On the Sustainability of Renewable Energy Sources

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Abstract

This article examines renewable energy (RE) technologies in a multiple-objective framework of sustainable development. We begin by locating RE in a portfolio of options available for climate change mitigation. Observing current trends in technologies, deployment levels, and costs, we discuss the future deployment levels envisioned in mitigation scenarios. We focus on biomass, given its importance in climate mitigation scenarios and because of the ongoing debates about its role in sustainability objectives. We also examine trends and successes in RE support policies. We conclude by linking the multiple objectives of sustainability to multiple policy instruments, emphasizing the need to closely consider the interaction between different policy instruments incentivizing sustainable development.

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1. SETTING THE SCENE

CO_2: carbon dioxide

Until now, attempts to decouple economic growth from rising greenhouse gas (GHG) emissions have been largely unsuccessful. Global emissions are continuing to rise unabated. It is becoming increasingly clear that, over the long term, the limiting factor of global energy supply is not that humankind is running out of fossil fuels but rather that the atmosphere has a limited ability to absorb additional GHGs. Mitigating climate change to a manageable level requires a transformation pathway toward huge reductions in GHG emissions (for an overview, see Reference 1).

Figure 1 depicts the available solutions for mitigating climate change. This figure shows the role of renewable energy (RE) technologies [as a carbon dioxide (CO_2) mitigation option to reduce carbon intensity through non–fossil fuel energy] within a broader portfolio of mitigation options. Note that it includes not only technologies in a narrow sense but also the provision of low-carbon infrastructures and associated behavioral changes as they affect energy or carbon intensity. This review is limited to a discussion of RE in its role of reducing carbon intensity and its links to CO_2 removal technologies, for example, when bioenergy is combined with carbon capture and storage. We do not explicitly consider population policies (which are, in effect, investments in education and public health) or sufficiency strategy policies that address lifestyle changes related to consumption. The reason for this omission is twofold. First, these policies are only indirectly linked to the deployment of RE technologies. Second, a coherent discussion of these options would require an in-depth analysis of the ethical, social, and economic problems of these policy options, which is beyond the scope of this review.

This review focuses on the role of RE in decarbonizing the energy supply, which is essential for mitigating climate change—a crucial global goal that contributes to sustainability. We operationalize sustainability by discussing multiple objectives of RE deployment, such as energy security, employment effects, green growth, local environmental improvements, and energy access.

In Section 2 of this review, we discuss sustainable development (SD) in terms of a

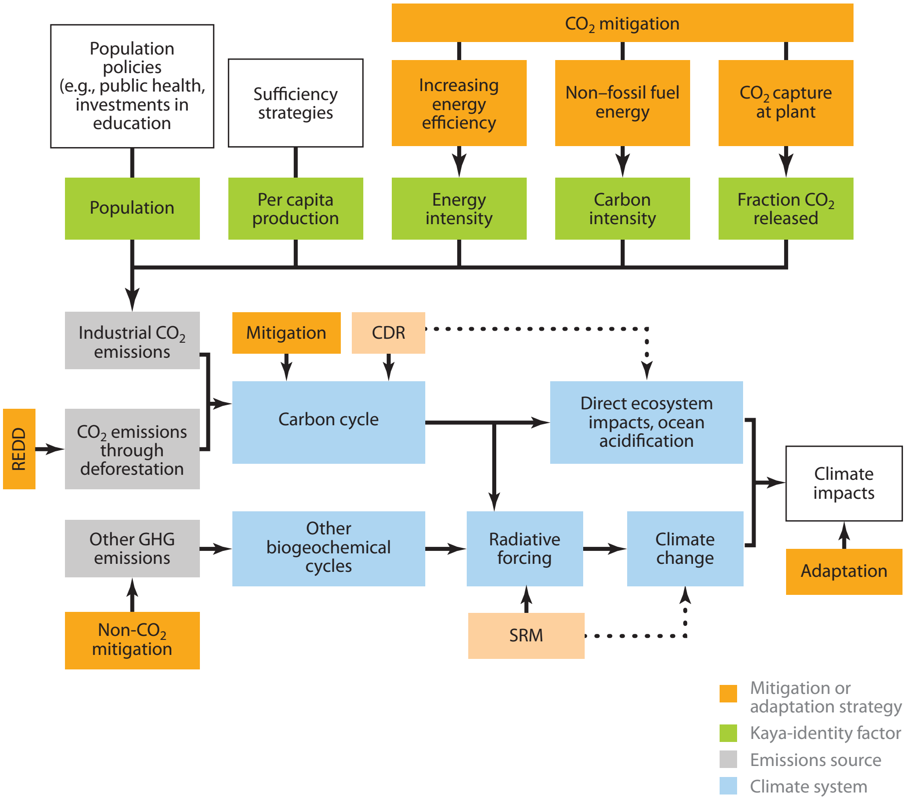


Figure 1

Technology-focused solution space relative to mitigation of and adaptation to climate change. Abbreviations: CDR, CO_2 removal technologies; REDD, reducing emissions from deforestation and degradation; SRM, solar radiation management technologies. Adapted from Reference 2.

multiple-objective framework and relate RE technologies to each objective. In Section 3, to link this discussion to the current status of and the future projections for RE technologies, we discuss current trends. Given the importance of biomass in climate mitigation scenarios and because of the ongoing debates of its role in sustainability objectives, we highlight bioenergy in Section 4. Section 5 links the trends discussed in Sections 3 and 4 to policies that have been implemented in support of RE technologies. We conclude this review by linking the multiple objectives of sustainability to multiple policy instruments, emphasizing the need to closely consider the interaction between policy instruments.

2. RENEWABLES AND SUSTAINABLE DEVELOPMENT: CONCEPTS AND NARRATIVES

The prioritization of the aforementioned objectives that are relevant for the deployment of RE technologies is not well defined in the literature and cannot be defined by scientists alone. In Section 2.1 we argue that the potential synergies and trade-offs between these social objectives must be embedded in a public discourse that is informed by science but not determined by it. In Section 2.2 we discuss the different objectives and identify potential inconsistencies and links among them. In Section 2.3 we discuss market and government failures that provide justification for RE polices.

Energy security: the goal of maintaining an uninterrupted provision of vital energy services; also entails the avoidance of sudden disruptions of energy supply

Sustainable development (SD): a process of change that integrates political, social, economic, and environmental dimensions that together ensure that the current and future potential to meet human needs and aspirations is uncompromised

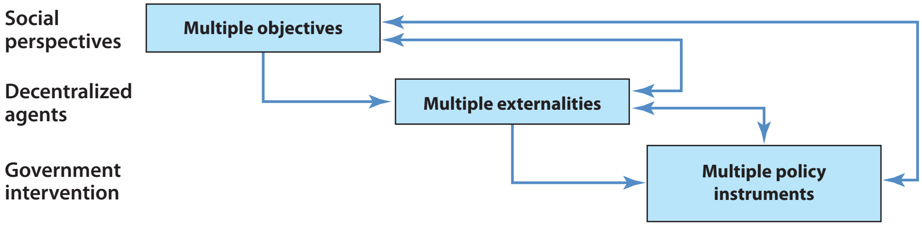


Figure 2

A public policy framework has three levels. From a social perspective, multiple objectives can lead to multiple externalities when decentralized agents lack incentives to achieve these goals. These market and/or government failures require an institutional response. In the public policy cycle, adverse side effects can lead to a reconsideration of objectives, externalities, and instruments.

2.1. The Public Policy Framework

It is not the role of scientists to prescribe social objectives to the public. Scientists can facilitate a public discourse about particular objectives by exploring (*a*) the underlying synergies and trade-offs among social goals (multiple objectives), (*b*) the externalities that justify political support (multiple externalities), and (*c*) the potential instruments and strategies that cure the market and government failures to achieve these objectives (multiple policy instruments). Scientists can critically reflect on both social objectives and instruments in light of all the related practical consequences of the instruments (2, 3). Such a critical inquiry might reveal positive or adverse side effects of some instruments with respect to individual objectives because of uncertainties or incomplete knowledge of the underlying system. Scientists have long known that the appropriate way to deal with complex coupled socioeconomic and environmental dynamics requires (*a*) the constant reconsideration of boundaries of analysis (4) and (*b*) a public discourse on underlying value conflicts and the applied evaluation methods (5). Critical inquiry may result in substantial revision to or abandonment of social objectives. Consequently, social objectives and instruments are interdependent and cannot be evaluated separately. However, there is an additional layer that must be taken into account for a reasonable assessment: the behavior of the agents responding to policy instruments. **Figure 2** summarizes the three levels of a public policy framework.

Green growth: economic growth that is in line with SD objectives

Renewable energy (RE) source: any form of energy from solar, geophysical, or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use (10)

Land-use change (LUC): the transformation of land from one use to another. In the context of RE, direct LUC may be directly attributable to land management decisions; indirect land use change (ILUC) cannot be directly attributed to land management decisions

To illustrate the necessity of iteration within this framework, we consider the example of a limit of global temperature increase of 2°C as a climate policy objective. Scenarios show that a substantial amount of bioenergy would be required to achieve this objective (Section 3.4). The extensive use of biomass may help realize very low stabilization levels (depending on contested assumptions), but the side effects of extensive use of biomass must be taken into account, particularly in light of possible adverse effects on food production prices, deforestation, loss of biodiversity, and land-use change (LUC) (6; see Sections 4.1 and 4.2, below). A risk analysis of this pathway might lead to a revision of the social objectives and/or the applied policy instruments. One might also argue that if land-use policy instruments and institutions are available, even high deployment rates of bioenergy can be managed according to SD. Thus, the interaction between different instruments and their effects on different objectives should be explored in an assessment process to identify sustainable mitigation pathways. It is essential that the iteration between social objectives, market or government failures, and policy instruments be organized as a social-learning process in which scientists and stakeholders are continuously involved.

2.2. Multiple Objectives and Cobenefits of Sustainable Development

Climate change mitigation is one (but not the only) critical argument in favor of policy interventions intended to foster and develop RE technologies. Greater energy security, green jobs, green growth, reduced local environmental damage, and reduced poverty are prominent examples of positive side effects that justify RE policies and are often referred to as cobenefits. However, accounting for cobenefits needs to be carefully considered. Positive side effects do not automatically reduce the costs of mitigation. There is no agreement in the literature on the specific definitions surrounding cobenefits. For the purposes of this review, we use the following. We refer to physical positive side effects as cobenefits (e.g., the physical reduction of particulate emissions that may occur as a result of a climate policy). This reduction is complementary to the direct effect of a climate policy. Social benefits refer to the welfare evaluation of the direct effect together with all positive and negative side effects, including the cost of the policy. However, this positive side effect would not reduce the overall policy costs of mitigation if local air pollution were already regulated in a socially optimal way through an appropriate policy instrument. In other words, if all the externalities caused by local air pollution were addressed properly, climate policy would increase society's welfare only because of the reduction of CO_2. Social benefits (as welfare-enhancing positive side effects) can occur in a so-called second-best setting when some externalities are not optimally addressed. Consider the case in which cobenefits influence the selection of policies: In this case, a specific climate policy with costs A and a specific air pollution policy with costs B. An alternative policy of costs C leads to both climate change mitigation and better air quality, but $C > A$ and $C > B$. Therefore, C is not pursued, because it has only climate change or air pollution as a point of reference. In both cases, the point of reference describes a second-best setting because the optimal air pollution policy and the mitigation policy are not taken into account simultaneously. However, if $C < A + B$, then pursuing C would produce a cost saving of $A + B - C$. Thus, taking into account all relevant objectives and all relevant policy instruments—that is, opening up the boundaries of analysis to considering multiple objectives—can be very useful. The discussion of specific co-objectives in the remainder of this section is based on Reference 7.

Energy security refers broadly to the uninterrupted provision of vital energy services (8) or robustness against sudden disruptions of energy supply (9). In maintaining an adequate energy supply, energy security may encompass safeguarding access to energy resources and ensuring enforceable contracts of delivery, as well as affordable prices for specific groups in a society (10). It may be measured by reduced global interdependence via reduced import/export balances or increased diversity and resilience of the energy supply (as in Reference 8). Many studies argue that RE technologies help facilitate countries' energy security goals because of their local or regional availability. Renewables therefore reduce vulnerability to supply disruption and market volatility by increasing the diversification of energy sources (11). The different facets of energy security are prioritized differently across countries. Industrialized countries may, for example, consider imported fossil fuels, particularly oil, to be a key challenge. In such cases, for countries such as the United States that have more substantial domestic supplies of fossil fuels (particularly coal and gas), the contribution of RE to the electricity sector may therefore be perceived as less of an aid to energy security (7). Sometimes an increasing share of variable and unpredictable renewables in the electricity sector is perceived as an energy security issue. However, dealing with variable RE sources is not an objective in itself but rather a way to manage the integration of RE sources in an energy system that is dominated by fossil fuels (7; see Section 3.3.5).

Positive employment effects of RE technologies are also often used to justify support for the technologies as part of stimulus packages or other political support (7, 9, 12). Some economists expect the employment effects related to RE technologies to be quite favorable over the long term, largely due to their impact on the domestic economy. However,

PV: photovoltaic

employment effects related to the deployment of RE technologies may be more global in nature. An example is the photovoltaic (PV) installations in the United States and Germany, which are based partly on panel imports from China (12). Some economists argue that RE systems are more labor intensive than conventional energy systems and are therefore favorable in terms of generating employment (13). However, from a welfare-economics point of view, the deployment of renewables should be determined by (*a*) their short-term social returns on investments when they are evaluated as part of fiscal packages stabilizing economies or (*b*) their long-term social returns when their sustainable deployment level is calculated. Such short-term welfare comparisons are not typically included in the literature discussing employment effects.

With regard to reduction of local environmental damage, by displacing fossil fuels RE technologies can reduce negative environmental effects of both fossil-fuel extraction and the combustion of fossil fuels. The former includes damage from mountaintop mining, coal mining, and tar sands extraction. The latter includes local air pollution problems such as the release of particulate matter, nitrous oxide, sulfur dioxide, and nonmethane volatile organic compounds that are associated with negative health effects (9). Additional environmental benefits of RE technologies are discussed in Section 3.5, below.

Mostly because it combines economic growth and environmental benefits, green growth is a popular framework in which RE technologies are key. A recent UN Environment Programme (UNEP) report (14) describes green growth as a win-win strategy because it relates to other social objectives such as well-being, job creation, and tax revenues. As mentioned above, scientists have argued that renewables are tied to employment benefits and therefore to long-term GDP growth, as well as to a reduction in environmental damages such as GHG emissions. However, as described below in Section 5.3.1, in terms of decreasing emissions, there is a risk of adverse consequences if policies to support the development and deployment of RE technologies are viewed as an alternative, rather than a complement, to carbon pricing. Without carbon pricing, emissions may not decrease and may even increase when renewables are subsidized as the result of carbon leakage (7, 15).

With regard to poverty reduction and energy access, the often decentralized nature of RE technologies, together with their local and cost-independent sources, make them well suited to and (often) more competitive for remote and poor rural areas lacking centralized energy access (9). The *Special Report on Renewable Energy Sources and Climate Change Mitigation* by the Intergovernmental Panel on Climate Change (IPCC) (11, p. 18) observed that "renewable energies can help to accelerate access to energy, particularly for the 1.4 billion people without access to electricity and the additional 1.3 billion using traditional biomass." The use of RE technologies in such contexts is also linked with a shift to more modern energy technologies, which tend to be more environmentally benign and have fewer negative health impacts (16). This description is particularly apt for the replacement of traditional biomass fuels often used for cooking purposes in poor areas (9). The UN Secretary General's Advisory Group on Energy and Climate Change (AGECC) (17) has described increments in energy access that may be served by REs: (*a*) basic human needs such as electricity and modern fuels for cooking and heating; (*b*) the use of electricity and modern fuels to aid productivity in agriculture and transport; and (*c*) modern societal needs for domestic appliances, private transportation, and space heating and cooling.

In a recent study, McCollum et al. (18), by linking an integrated assessment model with an air quality model, explored the impact of multiple objectives on mitigation costs and mitigation strategies. They showed that with the application of more stringent climate policies, synergies among other policy objectives such as energy security, reduced air pollution, and improved health ultimately lead to lower policy costs. The synergies related to the fulfillment of all three policy goals also require a substantial investment in low-carbon technologies in the energy supply, for which RE is key. As this study quantitatively showed, climate policies can affect nonclimate societal objectives, resulting in synergies or trade-offs. McCollum et al. implicitly assumed that local air pollution is not regulated optimally and therefore that air quality improvements have welfare-enhancing effects. Specifically, McCollum et al. (18) calculated the policy costs of achieving different social objectives. For this purpose different constraints are imposed on an optimization model. If local air pollution is regulated at the current level and a climate mitigation target is imposed on the model, then climate mitigation also reduces local air pollution. In such a scenario the additional policy costs of the local air pollution constraint are lower than in a situation in which local air pollution has to be achieved without climate policy. More generally, from a welfare-theoretic point of view, for two social objectives Q_1 and Q_2 we obtain the following formula: $W(Q_1{}^{*}, Q_2{}^{*}) - W(0,0) > W(Q_1{}^{**},0) - W(0,0) + W(0,Q_2{}^{**}) - W(0,0)$. The welfare level for the jointly optimally achieved objectives (compared with a point of reference defined as the zero scenario) is higher than the welfare level for a scenario in which both objectives are achieved separately in the sense that each objective is achieved optimally (at the levels $Q_1{}^{**}$ and $Q2^{**}$, respectively), given that the other objective is fixed to its point of reference. The point of reference refers to a counterfactual baseline scenario.

To summarize, the synergies and trade-offs between social objectives have welfare implications only when market or government failures exist and are not fully addressed by policy instruments and/or when synergetic policy instruments are cheaper than the piecemeal achievement of social objectives. The welfare implications of social objectives can be evaluated only if a clear understanding of externalities is achieved. In the next section we discuss externalities regarding the deployment of renewables.

2.3. Externalities and the Justification for Policy

Two fundamental market failures that are mainly discussed in the economic literature justify political support for RE technologies: (*a*) externalities related to the GHGs emitted during the combustion of fossil fuels and (*b*) technological externalities related to the innovation and diffusion of technologies (19). Climate externalities occur because the environmental effects of releasing CO_2 emitted from burning fossil fuels are not inherently captured in the price of fossil fuels. Technological externalities occur because there are insufficient incentives for private agents to invest in the invention, innovation, and diffusion of technologies. The discussion in the remainder of this section is based on Reference 7.

R&D: research and development

Invention and innovation–phase failures refer to an underinvestment in basic research and development (R&D) that arises when the rewards of an innovation benefit society above and beyond the individual responsible for the innovation. This problem is more generally applicable to markets; that is, it is not restricted to energy and RE technologies. As a solution to this market failure, many economists recommend patents, which are viewed as more technologically and sector-neutral policies. If there are good reasons to assume that patents are insufficient incentives (7), then one may use other, complementary policy instruments such as subsidies for basic R&D investment. In contrast, the applied energy research perspective argues that R&D in energy has decreased substantially since the 1970s and that R&D is likely to produce huge social returns (20). The construction of power plants and grids may have transformed the utility sector into a rent-seeking economy that became less and less interested in innovation. Further research is needed to investigate this hypothesis.

Diffusion and adoption–phase market failures relate to the influence on cost of the status of technology and infrastructure (19). For example, the costs of a new technology may depend on how many other users have adopted it. These so-called dynamic increasing returns may be caused by learning-by-using, learning-by-doing, or network externalities (19). In an ideal setting, prices would provide an incentive for investments in new technologies. Stiglitz (21) argues that the price system cannot provide this incentive in the absence of future markets. The lifetime of energy infrastructure is typically on the order of 20 to 30 years, whereas future trading of electricity rarely spans more than a few years. Thus, policy support is justified to create a long-term market environment that can trigger investments beyond the scale of the short-term electricity market.

Technological lock-in effects can provide an additional justification for policy support of RE technologies. A recent study (15) shows that technological market failures (as mentioned above) may have a greatly exaggerated effect because they may lock in a potentially inferior technology over a period of decades. Electricity markets are more prone to these effects than are other markets, given that electricity generated from different technologies is almost perfectly substitutable. Moreover, if there is uncertainty about the stringency of climate change mitigation policies or technology policies to support REs, investment risks may increase, thereby also contributing to the lock-in effect.

When the market share of renewables in electricity markets is increased, the short-term marginal cost pricing may be zero. Therefore, there is a risk that RE sources would not recover their capital costs and would not attract sufficient investment flows from private capital markets. In addition to this effect, a higher share of RE technologies may reduce overall capacities. In an ideal market, this reduction of capacities would increase the scarcity of rents and would therefore ensure an optimal long-term equilibrium. However, some authors doubt that electricity markets are operating close to ideal market conditions, which can lead to an undersupply of capacities. These market failures, already present in electricity markets without a high share of renewables, would be substantially exacerbated when the share of variable RE sources increases. For a detailed discussion, see Reference 7.

The market failures described here suggest that an optimal deployment of renewables requires at least three fundamental policy packages: carbon pricing, RE support schemes at the innovation and diffusion stages, and appropriate instruments that would cure the potential failure of short-term marginal cost pricing in electricity markets with server distortions (7). How these policy instruments might interact and what outcome can be expected from these interactions are the subject of an ongoing debate between practitioners and scientists. There is a serious risk that ill-designed policy instruments limit the cost-efficient deployment of renewables. Studies that explore multiple externalities in world of multiple policy instruments are, however, rare.

3. CURRENT TRENDS AND FUTURE PROSPECTS OF RENEWABLE ENERGY SOURCES

Sections 1 and 2 explain the multiple objectives of SD and place RE technologies within this framework. With this conceptual framework as a basis, we now turn to RE sources and technologies (Section 3.1) and the potential of those technologies (Section 3.2), then broaden our discussion to technoeconomic considerations (Sections 3.3 and 3.4). Before moving to a more focused discussion on bioenergy (4), we describe several additional social and ecological considerations of noncombustible RE sources (Section 3.5).

3.1. Renewable Energy Sources and Key Technologies

RE sources include solar, geothermal, hydropower, wind, ocean, and biomass. The energy originates from solar, geophysical, or biological sources and is replenishable by natural processes. See the sidebar titled Renewable Energy Sources for a detailed description of the six RE sources.

RENEWABLE ENERGY SOURCES

1. Solar energy comes from the sun (solar irradiance) in the form of heat or light.
2. Geothermal energy refers to thermal energy from the Earth's interior; it is either residual energy made available by the formation of the planet or energy that is continuously generated from radionuclide decay. The energy can be stored in rock, trapped steam, or liquid water (10).
3. Hydropower arises from solar radiation that causes the evaporation of water from the Earth's surface and thereby drives the hydrological cycle. The precipitation that results from the condensation of water vapor provides water at high elevations. The movement of such water from high to low elevations, driven by gravity, is the source of hydropower (22).
4. Wind energy is also driven by the sun. The uneven heating of the Earth's surface causes air currents whose kinetic energy may be harvested.
5. Ocean energy arises from one of four sources: (*a*) the kinetic energy of the wind (creating waves and contributing to the circulation of the oceans); (*b*) the gravitational forces of the Earth, the moon, and the sun (the creation of tides); (*c*) salinity differences between freshwater and salt water in, for example, the mouths of rivers; and (*d*) temperature differences between the solar-heated, upper layer of the ocean and the colder, deeper layers.
6. Biomass is plant or animal matter, excluding that embedded in geological formations (e.g., fossil fuels, peat). Various biomass feedstocks can be used to produce bioenergy and can be differentiated into traditional biomass and modern biomass. Traditional biomass refers to wood, charcoal, animal dung, and agricultural residues used for cooking and heating, often in residential stoves with very low efficiencies (10, 24). Modern biomass feedstocks include dedicated energy crops (e.g., palm oil and oil from rapeseed and soybeans; lignocellulose from switchgrass, *Miscanthus*, or other plants); residues from forestry, agriculture, and livestock; and organic waste streams.

RE technologies are diverse and use different mechanisms to capture the energy provided by the different RE sources. Depending on the source, they may produce electricity, provide thermal or mechanical energy, or be stored in a liquid or gaseous fuel for transport. The maturity of the different technologies ranges substantially from later-stage commercial development (competitive with fossil fuels) to early stages of R&D.

Solar energy may refer to either active technologies or the passive design and construction of buildings that use the sun's heat or light. Active technologies can be used to produce electricity (via PV or concentrating solar power), thermal energy, or fuels that can be employed in transport applications (25). Thermal solar applications are also available in various designs. In each, carrier fluid is circulated (e.g., through panels) and heated by the sun. That heat is then transferred either to a storage tank or to transfer fluid for direct use. Solar technologies, as they apply to fuels for transport, are much less mature than electricity and the thermal energy technologies described above. In general, solar technologies use different thermochemical routes to transfer solar energy into chemical fuels such as hydrogen and syngas.

Geothermal energy can be used to produce (*a*) electricity via deeper, intermediate-temperature (e.g., 100–180°C) or high-temperature (e.g., >180°C) applications and (*b*) thermal energy via shallower, low-temperature (e.g., ≤100°C), direct-use applications. These technologies use wells or other means to extract heat energy from hydrothermal, conductive, or deep aquifer systems. The most common systems for electricity production use steam from production wells to power a generator. Enhanced geothermal systems, more commonly known as hot dry rock, provide an alternative for electricity production from geothermal sources, although

Technical potential: the amount of energy output by full implementation of demonstrated technologies without reference to cost

this technology is at a much earlier stage of development. Direct-use applications include geothermal heat pumps that, with the addition of electricity, circulate heated liquid in either open-loop or closed-loop systems (26).

There are three types of hydropower installations: run-of-river, reservoir, or pumped storage. Run-of-river plants harness the energy of flowing rivers by means of hydraulic turbines. Reservoir plants store water by, for example, a dam. Energy is generated when water is released from the reservoir into a generating station (via tunnels or pipelines) (22). Pumped storage plants do not make use of water from high elevations; instead, they use energy to pump water from a lower-elevation reservoir to a higher-elevation reservoir. Pumping typically takes place during off-peak hours, such that energy can be used during periods of high demand.

Wind energy installations capture the kinetic energy of moving air by means of a turbine, then convert that energy into mechanical energy and ultimately to electricity (27). Wind turbines can be erected either onshore or offshore. Onshore applications include small turbines of a few kilowatts to large turbines of up to 2.5 MW that may stand on towers taller than 125 m. Offshore applications are typically larger than onshore ones. Although there are some minor differences (e.g., in their foundation) between these two turbine technologies, they are largely the same (27).

Ocean energy technologies (with the exception of tidal range) are in early stages of development. Thus, various possible ocean energy–based technologies that harness the different energy sources mentioned in the sidebar are being tested for wider deployment. For example, tidal range plants generate electricity by means of a barrage-enclosed estuary to which a low-head hydroturbine is applied (23).

Through various technologies, biomass feedstocks can be used directly to produce electricity or heat or indirectly to create gaseous, liquid, or solid fuels (11). Conversion routes in commercial stages of development include combustion, transesterification or hydrogenation, fermentation, gasification, pyrolysis, and anaerobic digestion (28). **Figure 3** shows a comprehensive flow of biomass feedstock to energy.

3.2. Resource Potential for Renewable Energy Technologies

The theoretical supply potential of RE sources, which examines only natural and climatic parameters (10), greatly exceeds energy demand (11). The technical potential of REs, which examines the amount of energy output by full implementation of demonstrated technologies without reference to cost (10), also exceeds demand (**Figure 4**), although the exact estimates differ according to the methodologies and set of constraints used to derive technical limits. However, studies consistently find that the global growth of RE technologies will not be limited by their technical potential (16, 29).

For some RE sources, the technical potential exceeds demand by orders of magnitude. Despite this global estimate, some resources may be constrained by limited availability or poor quality in certain regions. Economic or market potentials of RE technologies, which include forecast market conditions or externalities respectively (10), may be considerably lower.

3.3. Current Trends

In this section we provide an overview of past and recent trends in energy supply from RE sources (Section 3.3.1) as well as total investment into new power-generation capacities (Section 3.3.2). We briefly discuss the mutual relationship between past and expected future use and technological changes in the RE sector (Section 3.3.3), then describe the historical development of costs for newly built power-generation equipment, as well as the ultimate costs per unit of energy, and how they affect the dynamics of the sector (Section 3.3.4). Finally, we discuss costs associated with integration (Section 3.3.5).

3.3.1. Past and recent use. The use of RE technologies has been increasing rapidly.

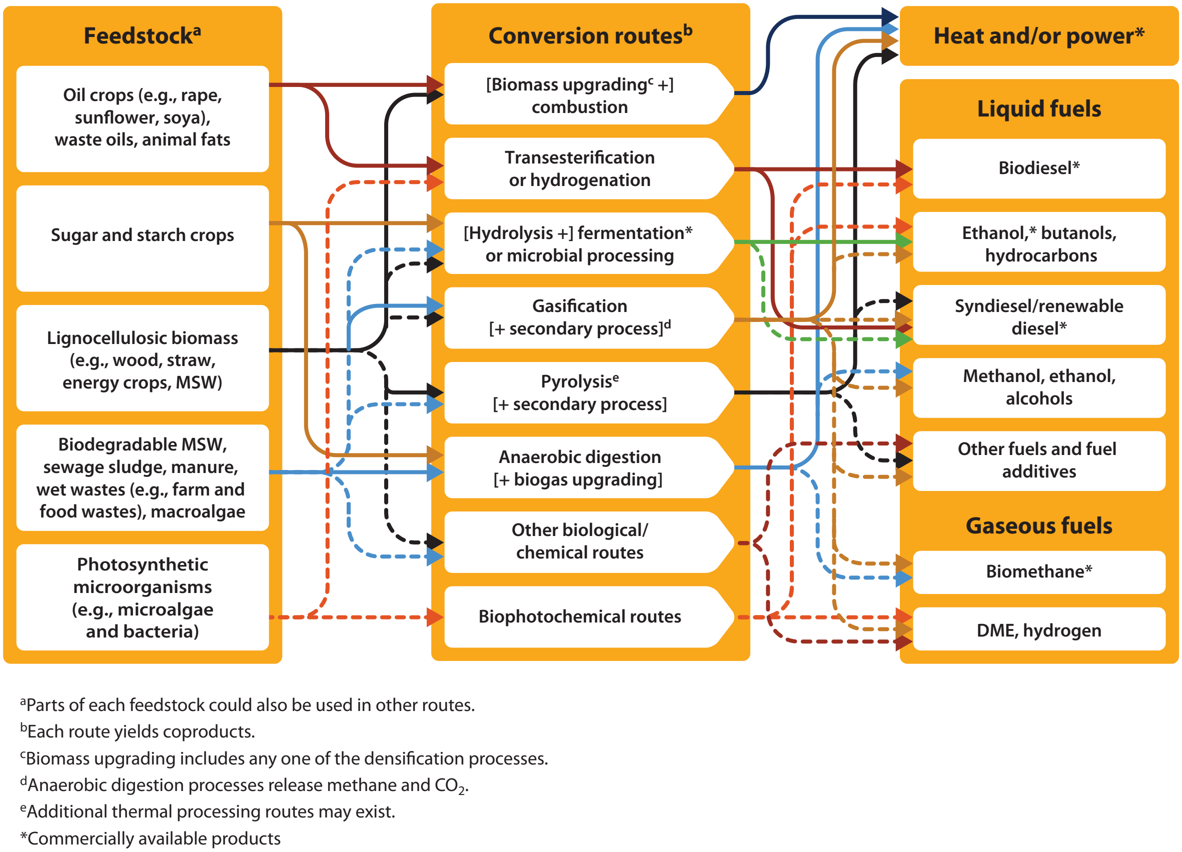


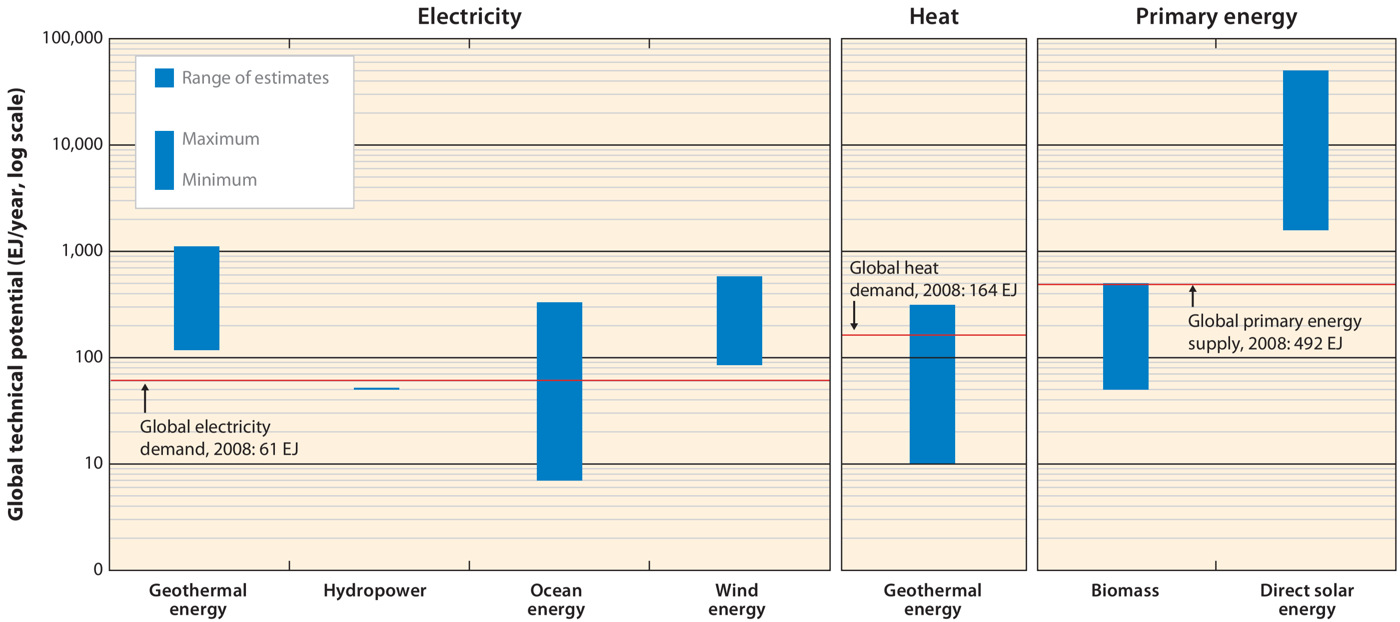
Figure 3

The conversion of biomass feedstocks to bioenergy by commercial (*solid lines*) and developing (*dotted lines*) bioenergy routes. The square brackets enclose optional processes. Abbreviations: DME, dimethyl ether; MSW, municipal solid waste. Modified from Reference 28.

Between 2000 and 2010, global primary energy supply from solar PV increased by an average of 42% each year, 27% for wind power, 18% for biofuels, and 12% for solar thermal heat. Other RE technologies (hydropower, solid biomass, geothermal energy, and municipal solid waste) have increased at a slower pace of 2% to 4% per year on average, whereas ocean energy supply has basically stagnated. **Figure 5** depicts trends in total primary energy supply from RE sources between 1971 and 2010.

3.3.2. Investments in renewable energy technologies. The growth of the primary RE supply is due to significant financial investments into the installation of new RE generation capacity. In 2011, global investments in RE amounted to US$257 billion—more than the US$223 billion invested during the same year in fossil-fueled power plants (32). **Figure 6** shows how global investments have increased continuously since 2004, with only a temporary decline at the time of the financial crisis in 2009.

3.3.3. Technological change. With investments and deployment increasing and reaching significant levels, more and more RE technologies have become technically mature. Several others remain at less mature stages of technical development as well as at lower



Range of estimates of global technical potentials

	Geothermal energy	Hydropower	Ocean energy	Wind energy	Geothermal energy (Heat)	Biomass	Direct solar energy
Max (in EJ/year)	1,109	52	331	580	312	500	49,837
Min (in EJ/year)	118	50	7	85	10	50	1,575

Figure 4

Ranges of global technical potentials of renewable energy (RE) sources. Biomass and solar are shown as primary energy due to their multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being used. Modified from Reference 16.

levels of commercial use, often serving niche markets rather than mass markets. R&D, learning from deployment experience, the use of economies of scale in production, and increased competition between suppliers along the entire value chain of RE supply are among the factors that contribute to improvements of less mature technologies (11).

Technological changes in RE are often measured by proxies such as the prices of key components [for example, the price per watt of turbine capacity in the case of wind power (33)]. Of course, these micromeasures of technological change are only a weak indicator of (the increase in) the RE technologies' social value. They can be affected by several variables, including changes in macroeconomic conditions. Also, the relative contributions of the factors that reduce costs are not always fully understood due to attributional problems (e.g., 11, 34). Nonetheless, historical cost reductions in key components of RE technologies can provide some insight into technical advances.

3.3.4. Past and present private costs of renewable energy generation.

The costs of key components of many RE technologies have declined considerably (**Figure 7**). Despite attributional ambiguities, technological advances are a driver of cost reductions, and continued technical progress is expected to contribute to further decreases in the prices of technologies that have not yet fully matured.

The effect of reductions in the cost of key components on the total cost of production[1] is particularly strong for RE technologies (excluding bioenergy), for which no costs are incurred for purchasing fuels. This effect is counterbalanced to some degree by competition for locations with the best resources. However, as indicated in Section 3.2, from

[1]The costs of production include all costs incurred over the entire productive lifetime of the technology, that is, not only the investment cost, which occurs before production commences and includes the costs of key components, but also operation and maintenance costs as well as decommissioning costs.

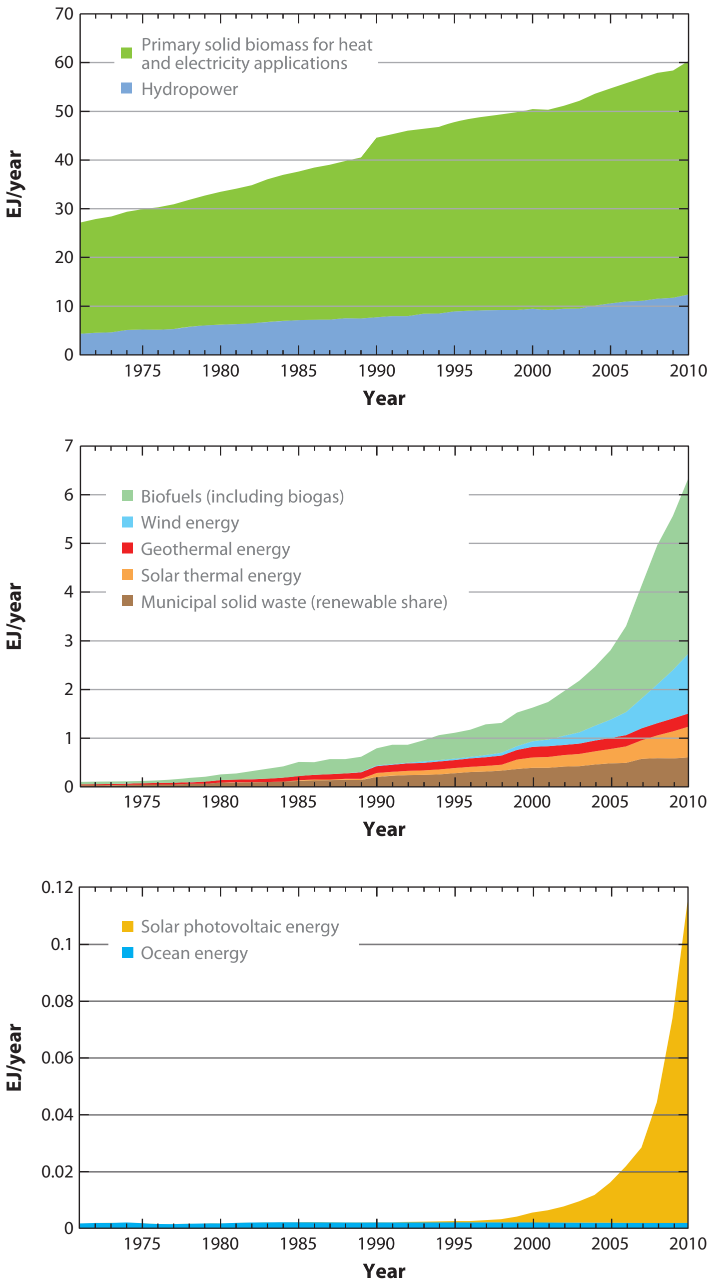


Figure 5

Historical development of global primary energy supply from renewable energy, 1971–2010. Data are from Reference 30. Technologies are referenced to separate vertical units for display purposes only. The underlying data have been converted to the direct equivalent method of accounting for primary energy supply (31), except that the energy content of biofuels is reported in secondary energy terms [the primary biomass used to produce the biofuel would be higher due to conversion losses (28)].

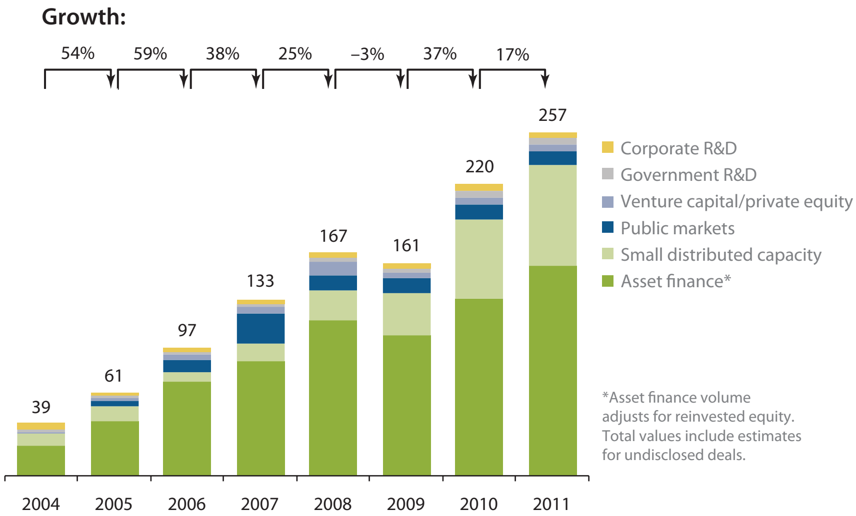


Figure 6

Global new investment in renewable energy generation capacity by asset class, 2004–2011, in billions of US dollars. Abbreviation: R&D, research and development. Modified from Reference 32; data are from Bloomberg New Energy Finance.

a global perspective resource availability is of no concern. On the local scale, however, deterioration of good sites can become an important driver of production cost.

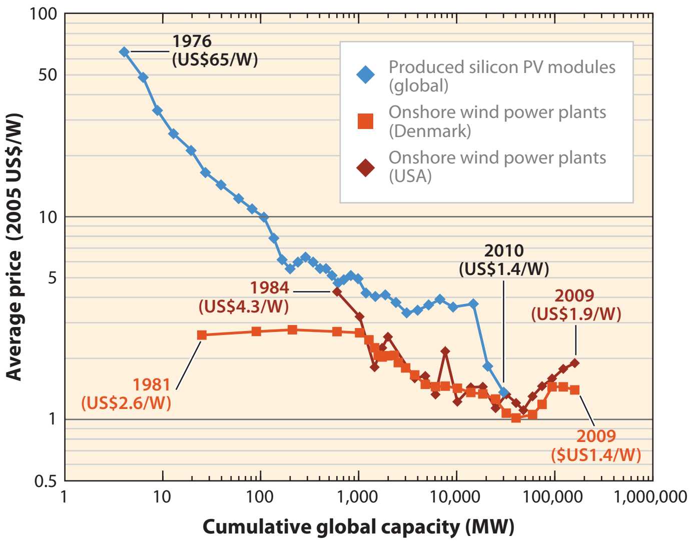


Figure 7

Selected experience curves in logarithmic scale for the price of silicon photovoltaic (PV) modules and onshore wind power plants per unit of capacity (11).

The levelized cost of energy (LCOE) is a measure of the life-cycle cost of energy production. Around 2009, the LCOE was higher for many RE technologies built at typical sites than for existing energy prices, although a comparison between RE costs with those of non-RE supply shows considerable overlap (**Figure 8**). A comparison between LCOEs and unweighted average energy prices can provide only an approximate first-order indication of the competitiveness of energy supply technologies and, in particular, of power supply technologies (7, 35). Acknowledging this fact, the IPCC (11, p. 9) nonetheless concludes that "in various settings RE is already economically competitive."

Since 2009, the costs of some technologies have declined substantially. The investment cost of rooftop-mounted PV systems (up to 10 kW_p) in Germany, for instance, decreased by an average of more than 50% between the first quarter of 2009 and the first quarter of 2013 (see **http://www.solarwirtschaft.de/preisindex**). However, other RE technologies have witnessed at least temporary production cost increases, such as offshore wind power between the first quarters of 2011 and 2012 (35).

The relative competitiveness of RE technologies would improve if the external costs (which include, for instance, an appropriate price on GHG emissions and other local pollutants) of energy supply were fully monetized (11). External costs would increase the production cost of competing fossil fuel–based energy supply technologies. The same is true for the removal of fossil-fuel subsidies, which the IEA (11) estimated to total US$523 billion globally in 2011 (an increase from US$412 billion in 2010).

3.3.5. Integration costs and the cost of energy consumption with increasing shares of renewables. Ultimately, the policy goal of providing affordable energy services must be measured against the cost of energy to consumers. Such costs are affected considerably by the challenges arising from energy transmission and timely distribution to consumers. Additional costs from the integration of increasing shares of RE technologies into an existing energy supply system depend on various factors, including the already-existing shares of RE technologies, the regional resource availability and characteristics (in particular the temporal variability of resource availability), and the design of the overall energy system (11; also see References 7, 35, 37, and 38).

3.4. Renewable Energy in Climate Change Mitigation Scenarios

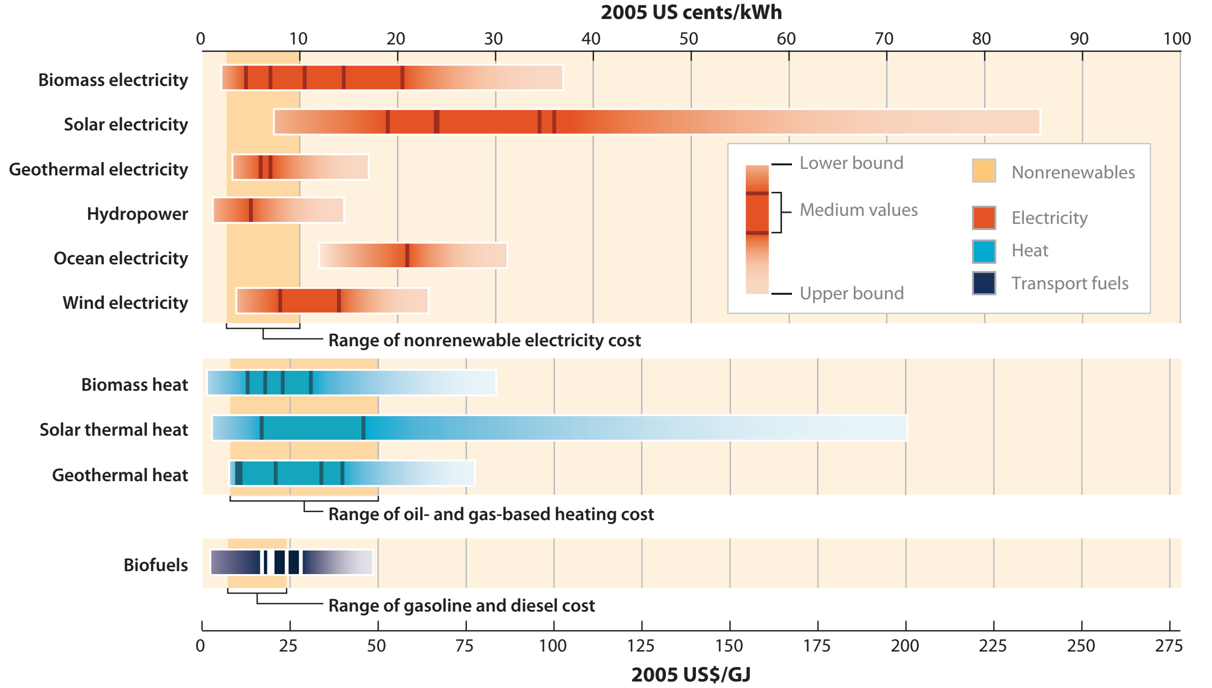
Past cost reductions suggest that RE could also play an increasingly important role in future energy systems. The IPCC's (36) assessment of 164 scenarios [including modeling intercomparisons (39, 40)] of the future development of the energy sector provides several interesting insights. Many models show a significant increase in the deployment of RE technologies by 2030, 2050, and beyond, even under baseline scenarios, namely scenarios without climate policy. In ambitious mitigation scenarios that impose corresponding climate policies, however, the increase in RE technology deployment is much more significant (**Figure 9**). In most these scenarios, RE would become the dominant low-carbon energy supply option by 2050, and growth would be spread widely throughout the world. However, the costs induced by the variability of some RE sources need to be taken into account to produce a realistic assessment of the deployment of RE technologies. How to properly include these costs in models involving deployment scenarios is only beginning to be discussed in the literature (e.g., 7). If RE deployment is limited or the climate policy regime is not ideal, then global mitigation costs increase (**Figure 10**) and low-GHG targets may not be achieved (11).

Bioenergy plays a crucial role in scenarios in part because of its possible coupling with CO_2 removal technologies (**Figure 1**), which would enable back transfer from atmospheric carbon to belowground carbon. The role of bioenergy carbon capture and storage has been investigated in detail (e.g., 42). Scenarios suggest that there would be high biomass deployment rates of approximately 100 to 500 EJ per year. Such an extensive use of biomass could also affect other SD goals, such as food security for the poor, protection of biodiversity, and reduction of deforestation. See Section 4 for further discussion.

3.5. Environmental Aspects of Renewable Energy Technologies

The environmental aspects of noncombustible RE technologies such as wind and solar are usually not taken into account in integrated scenario assessments of climate change mitigation. McCollum et al. (18, 43) point out a notable exception in which local environmental externalities and their health impacts are explicitly included as factors affecting social objectives. If environmental externalities exist and remain unaddressed (which is one variant of a second-best setting), the use of technologies that contribute to lowering negative environmental impacts provides cobenefits, potentially reducing welfare losses from climate change mitigation. Therefore, it is useful to assess RE technologies in relation to their

Levelized cost of energy (LCOE): a measure of the life-cycle cost of energy production, measured in, for example, US cents per kilowatt hour or US dollars per gigajoule



Notes: Medium values are shown for the following subcategories, sorted in the order as they appear in the respective ranges (*from left to right*):

Electricity	Heat	Transport fuels
Biomass: 1. Cofiring 2. Small-scale combined heat and power (CHP) (gasification internal combustion engine) 3. Direct dedicated stoker and CHP 4. Small-scale CHP (steam turbine) 5. Small-scale CHP (organic Rankine cycle) **Solar electricity:** 1. Concentrating solar power 2. Utility-scale PV (1-axis and fixed tilt) 3. Commercial rooftop PV 4. Residential rooftop PV **Geothermal electricity:** 1. Condensing flash plant 2. Binary cycle plant **Hydropower:** 1. All types **Ocean electricity:** 1. Tidal barrage **Wind electricity:** 1. Onshore 2. Offshore	**Biomass heat:** 1. Municipal solid waste–based CHP 2. Anaerobic digestion–based CHP 3. Steam turbine CHP 4. Domestic pellet heating system **Solar thermal heat:** 1. Domestic hot water systems in China 2. Water and space heating **Geothermal heat:** 1. Greenhouses 2. Uncovered aquaculture ponds 3. District heating 4. Geothermal heat pumps 5. Geothermal building heating	**Biofuels:** 1. Corn ethanol 2. Soy biodiesel 3. Wheat ethanol 4. Sugarcane ethanol 5. Palm oil biodiesel

The lower range of the levelized cost of energy for each RE technology is based on a combination of the most favorable input values, whereas the upper range is based on a combination of the least favorable input values. Reference ranges in the figure background for nonrenewable electricity options are indicative of the levelized cost of centralized nonrenewable electricity generation. Reference ranges for heat are indicative of recent costs for oil- and gas- based heat supply options. Reference ranges for transport fuels are based on recent crude oil spot prices of US$40–130/barrel and corresponding diesel and gasoline costs, excluding taxes.

Figure 8

Global range of levelized costs of energy for selected commercially available renewable energy (RE) technologies in comparison to non-RE costs for the year 2009 and under a wide variety of conditions (36).

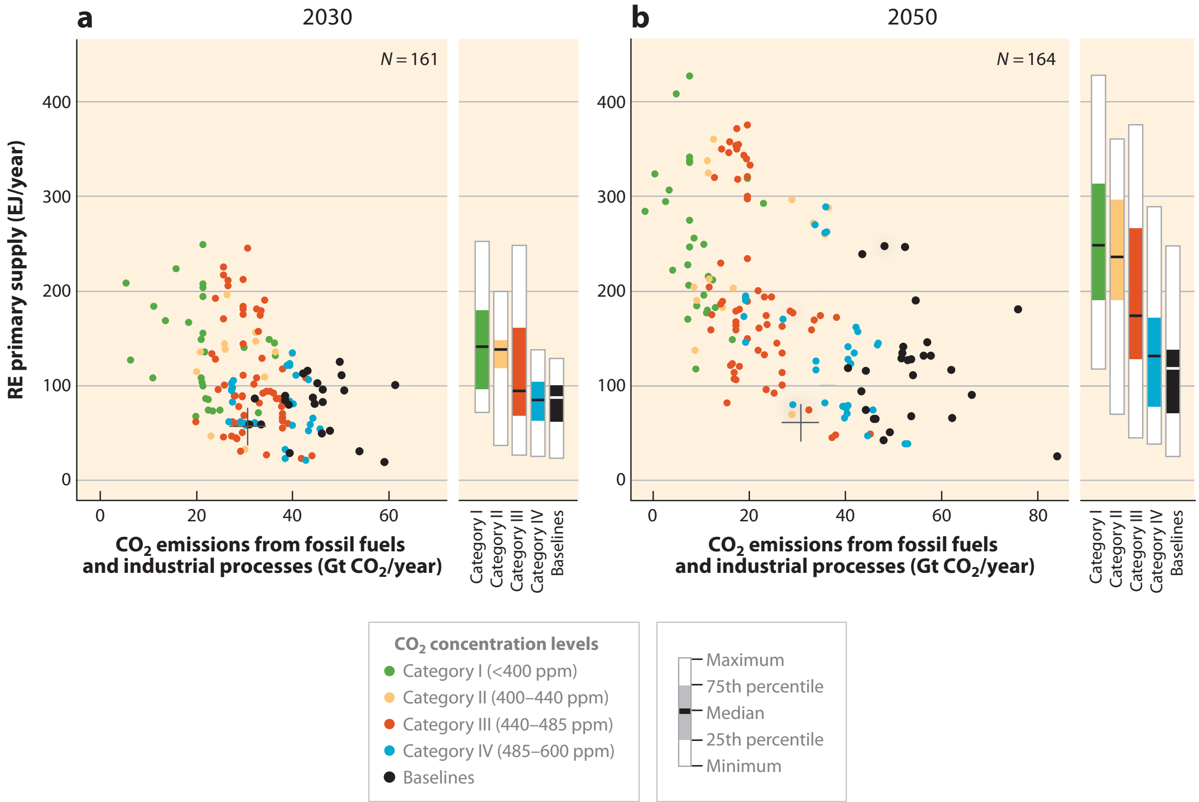


Figure 9

Global renewable energy (RE) primary energy supply (direct equivalent) plotted against CO_2 emissions from fossil fuels and industrial processes from (*a*) 161 and (*b*) 164 model-based, long-term mitigation scenarios in the years (*a*) 2030 and (*b*) 2050 for different mitigation scenarios and the baseline, respectively. The different colors indicate the level of ambition in terms of the exogenously set mitigation targets in the scenarios' atmospheric CO_2 concentration levels in 2100, ranging from unrestricted baseline scenarios (*black*) to low-stabilization scenarios with less than 400 ppm (*green*). Crosses indicate the relationship in 2007. Modified from Reference 11.

effect on air pollution, water use, land use, and biodiversity. The IPCC (9) has performed such an assessment, which is summarized below.

Modern RE technologies reduce air pollution and cause fewer health concerns compared with fossil fuel–based technologies. Traditional biomass, in contrast, causes significant local and indoor air pollution, which negatively affects health, especially that of women and children in developing countries.

Only a few RE technologies, such as hydropower and bioenergy, may place additional stress on water resources. These technologies depend on the availability of water resources. Their effect, however, is ambiguous. They do not necessarily lead to fiercer competition for water, but they may ameliorate water scarcity. These and other detrimental effects can often be reduced or avoided by siting considerations and integrated planning.

The land requirements of most energy technologies are substantial. Land-use requirements for bioenergy from dedicated feedstocks, however, are substantially higher than for any other energy technology.

Finally, RE-specific impacts on biodiversity may be positive or negative. No framework for a comparable assessment of impacts across technologies is currently available. Large-scale exploitation of bioenergy potentials is a reason

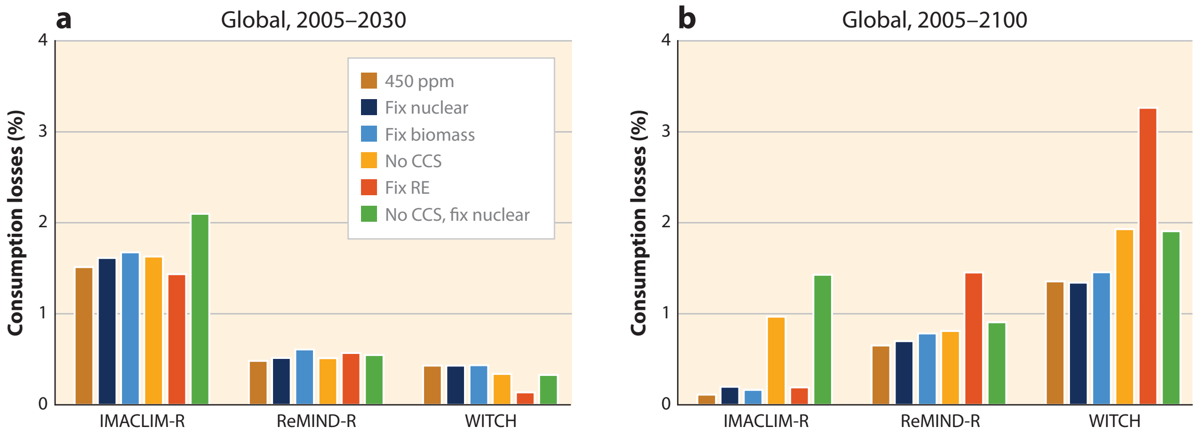


Figure 10

Mitigation costs under varying assumptions regarding technology availability for a long-term stabilization level of 450 ppm CO_2 (41). Option values of technologies in terms of consumption losses for scenarios in which the option indicated is foregone (CCS) or limited to baseline levels (all other technologies) for the periods (*a*) 2005 to 2030 and (*b*) 2005 to 2100. Option values are calculated as differences in consumption losses for a scenario in which the use of certain technologies is limited with respect to the baseline scenario. IMACLIM-R is a recursive computable general equilibrium model. WITCH and ReMIND-R are intertemporal general equilibrium models. Note that for WITCH, the generic backstop technology was assumed to be unavailable in the Fix RE scenario. Abbreviations: CCS, carbon capture and storage; RE, renewable energy. Modified from Reference 36.

for concern, given that there are already fragmented and degraded areas that are rich in biodiversity, including endangered species. The most evidence exists for the effects of hydropower projects, followed by onshore and offshore wind farms and some solar technologies.

4. THE CASE OF BIOENERGY

Bioenergy is one of several RE options described in the sections above. We focus on bioenergy because the complexity and uncertainty involved in evaluating this RE technology make it an intricate example of the challenges in appropriately determining sustainability outcomes. The primary issue is that the extensive interconnectedness between bioenergy and other systems may lead to numerous unforeseen consequences. In particular, bioenergy systems are much more land-use intensive than are other RE technologies, and they influence specific sustainability outcomes mostly via land use–related effects (**Figure 11**).

In the remainder of this section, we first provide an overview on the current dynamics and projected scale of deployment. Then we discuss the various sustainability implications in turn, with a focus on complicated climate change dynamics (**Figure 11**).

Modern bioenergy, including bioethanol and biodiesel, constitutes approximately 12 EJ of annual energy consumption. In contrast, the use of traditional bioenergy, mostly for household cooking and heating, averages approximately 40 EJ annually (28). However, the use of modern bioenergy is rapidly expanding worldwide. Energy security considerations, the wish to support agroindustrial economies, and the goal of mitigating climate change all motivate ambitious bioenergy policies in every major world region. Climate change mitigation scenarios foresee a deployment of 100 to 200 EJ of bioenergy by 2050 (compare with the total of approximately 500 EJ in 2010) (36). Therefore, bioenergy is considered a crucial component of any demanding climate stabilization effort. But how sustainable could such a deployment be? Scientists disagree considerably on this

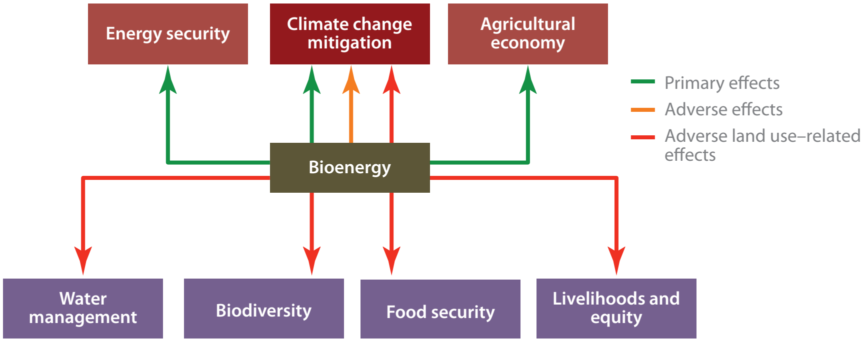


Figure 11

Climate change mitigation, energy security, and the wish to support agricultural industries all motivate bioenergy deployment; the positive effects of bioenergy deployment on these dimensions constitute adverse effects. At the same time, bioenergy deployment may also cause adverse (negative) climate effects. Bioenergy deployment may also have unintended effects on other sustainability dimensions, most but not all of which have negative consequences. Adverse side effects are induced mostly by land-use change.

question because of significant structural uncertainty related to the evaluation of various complex effects; that is, our knowledge is incomplete and cannot be captured even by probability distributions. Crucially, the global warming potential of bioenergy deployment itself is highly variable and, to some degree, simply unknown; it particularly depends on the replacement effects of fossil-fuel sources. From a broader perspective, land-based sustainability effects are well known but not systematically captured, and they depend on the specificities of management and technologies.

4.1. Climate Effects of Bioenergy Deployment

Articles about the climate effects and global warming potential of bioenergy sources are broad and numerous. Bioenergy was initially considered carbon neutral because the CO_2 emitted with the combustion of biofuels was seen as sequestered directly from the atmosphere (28). This assertion is increasingly being contested from various perspectives, and it may not even be the most appropriate starting point for analysis (e.g., 6, 44, 45), as it depends crucially on baseline assumptions in land–carbon stock dynamics (46, 47).

Accounting for GHG emissions constitutes the first-order approach to measuring the climate effects of biofuels. For first-generation crop-based biofuels, such as corn or soy, emission of N_2O from agricultural soils is the single largest contributor to life-cycle emissions (48). At the same time, emission rates vary enormously between crops (49) and for different nitrogen fertilizer application rates (50). If we rely on higher estimates of N_2O emissions, some biofuel systems might be net sources rather than net sinks of GHG emissions (51, 52).

Open questions are what to include in such accounting analyses and where to set the system boundaries. In a seminal paper, Farrell et al. (53) demonstrated that harmonizing system boundaries allows for consistent accounting of some processing pathways for US corn ethanol. Farrell et al. conclude that considerable GHG emissions are associated with the production and processing of corn ethanol but that its use is still advantageous compared with that of gasoline. Numerous analyses and summary figures have relied on such accounting techniques to compare various sources of bioenergy (e.g., 28, 54).

However, several issues qualify the results of such analyses, so the resulting numbers may represent the accounting of only some effects and may ignore wider system effects and stop short of measuring total marginal changes in GHG emissions (55). The elephant in the room is LUC. Land-use demand of bioenergy is two orders of magnitude higher than that of other RE technologies (56). As a result, considerable climate effects and nearly all sustainability effects are associated with LUC (**Figure 11**) (57).

When land is first used for bioenergy plants (often labeled direct LUC), considerable GHG emissions can result. The predominant example of direct LUC is deforestation, in which considerable land carbon stock is turned into atmospheric carbon stock and some soil carbon is released, opposing the intended mitigation effects. Notably, tropical forests were the primary source of agricultural land (food, fodder, livestock, and bioenergy) in the 1980s and 1990s (58).

More difficult to estimate and to control, and also very uncertain in its magnitude, is indirect land-use change (ILUC). ILUC denotes market-mediated land-use effects (59, 60). ILUC is calculated mostly by partial equilibrium models, known as consequential life-cycle analysis, and is always subject to model assumptions. For example, when US-produced soy is dedicated to biodiesel instead of fodder, soy demand and prices increase globally, possibly inducing deforestation in the Amazon to make way for soy plantations (61). The resulting GHG emission effects are difficult to estimate but may render some sources of bioenergy as net emitters (62). The total LUC emissions or, more generally, the negative impact on carbon stock dynamics could lead to high emissions from large-scale bioenergy deployment schemes, making it difficult to meet an ambitious 2°C temperature mitigation target (6).

Another incompletely understood factor involves changes in land use that translate into biogeophysical changes in albedo (surface reflectivity), surface roughness, or evaporation (e.g., 63, 64). Notably, changes in albedo can dominate overall climate forcings, especially when snow cover is involved, as in the case of boreal forests (65). Sometimes albedo changes can partially or completely offset climate forcings from GHG emissions (e.g., 66).

All of these factors leave open the question of net climate forcing related to bioenergy deployment. The total marginal change also depends on replacement effects in fossil-fuel and fertilizer markets and, possibly, other second-round effects (e.g., 67). Biofuels may replace only 12–15% of the energy-equivalent petroleum fuels (68) or up to 30–70% (69, 70), depending on modeling assumptions. The policy context is crucial: A cap on emissions, from both fossil fuels and land emissions, could control this rebound effect.

Nonetheless, some options can provide relatively low carbon bioenergy. Ethanol from sugarcane has considerably lower global warming potential than, for example, corn [subject to avoiding deforestation (e.g., 71)]. Cellulosic biofuels and algae promise low land-use intensity and, hence, fewer relevant climate effects (28). The sustainable exploitation of agricultural and forest residues and the use of organic wastes provide other, less land use–intensive opportunities. Good management practices may be the most important way to improve overall climate effects (72). Even conservative studies estimate a sustainable potential of up to 100 EJ (e.g., 73, 74).

4.2. Impact of Bioenergy Use on Livelihoods

Scientific studies often focus on a particular biophysical dimension, such as GHG emissions or land cover, but there are other aspects of large-scale bioenergy use that affect lives and livelihoods and should therefore be carefully considered (75). Bioenergy deployment affects livelihoods directly and indirectly through, for example, water, food, and biodiversity.

Bioenergy plantations require considerable amounts of water. The water footprint of biofuels is on the order of 104 to 105 liters water/liter biofuel; it seems to be less for bioethanol than for biodiesel and less for bioelectricity than for biofuels (76). This increased water demand may imply water competition between food and fuels, even when there is no competition over land but rather for irrigation and other water (e.g., in the case of *Jatropha*). Increased bioenergy deployment may induce a significant increase of water prices in some world regions, reducing water availability for poorer populations.

The competition between food and fuels has received much more attention. With increased demand for bioenergy, more and more land is being dedicated to energy crop plantation, reducing the availability of land for growing food. Although the world's food supply can nourish more than seven billion people (if equitably distributed) during "normal" years, food-fuel competition can be exacerbated in years affected by droughts, fires, and floods that affect crop production in different regions. As a result, food prices can increase dramatically, which has a modest effect on industrial countries but significantly affects the world's poor, who live on less than $2 a day and spend most of their money on food.

Biodiversity is similarly affected by bioenergy deployment. In US corn and soy fields, biodiversity is reduced by ∼60%, whereas in Southeast Asian oil palm plantations, biodiversity may decrease by 85% compared with unconverted habitat (57). Such a loss of biodiversity is important not only because of the rapid decline of global ecosystem health but also because of the loss of its biomedical value and, perhaps most importantly, its effect on people who depend on forests for fuel and food. For example, a transition from primary forests to energy crop plantation, and the associated loss of biodiversity and forest commons, can directly affect communities who live on these forest resources (77). More generally, nonmarket values of natural resources for subsistence, for leisure, and for aesthetic experience, and possibly the intrinsic value of ecosystems, should be considered in a comprehensive evaluation of different land-use climate strategies.

The livelihoods of local communities are affected not only by global food price dynamics and indirectly via biodiversity values but also (and very often) via bioenergy deployment schemes. F. Creutzig, C. Hunsberger, S. Bolwig & E. Corbera (manuscript submitted) systematically conceptualize the effects of bioenergy deployment on livelihoods, as measured in flow dimensions of food and income but also in terms of land and other assets. Crucially, although some agents profit from bioenergy plantations (e.g., migrant workers), others often lose out (78). In turn, local ownership of refining and processing steps enables a more equitable outcome (79). Thus, although the aggregate welfare effect measured in, for example, income might be advantageous, inequality often rises significantly.

Livelihood and quality of life are more difficult to measure than is aggregate income or economic turnover, but research should not shy away from systematically addressing these issues. This observation opens up important arenas for research. On the climate side, top-down long-term scenarios and bottom-up short-term assessments remain surprisingly disconnected; both could further enrich one another when it comes to estimating the climate effects of deployment (6). In light of the possibly detrimental climate effects of bioenergy deployment, climate stabilization scenarios might also explore the potentially harmful effects of deployment schemes on various livelihood dimensions (75). In addition, field research and regional assessments can provide valuable insights to more comprehensively estimate the impact of bioenergy deployment, differentiating between geographical regions but integrating goals (80). In summary, the bioenergy case demonstrates that we need to map out and integrate all relevant dimensions into an analysis, merging qualitative insights with results from quantitative models.

5. RENEWABLE ENERGY POLICY: TRENDS AND CHALLENGES

5.1. Current Trends in Renewable Energy Policies

Since 2005, the number of countries with RE targets has more than doubled (**Figure 12**).

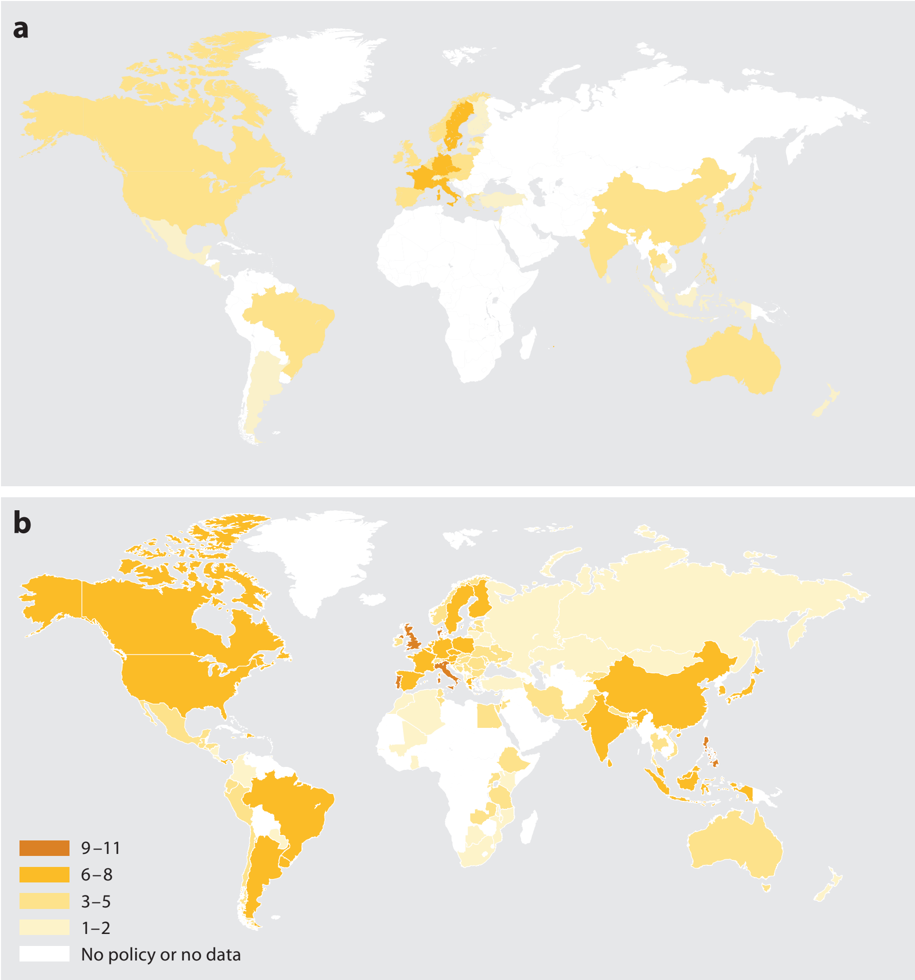


Figure 12

Countries with renewable energy policies in (*a*) 2005 and (*b*) early 2012. The colors denote the number of national policy types in place to directly support renewable energy. Modified from Reference 81.

There are now targets for RE in at least 118 countries (81).

R&D policies may be implemented to support technologies at very early stages of development or to help refine more mature technologies. The success of R&D policies depends on the amount of funding allocated, the consistency of annual funding, and the package of support in which the policy is embedded (e.g., deployment) (82). In 2011, the dollar amount of R&D invested in RE technologies worldwide fell by 16% to US$8.3 billion. Most of this investment (both corporate and governmental) was in solar and biofuel technologies, which attracted $4.1 billion and $1.9 billion, respectively (32).

RPS: renewable portfolio standard

FIT: feed-in tariff

Policies to support the deployment of RE technologies come in many forms, ranging from fiscal incentives (such as grants and tax credits) to public finance (such as loan guarantees) to regulations [such as renewable portfolio standards (RPS) and feed-in tariffs (FITs)]. Much of the literature on policies for RE electricity is based on experiences in Europe and

North America and therefore has limited relevance for developing countries. Much debate centers on which policy (RPS or FITs) has been more successful in promoting RE deployment. Both instruments have advantages. Because of the security of investment that they provide in the fixed prices for energy generated, thereby reducing risk, several studies have claimed that FITs are more effective in terms of supporting increased deployment (82–84). Prices for RE-generated energy under RPS policies may fluctuate, providing a less secure investment (85). An advantage of RPS policies is that the mechanism by which they function tends to support the most mature, least-expensive technologies (82, 86).

To date, most policies implemented in support of renewable heating and cooling technologies have been fiscal incentives—largely grants, which have been met with varying degrees of success (87, 88). There is increasing interest in FITs for heat, similar to those in place for electricity, although we have only limited practical experience with these innovative instruments. Policies for RE in transport relate largely to bioenergy and are therefore covered in Section 5.2, below.

As discussed above, policies that support RE technologies typically target the development and deployment of ways to produce electricity, heat, and fuel for transport. However, policies may also support the integration of those technologies into the existing energy system. For electricity, such policies may support the construction of and access to distribution networks. For variable RE technologies (e.g., wind and solar), policies may also address the challenges of their integration by supporting the interconnection of systems; improving flexible generation (by means of new investment or upgrades in existing power plants); increasing demand-side management; increasing storage capacity; and improving operational, market, and planning methods (82, 89).

Policy design and implementation strategies are continuously being revised to reflect policy learning as well as decreasing costs and technological advances. For example, policies in support of bioenergy and the impacts of those policies have been the subject of much debate and revision. This topic is discussed in more detail in the next section.

5.2. Policy Learning: Experiences with Bioenergy Policy

Policies addressing biofuels and bioenergy constitute an excellent example of the evolution of RE policy instruments and closely follow the evolution of the scientific literature (Section 2). The proposed public policy framework serves as a heuristic tool.

The first large-scale implementation of modern biofuel policies, which occurred in Brazil in the 1970s, involved using ethanol created from sugarcane to become more energy independent (90). With increasing oil prices and climate change concerns, the European Union and the United States implemented blending mandates around 2005. The assumption was that biofuels are climate neutral and renewable and, hence, should contribute to climate change mitigation. Although the literature reflected climate change mitigation effects before 2005, an increasing number of publications indicated that considerable climate effects are often associated with bioenergy deployment (e.g., 44, 53, 57, 91). Policy makers reacted by refining their legislation to introduce low-carbon or renewable fuel standards (54, 92). These standards specify the specific GHG intensity of fuels, requiring biofuels to be substantially below the gasoline benchmark. However ILUC effects were not included. The low-carbon fuel standard implemented in California adds an ILUC multiplier to the GHG intensity estimates, ignoring the uncertainty involved in ILUC estimates. The integration of ILUC into European fuel quality standards has also been proposed (93), but the revision of the policy instrument stopped short of including ILUC, probably in an acknowledgment of agroindustrial interests.

The application of quantity-based policy instruments, however, is problematic (55) because the life-cycle accounting underlying the estimation of induced GHG emissions is limited to a specific framework and stops short of estimating total marginal changes in GHG emissions. This total marginal change in emissions is inherently difficult to measure and is subject to large structural uncertainties and, to some degree, arbitrary assumptions in models. The risk of ignorance of these uncertainties is making potentially harmful decisions. An awareness of risks and the underlying uncertainties and ambiguities seems to be a precondition for improved policies (6, 94).

The sustainability dimensions, and especially the livelihood implications, of bioenergy deployment have also received increased attention recently (e.g., 57, 79). Policy makers have implemented sustainability certifications. Although certification schemes such as the EU-RED (EU Renewable Energy Directive) constitute an improvement in that they shift production to modes that are sometimes more sustainable, they are particularly weak in fostering social sustainability and improving rural livelihoods (95).

In sum, an interesting pattern emerges. Policy instruments initially attempted to address a particular objective (energy security, climate change mitigation). Then policy makers learned about the numerous and substantial adverse effects (e.g., indirect GHG emissions) of specific policies (e.g., biofuel mandates) and tried to address these adverse effects with second-round legislation. This second-round legislation improved the outcomes considerably but may have been insufficient to address significant climate effects such as ILUC and the endangered livelihoods of the global poor. The open question is whether improved second- or third-round legislation can solve the issue. Here we suggest an alternative approach and argue that several policy objectives (improved climate, energy security, food security, biodiversity, livelihoods) require a consistent set of policy instruments. Because both the consequences and the objectives of bioenergy deployment are diverse and subject to values held by the public, by policy makers, and by scientists, bioenergy policies should be consistently evaluated within an explicit science-policy framework that allows scientists to (re)consider deployment schemes in light of continued public discourse on values and objectives (3).

5.3. Renewable Energy Policy in Context

In the preceding two sections we discuss policies implemented to address a single objective, as well as the role of policy learning. Here we first examine the interactions among multiple policies implemented to address a single objective (e.g., climate change), focusing on carbon-pricing policies and typical technological support policies for RE technologies. Then we discuss the interplay between multiple objectives and multiple policies with regard to RE and fossil-fuel energy subsidies.

The relationship between multiple externalities, multiple objectives, and multiple policies was described first in Section 2.1. Here we focus only on multiple objectives and multiple policies and on the different possible combinations thereof (**Figure 13**).

Analyses should investigate the situation of multiple policy instruments and multiple benefits within one setting, further pushing the boundaries of analysis (several policy instruments, several objectives). For example, in the applied setting of urban transport, recent studies have demonstrated that combined supply, demand, and land-use policies can simultaneously produce multiple benefits such as climate mitigation, better air quality, less congestion, and reduced fuel expenditures (i.e., energy security) (96, 97). As mentioned above, cobenefits can occur when existing policies do not address the different market failures optimally; this second-best setting requires a broader perspective allowing for a comprehensive understanding of how multiple objectives interact with multiple policy instruments.

5.3.1. Interactions among multiple policies.

Recently, the relationship between carbon-pricing policies and policies that support RE technologies directly by means of, for example,

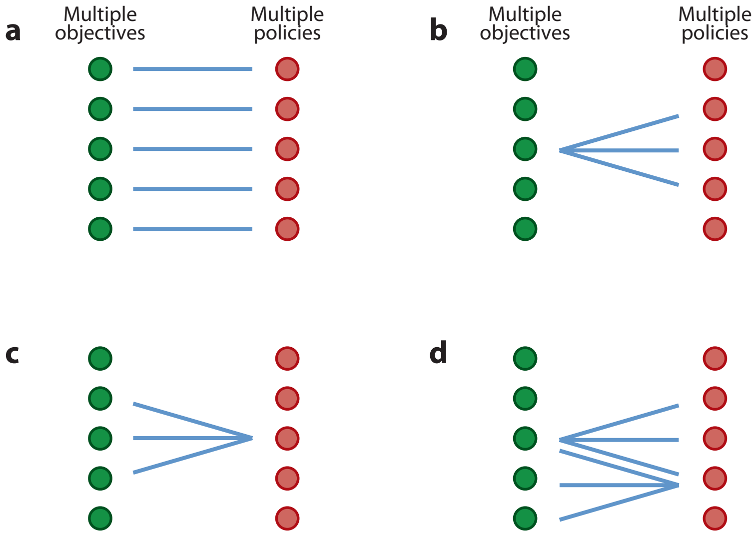


Figure 13

Multiple objectives and multiple policies in a second-best setting. (*a*) Narrow boundaries of analysis: One objective is targeted by one policy. (*b*) One objective is addressed with multiple policies. (*c*) One policy addresses multiple objectives. (*d*) Wide boundaries of analysis: Multiple objectives are targeted by multiple policies.

RPS or FITs (several policy instruments, one objective) has attracted increased attention. To address climate change, the theoretical literature argues that carbon-pricing policies (via either a carbon tax or an emission trading scheme) are essential. At the same time, as demonstrated in Section 1, developing or deploying RE technologies may also mitigate climate change by decreasing carbon intensity. Although there may be other justifications for the deployment of technology-based policies, such as innovation market failures (Section 2.3), we focus solely on the objective of climate change mitigation.

With a carbon-pricing policy, introducing RE policies such as FITs or RPS (thereby stacking multiple policies) may have undesirable consequences that could undermine the carbon price and thereby increase mitigation costs (98). This possibility may apply to different levels of governance. For example, the European Emissions Trading Scheme provides an overarching carbon price, and the German government provides support for RE technologies via its FIT. Rathmann (99) argues that when electricity produced by fossil fuels is substituted by RE, the demand for emission reduction decreases, thereby lowering the carbon price. A similar phenomenon may be observed at subnational levels. For example, state-level RPS policies in the United States may interact with regional emission trading schemes, such as the Regional Greenhouse Gas Initiative in the eastern United States. By means of a computable equilibrium model, Morris et al. (100) show—consistent with fundamental economic reasoning—that an increasing RPS (5–20%) has no effect on emission reductions and that it reduces the carbon price substantially. However, whether the declining CO_2 price, due to an additional RE target, has negative welfare effects is open to debate. When there are no technology externalities in the RE sector, a declining CO_2 price has welfare-reducing effects because the marginal abatement costs are not equalized across sectors and technologies. However, when the diffusion of renewables shows further technological externalities (7, 15), then a declining CO_2 price has positive welfare effects because a given emission can be achieved at lower long-term costs. The long-term cost reduction potential within the RE sector cannot be realized when the whole sector benefits from learning-by-doing caused by the investments of an individual firm into RE technologies.

These examples highlight the negative interactions among multiple uncoordinated policies to address the single objective of climate change mitigation. They show that such efforts may even counterbalance the original objective. Fankhauser et al. (98) argue that such adverse consequences can be mitigated with carefully designed and coordinated hybrid policies. Additional literature analyzes the interaction between policy instruments, which is well known as the double-dividend hypothesis. According to this hypothesis, carbon pricing can both improve the environment and provide revenues to reduce other distorting taxes under specific circumstances. We do not discuss this important literature further because its links to RE policies are very loose. For a good theoretical and empirical overview of this topic, see Parry & Williams (101).

5.3.2. Subsidies for other energy sources. Subsidies for fossil fuels are long-standing and are provided to address objectives that are independent of climate change mitigation. Policies provided for this objective indirectly affect the technology policies subsidizing RE technologies, which were implemented to address the objectives mentioned in Section 2.2.

In 2011, RE technologies received only US$88 billion in subsidies compared with $523 billion allocated to fossil fuels—a sixfold difference (24). Most (54%) fossil-fuel subsidies were provided to the oil industry. Subsidies for fossil fuels tend to be concentrated in energy-exporting countries. The Middle East, for example, accounts for 34% of the global total; Iran leads with $82 billion (24).

Although in some cases RE technologies are cost competitive with fossil fuels, many are not yet competitive (Section 3.2.2). The difference in subsidies allotted to the different energy sources further skews the cost differential. Subsidies to fossil fuels artificially lower the consumer price, and as a result serve to make RE technologies less attractive, particularly when the externalities of using fossil fuels are not incorporated into the market price.

The literature often refers to the distortion of a level playing field for RE technologies in this framework (e.g., 102). For renewables to become fully cost competitive, several barriers, including distorted playing fields, must be removed. The participants of the 2009 G-20 Summit agreed to "phase out and rationalize over the medium term inefficient fossil-fuel subsidies," which impede investment in clean energy sources such as RE, among other effects (103, p. 3). In response, IEA, OECD, World Bank, and OPEC published a road map for phasing out fossil-fuel subsidies (104) and a subsequent update to further inform the process of implementation (105).

Where fossil-fuel subsidies are implemented, however, one should take care that the removal of the subsidy does not adversely affect complementary objectives such as development and energy access. Fair redistribution of the revenues saved can accomplish this task.

6. CONCLUSION

As part of the framework of SD, RE is often discussed in its capacity to address objectives such as climate change mitigation, energy security, and the reduction of local air pollution. We argue that the potential synergies and trade-offs between these social objectives must be embedded in a public discourse that is informed by science but not determined by it. The synergies and trade-offs among social objectives have welfare implications only if externalities exist and are not adequately addressed by policy instruments or if the costs of overall policies are synergistically reduced.

Two fundamental market failures motivate policy intervention as related to RE: (*a*) climate- and environment-related externalities associated with fossil-fuel energy generation and (*b*) technological externalities related to innovation failures. The RE technologies that those policies are meant to address are diverse and at various stages of maturity. Above we illustrate the great technical potential (which substantially exceeds demand), the increasing deployment levels, and the costs of these technologies versus fossil fuels. RE technologies are only one component of a portfolio of climate change mitigation options, but the percentage of their contribution to the energy supply increases substantially in all integrated assessment models, both with and without climate change mitigation policies. Biomass is an important part of this portfolio. However, its use must be carefully evaluated because of potentially negative consequences that may undermine the original objective.

Political support for RE technologies has been increasing, and we have learned many important lessons about their key design features as well as about policy implications, as shown by the example of bioenergy policy. It is useful to embed policy discussions in a broader framework that examines multiple objectives and multiple policy instruments and the interactions between them. By examining several policy instruments and one objective, we show that uncoordinated policies may counterbalance the original objective. Similarly, in a case with multiple objectives and multiple policies, uncoordinated policies can affect the achievement of separate objectives. More research on these interactions is needed.

SUMMARY POINTS

1. Multiple externalities, multiple objectives, and multiple policy instruments must be taken into account for an assessment of the sustainability of RE to be comprehensive.
2. As part of a public discourse, an examination of the impacts of RE support policies (including possible trade-offs between objectives) should be included in policy design, which would provide opportunities for policy learning.
3. Biomass may be an important component of the portfolio of mitigation options. However, its deployment must be carefully evaluated because of potentially negative consequences that may undermine the original objective.

FUTURE ISSUES

1. Researchers should investigate in more depth the interplay between multiple externalities, multiple objectives, and multiple policy instrument analyses.
2. More information is needed on the ability of RE technology policies to effectively counterbalance the deficiencies that occur when carbon pricing (and other policies) are suboptimally implemented.
3. Researchers should reconcile top-down and bottom-up approaches in evaluating environmental impacts of mitigation policies, such as the water-energy nexus.

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