the energy sector thus requires a reduction in either energy or carbon intensity, or both. Actively constraining global GDP growth[21] would also limit emissions; this option, however, falls outside the scope of this Perspective, which explicitly focuses on the energy system.

Two of the three SE4ALL objectives are directly linked to the two abovementioned dimensions and can therefore, in principle, help to protect the climate (Fig. 1). The renewable energy objective will improve the carbon intensity of the energy system, and the energy efficiency objective aims to lower its energy intensity. Critical questions remain, however, regarding the extent to which the SE4ALL energy objectives are consistent with climate protection. Herein lies our motivation for exploring the potential of the SE4ALL energy objectives to serve as an entry point for stringent climate protection, and the question of whether the energy indicators can be robustly and reliably used as yardsticks for tracking progress on climate action.

Our modelling approach

Like others before us[22–24], we approach such research questions through scenario analysis and integrated assessment modelling (IAM). IAM combines insights from various fields — such as economics and the geophysical, biological, social and engineering sciences — for the systematic analysis of possible future development pathways. Generally, the interactions between different sectors of the economy are represented within a single framework in order to evaluate the impact of a variety of energy and environmental policies (for example energy security[25,26], air pollution[27], climate change[28,29] or land-use change[30]) or to better understand the uncertainties of alternative future development paths[31]. Scenarios developed by IAM thus describe, under an internally consistent set of assumptions, how the future could potentially unfold, what the impact of specific policies might be, or what costs and benefits they would entail. IAM scenarios are neither predictions nor forecasts and have even been described as "stories about what happened in the future" (note the past tense)[32]. Their value rests on their ability to shed light on the dynamics of future changes and to provide valuable insights into the circumstances that could lead to robust and cost-effective paths for achieving specific objectives.

Here we develop a large ensemble of more than 500 detailed energy–environment–economy–engineering (E4) scenarios that minimize the total cost of climate mitigation over time with the MESSAGE IAM framework[25,33,34]. We vary the stringency of climate protection and the underlying technological and socioeconomic assumptions (described in ref. 35). Our scenarios build on the IAM work from the recently published Global Energy Assessment[25], which explored a variety of potential pathways for achieving the energy transformation. For example, our scenarios distinguish between vastly different future developments in energy demand, ranging from high-demand futures to scenarios that envisage aggressive efforts to temper growth in energy demand. In addition, we delve into the highly uncertain technological dimension by exploring scenarios with future restrictions on key technologies, such as the phase-out of nuclear energy or limitations on carbon capture and storage, and also exploring scenarios that allow for possible technological breakthroughs, such as greater-than-expected advances in electric vehicles or non-CO_2 mitigation measures (for details see refs 25,36).

The scenarios identify portfolios of measures consistent with climate protection. They do not, however, prescribe the policy instruments (such as feed-in tariffs or carbon tax) that would trigger the implementation of specific measures. With this diverse set of GHG mitigation scenarios, we evaluate the consistency of the near-term SE4ALL energy objectives with the long-term goal of limiting global temperature increase to below 2 °C relative to preindustrial levels. (Climate impacts are computed with the probabilistic climate model MAGICC[5,37] in a set-up[38] consistent with ref. 39.)

Renewable shares and energy efficiency improvements have not been used as 'exogenous' control variables in our analysis; rather, they can be seen as emerging properties of a low-carbon energy system on a path towards mitigating climate change. We can therefore only determine whether the SE4ALL energy objectives are consistent with stringent climate protection, not whether they represent necessary preconditions for it to take place. And although our

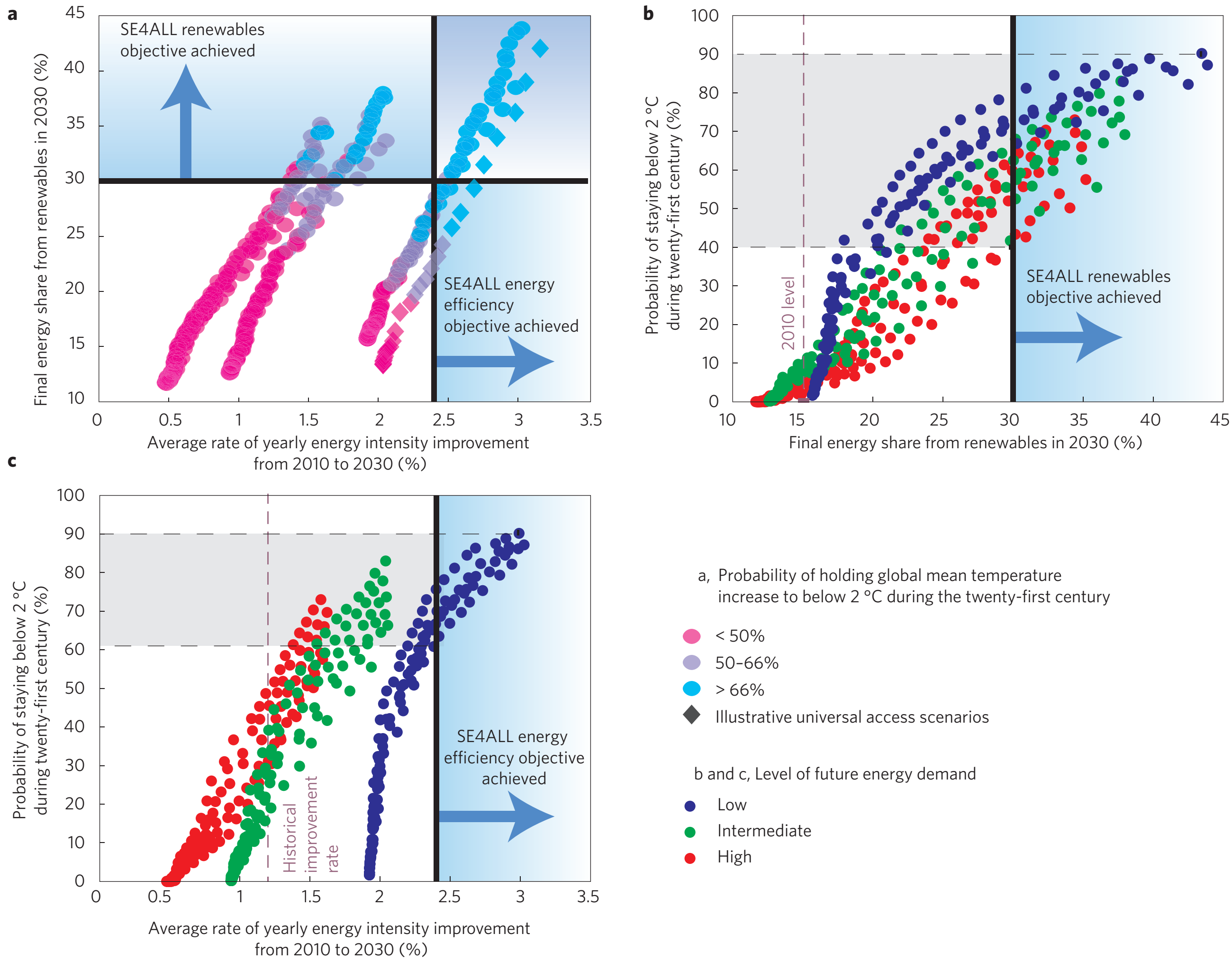

Figure 2 | Consistency of the three SE4ALL energy objectives with a global temperature limit of 2 °C. a, Yearly rates of energy intensity improvement against share of renewable energy in terms of final energy (FE) in our scenarios. Scenarios are colour-coded as a function of their probability of limiting warming to below 2 °C during the twenty-first century. Diamonds show scenarios with low future energy demand that additionally ensure universal access to modern energy services. **b**, Probability of limiting warming to below 2 °C as a function of the share of renewable energy in terms of final energy in 2030 in our scenarios, and for three levels of future energy demand. **c**, Same as **b**, but plotted against average yearly energy intensity improvements between 2010 and 2030. Horizontal grey shading in panels **b** and **c** indicates the range of probabilities of staying below 2°C in our scenarios which achieve the renewable energy and energy efficiency objective, respectively.

scenarios span a fairly large range, they are by no means exhaustive of all possible future outcomes.

SE4ALL objectives and climate protection

Analysis of the scenario ensemble indicates that simultaneously achieving all three SE4ALL energy objectives by 2030 would be consistent with limiting global temperature increase to below 2 °C with high likelihood (Fig. 2a). Despite their near-term nature, fulfilling the objectives would help to kick-start the energy system transformation and thus put it on course to ensure the long-term protection of the global climate. Likewise, global climate action would aid in reaching the SE4ALL objectives. It must be emphasized, however, that to be consistent with limiting temperature change to below 2 °C, the SE4ALL objectives will have to be implemented concertedly and globally (see further below), and be complemented by other GHG mitigation measures. Furthermore, efforts to reduce GHG emissions will need to continue long after 2030 at the same level of stringency.

Renewable energy indicators. The share of renewable energy in 2030 (as a percentage of total final energy) is closely related to climate protection. More specifically, the subset of our scenarios that achieve the renewable energy objective scores much better in terms of climate protection than the bulk of scenarios that do not. Yet, although this may be intuitive, it is interesting to note that the probability of staying below 2 °C in these scenarios ranges from 40% to about 90%. In other words, if only the SE4ALL renewable energy objective is fulfilled, the chance that temperatures could rise above 2 °C is still over 50%. Such a result makes clear that an increase in the global share of renewable energy sources will not necessarily guarantee sufficient reductions in total emissions. Whether this is the case depends on total global energy demand. For example, in the not unlikely case that future energy demand is high (Fig. 2b, red dots), a doubling of the renewable energy share in the global energy mix seems to be a rather weak indicator for stringent climate protection.

Energy intensity improvement indicators. Similar to the renewable energy objective, the likelihood of successful climate protection generally seems to be higher in the scenarios of our ensemble that see a doubling of the average rate of global energy intensity improvement (Fig. 2c). Probabilities of staying below 2 °C range from about

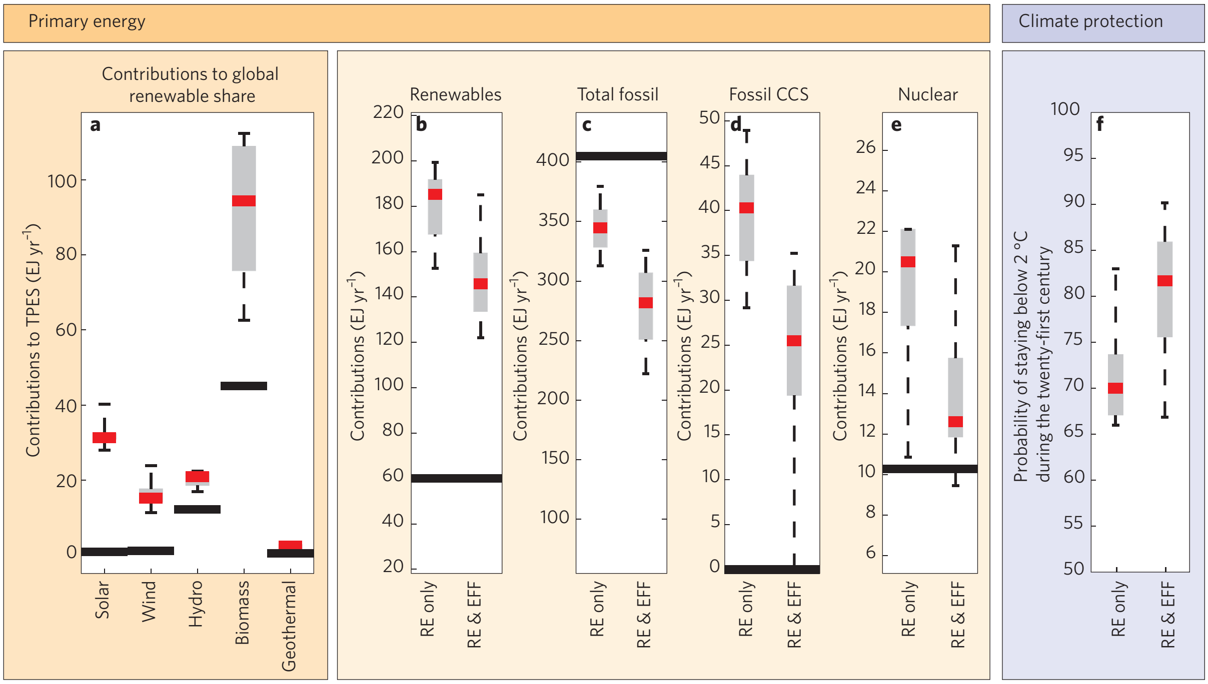

Figure 3 | Global contributions of key technologies to primary energy supply in scenarios consistent with 2 °C. a, Global absolute contributions to total primary energy supply (TPES) of renewable energy technologies in 2030 in those of our scenarios that reach the renewable energy target and limit warming to below 2 °C with at least 66% probability during the twenty-first century. **b–e**, Global contributions to TPES of renewables, fuels (total fossil), fossil fuels in combination with CCS (fossil CCS) and nuclear power in scenarios that limit warming to below 2 °C with at least 66% probability for scenarios achieving the renewable energy target only (RE only), and for scenarios achieving the energy efficiency and renewable energy target (RE & EFF). **f**, Probabilities of limiting warming to below 2 °C for the groups defined in **b–e**. Red lines show median values, grey boxes the 25th to 75th percentile range, whiskers the full range. Black horizontal lines show the 2010 contributions. Note that TPES of renewables is computed with the direct equivalence method. Accounting primary energy using the substitution equivalent method would result in higher contributions of renewables.

60% to 90% in these cases. These results are sensitive, however, to our underlying assumptions, in particular for future global GDP growth (discussed further below). In Fig. 2c, we show that only in scenarios with relatively low future growth in energy demand (through the implementation of substantial energy efficiency and conservation efforts in all end-use sectors: residential/commercial, industry and transport) can the SE4ALL energy efficiency target be achieved. Such moderation of demand, while still allowing for improved living standards globally, would require a suite of aggressive policies aimed at promoting behavioural changes with respect to energy consumption and the rapid introduction of stringent efficiency regulations, technology standards and the inclusion of environmental costs in energy prices (commonly called 'externalities', for example health and ecosystem damages from air pollution)[25]. To achieve all of this, major societal and political efforts are indeed required.

Yet, despite its apparent robustness, the main disadvantage of the energy intensity indicator is that the resulting energy demand and associated emission reductions are strongly dependent on future economic growth. High economic growth would entail relatively lower climate change mitigation from this objective, and vice versa. In our analysis we have adopted the intermediate economic growth assumptions from the Global Energy Assessment[25], which correspond to an average global GDP growth rate of about 2.8% per year between 2010 and 2030. This compares to a literature range of 2.1–3.3% per year (10–90 percentile range, based on ref. 22). Simple calculations outside our modelling framework reveal that for the same levels of energy demand as in our intermediate projections, future energy intensity improvements would shift under the alternative GDP assumptions by between −0.7 and +0.4 percentage points per year (relative to the initial 2.4%). This would shift the vertical line in Fig. 2c to the left or right accordingly, resulting in a greater or lesser number of scenarios fulfilling the SE4ALL energy efficiency objective. Nevertheless, our main conclusion remains: unless the world embarks on a high-efficiency, low-energy-demand pathway (blue dots, Fig. 2c) in the near future, the SE4ALL energy efficiency objective seems to be out of reach.

Another way of illustrating the possible effect of different GDP assumptions is to assume that the change in economic growth would alter final energy demand to the same degree, with energy intensity thus remaining constant. Assuming that carbon intensity is unchanged, we find that emissions could be 13% lower to 9% higher (10–90 percentile range) relative to the scenarios based on our 'middle-of-the-road' GDP assumption. This shows that emissions in 2030 could vary by 22 percentage points while energy intensity remains virtually the same. Because it is emissions that ultimately affect the global climate, our analysis suggests caution against the isolated use of energy intensity as a climate action indicator.

Universal energy access and climate action. Finally, we find that although it is essential for eradicating poverty, the provision of universal access to modern energy services has a limited impact on the achievement of the other SE4ALL objectives and on climate protection. Energy access gradually improves over time in our scenarios owing to increasing economic growth and affluence in the developing world. In the absence of targeted efforts to speed up this process, however, we find that universal access is not likely to be achieved before the 2060s. To study the potential impact of the SE4ALL objective, we explicitly modify a subset of our scenarios so that the timing of achieving universal access is brought forward to 2030.

As indicated by other studies[40,41], the GHG effect of providing universal energy access is negligible, particularly compared with the total GHG emissions levels expected by 2030. Our analysis further

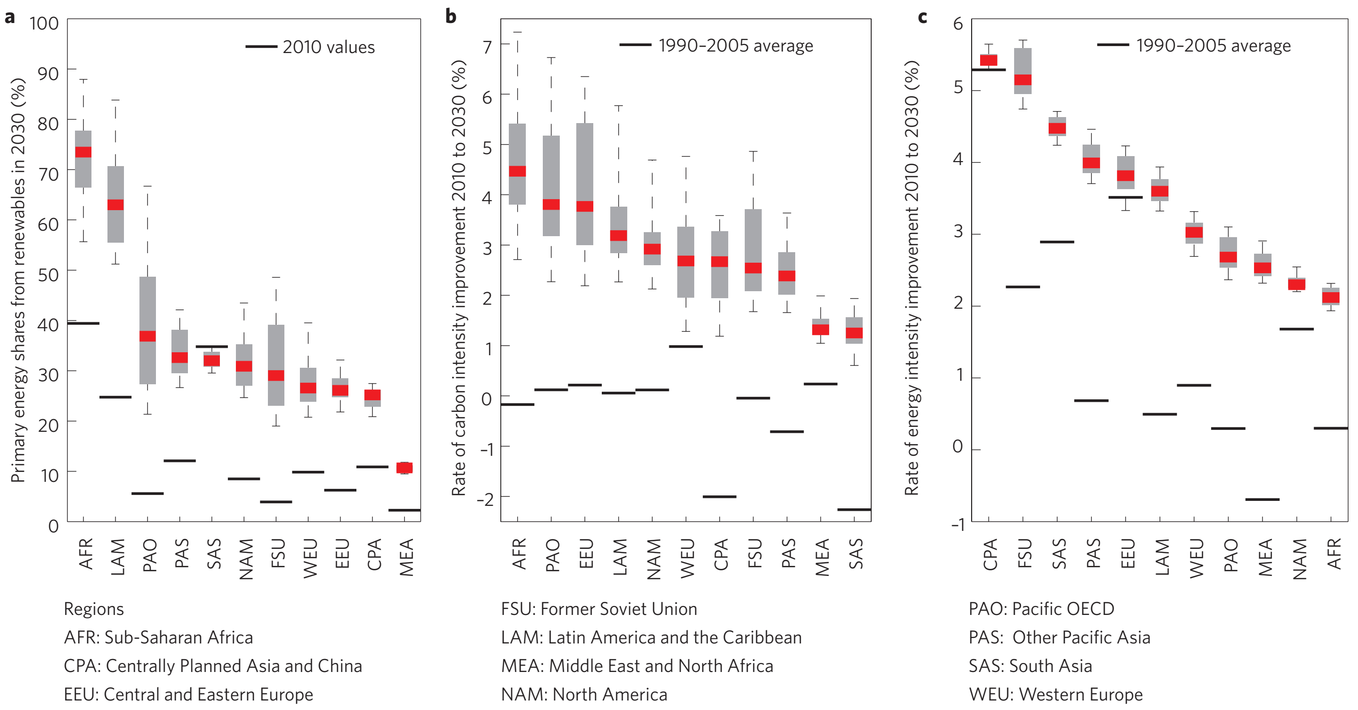

Figure 4 | Regional differences in energy indicator values in our 2 °C-consistent scenarios that meet both the energy efficiency and renewable energy SE4ALL objectives. a, Primary energy share from renewable energy sources in 2030. Note that TPES of renewables is computed with the direct equivalence method, arguably understating their contributions. **b**, Average regional carbon intensity improvement rates between 2010 and 2030 (in final energy). **c**, Average regional energy intensity improvement rates between 2010 and 2030 (in final energy). Regions are described in detail in ref. 36. Red lines show median values, grey boxes the 25th to 75th percentile range, whiskers the full range, thick black lines historical values based on data from the International Energy Agency[48] and ref. 49.

suggests that ensuring universal access to modern energy services by 2030 would help in reaching the SE4ALL energy efficiency objective but would in turn reduce the global renewables share of final energy by about 2 percentage points in the same year (Fig. 2a). The former is brought about by the substitution of inefficient traditional energy use (biomass burning for cooking has an average efficiency of about 10–15%[42,43]) by modern carriers and cooking appliances with higher efficiencies (LPG: 60%; electricity: 75%[42]). The slight reduction in renewable energy shares, on the other hand, occurs because, in our framework, energy access (for cooking and heating) is provided mainly by switching from biomass to low-pollution fossil alternatives (with fuel-price support for LPG). Of course, whether traditional biomass should be considered a truly renewable resource is debatable, as it is often harvested in an unsustainable way. (This is anecdotal: essentially no studies are available on the topic.) In conclusion, the interplay between the decreased renewables share and increased overall efficiency of the energy system results in scenarios that have very similar probabilities for holding warming to below 2 °C, irrespective of the timing of when universal access to modern energy services is achieved, whether by 2030 or much later.

How to meet multiple targets

So if it is true, as our analysis illustrates, that the concurrent achievement of all three near-term SE4ALL objectives can provide an entry point to long-term climate protection, the question then becomes: how daunting is the task? An in-depth look into the transformational changes required in our scenarios reveals that it is daunting indeed.

For starters, the contribution of renewables to total primary energy in scenarios that achieve the renewable energy target (in terms of final energy) and limit global warming to below 2 °C (with >66% probability) almost triples between 2010 and 2030, whereas the contribution of fossil fuels is reduced by 10 to 20% (Fig. 3b,c). In certain instances, namely for those renewable energy options that have a large potential but are currently underdeveloped globally, this change could be up to an order of magnitude larger, for example more than 10-fold for wind and more than 30-fold for solar energy (Fig. 3a). This translates to double-digit annual growth rates for these technologies over the coming two decades (consistent with similar historical growth rates for these technologies between 2000 and 2010). Although the values given here should only be taken as illustrative, the scale and relative magnitude of such an endeavour are arguably model-independent[44].

The good news is that the massive task of scaling up renewable energy supply options can be complemented by the simultaneous achievement of the SE4ALL energy efficiency target. Energy efficiency improvements will reduce the overall energy demand of the economy, and therewith ease the pressure on energy supply options to scale up massively in the short term. As illustrated in Fig. 3b, the global contribution of renewable energy sources to primary energy supply is reduced in absolute terms by about 20% in scenarios consistent with 2 °C that achieve both the renewable energy and energy efficiency objectives. In other words, only trying to achieve the renewables target, without achieving the energy intensity objective, would make the climate protection endeavour even more ambitious.

But renewables are not the only potential source of low-carbon energy in the future. Other options in our scenarios include fossil fuels in combination with carbon capture and storage, and nuclear power. The former allows for the continued use of fossil fuels by capturing the CO_2, compressing it and putting it into pipelines for permanent storage in geological formations[45]. The latter obviates the need for fossil fuels altogether. In either case, great reductions in CO_2 emissions can be achieved. The problem is that massive deployment of both of these technologies is contingent on a range of factors, many of them uncertain. These uncertainties relate not only to a host of economic and technological challenges but also to the public's acceptance of these technologies and its perception of the risks involved. These issues acknowledged, we find that in our scenarios, trying to achieve the 2 °C climate objective in the absence of concerted energy efficiency and conservation efforts requires contributions both from nuclear power and from fossil fuels with carbon capture (Fig. 3d,e). On the other hand, if substantial progress is made along the energy efficiency path, then future reliance on these technologies can be significantly reduced and in some cases eliminated. Higher demand-side efficiency also increases flexibility within the portfolio of renewable energy technologies: if one technology were not to be able to scale up as expected, the shortfall could be picked up by another.

Regional contributions to the global objectives

When zooming down to the regional level, we see that although the SE4ALL objectives are formulated as global targets, a cost-effective regional approach towards their implementation can result in some regional differences.

In our scenarios, all regions, whether from the developed or developing world, make a significant contribution to the global 30% renewable energy share target (Fig. 4a). The exact portfolio of renewables varies markedly by region, however, in accordance with available potentials and relative economics. For example, biomass energy is likely to play a more important role in sub-Saharan Africa and Latin America by 2030 than it is in North America or China. Wind power, in turn, is likely to make up a bigger slice of the pie in North America and Europe, whereas solar power capacity is projected to be the preferred option in the Middle East, Centrally Planned Asia (China) and South Asia (India). The SE4ALL process would do well to appreciate this need for a differentiated regional approach, as it will be fundamental to achieving the 30% global renewable target in the most cost-effective manner.

Carbon and energy intensity improvements are also likely to vary regionally towards the global goals. For example, whereas our scenarios foresee sub-Saharan Africa undergoing the most rapid declines in carbon intensity over the next decades, they would at the same time see the lowest rates of energy intensity improvement (Fig. 4b,c). In other words, energy production in sub-Saharan Africa would become less carbon-emitting but would see comparatively slower decreases in the amount of energy consumed per unit of GDP. This is owing to the currently rapid growth of population in Africa, which increases demand for energy at relatively lower economic productivity. However, economic development in our scenarios is certainly not impaired by the SE4ALL objectives. In fact, GDP growth is projected to remain strong in those parts of the world where it has remained so over the past decade — China, India and Pacific Asia (for example Vietnam, Thailand and Malaysia). Historical experience shows that energy intensity can drop most rapidly during periods of such marked growth, owing to rapid turnover of the capital stock and modernization of the economy[46] (historical values in Fig. 4c). The energy intensity improvements in Asia are thus among the highest among all regions in our modelling framework, a key finding given that the contribution of this region to the fulfilment of the global SE4ALL energy efficiency objective will be critical.

Investing in a sustainable energy future

The energy efficiency and renewable energy transitions described above will clearly not occur without mobilizing the necessary financial resources. Table 1 summarizes the required investments for achieving the three SE4ALL objectives. Meeting the renewables and energy efficiency targets, for instance, would require scaling up average annual investments by 2030 to roughly the same order of magnitude — about US$430 billion and US$350 billion per year, respectively. For renewables, this would imply an increase of a factor 2.3 relative to the current level of global investment[25]. The energy efficiency figures represent the required demand-side investment and are estimated as the additional investment required to double the energy intensity improvement rate from its historical 1.2% per year level. Finally, estimated annual investments in the range of US$36–41 billion are required by 2030 to ensure universal access to modern energy services[25].

The sum of all investments that work towards achieving the SE4ALL objectives would amount to about half of the total investment into the entire global energy system in 2030. Although large in absolute terms, as a share of economic output the additional investments required to achieve the three SE4ALL objectives by 2030 would be relatively small: some 0.1 to 0.7% of global GDP over and above investment in the baseline scenario. (For comparison, total energy sector investments in a baseline scenario that assumes no climate action and no increased energy efficiency efforts are projected to amount to roughly US$1,360 billion in 2030.) The increase in total investments is thus far smaller than the financial requirements for renewables and efficiency. This is so because investments into these two options reduce the need to invest in other energy options, in particular fossil extraction, supply and conversion technologies.

As noted earlier, sustained investments will also be critically needed in areas outside the scope of the SE4ALL initiative (for example prevention of deforestation). Moreover, an effective implementation of the SE4ALL objectives will not necessarily put us on the cost-optimal path to climate protection; and in terms of who pays for the transformational change required globally, there is still no clear consensus. How the investment burden ought to be distributed over countries and regions is not a scientific or technical question, but rather a political and ethical one.

Table 1 | Overview of global investments in the energy sector in scenarios achieving the SE4ALL objectives for renewables and energy intensity

	Annual energy investments (2005 US$ billion per year)	
	Average in 2010	Average in 2030 (minimum–maximum)
Energy efficiency objective	Not applicable	357 (322–429)[a]
Renewable energy objective (total)	187	432 (326–572)
Renewable electricity	151	302 (246–357)
Bioenergy extraction and liquid fuels from renewable sources	35	130 (80–215)
Universal energy access (from ref. 25)	–	– (36–41)[b]
Total investments in the energy sector in scenarios achieving SE4ALL objectives	966	1,620 (1,457–1,959)
Total investments in entire energy sector in absence of any SE4ALL policies	966	1,361
Global GDP in our scenarios	50,265	88,165

[a]Additional efficiency-related investments to double energy intensity compared with historical rates of intensity improvement of 1.2%. [b]Only a range and no average was provided in ref. 25.

Conclusion

We find that concertedly achieving the three SE4ALL objectives could put the world on a path towards global climate protection (Fig. 3f). Taking into account various uncertainties — some outside the energy field — we find that the SE4ALL objectives could provide multiple sustainability benefits that go hand in hand, such as eradicating poverty, improving energy security[26] and public health[26,47], and kick-starting the process of climate protection.

Our results also show, however, that using energy indicators such as energy intensity as the sole yardstick to measure climate action would be inappropriate, as additional measures are required, and such a strategy could therefore result in unintended, undesirable consequences on the climate protection side. Although achieving the SE4ALL objectives in the energy sector would represent an important step towards climate protection, climate action can only be measured and assessed in terms of the actual effectiveness of policies in limiting and reducing the absolute amount of greenhouse gases emitted to the atmosphere.

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References

1. Rogelj, J. *et al.* Copenhagen Accord pledges are paltry. *Nature* **464,** 1126–1128 (2010).
2. Peters, G. P. *et al.* Rapid growth in CO_2 emissions after the 2008–2009 global financial crisis. *Nature Clim. Change* **2,** 2–4 (2012).
3. Friedlingstein, P. *et al.* Update on CO_2 emissions. *Nature Geosci.* **3,** 811–812 (2010).
4. Montzka, S. A., Dlugokencky, E. J. & Butler, J. H. Non-CO_2 greenhouse gases and climate change. *Nature* **476,** 43–50 (2011).
5. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
6. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
7. Smith, S. M. *et al.* Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Clim. Change* **2,** 535–538 (2012).
8. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106,** 16129–16134 (2009).
9. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459,** 829–832 (2009).
10. Solomon, S. *et al.* Persistence of climate changes due to a range of greenhouse gases. *Proc. Natl Acad. Sci. USA* **107,** 18354–18359 (2010).
11. Huber, M. & Knutti, R. Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geosci.* **5,** 31–36 (2012).
12. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35,** http://dx.doi.org/10.1029/2007gl032388 (2008).
13. RCP Database (version 2.0), http://www.iiasa.ac.at/web-apps/tnt/RcpDb (2009).
14. Meinshausen, M. *et al.* The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change* **109,** 213–241 (2011).
15. Boden, T. A., Marland, G. & Andres, R. J. & *Global, Regional, and National Fossil-Fuel CO_2 Emissions* http://dx.doi.org/10.3334/CDIAC/00001_V2012 (2012).
16. United Nations in *The Future We Want. Proc. Rio+20 UN Conference on Sustainable Development: A/CONF.216/L.1*, 20–22 June 2012, 1–53 (United Nations, 2012).
17. United Nations *Sustainable Energy for All* 1–12 available via http://go.nature.com/F5eqSc (2011).
18. The Secretary-General's High-level Group on Sustainable Energy for All. *Sustainable Energy for All: A Framework for Action* 23 Available via http://go.nature.com/IDerp6 (2012).
19. UNEP and WHO *The Energy Access Situation in Developing Countries: A Review Focussing on the Least Developed Countries and Sub-Saharan Africa* 142 (UNEP/WHO, 2009).
20. Kaya, Y. Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios. (Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group, 1990).
21. Lawn, P. The need to move to a qualitatively-improving steady-state economy to resolve the climate change dilemma. *Int. J. Green Econ.* **4,** 393–428 (2010).
22. IPCC *Climate Change 2007: Mitigation* (eds Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. & Meyer, L.A.) 860 (Cambridge Univ. Press, 2007).
23. Fischedick, M. *et al.* in *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Edenhofer, O. *et al.*) Ch. 10 (Cambridge Univ. Press, 2011).
24. Yumkella, K., Nakicenovic, N., Bazilian, M. & Jewell, J. The Sustainable Energy for All initiative and climate change mitigation. *WMO Bull.* **61,** 15–17 (2012).
25. Riahi, K. *et al.* in *Global Energy Assessment: Toward a Sustainable Future*, 1203–1306 (Cambridge Univ. Press and IIASA, 2012).
26. McCollum, D. L., Krey, V. & Riahi, K. An integrated approach to energy sustainability. *Nature Clim. Change* **1,** 428–429 (2011).
27. Kelly, J. A. *An Overview of the RAINS Model.* Report No. 1-84095-208–3, 35 (Environmental Protection Agency, 2006).
28. Clarke, L. *et al.* International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.* **31,** S64–S81 (2009).
29. Van Vuuren, D. *et al.* RCP2.6: Exploring the possibility to keep global mean temperature increase below 2 °C. *Clim. Change* **109,** 95–116 (2011).
30. Wise, M. A. *et al.* Implications of limiting CO_2 concentrations for land use and energy. *Science* **324,** 1183–1186 (2009).
31. Nakicenovic, N. & Swart, R. *IPCC Special Report on Emissions Scenarios*, 570 (Cambridge Univ. Press, 2000).
32. Armstrong, J. S. & Green, K. C. *Forecasting Dictionary*, http://www.forecastingprinciples.com/ (2012).
33. O'Neill, B. C., Riahi, K. & Keppo, I. Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proc. Natl Acad. Sci. USA* **107,** 1011–1016 (2009).
34. Riahi, K., Gruebler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change* **74** (*Greenhouse Gases: Integrated Assessment* special issue), 887–935 (2007).
35. Rogelj, J., McCollum, D., Reisinger, A., Meinshausen, M. & Riahi, K. Probabilistic cost distributions for climate change mitigation. *Nature* **493,** 79–83 (2013).
36. Rogelj, J., McCollum, D., O'Neill, B. & Riahi, K. 2020 emission levels required to limit warming to below 2 °C. *Nature Clim. Change* http://dx.doi.org/10.1038/nclimate1758 (2012).
37. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6. Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
38. Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim. Change* **2,** 248–253 (2012).
39. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 994 (Cambridge Univ. Press, 2007).
40. IEA *World Energy Outlook 2010* (International Energy Agency, 2010).
41. Pachauri, S. *et al.* in *Global Energy Assessment: Toward a Sustainable Future* 58 (Cambridge Univ. Press and IIASA, 2012).
42. Ekholm, T., Krey, V., Pachauri, S. & Riahi, K. Determinants of household energy consumption in India. *Energy Policy* **38,** 5696–5707 (2010).
43. Reddy, B. S. Overcoming the energy efficiency gap in India's household sector. *Energy Policy* **31,** 1117–1127 (2003).
44. IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2011).
45. IPCC *Special Report on Carbon Dioxide Capture and Storage* (eds Metz, B. *et al.*) (IPCC, Cambridge, United Kingdom and New York, NY, USA, 2005).
46. Grubler, A. *et al.* in *Global Energy Assessment: Toward a Sustainable Future*, 99–150 (Cambridge Univ. Press, 2012).
47. McCollum, D. L. *et al.* Climate policies can help resolve energy security and air pollution challenges. *Clim. Change* http://dx.doi.org/10.1007/s10584-013-0710-y (in the press).
48. IEA *IEA Data Services (Online Statistics)* http://data.iea.org (2010).
49. Boden, T. A., Marland, G. & Andres, R. J. *Global, Regional, and National Fossil-Fuel CO_2 Emissions* http://cdiac.ornl.gov/trends/emis/overview.html (2010).

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Author contributions

J.R. and K.R. designed the research; J.R. performed the research; all authors contributed to writing the paper. D.L.M. and K.R. are listed in alphabetical order.

Additional information

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Competing financial interests

The authors declare no competing financial interests.