Available online at www.sciencedirect.com
SciVerse ScienceDirect
Current Opinion in Environmental Sustainability

An energy vision: the transformation towards sustainability — interconnected challenges and solutions

DP van Vuuren[1,2], N Nakicenovic[3,4], K Riahi[3,5], A Brew-Hammond[6], D Kammen[7], V Modi[7], M Nilsson[8] and KR Smith[9]

The energy system is currently facing a number of challenges, most notably high consumption levels, lack of energy access, environmental concerns like climate change and air pollution, energy security concerns and the need for a long-term focus. Addressing these critical issues simultaneously will require a fundamental transformation of the global energy system. Recent assessments show that such transformational pathways are achievable in technological and economic terms, but constitute formidable governance challenges across scales. In this paper, we discuss a long-term vision for the energy system and elements of the transition towards this vision. This transformation would need to be based on several key components, including taking an integrated approach as basis, the focus on high levels of energy efficiency and the scale up of investments, also in RD&D.

Addresses
[1] PBL Netherlands Environmental Assessment Agency, The Netherlands
[2] Utrecht University, Department of Geosciences, The Netherlands
[3] International Institute for Applied System Analysis (IIASA), Austria
[4] Vienna University of Technology, Austria
[5] Graz University of Technology, Austria
[6] Kwame Nkrumah University of Science and Technology, Ghana
[7] Columbia University, United States
[8] Stockholm Environment Institute (SEI), Sweden
[9] University of California, Berkeley, United States

Corresponding author: van Vuuren, DP (detlef.vanvuuren@pbl.nl)

Current Opinion in Environmental Sustainability 2012, **4**:18–34

This review comes from the Open issue
Edited by Rik Leemans

Received 29 September 2011; Accepted 6 January 2012
Available online 1st February 2012

1877-3435/$ – see front matter

DOI 10.1016/j.cosust.2012.01.004

Introduction

For most of modern history, energy systems have been central to economic development and social progress and in recent decades they are an increasingly major part of humanity's impacts on the global environment. Today more than ever, development of the energy system is of critical importance for achieving major societal objectives, such as sustainable economic development and achieving the Millennium Development Goals and avoiding disastrous climate change. Existing energy systems face several major challenges that need to be addressed, urgently and comprehensively. First, there is the need for meeting the rapidly increasing global demand for energy services, to support economic development. Second, access to modern and clean forms of energy need to be extended to the 40% of the global population who currently cook with solid fuels and in general lack reliable, affordable and low-pollution household energy resources. Third, it is necessary to reduce greenhouse gas emissions, air pollution and other environmental impacts from energy systems, in order to prevent dangerous climate change, adverse health effects and impacts on land, water and biodiversity. Fourth, the energy security for all nations and regions, including those with no significant conventional energy resources of their own, needs to be ensured. And finally, current energy investments and financing need to be put into a long-term context.

In order to address these challenges, major transformative changes of the energy system are needed. In this paper, we discuss the multiple challenges and possible sustainable energy pathways that would address these challenges in terms of principal technological and policy components, based on a review of existing literature. For our assessment, we relied on a set of recent, key studies, including the Global Energy Assessment (GEA) [1••], the work on the Representative Concentration Pathways (RCPs) [2••], the International Energy Agency's World Energy Outlook [3,4••], and several model comparison studies [5•,6•,7••]. Several recent studies have looked into transitions towards large-scale use of renewable energy and efficiency, some of which also were considered here [8–12].

Main energy challenges

Below, the five major energy challenges are discussed in more detail.

Increasing consumption levels

Energy demand has been growing at a rapid pace in many parts of the world. This trend started after the industrial revolution, which ignited the explosive growth in material consumption around the world, by enhancing human and animate labour and biomass fuels by inanimate sources of energy, mainly fossil fuels. Globally, over the 1850–2005 period, energy demand grew by about 2.2%, annually [13].

Almost all '*conventional worlds*' energy scenarios (i.e. assuming no major policy changes, also called '*business-as-usual*' scenarios) anticipate energy demand to continue to grow, worldwide. On average, scenarios in the literature project an increase in world energy demand by a factor of 3 over the 21st century, with a range of between 2.5 and 5.5 [14•,15]. An important driver is the increasing demand in low-income regions. In 'conventional worlds' scenarios, fossil fuels retain a dominant market share. This is mostly because these scenarios assume the prices of fossil energy to remain lower than those of alternative sources. For conventional oil and possibly also for natural gas, current world scenarios show a production peak as depletion of cheap and easily exploitable deposits is likely to lead to price increases. For coal, however, resource scarcity is not expected to limit production or drive up prices in the foreseeable future (please note that there is some discussion on the size of economically viable coal resources [16]). Despite the dominance of fossil fuels, most '*conventional worlds*' scenarios also project a significant increase in non-fossil energy production, including modern biomass and other renewables [7••].

An important issue related to the future of fossil fuels concerns the less-conventional resources and their environmental impacts. For oil, these include enhanced oil recovery techniques, tar sands, and shale rock. When these resources are tallied, not only is the overall resource far larger, but so too is the greenhouse gas signature per barrel. A recent literature review found some of the 'unconventional' resources to have per-barrel life-cycle emissions of more than twice to that of conventional petrol [17]. Unless technology and policy combinations hasten the transition away from petroleum, the resource of increasingly polluting fuels will make protecting the global climate more difficult. Another important non-conventional resource is shale gas. Recent technology advances imply significant increases in the natural gas reserves that can be extracted from some regions (in particular in the United States).

Energy-intensive lifestyles and inefficiency of large parts of the energy system, particularly at the level of energy services, are major drivers of further growth in energy consumption. Although efficiency enhancements potentially are regarded as very low-hanging fruit with low or even 'negative' costs, they have proven difficult to realise, due to institutional, market, educational and political barriers. One of the main challenges for transformation of the energy system, thus, will be to identify appropriate measures to overcome implementation barriers to efficiency measures, and to promote energy conserving and sustainable lifestyles.

Lack of energy access

The energy inequalities of the modern world run deep. At the moment, the poorer three-quarters of the world's population use only 10% of the world's energy. About 1.5 billion people still lack proper access to electricity, and around 3 billion are without access to modern fuels and appliances for cooking [18•,19••]. Most rural and low-income urban households in developing nations still depend predominantly on traditional biomass (including charcoal and to a lesser extent coal) to meet their cooking energy needs. Although the fraction of people without clean fuels for cooking has been falling, the absolute number is larger than anytime in human history.

Studies find that, in absence of dedicated policies and investments into infrastructure, the number of people without access will not decline [4••,19••,20]. This implies that existing health impacts from household air pollution remain (see Section 'Environmental risks') [21,22,23•]. Figure 1 shows the hot spots of populations most severely affected by the lack of energy access, as well as premature deaths caused by household air pollution. The figure also shows the investment needs (and associated uncertainties) to achieve universal access by 2030 (see also Section 'Solutions' on investments).

Environmental risks

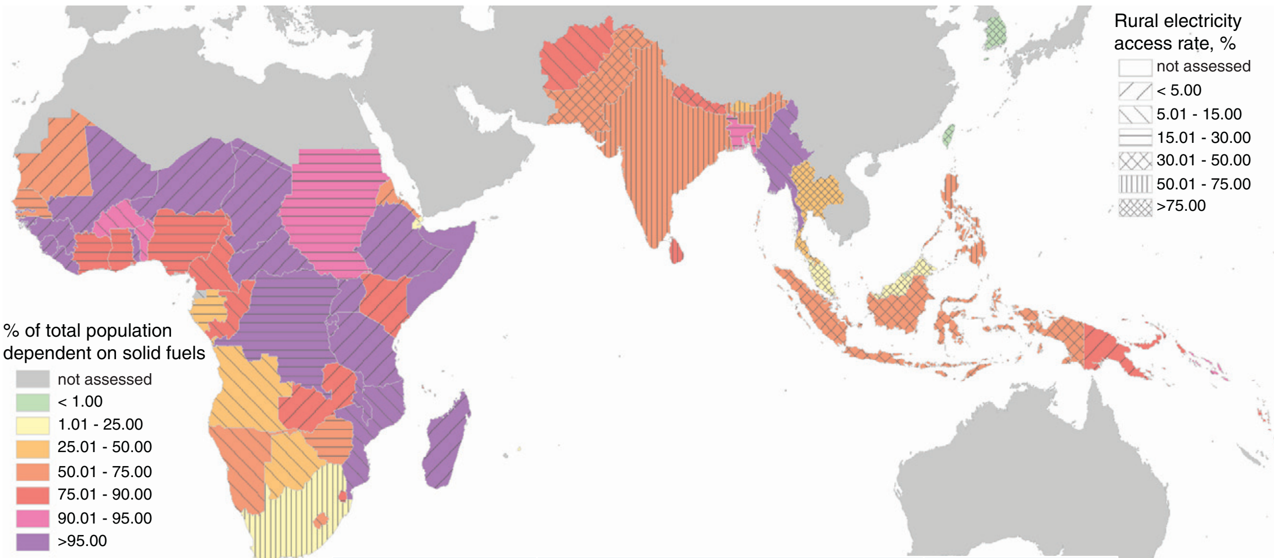
Energy use plays a key role in most environmental challenges, ranging from local to global and including climate change, household and regional air pollution and problems related to the use of land and water.

Climate change

Energy-related emissions from CO_2 and other greenhouse gases have also been increasing rapidly throughout the last century. The major share of current greenhouse gas emissions originates from energy consumption and production, and this share is expected to increase further [5•,24]. Emission scenarios show that, without new policies, emissions would continue to grow at the historical rate, throughout the 21st century (Figure 2). This is expected to lead to an increase of the global mean surface temperature of between 4 and 5°C, compared to pre-industrial levels [25,26], for average climate sensitivity values. This does lead to increasing risk levels for a number of different climate impacts, including risks to unique ecosystems and large-scale discontinuities [27,28].

In order to limit climate change, significant emission reductions are necessary. The work on low-emission scenarios, for instance, shows that emissions need to be reduced to around 50% of the 2000 level, by 2050, and to around zero by the end of the century, in order for there to be at least a 50% probability of meeting the 2°C target [29,30•,31,32,33]. This complies to a radiative forcing level around 2.6 W/m^2 in 2100 (450 ppm CO_2 equiv).

Figure 1



	Required Access Financing Billion 2005US$ (2010-2030)		Health benefits (average annual deaths avoided - millions)
	Cooking	Electricity	
Sub-Saharan Africa	130-140	160-210	0.5
South Asia	160-180	55-60	0.8
Pacific Asia	~ 20	10-60	0.3

Current Opinion in Environmental Sustainability

Illustrative figure for populations lacking access to clean cooking and electricity in major problem regions of Sub-Saharan Africa, and South and Pacific Asia. Colours denote lack of access to clean cooking and hatched areas the lack of access to electricity. The insert gives the regional costs and related health benefits from reaching universal access by 2030 in these regions. Note that these regions account for over 85% of the total global population without access to electricity and over 70% of the global population still dependent on solid fuels.
Source: based on [17,74••].

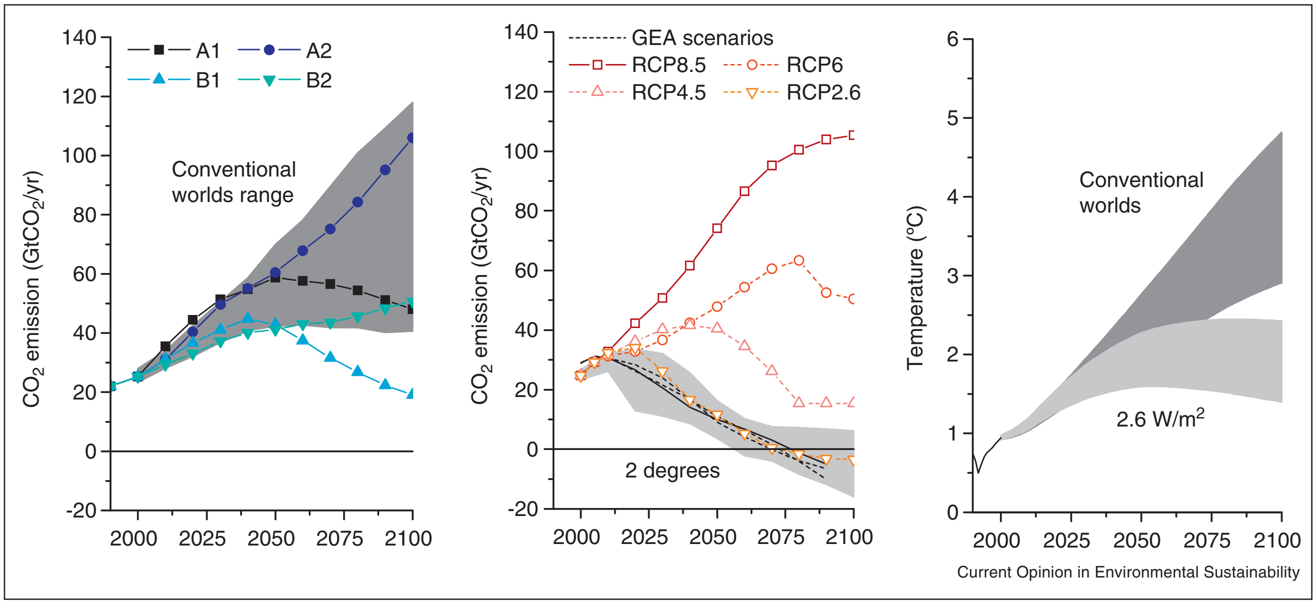
According to different studies, access to modern energy for all may add at maximum a few per cent of total global greenhouse gas emissions [4••,19••,34••,35]. Accounting for the full suite of greenhouse gases, including the emissions associated with production of traditional bio-energy and products of incomplete combustion, universal access to modern energy for all may even result in a marginal decline of GHG emissions [19••,36]. The decline in emissions is due to the large efficiency gains of modern appliances as well as accounting for unsustain-able harvest of biomass in some regions.

Air pollution

Energy systems are currently responsible for a large portion of the global burden of disease which is in the order of 5 million premature deaths annually from air pollution and other energy related causes and more than 8% of all ill health (lost healthy life years from both morbidity and premature mortality [23•].

Outdoor air pollution from energy systems is currently responsible for a large portion of the global burden of disease of around 2.7 million premature deaths annually among both urban and rural populations. In addition, household pollution from incomplete combustion of solid fuels is the single most important link between energy and ill-health. The largest exposures to this pollution occur within and around homes, particularly in develop-ing countries where unprocessed biomass and coal is used for cooking and heating in simple unvented appliances. The GEA estimated that around 2.2 million premature deaths occur annually from exposure to household air pollution [23•]. In addition, a significant portion of out-door air pollution in developing countries comes from poor combustion of household fuels. Thus, the total impact from household fuels is roughly equal to that from all outdoor air pollution, with some overlap. The impacts of household pollution occur mainly among the poorest portions of the world's population, and particularly

Figure 2



Range in emissions for scenarios without climate policy (grey area, left panel) compared to scenarios that aim at stabilisation of CO_2 concentrations consistent with a target of 2°C (grey area middle panel; all scenario's with a 2100 forcing level below 3 W/m^2 have been included). For illustration, the SRES scenarios (left panel) and GEA scenarios and RCP scenarios (middle panel) are shown. Finally, the right panel shows the temperature outcome of a typical scenario without climate policy and a 2.6 W/m^2 stabilisation scenario (uncertainty range here represents the uncertainty in carbon cycle and climate sensitivity). Based on: [2••,15,19••,25,75].

women and young children, because they experience the highest exposures. Occupational health impacts, particularly from harvesting and processing solid fuels (biomass and coal), are the next most important impact on health from energy systems [19••,23•].[1]

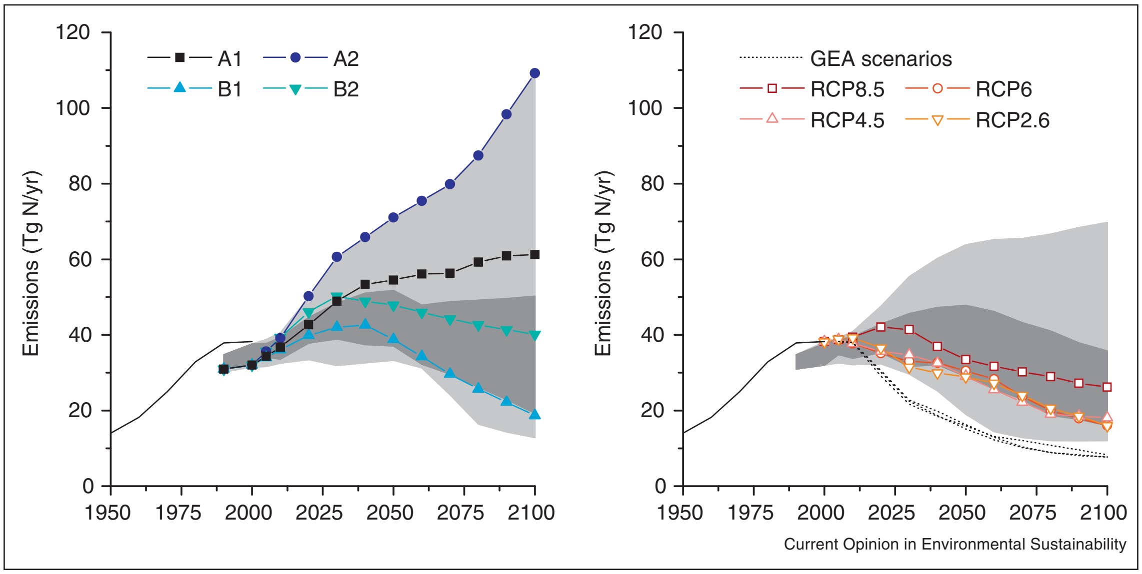
The trends in air pollution derived from energy consumption are anticipated to be very different across the world, depending on local policies. In OECD countries, the enactment of all current and planned air quality legislation is expected to decrease emission levels for most pollutants even further. In non-OECD countries, emission trends are a result of not only rapidly increasing energy demand, but also, at several places, increasingly tight energy policies. In other countries, air quality legislation is non-existent (e.g. in Africa). Together, this implies, even if currently legislated air pollution control policies were implemented everywhere, only modest declines in pollutants would be expected, as emissions in developing countries are expected to increase. Further tightening of air pollution policies or integration of these policies into other policies (in particular in climate policy), thus, are needed to reduce the burden of disease from the energy sector [19••], as illustrated in Figure 3 for NO_x emissions.

Land and water systems

Energy systems based on fossil sources result, among others, in climate change and air pollution; renewable energy, however, can still have serious impacts on land and water systems. Bio-energy production using dedicated crops, especially, could require vast land areas and increase freshwater use [37]. Still, bio-energy plays an important role in many mitigation scenarios. The land use of bio-energy may compete with other activities that require scarce productive land, such as food production and biodiversity [38–40]. Some studies have reported that considerable food price increases may occur as a result of direct and indirect land-use impacts of bio-energy. The impact of bio-energy use depends on several factors, such as type of crop (e.g. first-generation versus second-generation crops), assumed yields, and trends in land-use systems [41]. As a result, quite a wide range of impacts are reported in the literature. The focus on water use is more recent, but may still be important. Secondly, bio-energy may have considerable greenhouse gas emissions associated with its production. These include not only emissions from nitrogen fertilisers and fuel, but also CO_2 emissions from direct and indirect land-use change [38,42]. These impacts may partly be mitigated; for instance, by carefully choosing the specific bio-energy supply chains. Other renewable sources (e.g. hydropower

[1] A comprehensive update of the global health impacts of outdoor and household air pollution along with impacts from a many other important risk factors is forthcoming in the Global Burden of Diseases, Injuries, and Risk Factors Study (the GBD 2010 Study). See http://www.globalburden.org/.

Figure 3



Trends in NO_x emissions as examples of possible air pollution emission trends (left all scenarios; right only scenarios with climate policy). For illustration, the SRES scenarios (left panel) and GEA scenarios and RCP scenarios (right panel) are shown.
Source: [76].

and wind power) may also impact land use, although their impacts are mostly important at local scale.

Energy security

Uninterrupted provisioning of vital energy services — 'energy security' — is a high priority for every nation, city and community. The notion, however, is strongly context-dependent [1,19••,43]. For most industrialised countries, energy security is related to import dependency and aging infrastructure. Many emerging economies have additional vulnerabilities, such as insufficient capacity, high-energy intensity and rapid growth in demand. In many low-income countries, finally, supply and demand vulnerabilities overlap, making them especially insecure.

Oil plays a dominant role in the current transport system, while its resources are geographically concentrated in only a few countries and regions. Moreover, production capacities are perceived as limited, resulting in price volatilities affecting especially low-income countries. For natural gas, supply concerns are mostly regional, given the smaller role of global trade (e.g. in Europe). However, the trade in liquefied natural gas (LNG) is, more and more, connecting natural gas markets globally. Interestingly, transitions towards electricity, as projected in many climate mitigation scenarios, may imply that energy security concerns with respect to electricity might increase. With most energy scenarios leading to roughly a doubling in fossil-fuel consumption assuming the absence of sustainability policies, the increased dependency would worsen energy security concerns, particularly in resource-poor regions in Asia.

Although ensuring energy security is an important goal, the notion has such a different meaning across countries and regions that we have not attempted to describe the challenge at a more aggregated scale. This implies that we have not set a universal global goal in Section 'A vision towards 2050'.

Investments need to put into long-term context

One factor that contributes to the challenges described above is the lack of long-term focus in current energy policies. For most energy infrastructure, inertia and possibility of a lock-in play a key role given their long lifetimes. Current policies, however, often lack such a long-term focus. One obvious indicator regarding a long-term focus concerns trends in RD&D. Several studies have tried to assess historical trends in RD&D, as well as the current deployment of RD&D investments. These studies show that the RD&D investments, already for decades, have been seriously lagging behind the growth in energy consumption — leading to a decline in RD&D efforts. In fact, they have declined even in absolute terms since the 1970s but show a trend reversal in recent years [44,45•]. Traditional 'laboratory' research leading to private-sector spin-offs, which has long been the model of the R&D-to-market pathway, may give way to a more field-based model where innovation and application are tied together in settings outside of traditional university and national laboratory settings. Similarly, also investments in the energy system and infrastructure should be consistent with the long-term vision. It is clear that this is currently not the case. Ensuring sufficient finance will certainly be a key challenge in the near future, given the difficulties in the financial markets.

A vision towards 2050

Policy objectives

In 1992, the world committed itself in the form of the Rio declaration to (i) eradicating poverty (Principle 5), while (ii) conserving, protecting and restoring the health and integrity of Earth's ecosystem (Principle 7). Since then, several more specific objectives have been formulated in various international agreements. Furthermore, there has been scientific literature on sustainability criteria, most noteworthy the recently advanced notion of planetary boundaries, which defines a set of global environmental sustainability criteria [46]. Taken together, a vision of a sustainable energy future can be formulated that recognises the importance of the energy system for human development and the need for maintaining the integrity of Earth's biophysical systems. Such a vision should entail the following elements:

- *Universal access to electricity and clean cooking by 2030*. The electricity target is specifically motivated by the economic and environmental gains possible from access to electricity. Access to clean cooking is important as the environmental impacts of traditional stoves and fuels impact all aspects of household quality of life including health. Development of clean stoves and fuels lead directly to reduced health problems [22]. Both the electricity and cooking target would reduce the current reliance of a large fraction of the population in developing countries on traditional biomass to satisfy basic energy needs [47••].
- *Energy for development by 2050*. Although universal access to modern energy services is a necessary part of combating poverty in the medium term, over the longer term it is necessary to frame the energy challenge also in terms of energy demand associated with productive uses, including in industry — consistent with long-term economic development aspirations of countries around the world.
- *Reducing air pollution in compliance with the WHO air quality guidelines* (*annual $PM_{2.5}$ concentration $< 10\ \mu g/m^3$*)[2] for the majority of the world population, while the remaining populations stay well within the WHO Tier I–III levels by 2030 [48]. This target is consistent with the fact that many countries around the world have adopted anti-pollution legislation and have specific plans for further implementation of legislation in the short term. However, current legislative plans in the aggregate are not sufficient to achieve this target.
- *Limiting global average temperature change to 2°C above preindustrial levels with a likelihood of more than 50%*.[3] This target is consistent with EU and UN policy formulations [49,50] (it should be noted that the scientific findings and current negotiations also indicate the need to consider even more stringent targets). This ambitious target is based on the ambition to limit the mean global temperature increase to a level that does not lead to dangerous anthropogenic climate change. It should be noted that even at 2°C significant climate impacts may occur and adaptation will be required.
- Finally, improving energy security is also an important goal. The notion, however, is interpreted so differently in different countries and regions that we have not set a universal global goal.

A formal adoption of such a long-term and coherent vision of sustainable energy access may work as a guiding principal for a global policy frameworks that have potential to advance faster than the global climate policy agreements. Clearly, many actors (state and non-state) need to be involved, on local, national and international levels, in implementing energy objectives. There are several reasons why, certainly in the long-run, international cooperation is important: (1) measures can be more effective; (2) parties can agree on a fair burden-sharing avoiding free-riding and/or competition; and (3) measures may often be implemented at lower costs. At the same time, as the current negotiations within UNFCCC show, different national interests tend to slow down multilateral policy-processes. As such, internationally binding policies should certainly not be seen as the only possible way to induce a transition towards a more sustainable energy system. The nation state maintains the initiative in deciding on energy policy instruments and measures for the foreseeable future. We have also seen that bilateral agreements or agreements between groups of countries may advance agendas further, as well as bottom-up initiatives from civil society, the private sector and/or cities and local governments. Also within the context of such multilevel governance, the formulation of long-term visions and objectives increases the coherence and effectiveness of policy formulation [51•].

The need for integrated solutions

Many assessments indicate that simultaneous achievement of the policy objectives would be possible, but that this would require a transformation of the global energy

[2] Particles small enough to penetrate into the deep lung (PM2.5) are considered the best indicator of the risk of pollution from combustion sources.

[3] The likelihood of 50% refers to physical climate change uncertainties, including climate sensitivity, aerosol forcing, and ocean diffusivity. It thus depicts the chances that a specific GHG pathway would stay below the 2°C temperature target. The likelihood does not imply any political or technological probability of staying below the target.

system over the next decades [1••]. Studies have shown that such a transformation would have important synergistic co-benefits. At the moment, these synergies are often overlooked, both in policy development and in actual investments occurring on the ground. In most countries, separate ministries and agencies are responsible for dealing with each of the objectives, and few jurisdictions have made progress in more integrated policy-making. At the investment level, a principal problem is that the strengths/weaknesses of different proposals and incentives relate to different objectives. For example, economic benefits, especially those accrued over longer periods of time, from efficiency investments in buildings, or health improvements from cleaner energy supply are often not appropriable for the investors.

A large body of literature illustrates that climate change mitigation can be an important entry point for achieving other energy objectives. For instance, decarbonisation of the energy system also leads to improved air quality [25,52,53] (see also Figure 3). The GEA shows that, globally, up to 22 million DALYs could be reduced by 2030, as a result of climate policy [19••]. Decarbonisation may help to further the energy security goals of individual countries and regions by promoting a more diversified energy portfolio that sees an increased utilisation of domestically available renewable energy sources. Conversely, energy system transformations could be an important entry point for avoiding climate change.

Many of the energy objectives have important benefits for a broader sustainability strategy (e.g. ensuring access to modern energy and the health benefits of reduced air pollution). At the same time, several measures that could promote a more sustainable development, in general, could also have a positive impact on achieving energy targets. For instance, women's education is shown to have benefits, such as in raising incomes, reducing population growth (and thus energy use), and improving access to modern energy [54]. In high-income countries, improving efficiency of material use not only may help to avoid resource depletion, but also to reduce energy use. There are, however, also a number of critical linkages that need to be monitored.

As mentioned before, an important example is that of bio-energy. Given the linkages between bio-energy, climate change, land use and water, an integrated consideration of the energy system, land and water use is required. In fact, this can be made more general for climate change, biodiversity, food and energy concerns [55].

A second example is the recent emphasis on short-lived climate forcers and 'black carbon'. Here, important synergies, and sometimes trade-offs, exist between air pollution policies, climate change and energy access, calling for integrated policies. Black carbon, which is part of the particle pollution from incomplete combustion of fuels with major health impact globally, deposits on snow and ice to contribute to the melting of polar and mountain ice [56]. Eliminating coal use in households, as has already occurred in many parts of the world, and promoting modern biomass cooking and heating stoves with advanced combustion are major components of the strategy required.

Solutions

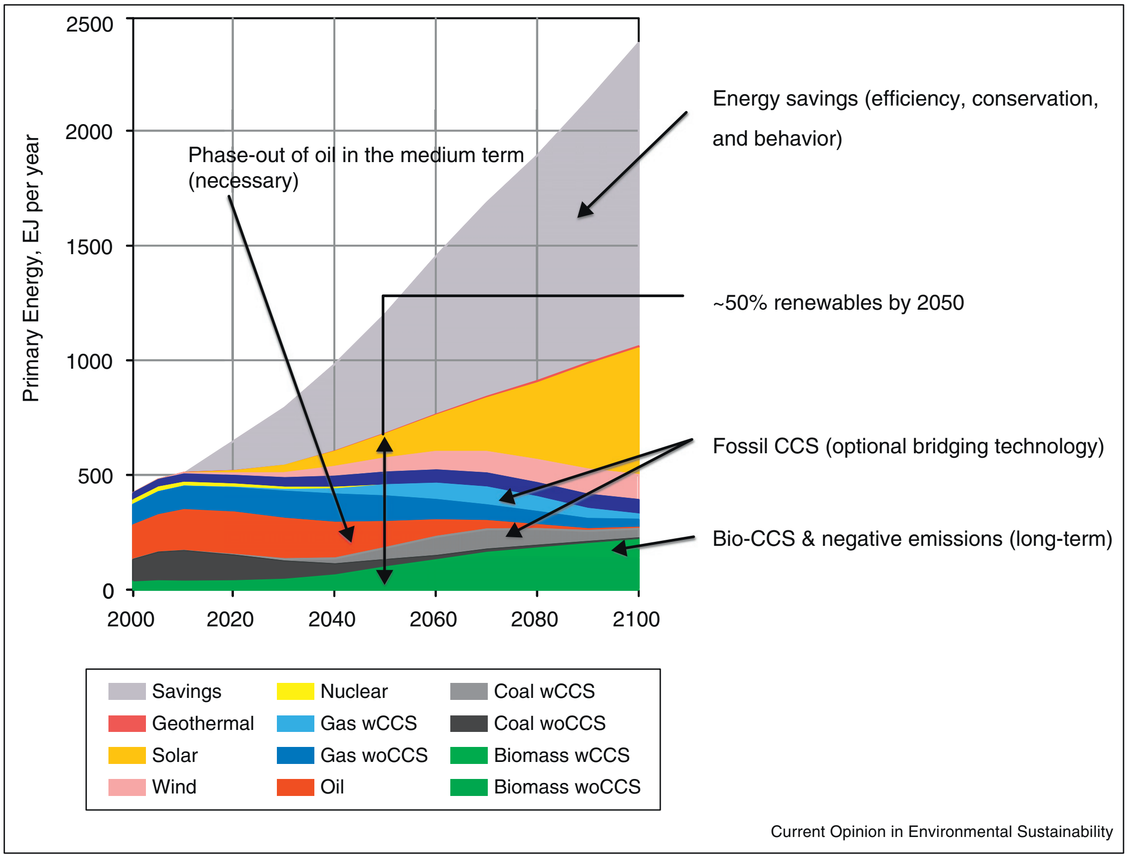
There are technology pathways that fulfil the vision

Quite a number of studies have developed scenarios to show that pathways can be identified that are consistent with stabilising greenhouse gas concentration at 2.6 W/m^2 or 450 ppm CO_2 equiv. Such stabilisation targets were also explored in several recent model comparison studies [5•,6•,33,57]. These studies typically look into greenhouse gas emission reductions by 2050, in the order of 50–60%. The GEA scenarios [19••] represent an interesting addition to this literature, as they were developed specifically to achieve the multiple targets discussed in Section 'A vision towards 2050' (i.e. universal access, reduction in air pollution and reduction in greenhouse gas emissions consistent with the 2°C target). At the aggregated level, the results of these scenarios are very comparable to the climate policy scenarios summarised above. Figure 4 shows one of the GEA scenarios compared to a case with energy intensity improvement rates following historical experience. This again emphasises the role of energy efficiency improvement and the penetration of zero-carbon energy sources.

Focusing more specifically on individual technologies, energy efficiency improvement represents the most crucial contribution towards achieving the vision, given its contribution to multiple policy objectives. For instance, for the 2.6 W/m^2/450 ppm CO_2 equiv. scenarios, the EMF-22 study reports a 20% efficiency improvement, on average, compared to the baseline (and a 30% improvement in 2100). Many studies have identified the reduction in wasteful energy use in buildings, transport and industry as the single most important strategy for achieving energy sustainability, especially in the near and medium term [9,19••,24]. Successful strategies include, for instance, the rapid introduction of strict building codes, increased retrofit rates in buildings, introducing efficient transport modes (or even replacing transport, for instance, by teleconferencing) and wide-spread adoption of best-available-technologies in industry and appliances [19••].

On the supply side, there are several important options. Taking the EMF-22 study as a starting point: in the 2.6 W/m^2 scenarios, the share of unabated fossil-fuel use declines from 80% of total primary energy in the baseline to only 35% in the 2.6 W/m^2 case in 2050. Table 1 also

Figure 4



One of the GEA scenarios with various options for increasing efficiency and decreasing emissions, compared to a hypothetical case with energy intensity improvement rates following historical experience. (wCCS indicates ''with carbon-capture-and-storage''; woCCS indicates ''without CCS''). *Source*: [19••].

shows the range across scenarios, for the fossil fuel share 13–48%. Bio-energy use, other renewables, nuclear and fossil-fuel use combined with carbon capture and storage (CCS), all increase their share. This is already the case in the baseline — but even more so in the 2.6 Wm^2 scenario (15%, 16%, 14% and 20%, respectively), indicating the importance of all these options for mitigation. Again, the ranges across the different scenarios show that the increase for these options is robust — but that there is a wide uncertainty range for individual options.

Table 1

Characteristics of 2.6 W/m^2/450 ppm CO_2 equiv. scenarios in EMF-22 compared to their respective baselines — 2050 and 2100. Calculations are based on EMF-22 (includes 8 scenarios from 5 different modelling systems). Numbers indicate averages while numbers between square brackets indicate the full range. The numbers between round brackets indicate values of the 2.6 W/m^2 scenarios relative to the baseline.

	2000	Baseline		2.6 W/m^2 scenarios	
		2050	2100	2050	2100
Change compared to 2000 (2000 = 100%) (%)					
CO_2 emissions	100 [100–100]	171 [145–242]	206 [122–347]	56 [24–96] (33)	13 [1–20] (7)
Energy	100 [100–100]	193 [169–234]	275 [256–352]	159 [79–184] (82)	200 [93–243] (72)
Share in primary energy (%)					
Fossil	87 [84–94]	79 [68–95]	67 [46–92]	35 [13–48]	8 [1–20]
Fossil + CCS	0 [0–0]	0 [0–0]	0 [0–0]	20 [0–31]	14 [0–32]
Bio-energy	7 [1–9]	9 [0–13]	12 [0–23]	15 [0–28]	18 [0–29]
Nuclear	2 [2–3]	3 [1–6]	8 [1–14]	14 [3–37]	33 [4–52]
Renewable	3 [3–5]	9 [2–14]	13 [3–27]	16 [8–24]	27 [13–45]

An important challenge here is that many available options are associated with sustainability problems of their own. For wind power and CCS, there is clear local opposition based on landscape consequences and risks. Nuclear power is associated with risks of accidents and storage of spent fuel. Bio-energy may have severe consequences for the use of land and water. Among the different options, renewables stand out as a key option with multiple benefits [37,58]. Renewables (with some limitations and a possible exception of bio-energy) may reduce greenhouse gas emissions, help to improve energy security, stimulate economic development and offer possibilities of both centralised and off-site energy conversion. The challenge here would be that renewable energy options require high upfront capital costs, but are characterised by low long-term costs (for the overall sum, they are currently usually more expensive than fossil-fuel alternatives). Most are also intermittent in nature so that they require storage, still generally very expensive, and/or back-up capacities usually natural gas or hydropower [59]. As most advanced storage technologies are costly, 'virtual' storage through back-up natural gas power plants is an important bridging technology that already today supports increasing shares of intermittent renewables. The need for effective storage can be greatly reduced through smart grids and super grids that would connect remote renewable resources to large, urban demand centres.

A number of studies show the need for massive scale-up of renewables for achieving societies' sustainability objectives. Debate exists on the contribution of renewable energy to a global energy system. Some studies show that, theoretically, nearly all energy can be produced from renewable energy [8,10,11,60]. However, there are large economic and infrastructural constraints to such high penetration rates in the next decade. As a consequence, most energy models show much lower rates even for stringent mitigation scenarios (in the order of 25–70% by 2050) [7,19••,37]. The deployment rates of renewable energy can differ substantially across regions (Table 2).

CO_2 capture and storage in geological formations (CCS) is another important option to decarbonise fossil energy conversion processes. Many studies indicate that the future contribution of this technology will strongly depend on a number of factors, such as the regional availability of alternatives (e.g. renewable energy sources), the relative costs of fossil fuels, and the availability of prospective geological storage sites. As a result, the amount of CO_2 captured and stored, or shipped to appropriate storage elsewhere, may vary significantly across different regions.

An important constraint on the transformation of energy systems is inertia. Energy systems can only be changed slowly over timescales of decades. Many energy technologies, such as power plants, on average, have a lifetime of several decades [61]. The underlying infrastructure often takes even longer to change. This implies that a transformation towards a more sustainable energy system will take a considerable amount of time, and decisions today will influence the future for a long time. For climate change, in fact, this is even a more prominent issue, as many greenhouse gases will continue to stay in the atmosphere for more than a century. The compound inertia implies that not acting now runs the risks of putting the 2°C target out of reach within around 5–20 years [33].

Investments need to be scaled up and put into a long-term focus

Achieving the energy transformation towards sustainable development requires dedicated efforts to increase global energy-related investments. Although different studies reveal considerable uncertainty about future needs for energy investments in specific technology options, they

Table 2

Regional ranges of renewable energy deployments to meet stringent climate mitigation and pollution objectives by 2050 (in Exajoules unless otherwise stated). Estimates from two modelling frameworks: IMAGE and MESSAGE [19••].

Region	Bio-energy	Hydro-power	Wind	Solar[1]	Geo-thermal	All renewables	All renewables as % of total
Sub-Saharan Africa	8.8–40.5	2.0–5.5	0.0–19.6	0.5–25.5	0.0–0.3	11.4–91.4	31–94
Centrally Planned Asia and China	6.9–24.7	9.7–10.3	3.7–8.8	0.9–40.1	0.0–0.3	21.2–84.2	24–50
Eastern Europe	1.3–2.8	0.8–1.0	0.7–5.0	0.2–6.1	0.0–0.3	2.9–15.3	23–85
Former Soviet Union	2.9–10.1	2.7–15.8	1.4–7.4	0.3–9.7	0.0–1.0	7.4–43.9	25–93
Latin America and the Caribbean	10.5–22.5	10.7–17.6	3.6–12.4	0.5–21.8	0.0–1.8	25.3–76.1	40–100
Middle East and North Africa	1.2–5.1	0.8–1.2	1.3–8.7	0.5–15.8	0.0–0.3	3.8–31.1	17–40
North America	10.0–21.5	7.2–7.9	2.6–36.7	1.2–41.6	0.0–3.4	21–111	38–89
Pacific OECD	3.4–11.3	1.4–1.7	0.6–4.9	0.2–5.4	0.1–0.8	5.7–24	26–89
Pacific Asia	5.0–11.9	1.9–7.2	1.0–2.0	0.4–14.5	0.2–1.3	8.6–36.9	15–63
South Asia	5.2–20.8	3.5–4.3	1.1–6.7	1.0–79.0	0.0–0.2	10.7–111	21–65
Western Europe	3.9–11.0	5.7–7.6	3.0–30.2	0.7–28.9	0.1–2.1	13.4–79.8	34–83
World	78.3–139	49.9–80.1	28.5–134	7–285	0.6–11.9	164–651	28–74

clearly illustrate that present investment in energy is neither sufficient nor compatible in structure with a sustainable investment portfolio.

The global investments required for achieving a set of sustainability targets are estimated to be around USD 1.7–2.2 trillion, annually (supply and efficiency), compared to the present level of some USD 1.3 trillion (less than 2% of current world GDP) [19••,34••]. On the one hand, this constitutes a considerable financial flow, but, on the other, these investment levels can be compared to estimates of annual global fossil-fuel subsidies amounting to more than USD 0.4 trillion [4••]. Current spending on environmental policies in OECD countries is also around 1–2% of GDP.

Table 3 indicates the magnitude of required investments for key energy options over the coming decades to meet the main energy challenges from climate to pollution, and energy access [1••,19••].

Investments are subject to uncertainty. While there is relatively high agreement across studies with respect to current supply-side investments [19••,62], there is significant uncertainty about investments into demand-side energy components and appliances. The total of USD 1.3 trillion considers, for example, 300 billion of investments into energy components. The full uncertainty of estimates for energy components ranges between USD 100 and 700 billion [45•]. As illustrated in Table 3, future uncertainties for the required investments are relatively wide as well, however, priority areas with particularly large investment needs can be identified. These include particularly, renewables, efficiency and energy infrastructure. Investments needed in these areas are an order of magnitude bigger than the investment requirements for achieving universal energy access (Table 3).

The goals described in Section 'A vision towards 2050' may help to evaluate short-term decisions in the context of long-term objectives. WBGU [63••] identifies four measures for financing the long-term transformation of energy systems: (1) Provide stable framework conditions for energy investments based on stable policy framework conditions with ambitious targets, for example a decarbonisation strategy including carbon pricing and phasing out of subsidies for fossil energy. (2) Open up new financing sources for developing and newly industrialising countries within the scope of the UN Framework Convention on Climate Change (UNFCCC), though grants for mitigation projects in developing countries by increasing existing multilateral funds, by increasing the current Official Development Assistance well beyond USD 100 billion per year. For example, levies on international shipping and aviation and the introduction of a tax on international financial transactions could generate further funds. (3) Strengthen mechanisms to encourage private investment because considerable private capital exists that could be channelled towards energy financing through suitable framework conditions and government measures to raise the rate of return for investments (e.g. low-interest loans), to mitigate investment the risks (e.g. through credit guarantees), to promote institutional investors with a long-term investment horizon (e.g. pension funds and insurance companies) and to strengthen venture and equity capital markets through favourable taxation or the Green Investment Banks. Existing microfinancing approaches in development cooperation could further promote decentralised energy generation from renewable energy. (4) Encourage new business models to overcome the high up-front investment burden for individual investors with new financing and ownership structures. These would allow businesses to offer their customers combined packages in certain areas (e.g. mobility, housing, production and consumption) that include services as well as real assets, instead of just tangible goods. Examples are car sharing and energy contracting provided by energy service companies.

Policies and incentives need to be put in place

Different policy mechanisms need to be put in place to implement various technology options (and attract the required level of resources). The correct combination of policy mechanisms depends on the types of technologies and objectives. Table 3 identifies 'essential' policy mechanisms that must be included for a specific option to achieve the rapid energy system transformation, 'desired' policy mechanisms that would help but are not a necessary condition, 'uncertain' policy mechanisms in which the outcome will depend on the policy emphasis and, thus, might favour or disfavour a specific option, and policies that are inadequate on their own but could 'complement' other essential policies.

A careful consideration of the portfolio of policies is required. It needs to include regulations and technology standards in sectors with, for example, relatively low price elasticity in combination with externality pricing to avoid rebound effects, as well as targeted subsidies to promote specific 'no-regret' options, while addressing affordability. In addition, focus needs to be given to capacity building to create an enabling technical, institutional, legal and financial environment to complement traditional deployment policies (particularly in the developing world).

For some objectives, such as energy access, future investment needs are comparatively modest (see Table 3). However, a variety of different policy mechanisms — including subsidies and regulation as well as capacity building — need to be in place. Regulations and standards are also essential for almost all other options listed in the table, while externality pricing might be necessary for capital-intensive technologies to achieve

Table 3

Energy investments needed to achieve sustainability objectives (limiting climate change to 2°C, reducing energy-related air pollution, improving energy security, and achieving universal energy access by 2030), and illustrative policy mechanisms for mobilising financial resources.

	Investment (billion USD/year)		Policy mechanisms			
	2010	2010–2050	Regulation, standards	Externality pricing	Carefully designed subsidies	Capacity building
Efficiency	n.a.[a]	290–800[b]	*Essential* (elimination of less efficient technologies every few years)	*Essential* (cannot achieve dramatic efficiency gains without prices that reflect full costs)	*Complement* (ineffective without price regulation, multiple instruments possible)[c]	*Essential* (expertise needed for new technologies)
Nuclear energy	5–40[d]	15–210	*Essential* (waste disposal regulation and, of fuel cycle, to prevent proliferation)	*Uncertain* (GHG pricing helps nuclear energy but prices reflecting nuclear risks would hurt)	*Uncertain* (has been important in the past, but with GHG pricing perhaps not needed)	*Desired* (need to correct the loss of expertise of recent decades)[5]
Renewable energy	190	260–1010	*Complement* (feed-in tariff and renewable portfolio standards in order to overcome implementation barriers)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complement* (tax credits for R&D or production can complement GHG pricing)	*Essential* (expertise needed for new technologies)
CCS	<1	0–64	*Essential* (CCS requirement for all new coal plants and phase-in with existing)	*Essential* (GHG pricing is essential, but even this is unlikely to suffice in near term)	*Complement* (would help with first plants while GHG price is still low)	*Desired* (expertise needed for new technologies)[e]
Infrastructure[f]	260	310–500	*Essential* (security regulation critical for some aspects of reliability)	*Uncertain* (neutral effect)	*Essential* (customers must pay for reliability levels they value)	*Essential* (expertise needed for new technologies)
Access to electricity and cleaner cooking[g]	n.a.	36–41	*Essential* (ensure standardisation but must not hinder development)	*Uncertain* (could reduce access by increasing costs of fossil-fuel products)	*Essential* (grants for grid, micro-financing for appliances, subsidies for cooking fuels)	*Essential* (create enabling environment: technical, legal, institutional, financial)

Source: [1••,19••].

[a] Global investments into efficiency improvements for the year 2010 are not available. The best-guess estimate for investments into energy components of demand-side devices is by comparison about 300$ billion per year [45•]. This includes, for example, investments into the engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. Uncertainty range is between US$100 billion and US$700 billion annually for investments in components. Accounting for the full investment costs of end-use devices would increase demand-side investments by about an order of magnitude.

[b] Estimate includes efficiency investments at the margin only and is thus an underestimate compared with demand-side investments into energy components given for 2010 (see note 1).

[c] Efficiency improvements typically require a basket of financing tools in addition to subsidies, including, for example, low- or no-interest loans or, in general, access to capital and financing, guarantee funds, third-party financing, pay-as-you-save schemes, or feebates as well as information and educational instruments such as labeling, disclosure and certification mandates and programs, training and education, and information campaigns.

[d] Lower-bound estimate includes only traditional deployment investments in about 2 GW capacity additions in 2010. Upper-bound estimate includes, in addition, investments for plants under construction, fuel reprocessing, and estimated costs for capacity lifetime extensions.

[e] Note the large range of required investments for CCS and nuclear in 2010–2050. Depending on the social and political acceptability of these options, capacity building may become essential for achieving the high estimate of future investments.

[f] Overall electricity grid investments, including investments for operations and capacity reserves, back-up capacity, and power storage.

[g] Annual costs for almost universal access by 2030 (including electricity grid connections and fuel subsidies for clean cooking fuels).

rapid deployment (e.g. a carbon tax to promote diffusion of renewables, CCS or efficiency). Capital requirements for energy infrastructure are among the highest priorities of the options listed and, hence, innovative policies would be needed to promote leapfrogging, such as the development of smart grids [64].

Transformation is based on RD&D effort

RD&D forms a special form of investment. Improved technologies are needed to make the required transformation, additional and redirected RD&D investments are required. Comparison of the current RD&D expenditures to the expected future contribution of mitigation options shows a mismatch between RD&D effort and the required technologies. Especially, there is too little R&D and investments spent on efficiency, while compared to the future needs for a sustainable transformation, the investment in nuclear and fossil fuels are overrepresented [65] (Figure 5). Efficiency is often a low-cost option and essential for the transformation. However, it requires significant up-front investments to achieve low costs in the long run. This is difficult to finance under the current market conditions that require high and immediate rates of return. Other barriers to increasing efficiency investments include behavioural issues. In both cases, policy frameworks are needed for providing incentives for efficiency investments. Enhanced public RD&D efforts can help reduce the costs and make the transformation more attractive.

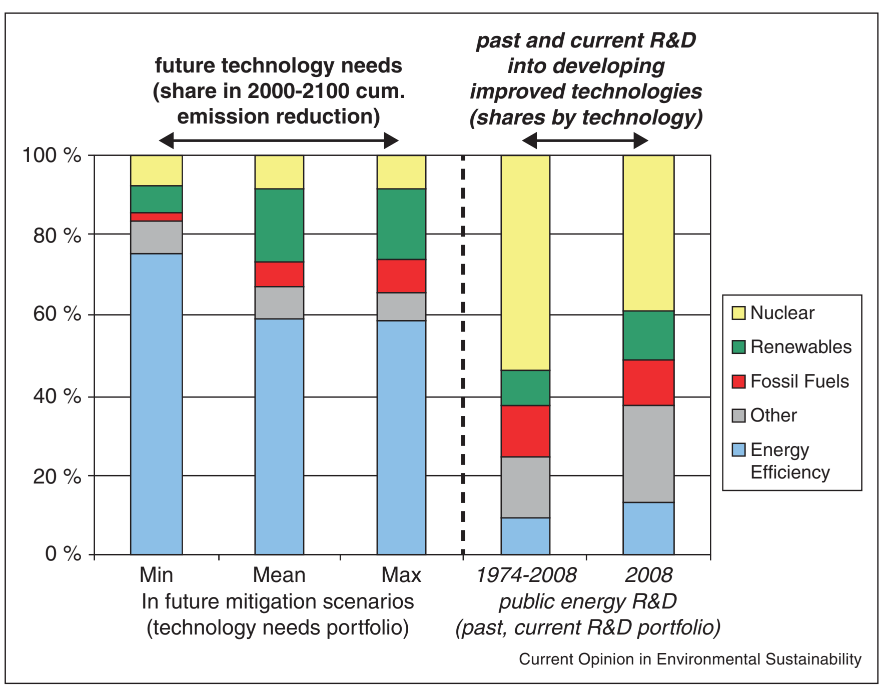
To be effective in the context of sustainable development transitions, RD&D policies need to move towards a more integrated approach, simultaneously stimulating development and adoption of efficient and cleaner energy technologies and measures. RD&D initiatives without simultaneous incentives for consumers to adopt the outcomes of innovation efforts not only risk being ineffective, but also preclude the market feedbacks and learning that are critical for continued improvements in technologies.

Research has also shown that policies have to support a wide range of technologies. However seductive they may seem for decision makers, silver bullets do not exist (certainly not without the benefit of hindsight). Innovation policies should use a portfolio approach under a risk hedging and 'insurance policy' decision-making paradigm. The entire suite of innovation processes should be included, not just particular stages or individual mechanisms. Less capital-intensive, smaller scale (i.e. granular) technologies or projects are a lower drain on scarce resources, and failure has less serious consequences.

Integrated policy-making can reap important synergies

As shown in Section 'A vision towards 2050', an integrated approach to energy policy and planning would reduce the combined costs of energy access, climate change mitigation, energy security and air pollution control. This would result in a significantly reduced total energy bill if the

Figure 5



Distribution of past and current energy R&D as compared to future technology needs from energy scenarios.
Source: [65].

multiple benefits of each are properly accounted for in the calculation of total energy system costs (see Section 'Investments need to be scaled up and put into a long-term focus' on investments).

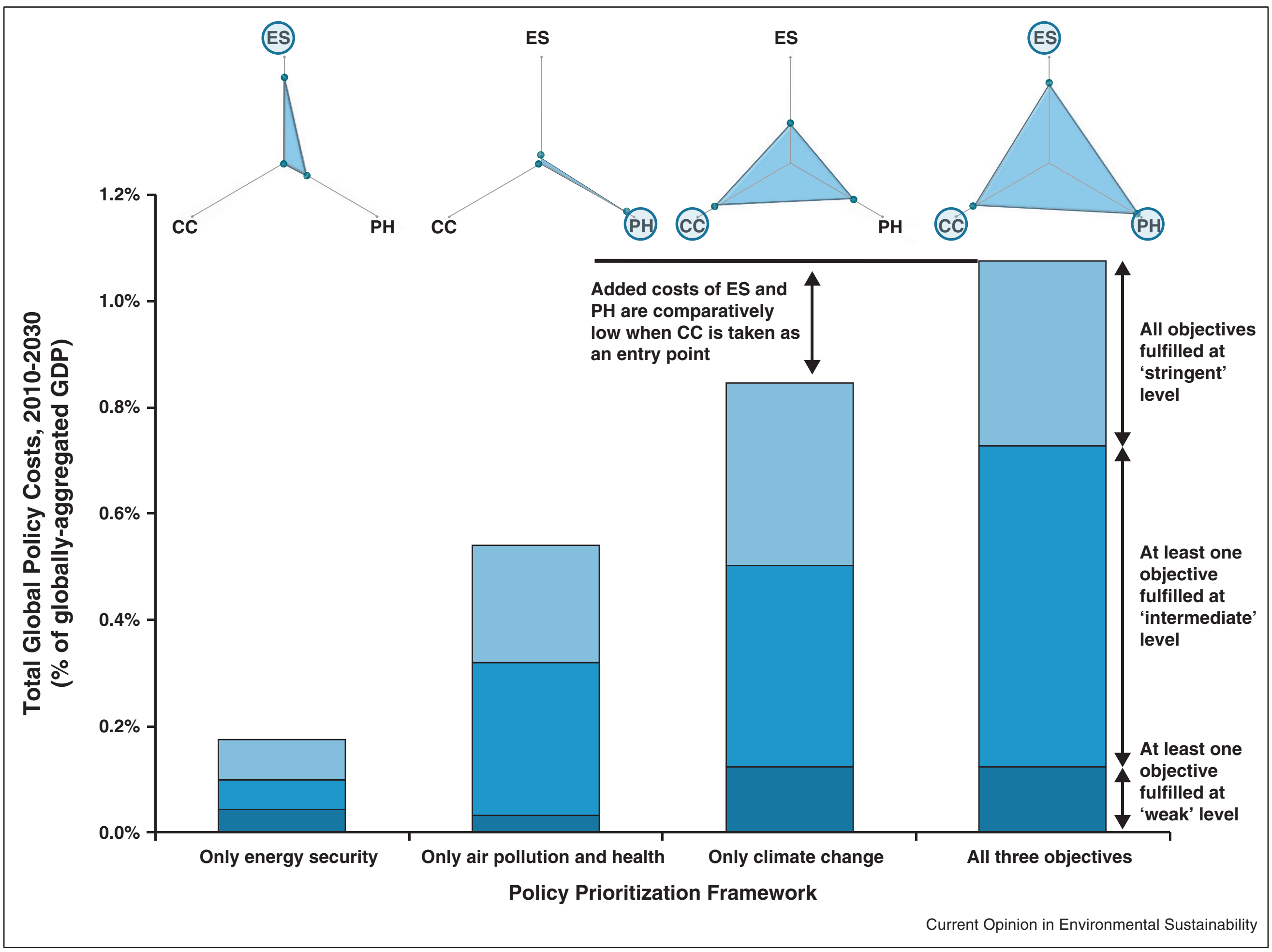
The benefits of integrating policies across different objectives are illustrated in Figure 6 [66••]. The figure shows that the sum of required investments for resolving three energy-related global challenges independently of each other — mitigating climate change, reducing pollution and increasing energy security (three bars towards left). The total investment required is much larger than that for an integrated policy approach to achieve the same three targets simultaneously (right-most bar).

The challenge of achieving more integrated policy-making is both an institutional and political one. Institutional, because governmental and sectoral organisations have established practices, decision-making procedures, and modes of operation, which often do not include coordination with other sectors. Political, because there are strong vested interests associated with business as usual pathways, both in economic terms and in terms of political influence. Coordination and integration always include opening up for external influences [67].

Energy policy should take account of heterogeneity

About half of the world's population lives in urban areas, which also accounts for the disproportionally large share

Figure 6



Policy costs for single-issue policy approaches to deal with climate, pollution and energy security (three bars towards left) compared to the policy costs required for an integrated policy approach achieving the same targets (right-most bar). Integrated policy approaches that target all objectives simultaneously benefit from synergistic effects and achieve the targets more cost effectively. Stringency of the policies varies from 'low' (dark blue) to 'stringent' (light blue). Policy costs represent the net financial requirements (energy-system and pollution-control investments, variable, and operations and maintenance costs) over and above a baseline energy-system development. Triangular schematics summarise the performance of scenarios that achieve fulfilment only for the objective(s) targeted under the corresponding policy frameworks (axis values are normalised from 0 to 1, indicating no to max fulfilment; CC = climate change, ES = energy security, PH = air pollution and health). Climate mitigation is found as an effective entry point for other objectives, while using energy security or pollution as the main focus would not create the same synergies.
Source: Adapted from [66••].

of global economic output and energy use of between 60% and 80% [45•,68]. Projections for the urban population is expected to approach 6.5 billion people by 2050 — about the size of the entire world population in 2005 — while the rural population would stabilise around the current level of some 3.5 billion [69].

Given these trends, energy use in cities will dominate future energy demand. Obviously, issues such as infrastructure, air pollution, and the energy density mismatch between large demand centres (e.g. cities), and distributed generation options (e.g. renewables) play an important role here. The urban situation also provides options, such as availability of finance and the possibility of advanced distribution systems (smart and super grids).

In a rural situation, other forms of energy demand are more dominant (e.g. irrigation and transport). Often, access to modern energy is lower in rural areas, given the costs of infrastructure, requiring in some cases off-grid solutions. Successful energy policies need to account for this heterogeneity.

Governance and societal support

Reworking the incentive structures and governmental machineries 'top-down' for more integrated decision-making (see above) is only part of the solution. In addition, societal support 'bottom up' forms an essential element of a successful transformation process. In that light, it should be noted that local interest might not always be on a par with global interests. Experience in western Europe, for instance, has shown that both CCS and wind power may be exposed to strong local opposition, resembling popular movements against nuclear energy and infrastructural projects such as transmission lines. Gaining acceptance for major changes in the energy system will depend on significant efforts to ensure transparent and proactive decision-making processes with full accountability [63••].

Such efforts need to be nested within an overall strengthening of the institutional capacities for governing energy systems development. It needs to include the building of effective national institutions that can implement transparent energy planning and decision-making, contracting and procurements, capacities to track and monitor progress on energy access and other objectives and capacities to implement appropriate policy assessment frameworks to reduce environmental risks and vulnerabilities associated with strategic energy supply options.

Meeting the challenges of the energy transformation outlined in this paper will not be possible without governance enabling conducive political and institutional conditions [70•]. In the last two decades, policy analysts interested in transformation and innovation have learned more and more about such governance.

First, the state is a central agent but certainly not the only one. The transition should ultimately mobilise drivers of change from society as a whole [51•]. In this context, the state could play a role as goal setter, enabler and regulator, and also a key source of capital for the necessary investments in infrastructure and R&D. In order to 'organise the unplannable' the different roles of the state and other actors also need further articulation at different levels [63••].

Second, instruments for governing technological transformations need to be differentiated depending on the technology stage and maturity [71]. This insight from innovation studies has grown to become a central theme in the IEAs deployment analysis. Early-stage technologies require nurturing of niches and networks, whereas more mature technologies can benefit from more generic economic instruments [72].

Third, learning processes, through monitoring and feedback of transition processes need to be firmly institutionalised. The capacity of governments to provide timely regulatory mechanisms and incentives to promote analysis, feedback, learning and adjustment of enacted policies will be crucial for enhancing the transformation [73]. Instigating technological transformation on the scale required will depend on significant institutional reform within and across sectors, including altering not only the regulatory structures, but also cognitions and norms among key actors [70•].

International cooperation to speed up implementation

Most of the increase in energy use is expected to take place in low-income countries. This implies that also most of the investments mentioned in Section 'Policies and incentives need to be put in place' will have to be made in developing countries. Lack of capital and financial mechanisms in these countries currently represent important barriers. International cooperation can help address this barrier. This can be partly based on already existing, financial instruments developed as part of international climate policy, although these would need to be improved to reduce leakage. A second barrier is related to good governance. Stable institutional conditions are essential for reducing the perceived high risks by the investors. The increasing role of emerging economies, where much of the global economic development will take place in the future, is a factor that will also play a key role in the international negotiations, and is something that needs to be accounted for in institutional arrangements.

More generally, global cooperation to enable the transformation to some extent depends on nation states putting global concerns and the common good before their own short-term interests, in order to make a trend reversal, particularly as far as the global economy is concerned, towards more sustainable development pathways [63••]. In this context, the governance structure for the transformation simply has to take on the issues of equity and fairness [63••].

Indicators to watch

The energy transformation could be followed through monitoring and measurements of goals and interim targets, regarding achieving access for the poor, efficiency enhancements and renewable energy deployment. Important data to monitor trends in relation to the 2050 energy vision are still lacking. IEA is an important data source at the international level. Unfortunately, despite their importance, there are clear limitations to these data sources — in particular regarding the type of information that is collected. Data on several important topics for assessment, such as energy access and energy end-use, are lacking. A particular challenge is the patchy empirical foundation for the lack of energy access, and the spatial and behavioural dimensions of energy patterns.

In principle, two sets of indicators need to be established at the global level. The first set includes indicators that monitor the progress towards end-points of sustainability transformation, such as greenhouse gas emissions (also per capita), access to energy services, air pollution data and decarbonisation rates. The second set includes those that monitor the process, such as investments, policy implementation, institutional capacity building, penetration of non-fossil fuels and data on end-use efficiency.

Recommendations and conclusions

In order to achieve the multiple objectives of the energy system transformation, a large number of robust and non-discretionary components and systems changes would need to begin being implemented today. These energy system changes include:

- Efforts to double the historical rate of change in the energy intensity of the economy in order to reduce the risk of the sustainability objectives becoming unreachable. Efficiency increases the flexibility of supply and the overall cost-effectiveness of the energy system transformation.
- A broad portfolio of supply-side options, focusing on low-carbon energy from non-combustible renewables, bio-energy, nuclear energy, and CCS, achieving low-carbon shares in primary energy of at least 60–80% by 2050. These include:

  - ○ Strong growth in renewable energy, beginning immediately and reaching around 50% per year of primary energy by 2050.
  - ○ An increasing requirement for storage technologies, natural gas backup (virtual storage) and smart grids to support system integration of intermittent wind and solar energy.
  - ○ Growth in bio-energy in the medium term to 80–140 EJ by 2050 (including extensive use of agricultural residues and second-generation bio-energy to mitigate adverse impacts on land use and food production).
  - ○ Nuclear energy plays an important role in the supply-side portfolio of many but not all transformation pathways.
  - ○ Fossil CCS as an optional bridging or transitional technology in the medium term, and increasing the contribution of biomass with CCS in the long term.
  - ○ Aggressive decarbonisation in the electricity sector, reaching low-carbon shares of 75% to almost 100% by 2050; early phase-out of conventional coal power (i.e. without CCS); natural gas power could act as a bridging or transitional technology in the short to medium term.

- Transformative changes of the transportation sector, possibly through electrification or the introduction of hydrogen vehicles to improve end-use efficiency and increase the flexibility of supply. Freight and air travel, in contrast, are likely to be based on biofuels in order to reduce emissions.
- Attainment of universal access to *electricity and clean cooking* by 2030, which will require global partnerships and concentrated efforts especially in sub-Saharan Africa, Southeast Asia, South Asia and East Asia.

Acknowledgements

Most authors of this paper contributed to the Global Energy Assessment (GEA) and have benefited greatly from interactions and joint work with other GEA authors. The indirect contribution of other GEA authors to this paper is acknowledged with appreciation. The authors also thank Pieter Boot (PBL) for his useful suggestions in approving the draft.

References and recommended reading

Papers of particular interest published within the period of review have been highlighted as:

- • of special interest
- •• of outstanding interest

1. •• GEA: *The Global Energy Assessment: Toward a More Sustainable Future*. Laxenburg: Cambridge University Press, Cambridge and IIASA; 2012.

The Global Energy Assessment provides a comprehensive view on current energy challenges, based on work of experts worldwide.

2. •• Van Vuuren DP, Edmonds J, Thomson A, Riahi K, Kainuma M, Matsui T, Hurtt GC, Lamarque J-F, Meinshausen M, Smith S *et al.*: **Representative concentration pathways: an overview**. *Climatic Change* 2011, **109**:5-31.

The Representative Concentration Pathways play a crucial role exploring possible futures in research concerning the climate change challenge.

3. IEA: *World Energy Outlook 2010*. Paris: IEA; 2010.

4. •• IEA: *World Energy Outlook 2011*. Paris: International Energy Agency; 2011.

The World Energy Outlook published by the IEA is regarded as a key publication with respect to medium-term energy projections.

5. • Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M: **International climate policy architectures: overview of the EMF 22 International Scenarios**. *Energy Econ* 2010, **31(Suppl. 2)**:S64-S81.

This paper discusses the EMF-22 scenarios, a set of scenarios made by different models looking, among others, to ambitious mitigation scenarios.

6. • Edenhofer O, Knopf B, Barker T, Baumstark L, Bellevrat E, Chateau B, Criqui P, Isaac M, Kitous A, Kypreos S *et al.*: **The economics of low stabilization: model comparison of mitigation strategies and costs**. *Energy J* 2010, **31**:11-48.

Model comparison study exploring ambitious mitigation scenarios.

7. •• Krey V, Clarke L: **Role of renewable energy in climate mitigation: a synthesis of recent scenarios**. *Climate Policy* 2011, **11**:1-28.

This paper assesses the role of renewables in the scenarios created by integrated assessment models.

8. Jacobson MZ, Delucchi MA: **Providing all global energy with wind, water, and solar power. Part I: technologies, energy resources, quantities and areas of infrastructure and materials**. *Energy Policy* 2011, **39**:1154-1169.

9. Graus W, Blomen E, Worrell E: **Global energy efficiency improvement in the long term: a demand- and supply-side perspective**. *Energy Efficiency* 2010 doi: 10.1007/s12053-010-9097-z.

10. Teske S, Pregger T, Simon S, Naegler T, Graus W, Lins C: **Energy [R]evolution 2010—a sustainable world energy outlook**. *Energy Efficiency* 2010 doi: 10.1007/s12053-010-9098-y.

11. PWC: *100% Renewable Electricity: A Roadmap to 2050 for Europe and North Africa*. London: Price-Waterhouse-Coopers; 2010 http://www.pwcwebcast.co.uk/dpliv_mu/100_percent_renewable_electricity.pdf.

12. Parsons-Brinckerhoff: *Powering the Future: Mapping our Low-Carbon Path to 2050*. 2009 http://www.pbpoweringthefuture.com/pdf/pb_ptf_summary_report.pdf.

13. Grübler A, Jefferson M, McDonald A, Messner S, Nakicenovic N, Rogner H-H, Schrattenholzer L: *Global Energy Perspectives to 2050 and Beyond*. World Energy Council (WEC)/International Institute for Applied Systems Analysis (IIASA); 1995.

14. • Fisher B, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, Hourcade J-C, Jiang K, Kainuma M, La Rovere E, Matysek A *et al.*: **Issues related to mitigation in the long-term context**. In *Climate Change 2007. Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Metz B, Davidson O, Bosch P, Dave R, Meyer L. Cambridge University Press; 2007:169-250.

Relevant chapter from IPCC's 4th Assessment Report.

15. Van Vuuren DP, Riahi K, Moss R, Thomson A, Nakićenović N, Edmonds J, Kram T, Berkhout F, Swart R, Janetos A *et al.*: **A proposal for a new scenario framework to support research and assessment in different climate research communities**. *Global Environ Change* 2012, **22**:21-35.

16. Patzek TW, Croft GD: **A global coal production forecast with multi-Hubbert cycle analysis**. *Energy* 2010, **35**:3109-3122.

17. Farrell AE, Brandt AR: **Risks of the oil transition**. *Environ Res Lett* 2006, **1**: doi: 10.1088/1748-9326/1081/1081/014004.

18. • Modi V, McDade S, Lallement D, Saghir J: *Energy and the Millennium Development Goals*. New York: Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project, and World Bank; 2006.

Comprehensive study on energy access related issues.

19. •• Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, Klimont Z, Krey V, McCollum D, Pachauri S, Rao S *et al.*: **Energy pathways for sustainable development**. *The Global Energy Assessment: Toward a More Sustainable Future*. GEA: Cambridge University Press, Cambridge, UK and IIASA, Laxenburg; 2012.

The scenario chapter of the Global Energy Assessment provides a comprehensive analysis of the energy systems transformation toward sustainability objectives.

20. Van Ruijven B, Schers J, Van Vuuren DP: **A global model for rural electrification in developing countries**. *Energy* 2012 doi: 10.1016/j.energy.2011.11.037.

21. Venkataraman V, Sagar AD, Habib G, Lam N, Smith KR: **The Indian National Initiative for Advanced Biomass Cookstoves: The benefits of clean combustion**. *Energy for Sustainable Development* 2010, **14**:63-72.

22. Bailis R, Ezzati M, Kammen DM: **Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa**. *Science* 2005, **308**:98-103.

23. • Smith K, Balakrishnan K, Butler CD, Chafe Z, Fairlie I, Kinney P, Kjellstrom T, Mauzerall DL, McKone T, McMichael A *et al.*: **Energy and health**. *The Global Energy Assessment: Toward a More Sustainable Future*. GEA: Cambridge University Press, Cambridge, UK and IIASA, Laxenburg; 2012.

Chapter in the Global Energy Assessment addressing energy-related health impacts.

24. IPCC: **Climate change 2007. Mitigation of climate change**. In *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Metz B, Davidson O, Bosch P, Dave R, Meyer L. New York: Cambridge University Press; 2007.

25. Van Vuuren DP, Meinshausen M, Plattner GK, Joos F, Strassmann KM, Smith SJ, Wigley TML, Raper SCB, Riahi K, De La Chesnaye F *et al.*: **Temperature increase of 21st century mitigation scenarios**. *Proc Natl Acad Sci U S A* 2008, **105**:15258-15262.

26. IPCC: **Climate change 2007. The physical science basis**. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Solomon S, Chin D, Manning M, Marquis M, Averyt K, Tignor MMB, Le Roy Miller Jr H, Chen Z. New York: Cambridge University Press; 2007

27. Smith JB, Schneider SH, Oppenheimerd M, Yohee GW, Haref W, Mastrandreac MD, Patwardhang A, Burtonh I, Corfee-Morloti J, Magadzaj CHD *et al.*: **Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) reasons for concern**. *Proc Natl Acad Sci U S A* 2009, **106**:4133-4137.

28. IPCC: *Climate Change 2007 — Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; 2007.

29. Meinshausen M, Hare B, Wigley TML, Van Vuuren D, Den Elzen MGJ, Swart R: **Multi-gas emissions pathways to meet climate targets**. *Climatic Change* 2006, **75**:151-194.

30. • Rogelj J, Hare W, Lowe J, van Vuuren DP, Riahi K, Matthews B, Hanaoka T, Jiang K, Meinshausen M: **Emission pathways consistent with a 2°C global temperature limit**. *Nat Climate Change* 2011 doi: 10.1038/nclimate1258.

Article looks into short-term emissions by 2020 consistent with a long-term objective of 2°C.

31. Van Vuuren DP, Den Elzen MGJ, Lucas PL, Eickhout B, Strengers BJ, Van Ruijven B, Wonink S, Van Houdt R: **Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs**. *Climatic Change* 2007, **81**:119-159.

32. Riahi K, Grübler A, Nakicenovic N: **Scenarios of long-term socio-economic and environmental development under climate stabilization**. *Technol Forecast Social Change* 2007, **74**:887-935.

33. Van Vuuren DP, Riahi K: **The relationship between short-term emissions and long-term concentration targets**. *Climatic Change* 2011, **104**:793-801.

34. •• PBL: *Growing Within Limits*. Bilthoven: Netherlands Environmental Assessment Agency; 2009.

Report discussing the integrated analysis of transition towards more sustainable energy and land-use systems; looking at both possibilities and the effort levels that would be involved making these transitions.

35. Smith KR: **In praise of petroleum?** *Science* 2002, **298**:1847.

36. Van Ruijven BJ, Van Vuuren DP, de Vries HJM, Isaac M, van der Sluijs JP, Lucas PL, Balachandra P: **Model projections for household energy use in India**. *Energy Policy* 2011, **39**:7747-7761.

37. IPCC: *Special Report on Renewable Energy Sources and Climate Change Mitigation*. 2011.

38. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Hsiang T: **Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change**. *Science* 2008, **319**:1238-1240.

39. Azar C: **Emerging scarcities — bioenergy-food competition in a carbon constrained world**. In *Scarcity and Growth in the New Millennium.* Edited by Simpson D, Toman M, Ayres R. John Hopkins University Press; 2005.

40. Bringezu S, Schütz H, O'Brien M, Kauppi L, Howarth RW, McNeely J: *Assessing Biofuels*. France: UNEP — International Panel for Sustainable Resource Management; 2009.

41. Van Vuuren DP, Bellevrat E, Kitous A, Isaac M: **Bio-energy use and low stabilization scenarios**. *Energy J* 2010, **31**:193-222.

42. Smeets EMW, Bouwman LF, Stehfest E, van Vuuren DP, Posthuma A: **Contribution of N_2O to the greenhouse gas balance of first-generation biofuels**. *Global Change Biol* 2009, **15**:1-23.

43. Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H: **Indicators for energy security**. *Energy Policy* 2009, **37**:2166-2181.

44. IEA: *Global Gaps in Clean Energy R&D*. Paris: IEA; 2011.

45. Grubler A, Aguayo F, Gallagher K, Jiang K, Mytelka L, Neij L,
• Nemet GF, Wilson C: **Policies for the energy technology innovation system**. *The Global Energy Assessment: Toward a More Sustainable Future*. Cambridge University Press, Cambridge, UK and IIASA, Laxenburg; 2012.
Chapter in the Global Energy Assessment addressing innovation strategies.

46. Rockström J, Steffen W, Noone K, Persson Ã, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ *et al.*: **A safe operating space for humanity**. *Nature* 2009, **461**:472-475.

47. AGECC: *Energy for a Sustainable Future. Summary Report and*
•• *Recommendations*. New York: The Secretary-General's Advisory Group on Energy and Climate Change; 2010.
The report provides a vision on sustainable energy systems written on behalf of the UN's Secretary General.

48. WHO: *Air Quality Guidelines: Global Update for 2005*. Copenhagen, Denmark: WHO Regional Office for Europe; 2005 http://www.euro.who.int/Document/E87950.pdf.

49. European Commission: *Limiting Global Climate Change to 2 degrees Celsius: The Way Ahead for 2020 and Beyond*. Brussels: Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions; 2007:. p. 13, Communication from the Commission to the Council tEP, the European Economic and Social Committee and the Committee of the Regions (Series Editor).

50. United Nations Conference of the Parties: *Copenhagen Accord FCCC/CP/2009/L.7. Conference of the Parties*; *Copenhagen: 2009:5*.

51. Hajer M: *The Energetic Society. In Search of a Governance*
• *Philosophy for a Clean Economy*. Bilthoven: PBL Netherlands Environmental Assessment Agency; 2011.
Vision on the role of governments in transitions towards sustainable development in the current society.

52. Nemet GF, Holloway H, Meier P: **Implications of incorporating air-quality co-benefits into climate change policymaking**. *Environ Res Lett* 2010, **5**: doi: 10.1088/1748-9326/1085/1081/014007.

53. Van Harmelen T, Bakker J, de Vries B, van Vuuren DP, den Elzen MGJ, Mayerhofen P: **An analysis of the costs and benefits of joint policies to mitigate climate change and regional air pollution in Europe**. *Environ Sci Policy* 2002, **5**:349-365.

54. Lutz W, Samir KC: **Global human capital: integrating education and population**. *Science* 2011, **333**:587.

55. Hoff H: *Understanding the Nexus: Background Paper for the Bonn2011 Nexus Conference*. Stockholm, Sweden: Stockholm Environment Institute; 2011.

56. UNEP, WMO: *Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers*. Nairobi: United Nations Environment Programme; 2011.

57. Rao S, Riahi K, Stehfest E, van Vuuren D, Cheolhung C, den Elzen M, Isaac M, van Vliet J: *IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels*. Laxenbourg: IIASA; 2008.

58. Jacobson MZ: **Review of solutions to global warming, air pollution, and energy security**. *Energy Environ Sci* 2009, **2**:148-173.

59. Hoogwijk M, van Vuuren D, de Vries B, Turkenburg W: **Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy**. *Energy* 2007, **32**:1381-1402.

60. de Vries HJM, Hoogwijk M, van Vuuren DP: **The potential supply of renewable energy: wind, solar and bio-energy**. *Energy Policy* 2007, **35**:2590-2610.

61. Kramer GJ, Haigh M: **No quick switch to low-carbon energy**. *Nature* 2009, **462**:568-569.

62. IEA: *World Energy Outlook 2009*. Paris: IEA; 2009.

63. WBGU: *World in Transition — A Social Contract for Sustainability.*
•• *Flagship Report*. Berlin: German Advisory Council on Global Change (WBGU); 2011.
Report discussing the need and possibilities for society to make a transition towards sustainable development based on social contract.

64. Bazilian M, Welsch M, Divan D, Elzinga D, Strbac G, Howells M, Jones L, Keane A, Gielen D, Balijepalli VSKM *et al.*: *Smart and Just Grids: Opportunities for Sub-Saharan Africa*. London: The Energy Futures Lab, Imperial College; 2011.

65. Grubler A, Riahi K: **Do governments have the right mix in their energy R&D portfolios?** *Carbon Manage* 2010, **1**:79-87.

66. McCollum DL, Krey V, Riahi K: **An integrated approach to energy**
•• **sustainability**. *Nature Climate Change* 2011, **1**:428-429 doi: 10.1038/nclimate1297.
Analysis of the benefits of integrated strategies in the energy system.

67. Nilsson M, Eckerberg K: *Environmental Policy Integration in Practice: Shaping Institutions for Learning*. London: EarthScan; 2006.

68. MCKinsey Global Institute: *Urban World: Mapping the Economic Power of Cities*. 2011.

69. UN: *World Population Prospects: The 2008 Revision*. New York: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat; 2008.

70. Nilsson M, Nilsson LJ, Hildingsson R, Stripple J, Eikeland PO: **The**
• **missing link: bringing institutions and politics into energy future studies**. *Futures* 2011, **43**:1117-1128.
Paper discussing the relationship between institutional changes and the energy transitions as described by integrated assessment models.

71. Azar C, Sandén BA: **The elusive quest for technology-neutral policies**. *Environ Innovat Societal Transitions* 2011, **1**:135-139.

72. IEA: *Deploying Renewables — Best and Future Policy Practice*. Paris, France: International Energy Agency; 2011.

73. Loorbach D: **Transition management for sustainable development: a prescriptive, complexity-based governance framework**. *Governance* 2010, **23**:161-183.

74. Pachauri S, Brew-Hammond A, Barnes DF, Bouille DH, Gitonga S,
•• Modi V, Prasad G, Rath A, Zerriffi H: **Energy access for development**. *The Global Energy Assessment: Toward a More Sustainable Future*. GEA: IIASA, Laxenburg, Austria and Cambridge University Press, Cambridge UK; 2012.
This chapter within the Global Energy Assessment addresses the issue of access to energy.

75. Nakicenovic N, Swart R (Eds): *Special Report on Emissions Scenarios (SRES)*. Cambridge, UK: Cambridge University Press; 2000.

76. van Vuuren DP, Bouwman AF, Smith SJ, Dentener F: **Global projections for anthropogenic reactive nitrogen emissions to the atmosphere, an assessment of scenarios in the scientific literature**. *Curr Opin Environ Sustain* 2011.