

Renewable Energy Futures: Targets, Scenarios, and Pathways

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Key Words

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Abstract

Scenarios for the future of renewable energy through 2050 are reviewed to explore how much renewable energy is considered possible or desirable and to inform policymaking. Existing policy targets for 2010 and 2020 are also reviewed for comparison. Common indicators are shares of primary energy, electricity, heat, and transport fuels from renewables. Global, Europe-wide, and country-specific scenarios show 10% to 50% shares of primary energy from renewables by 2050. By 2020, many targets and scenarios show 20% to 35% share of electricity from renewables, increasing to the range 50% to 80% by 2050 under the highest scenarios. Carbon-constrained scenarios for stabilization of emissions or atmospheric concentration depict trade-offs between renewables, nuclear power, and carbon capture and storage (CCS) from coal, most with high energy efficiency. Scenario outcomes differ depending on degree of future policy action, fuel prices, carbon prices, technology cost reductions, and aggregate energy demand, with resource constraints mainly for biomass and biofuels.

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INTRODUCTION

Renewable energy has grown rapidly in recent years. Overall, renewables produced 16.5% of world primary energy in 2005. The share of world electricity from renewables was 19%, mostly from large hydropower (hydro) and the rest from other sources such as wind, biomass, solar, geothermal, and small hydro. In addition, biomass and solar energy contribute to hot water and heating, and biofuels provide transportation fuels. Although large

hydro is growing at modest rates of 1% to 2% annually, most other renewable technologies have been growing at rates of 15% to 60% annually since the late 1990s. It is this group of technologies that is projected to grow the fastest in the coming decades, making renewables a highly significant and potentially majority share of world energy (1–4).

Attention has become more focused on the future of renewables for a variety of environmental, economic, social, and security reasons. There is a growing body of literature describing that future, including policy targets, socioeconomic and technology scenarios, carbon-constrained scenarios, and future social visions. Policy targets for future shares of renewable energy are described for regions, specific countries, states or provinces, and cities. Shares of renewable energy are also described in scenarios that show future energy consumption on the basis of analytical models or projections. Some scenarios project forward using assumed growth rates or future technology shares on the basis of policy, technology, economic, or resource factors. Other scenarios project backward from specified future conditions or constraints, such as limits to global carbon emissions, stabilization of atmospheric CO₂ concentration, minimum or maximum energy consumption per capita, and sustainable land use. Scenarios can explore technologies, costs, policies, investments, emissions, time frames, social appropriateness, and shares relative to fossil fuels and nuclear energy.

Scenarios are part of the broader literature on renewable energy, which includes current technical-economic opportunities, resources, constraints and barriers of many forms, integration strategies, policy experience, and recommendations for the future (5–17). Many of the policy prescriptions found in this broader literature are common to policy frameworks or road maps that accompany renewable energy scenarios. Most studies show that geographic resources do not constrain aggregate amounts of renewables, with the possible exception of biomass and biofuels. “Renewable

Primary energy: energy available from coal, oil, gas, and biomass before burning or conversion to other forms; heat from nuclear fuel

energy flows are very large in comparison with humankind's use of energy. Therefore, in principle, all our energy needs, both now and into the future, can be met by energy from renewable sources" assert Johansson & Turkenberg (18). Rather, cited constraints to renewables commonly include (a) costs relative to conventional fuels; (b) intermittent and variable output relative to society's need for constant energy flows; (c) the geography of where energy is needed versus where renewable energy is most available; and (d) an array of institutional, social, and economic barriers.

This review focuses on global energy scenarios (19–36); Europe-wide energy scenarios (37–48); and scenarios for individual countries, including the United States (49–55), Japan (56, 57), and China (58–62); and other developing countries (63–69). Some global scenarios also give individual country cases. European scenarios show the largest amount of future renewables, which is no surprise, because Europe currently leads the world in most metrics of renewables development, including investment, installed capacity, industry size, policy action, and use of policy targets (3, 4). Chinese targets and scenarios also project high growth and large amounts. Some of the reviewed studies focus primarily on the role of renewables, but most are not renewables specific. Some works provide broader perspectives from which to understand the future (70–72). Also relevant is literature on emissions scenarios, including the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emissions Scenarios* (73) and a greenhouse-gas emissions database with over 700 scenarios (74).

The approach of this review is exploratory. It uses the scenario literature to ask the question: How much renewable energy can we expect or plan to have in the future? The scenarios presented were selected because they are the most recent, prominent, and comprehensive, although length and language limitations preclude many country-specific scenarios. The focus is on the results of scenarios—the lowest, moderate, and

highest levels of the renewables use in coming decades. By broadly examining both policy targets and scenarios together, something that is rare in the literature, targets can appear as “stepping stones” to scenario futures, and conversely scenarios can inform target setting.

SCENARIOS, MODELS, AND PARAMETERS

McDowall & Eames (75) offer a typology of energy future studies, categorizing them as either descriptive or normative. Under descriptive studies, “forecasts” predict likely futures from current trends, using extrapolation and modeling; “exploratory scenarios” emphasize the drivers of possible futures, without specifying a predetermined end state; and “technical scenarios” explore technology possibilities and configurations, emphasizing the feasibility and implications of different options. Under normative studies, “visions” elaborate desirable and plausible futures, emphasizing benefits; “backcasts” start with a predetermined end point—a desirable (or constrained) future—and then investigate the pathways and technology configurations leading there; and “road maps” prescribe sequences of policies and measures. Most of the studies reviewed here are simply called scenarios, although they represent a balance among primarily technical scenarios, backcasts, and visions according to the typology of McDowall & Eames.

Scenarios are an important tool for dealing with complexity and uncertainty about the future. They allow exploring alternative futures and can “provide insights to energy planners, influence the perceptions of the public and the energy policy community, capture current understanding of underlying physical and economic principles, or highlight key emerging social or economic trends,” note Craig et al. (76). However, scenarios are not predictions. Attempts to forecast energy futures have historically underestimated the importance of surprise and uncertainties. Rather, scenarios could be seen as “if...then” queries: If

policies accelerate the growth of renewables, what is the difference between situations with and without policies? If renewables' costs decline, how will markets shift investment patterns? If CO₂ emissions should be stabilized, what combinations of renewables and other technologies will achieve stabilization? These questions must be answered under a set of conditions, interrelationships, and/or constraints for population, economic growth, energy demand, technology changes, technology and fuel costs, environmental emissions, and changes in the structure of the economy.

Modeling tools are commonly used to carry out scenario analysis, with a range of software tools available (77–79). Categories of models include techno-economic, partial and general equilibrium, simulation, optimization, and end-use accounting (78, 79). The entire economy may be modeled, or just the energy system or energy demand. The International Energy Agency (IEA) World Energy Model, used for the *World Energy Outlook* (WEO) (21, 26), has been refined over more than a decade and comprises 16000 equations defining interrelationships among energy, economy, technology, investment, resources, and environment. MARKAL is a common cost-optimization tool that identifies least-cost mixes of energy technologies and fuels to meet energy demand within specified constraints (22, 66, 68). LEAP is a common accounting tool for energy planning that tracks energy consumption, conversion, and production under a range of assumptions (62, 80). European Commission (EC) studies use the energy modeling tools Green-X, PRIMES, and POLES, among others (20, 37–39, 46). Four U.S. studies use the NEMS modeling tool and variants (51–55). Greenpeace & European Renewable Energy Council (EREC) (19) scenarios use the MESAP/PlaNet and MESSAGE modeling tools together. The IPCC (73) uses AIM, MINICAM, MESSAGE, MARIA, ASF, and IMAGE modeling tools, and reports separately on the results of each applied to common “story lines,” with different results

depending on the model used. In general, the modeling approach has a significant impact on both data requirements and results (but these are not within the scope of this article).

Beyond the models themselves, many consider scenario construction to be something of an art, requiring skill at making good simplifying representations of social and economic dynamics and not just writing energy-balance equations or characterizing technological change (81). From this perspective, scenario construction is best done collectively, drawing upon diverse perspectives as Shell and the World Business Council for Sustainable Development (WBCSD) have done (25, 27, 32, 35).

Scenario Parameters

Most scenarios use parameters that include some combination of population, gross domestic product (GDP), energy intensity and demand, fuel costs, carbon prices, technology costs, and degree of policy action. These parameters could be considered the drivers for renewable energy and other energy technologies. Parameters may be based on story lines of socioeconomic conditions, expectations about technological change, policy drivers, projected growth rates, or other considerations. Below are some parameters from the global and European scenarios.

Population. The IEA WEO (21) projects 8.1 billion people by 2030, with an average population growth of 1% each year through 2030, although population growth is expected to increase faster at 1.1% in earlier years (2004–2015) and to slow down to 0.8% in later years (2015–2030). Many studies use and extend these figures to 2050. By 2050, a common projection in several studies is about 9 billion (19, 22, 25, 27). IPCC (73) scenarios give a range from 8.3 to 11.3 billion in 2050, with most scenarios projecting about 9 billion. For Europe, most recent scenarios share similar assumptions, with population constant or marginally increasing to 470 million by 2030,

up from 453 million in 2000 (38). After 2030, some scenarios show a decrease to 430 million in 2050 (20, 45).

Gross domestic product. The IEA WEO (21) projects world GDP will grow an average 3.4% per year from 2004 to 2030, compared with 3.2% from 1980 to 2004. Annual GDP growth is projected in two stages: 4% from 2004 to 2015 and then 2.9% from 2015 to 2030. China, India, and other developing countries are expected to continue to grow faster than these averages. Per capita GDP grows from \$9250 to \$17,200 and total GDP increases 2.4-fold from \$58 to \$140 trillion (2004 to 2030), using 2005 dollars on a purchasing-power parity basis.¹ Many other energy scenarios use the IEA projections. Greenpeace & EREC (19) assume a 3.4-fold increase to 2050 (using a 2.7% per year average). IPCC (73) scenarios show world GDP increasing between 1.5-fold and 4.8-fold from 1990 to 2050. For Europe, most scenarios project continued modest growth of ~2% (20, 38).

Energy demand and intensity. Energy intensity reflects both changes in the structure of the economy and improvements in energy efficiency. In the IEA's *Energy Technology Perspectives* (ETP) (22) "ACT Map" scenario, energy-efficient technologies reduce global energy consumption by 24% in 2050 compared to the reference scenario. The Global Wind Energy Council (GWEC) & Greenpeace (23) "high-efficiency" scenario projects 39% lower electricity consumption in 2050 compared to a reference scenario. In the Greenpeace & EREC (19) "revolution" scenario, energy intensity decreases threefold owing to energy efficiency, and world energy demand in 2050 is about the same as in 2003 despite economic growth. The German Advisory Council (28) scenario also shows global energy intensity falling threefold but

still results in a doubling of energy demand by 2050. Other studies show energy intensity declines of twofold to 4.8-fold by 2050 (25, 73). Overall, projected world energy consumption by 2050 ranges from 560 to 1600 exajoules (EJ), compared to 480 EJ in 2004. In European scenarios, projected energy growth is lower, with primary energy 55–90 EJ by 2030, compared to 73 EJ in 2005.

Fossil fuel and carbon prices. Scenarios differ in assumptions about fossil fuel prices. IEA scenarios show oil prices remaining in the \$48–\$62 (per barrel) range through 2030, with natural gas prices tracking due to continued oil-price indexation. In contrast, the Greenpeace & EREC (19) scenario expects oil prices to reach \$95 by 2030 and \$110 by 2050. EIA projects \$54 in 2025, revised from \$33 projected a year earlier (51). Scenarios also differ in assumptions about carbon prices with common values \$7 to \$15 (per ton CO₂) in 2050 and higher values up to \$50 (19, 22). European scenarios show a wide range of carbon prices under the European Emission Trading Scheme, from €5 to €20 (per ton CO₂) under low- or least-cost scenarios (37, 38, 44) and up to €65 under another prediction (44). Thus carbon prices have become a wild card in European scenarios, particularly because prices were fluctuating greatly in Europe in 2005/2006. (All preceding prices are given in 2004–2005 dollars or euros.)

Renewable energy technology costs. IEA studies have projected renewable energy technology cost reductions to 2010 and 2025 (13–15). Most policy-intensive scenarios show continued cost reductions through 2050. IEA's ETP (22) projects that solar photovoltaic (PV) electricity costs will decline to 6–30 cents per kWh (from 18–50 cents today); onshore wind, to 3.5–20 cents (from 4–22 cents); and offshore wind, to 6–18 cents (from 6.6–22 cents). Small and large hydro, biomass, and geothermal decline slightly. Others project declines of wind power to 3.5–5 cents per kWh, solar PV to 5–9 cents,

Exajoule (EJ or 10¹⁸ joules):

measures large quantities of primary energy; million tons oil equivalent (mtoe = 0.042 EJ) is also a common unit

¹All money amounts are in U.S. dollars.

Carbon stabilization: leveling of atmospheric concentration of CO₂, CO₂ equivalents, or annual CO₂ emissions by a future year

and concentrating solar thermal power (CSP) to 5–8 cents (19, 23). The European Solar Thermal Technology Platform (ESTTP) (41) shows solar heating capital costs per kW-thermal of capacity declining almost threefold from €1100 to €400 (2005–2030). IEA's ETP (22) shows reduced biofuel costs from the introduction of cellulose-to-ethanol technology and increased crop yields under one scenario. Some scenarios include learning curves in their models, which project future cost reductions on the basis of past history and cumulative technology production over time (82).

Carbon stabilization and emissions constraints. A number of scenarios set atmospheric CO₂ stabilization levels of either 450 ppm (19, 28), 500 ppm (20), or 550 ppm by 2050 (25, 30). Other scenarios constrain cumulative CO₂ emissions by 2050, starting from a base year, or reduce annual emissions relative to 1990 levels. For example, one Chinese scenario constrains cumulative carbon emissions from China to 66 gigatons (Gt) between 1995 and 2050 (59). The Greenpeace & EREC (19) scenario constrains global annual carbon emissions to 11 Gt CO₂ by 2050. A carbon constraint of 80% of 1990 emissions by 2050 appears in German and Dutch scenarios (83, 84).

Policy action. There is wide recognition that policies have underpinned renewable energy development over the past decades and that the need for policies will continue well into the future. Therefore, both the degree of policy action and the description of policies are central to scenarios. Reference scenarios typically envision low levels of policy action. The IEA's WEO (21) reference scenario “does not take into account possible, potential, or even likely future policy actions” and thus shows “how energy markets would evolve if governments do nothing beyond what they have already committed.” In contrast, the “alternative policy” scenario “analyses the impact of a range of policies and measures that countries are considering adopting or might rea-

sonably be expected to adopt” (21). Existing policy targets can serve as points of departure for higher levels of policy action and higher future targets. This is particularly true in scenarios for Europe, where considerable political attention is currently directed to policy targets. Reference scenarios tend to project less than full implementation of targets, whereas policy scenarios envision full implementation and more as well as continued increases in targets and mandates.

Scenarios envision a wide range of new and strengthened policies (8–11). Electric power policies include feed-in laws, portfolio standards, guaranteed grid access, net metering, and distributed generation policies. Biofuel policies include blending mandates and tax exemptions. Building policies include integration of solar hot water and solar PV into new construction. Economic incentives include tax credits, subsidies, and tax exemptions. Research and development policies (leading to reduced technology costs) include direct funding, technology cooperation agreements, joint ventures, and demonstration programs. Financing policies include loans and grants. Other policies include directing international development assistance to renewables, reducing subsidies for fossil fuels and nuclear power, incorporating external costs into energy prices, removing market and institutional barriers, strengthening human resources, restructuring or liberalizing energy markets, and enacting appliance, building, and vehicle efficiency standards and other efficiency measures. Some European scenarios also envision strengthening the European Emission Trading Scheme and carbon pricing as well as enacting post-Kyoto emission reduction targets.

CURRENT AND FUTURE SHARES OF RENEWABLE ENERGY

Targets and scenarios tend to be summarized in terms of the share of primary energy, electricity, or transport fuels from renewables,

Table 1 Share of world primary energy from renewables—four types of accounting (2004)^a

	Excluding traditional biomass				Including traditional biomass	
	Hydro (EJ)	Nonhydro renewables (EJ)	World primary energy (EJ)	Renewables share of primary energy	Traditional biomass (EJ)	Renewables share of primary energy ^b
BP method	28.9	6.8	438	8.2%	44	16.5%
IEA method	11.0	5.0	418	3.8%	44	13.0%

^a“BP method” and “IEA method” refer to accounting methodologies for calculating primary energy by BP and the International Energy Agency, respectively; see text for explanation. Figures calculated from 2004 data by BP, REN21 Renewable Energy Policy Network for the 21st Century, and IEA (1–4, 21). Total renewables equal hydro plus nonhydro renewables plus traditional biomass.

^bBoth total world primary energy and total renewables increase by the amount of traditional biomass.

although there are alternative indicators and portrayals found in the literature; some are discussed below. However, one quickly confronts a fundamental but mostly unacknowledged problem: The term “share of primary energy from renewables” is ambiguous and causes confusion because there are actually four different ways to define the phrase (see **Table 1**). Each way is legitimate but uses a different accounting method. In 2004, renewables provided 80 EJ of global primary energy (16.5% share) according to the “BP method” but only 60 EJ (13% share) according to the “IEA method” if traditional biomass is included. Excluding traditional biomass, the numbers become 36 EJ (8.2% share) according to the BP method and 16 EJ (3.8% share) according to the IEA method. (There are also other accounting differences between BP and IEA statistics of world primary energy.)

BP uses its method in its annual *Statistical Review of World Energy* (1). The BP method is also used in the REN21 Renewable Energy Policy Network for the 21st Century (REN21) *Renewables Global Status Report* (3, 4) and in other prominent portrayals of renewables in the global energy balance, such as the 2000 *World Energy Assessment* (6) by the UN Development Programme [which later changed to the IEA method for its 2004 update (5)], and it has been used by analysts in the literature for at least the past decade (55, 67, 85). Most agencies and governments around the world

now use the IEA method. Although the IEA method appears to be much more common in the scenario literature, authors often do not explain which method is used. This causes incompatibility across scenarios and makes reliable comparisons difficult if not impossible. It also distorts the numbers. The share of renewables for a scenario using the IEA method will become significantly higher if the BP method is applied.

The basic accounting problem is how to count the primary energy associated with renewable electricity. For electricity from fossil fuels, primary energy is the energy input to a power plant to generate the electricity. For electricity from nuclear, the convention has been to count the nuclear heat input (equivalent to fossil fuel primary input) to generate the electricity. Because renewables (except biomass) do not require a power plant, the IEA method simply counts the electricity itself as primary energy. The BP method counts the “equivalent primary energy” of fossil fuels needed to generate the electricity. The difference between the two methods is the energy loss (waste) in a power plant, which is usually about two thirds of the energy input. The correction required is to multiply renewable electricity by the inverse of typical power plant efficiency to get equivalent primary energy; BP uses a correction factor of (1/0.38), or 2.6.

A simple way to understand the issue is to compare hydro and nuclear in the reported

Traditional biomass:
unprocessed agricultural residues, fuel wood, and animal dung burned in stoves or furnaces, typically in rural areas

Terawatt-hour

(TWh): measures large quantities of electricity, equal to one billion kilowatt hours (kWh); kWh more commonly measures consumption

Final energy:

energy consumed by a building, factory, or car, counting the energy value of actual electricity, gasoline, coal, or gas used

share of primary energy. In 2004, hydro and nuclear produced roughly equal amounts of electricity worldwide, 2740 terawatt-hours (TWh) for nuclear and 2810 TWh for hydro (86). BP reports the share of world primary energy from nuclear as 6.1% and from hydro as 6.2%. The IEA reports the share of primary energy from nuclear as 6.5%, equivalent to BP given other accounting differences (e.g., different assumed conversion efficiencies and inclusion of traditional biomass). But the IEA reports the share from hydro as only 2.2%. This 2.2% share for hydro is cited widely (5, 87). When compared with 6.5% from nuclear, it appears that nuclear contributes three times as much useful value to the energy system as hydro, when in fact the useful value (kWh produced) of nuclear and hydro is exactly equal. Thus, the IEA method perceptually distorts the contribution of hydro to the world energy system. This is also true for wind and solar, which fall into the same analytical category, but not for biomass where physical energy inputs can be counted in a way similar to that for fossil fuels. Geothermal is sometimes treated like nuclear. (This review reports renewables' shares as given in source material without correction or notation as to whether they are based on the IEA or BP method. A reader may discern the method used in some scenarios with a close reading and may presume the IEA method in ambiguous scenarios.)

Another problem in reporting primary energy shares of renewables concerns the treatment of traditional biomass in developing countries. Worldwide, traditional biomass represents about 9% of primary energy consumption (3), yet many scenarios do not specify whether traditional biomass is included or excluded, making it difficult to judge the share and growth of other forms of renewables. Further complicating the picture is that IEA statistics do not separate traditional biomass from modern biomass (for large-scale power and heat, gasification), so primary energy shares of renewables reported by the IEA either include traditional biomass or exclude all forms of biomass (called combustible

renewables and waste) (88). Some authors have advocated future targets and scenarios for new renewables only, excluding traditional biomass by arguing that at least a portion of traditional biomass is not sustainable (because it can lead to deforestation and can also be a major cause of indoor air pollution, among other things) and therefore should not be considered renewable (89). (This review reports renewables' shares as given in source material without any correction for traditional biomass and mostly without notation as to whether traditional biomass is included.)

Share of primary energy remains the dominant indicator for most scenarios (**Table 2**). Four alternative indicators are gaining increased use in studies and policy discussions.

1. Share of final energy. Few statistics are available for this indicator, and few scenarios use it. (Scenarios often show share of final energy by end-use sector and sometimes by final biomass or solar heat use, but not by renewable shares of final electricity consumption.) This indicator counts the energy value of electricity equally for all forms—fossil, nuclear, and renewables, but in statistical practice, this is difficult to do.
2. Share of electricity. This indicator is common in many scenarios, and statistics are available for many countries (**Table 3**). In 2005, renewables provided about 19.5% of world electricity production of 17500 TWh (1–4). Large hydro accounted for about 16.2% and other renewables about 3.3%. Some scenarios separate large hydro from new renewables, allowing sharper focus on future increments of new renewables, which are growing much faster than large hydro (66, 80).
3. Share of low-temperature heat. This indicator is rarely used in scenarios but is becoming more important as biomass, solar, and geothermal increase their contributions to heating and hot water. A surrogate is the thermal capacity

Table 2 Share of primary energy from renewables—policy targets and scenarios^a

Region/ country	2004 actual ^b	2010 policy targets ^c	2020 policy targets or scenarios ^d	Up to 2050 scenarios ^e	References for scenarios
World	3.8% or 8.2% or 13.0% or 16.5%	—	5%–15% low/reference	10%–15% low/reference	19–22, 32, 73, 87, 142
			15%–20% medium	25%–30% medium	22, 29, 30, 32, 33, 73, 87
			25% high	40%–50% high	19, 25, 28–30, 31, 33, 35, 36
Europe (EU25)	6.5%	12%	10% reference/ carbon constrained	15%–20% reference (by 2030)/carbon constrained	20, 21, 46, 47
			20% target	30%–40% policies (by 2030)	37–40, 43, 46–48
			23% revolution	50% revolution	45
United States	4.2%	—	7% reference	8% reference	21, 51, 52, 54, 55
			20% revolution	50% revolution	19
Japan	1.2% ^f	3% ^f	—	6% (2030) reference 17%/22% (2030) 25%/50% (2050) high/community	21, 56, 57
China	7.5%	10%	16% target	20%–30% policies	19, 58–62
Brazil	41%	—	30% high	—	63
India	39%	—	30%–35% policies	15%–30% policies	21, 65
Mexico	10%	—	20%–30% high	—	64
Thailand	6%	8%	—	—	
Germany	3.9%	4%	10% target	50% advanced	83
Netherlands	2%	—	—	80% policies	84
Poland	4.7%	7.5%	14% target	—	99
Spain	6.2%	12.1%	—	—	

^aPolicy targets and 2004 actual are from International Energy Agency (IEA), REN21 Renewable Energy Policy Network for the 21st Century, and European Commission publications (2–4, 12, 63, 88, 93–94), supplemented by data from scenarios cited. Most targets and scenarios count (or are presumed to count) renewable electricity according to the IEA method (see text); but the numbers would be higher if the BP method were applied. Targets or scenarios may not specify which method is used. Most global scenarios include traditional biomass, but some country targets and scenarios do not (e.g., the numbers shown for Thailand and China exclude traditional biomass). “Policies” means policy-intensive; “reference” also means “baseline.”

^bWorld actual 2004 depends on the accounting method used; see **Table 1** and the text. For comparison with most targets and scenarios, the 13% actual (IEA method with traditional biomass) should be used. Estimates for Europe actual 2004 vary from 5.6% to 7.5%.

^cThailand target for 2011.

^dNo world policy targets exist; the Mexico scenario is for 2025.

^eMost scenarios in this column are for 2050, except the world (29) for 2040; and the following are for 2030: world (21), Europe (21, 38–40, 43), United States (21, 51), and Japan (21, 56).

^fJapan’s 1.2% share in 2004 and 3% target in 2010 exclude large hydro and geothermal. The share in 2004 including those sources has been reported as either 3.4% or 5.2%.

Table 3 Share of electricity from renewables—policy targets and scenarios^a

Region/country	2005 actual ^b	2010 policy targets	2020 scenarios or policy targets ^c	Up to 2050 scenarios ^d	References for scenarios
World	19%	—	15%–20% low/reference	15%–25% low/reference	19, 22
			20%–25% medium	30%–40% medium	20, 22, 23
			35%–40% high	50%–80% high	19, 25, 29
Europe ^e (EU25)	14%	21%	15%–20% reference	20%–25% reference (by 2030)	20, 21, 38–40, 43, 47
			25% carbon constrained	30% carbon constrained	20
			30% policies	45%–60% high (by 2030)	20, 25, 38–40, 43, 46, 47
			35% revolution	70% revolution	45
United States ^f	8%	5%–30% state targets	5%–33% state targets	9%–11% reference 11%–15% alternative (by 2030)	21, 51
			20% advanced and blueprint	50% high ^g	25, 49, 52, 53, 55
			30% revolution	80% revolution	50
Japan ^a	0.4% actual + 10% large hydro	1.35% target + large hydro	11% reference	11% (2030) reference 33%/41% (2030) high/community 50% high	21, 56 25
China	16%	—	15%–25% reference	15% reference (by 2030)	21, 60
			35% policies	20%–40% policies advanced/alternative	21, 25, 58–62
			—	50% revolution	19
Asia-Pacific region ^h	16%	—	17% reference 39% accelerated	17% reference 50% accelerated	67
Latin America region	—	—	—	33% reference 90% revolution	19
Brazil ^a	5%	—	22% high	—	63
India ⁱ	11%	5%–10% state targets	18% reference 27% policies	12%–25% reference 40% high mitigation (by 2035)	21, 61, 66, 67
Mexico	16%	—	15% high	—	63
Germany	10%	12.5%	20% target	—	—
South Korea	1%	7%	—	—	—

^aPolicy targets and 2005 actual figures are from International Energy Agency (IEA), REN21 Renewable Energy Policy Network for the 21st Century (REN21), and European Commission (EC) publications (2–4, 12, 63, 88, 93, 94), supplemented by data from scenarios cited. Most targets and scenarios include large hydro, but some may not. The scenarios for Brazil and Japan's target of 1.35% by 2010 exclude large hydro.

^bThe Europe actual is for 2004. The Asia-Pacific region actual is for 2000. Figures are rounded to nearest whole percent.

^cThe Asia-Pacific region scenario is for 2025.

^dMost scenarios are for 2050, except world (29) for 2040, and the following are for 2030: Europe (21, 38–40, 43), United States (21, 51), and Japan (21, 56).

^eThe EC in 2006 anticipated an actual 18% share of electricity by 2010.

^fPolicy targets are given equivalent to state-level renewable portfolio standards (RPS) policies in most U.S. states; no national-level target exists. California in 2005 proposed 33% share by 2020, up from 20% RPS by 2017 (<http://www.newrules.org>, viewed 1/31/07).

^gThe World Business Council for Sustainable Development (25) scenario for 2050 of 50% is for Canada and United States combined.

^hAsia-Pacific region includes Australia, Brunei Darussalam, Canada, Chile, China, Chinese Taipei, Hong Kong, Indonesia, Japan, Korea, Malaysia, Mexico, New Zealand, Papua New Guinea, Peru, Philippines, Russia, Singapore, Thailand, United States, and Vietnam.

ⁱIndia has national policy targets of 10% of new capacity added from 2003 to 2010, 15% of total capacity by 2032, plus RPS policies in several states that serve as state targets.

Table 4 Share of transport energy from renewables (biofuels)—policy targets and scenarios

Region/country	2008–2015 policy targets ^a	Up to 2050 scenarios with references in parentheses
World	—	3% low (22) 15% med (22, 25) 25% high (22)
Europe (EU25)	5.75% energy share	6%–7% by 2030 reference (40, 43) 14%–26% by 2030 alternative (40, 43) 21% by 2050 (25)
France	10% energy share	—
Germany	E2	—
United States ^b	E10 in 3 states	25% (25)
Brazil	E25	
China	E10 in 9 provinces	
India	E10 in 13 states/territories	
Philippines	E10 (proposed)	
Thailand	E10	

^aSource for policy targets: Renewable Energy Policy Network for the 21st Century (REN21) (3–4). E2, E10, and E25 refer to a blending mandate for blending all gasoline with 2%, 10%, or 25%, respectively, ethanol, which would result in a smaller share of transport fuels, taking into account other fuels not affected by the mandate, such as diesel and aviation fuel. Data on transport energy shares of biofuels implied by these blending requirements are often not readily available. Blending requirements for biodiesel are also appearing in several countries, typically B2 or B5; see REN21 (3–4).

^b2050 scenario is for the United States and Canada combined.

installed, expressed as GWth. No statistics are available for a world total, and this indicator exists only for a few countries. Europe’s share is about 7%.

4. Share of transport energy from renewable fuels. This indicator is becoming more common in scenarios as biofuels production has grown rapidly in recent years and new policy targets and mandates have been enacted (**Table 4**). No statistics are available for a world total. Europe’s share is about 1%.

GLOBAL SCENARIOS

Ten of the most prominent and recent global scenarios are described below. These are summarized in **Tables 2–4** along with several other global scenarios reviewed (29–31, 36).

1. The IEA’s *World Energy Outlook 2006* (21) provides an often-cited reference scenario for 2030 that predicts 720-

EJ world primary energy supply (up from 480 EJ in 2004) of which renewables are 100 EJ (14%). Electricity in 2030 is 33,800 TWh (up from 18,200 TWh in 2005) of which renewables are 7100 TWh (21%). The alternative policy scenario includes additional policies to support renewables that are contemplated or expected but not yet enacted. This scenario shows renewables achieving 16% of primary energy and 26% of electricity by 2030 with gains in biomass, wind, solar, and geothermal.

2. The IEA’s *Energy Technology Perspectives* (22) gives several scenarios that go beyond the *World Energy Outlook* and that differ on pace of cost reductions and technology development. The ACT Map scenario shows aggressive policy action, energy intensity reductions, and technology cost reductions through deployment and learning. Biofuels

Carbon capture and storage (CCS):

removal of carbon from power plant emissions or fuel and injection into geological formations or oceans

- becomes a viable transportation fuel with increased crop yields and commercial cellulose-to-ethanol technology. Carbon capture and storage (CCS) becomes viable, and nuclear power increases significantly. Three variations of ACT Map are a low-renewables case with slower cost reductions, a low-nuclear case, and a no-CCS case that assumes CCS remains commercially unavailable. Under ACT Map, the share of primary energy for renewables is 24% by 2050, compared to 11% in the reference scenario, and the share of electricity is 31%, compared to a 15% reference. A separate “TECH Plus” scenario envisions even higher technology progress for renewables, nuclear, hydrogen fuel cells, and advanced biofuels with renewables’ share of primary energy reaching 30% by 2050.
3. The German Advisory Council on Global Change’s (28) “exemplary path” scenario achieves 450 ppm CO₂ atmospheric stabilization. The scenario places several additional constraints on energy beyond carbon, including restrictions on land use for biomass energy crops, limits on urban air pollution levels, avoidance of nuclear power, and achieving a minimum economic output per capita for all countries. This scenario shows supply of 620 EJ of renewables in 2050 (up from 80 EJ total in 2004) of which 288 EJ is solar PV, 135 EJ is wind, and 100 EJ is modern biomass. Renewables reach 50% of primary energy supply by 2050.
 4. A World Business Council on Sustainable Development’s (25) scenario envisions 50% of electricity from renewables by 2050. Nuclear power triples by 2050, and CCS from coal becomes commercial after 2025, such that by 2050, half of world’s coal power generation uses CCS. Hydrogen becomes a fuel for vehicles after 2025, attaining a 25% share of vehicle transport fuel by 2050. Solar PV grows by an sustained annual average of 20% through 2050, spurred by distributed generation and local energy storage, to become 15% of world electricity consumption—one of the highest estimates for solar among global scenarios. Wind and geothermal grow by an annual average of 11% through 2050 to increase 160-fold, and hydro doubles.
 5. Shell produced three scenarios, with the original 1996 “sustainable development” scenario showing 50% of world primary energy from renewables by 2050 (35). That scenario was widely cited for a number of years. Subsequently, Shell’s “spirit of a new age” in 2001 showed a future energy system emerging by 2030, which employs hydrogen and fuel cells and limits the growth of renewables (with hydrogen initially produced from fossil fuels using carbon sequestration) (32). Renewables attain a 28% share of primary energy by 2050. Complimenting that scenario was “dynamics as usual,” with a continuing dominant role for electricity, hybrid vehicles, advanced biofuels, and renewables attaining a 33% share of primary energy. Then in 2005, “low-trust globalization,” “open doors,” and “flags” scenarios were envisioned with (a) varying fortunes of globalization, regulation, and markets and with (b) renewables reaching either 280 or 330 EJ by 2025 (27).
 6. The Greenpeace & EREC (19) revolution scenario envisions the complete phaseout of nuclear power, drastically lower energy demand through energy efficiency improvements, no carbon capture and storage, and attainment of 450 ppm CO₂ atmospheric stabilization. The result is a 50% primary energy share for renewables by 2050 and an aggregate energy demand in 2050 that is the same as 2003, even as population increases 1.4-fold and GDP increases

- 3.4-fold. Electricity share is 70% renewables with the rest mainly natural gas. The share of electricity from coal falls to 9% by 2050, from 35% in 2003. The study assumed annual growth rates for wind power of 26% through 2010, 20% for 2010–2020, 7% for 2020–2030, and then below 5%. Growth rates of solar PV are 36% through 2010, 25% for 2010–2020, 14% for 2020–2030, 7% for 2030–2040, and then below 5%.
7. The GWEC & Greenpeace (23) “advanced” scenario envisions aggressive policies and cost reductions leading to 34% of world electricity from wind by 2050 in a high-efficiency case where electricity consumption in 2050 is only 1.7-fold higher than 2003. (Without high efficiency, the advanced scenario for 2050 shows a 21% share of electricity and world electricity consumption 2.8-fold higher than 2003.) Under the advanced scenario, by 2020, wind power costs fall to US\$3.5 to 4.5 cents/kWh at good sites, and installed capacity reaches 1000 gigawatts (GW) (from 75 GW in 2006). Installed capacity exceeds 2000 GW by 2030 and 3000 GW by 2050.
 8. The EC’s *World Energy Technology Outlook (WETO)–2050* (20) study developed “carbon constraint” and “hydrogen” scenarios. The carbon constraint scenario works backward from stabilizing atmospheric CO₂ concentration at 500 ppm by 2050, using renewables, nuclear power, and carbon capture and storage. Early action is assumed in developed countries, with later action in developing countries. The hydrogen scenario assumes a deliberately optimistic series of technology breakthroughs that increase cost-effectiveness. World primary energy reaches 920 EJ in the reference scenario and about 800 EJ in both the carbon-constrained and hydrogen scenarios. The reference scenario predicts 15% primary energy and 21% electricity from renewables by 2050, which increases to 18% to 20% primary energy and 30% electricity in the carbon constraint and hydrogen scenarios.
 9. The International Institute for Applied Systems Analysis and the World Energy Council (33) developed six scenarios in the 1990s, showing different levels of global economic development and energy use. Scenarios A1–A3 show high economic growth, with A3 the most sustainable case showing a shift to renewables, nuclear, and natural gas. Scenario C is high growth for developing countries and uses carbon and energy taxes that promote renewables and efficiency; C1 sees a phaseout of nuclear power, whereas C2 sees development of the next generation of socially acceptable reactors, which limits renewables. Primary energy share from renewables ranges from 22% to 40% by 2050 among the six scenarios, with scenario C1 showing the highest.
 10. The IPCC’s *Special Report on Emissions Scenarios* (7, 73) used six different models and four story lines, resulting in 40 scenarios. The scenarios differ in population, economic development, and energy intensities, but they also differ because different models produce different results for the same conditions. The A1 story line envisions rapid economic development equalizing rich and poor, whereas A2 sees less growth and slower change. Story lines B1 and B2 envision high environmental consciousness, and B2 is policy intensive with policies and business influenced by environmental concerns and movement toward local self-reliance and community. Total primary energy supply ranges from 640 to 1600 EJ by 2050, and renewables range from 70 EJ to 440 EJ. The primary energy share of renewables is highest for the subscenario A1T and the B1 scenario, i.e., 16% to 35%, with

Gigawatt (GW or 10⁹ watts):

measures large amounts of electric power capacity; a typical power plant is about one GW

large technological change and reductions in renewables' costs for the A1T subscenario.

In summary, by 2050, renewable energy varies from 70 EJ to 450 EJ primary energy supply according to most of the global scenarios reviewed (**Figure 1**), with a few even higher. This compares with a range of total primary energy from the same scenarios of 600 to 1600 EJ. Global scenarios for share of primary energy by 2050 can be grouped into three categories: low (15%), medium (25% to 30%), and high (40% to 50%) (**Table 2**). For the share of world electricity by 2050, reference scenarios show 15%, medium scenarios 30% to 40%, and high scenarios 50% to 80% (**Table 3**) with total generation from renewables ranging from 7200 to 37,000 TWh (**Figure 2**). The few scenarios showing the share of transport energy from biofuels in 2050 show a wide range, from a low of 3% to a high of 25% (**Table 4**).

The IEA ETP (22) reference scenario is one of the lowest for renewables with 11% primary energy share by 2050. In contrast, several global scenarios show a 50% share by 2050, including Shell's sustainable development, Greenpeace & EREC's "revolution," the Germany Advisory Council's exemplary path, WBCSD's scenario (25), the EREC's (29) "advanced international policies scenario" (by 2040), the Aitken et al. (30) "10%/20%/50%" scenario (with 10% by 2010 and 20% by 2020), and the Stockholm Environment Institute & Global Scenario Group's "great transition" (31). One of the earliest was the Johansson et al. (36) "renewables-intensive global energy scenario," which envisioned, back in 1993, a 46% share by 2050. Other global scenarios fall between the IEA reference and these 50% scenarios.

CO₂ emissions by 2050 in the global scenarios range from 10 to 100 Gt (per year). (In 2004, CO₂ emissions were about 26 Gt from fossil fuels.) The low and reference scenarios show emissions in the range of 60 to

100 Gt, whereas the medium scenarios show 20–30 Gt, and the high scenarios (19, 25) show 10 to 12 Gt. For the IEA ETP (22), emissions are 58 Gt for the reference scenario, 26 Gt for ACT Map, and 21 Gt for TECH Plus. IPCC (73) scenarios show a wide range of emissions, from 30 to 100 Gt, corresponding to total energy consumption from 640 to 1600 EJ, and a range of renewable energy shares from 9% to 35%. In the EC's WETO (20) carbon constraint scenario, emissions stabilize between 2015 and 2030 and then decrease, but by 2050, emissions are still 25% above the 1990 levels.

EUROPE TARGETS AND SCENARIOS

Renewable energy in Europe is closely connected to issues of climate change, security of supply, import dependency, market competitiveness, sustainability, and future energy development. Directives of the European Commission have established aggressive policy targets for shares of primary energy (12%), electricity (21%), and transport fuels (5.75%) from renewables by 2010, as well as a solar hot water target (100 million m² of collector area). All European Union (EU) countries also have individual targets for share of electricity, ranging from 3.6% to 78%, which together should achieve the 21% EU target. The increases in electricity shares from 1997 are typically 5% to 10% for most EU countries. Several countries also have targets for share of primary energy by 2010, including the Czech Republic (5% to 6%), France (7%), Germany (4%), Latvia (6%), Lithuania (12%), Poland (7.5%), and Spain (12.1%). During 2005–2006, the European Commission prepared a "green paper," road map, and "biomass action plan" on strategies to achieve these targets and go beyond them, proposing targets of 20% primary energy and 10% of transport energy by 2020 (3, 4, 90–95).

During 2005–2006, there were a large number of new energy scenarios published for Europe, primarily for 2030, including

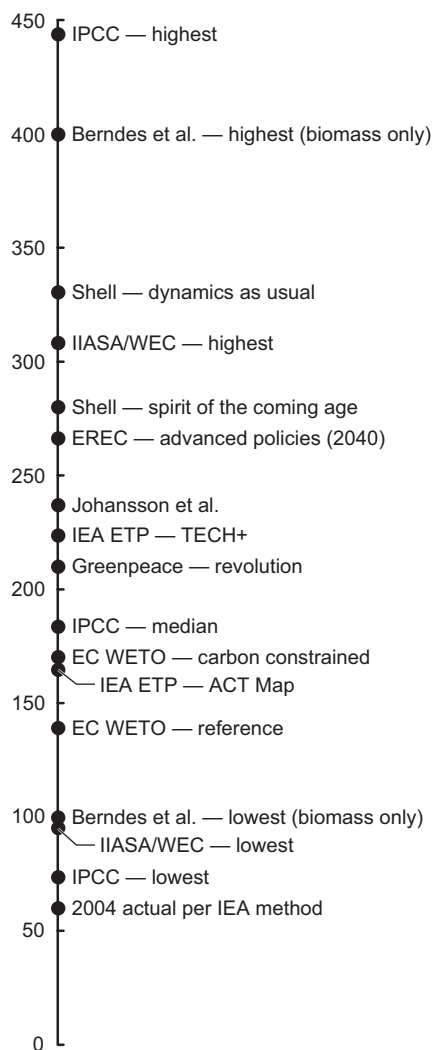


Figure 1

World primary energy from renewables in 2050 (EJ) as shown by various scenarios by Berndes et al. (112), European Commission (EC) (20), European Renewable Energy Council (EREC) (29), Greenpeace & European Renewable Energy Council (19), International Energy Agency (IEA) (22), IIASA/WEC (33), IPCC (73), Johansson et al. (36), Royal Dutch/Shell (32). Actual for 2004 from References 1–4.

scenarios by the Directorate-General for Energy and Transport (DG-Tren) (38, 39), Directorate-General for Environment (DG-Env) (37), the European Parliament Committee on Industry, Research and Energy

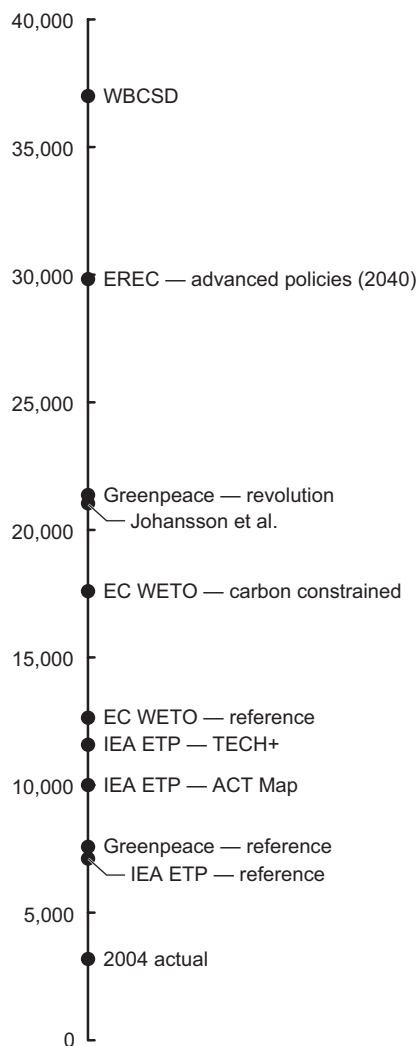


Figure 2

World electricity from renewables in 2050 (TWh) as shown by various scenarios by European Commission (EC) (20), European Renewable Energy Council (EREC) (29), Greenpeace & European Renewable Energy Council (19), International Energy Agency (IEA) (22), Johansson et al. (36), World Business Council for Sustainable Development (WBCSD) (25). Actual for 2004 from References 1–4.

(ITRE) (40), the Greens/EFA group of the European Parliament (43), the European Environment Agency (44), Greenpeace (45), WWF/Wuppertal (47), and Ragwitz et al. (46) of the Fraunhofer Institute. These add

to many other Europe-wide and individual country scenarios (83, 84, 96–100).

European reference scenarios expect that current trends in energy and economy will remain nearly the same, including existing barriers and grid restrictions. Climate policies, energy efficiency improvements, and technology developments are included, but policy targets may not be met, and post-Kyoto measures have not been taken. Primary energy supply grows very little, to around 80 EJ by 2030, compared to 73 EJ in 2005, owing to improvements in energy intensity, even as the GDP continues to increase. The share of renewables grows from around 7% in 2005 to 11% to 13% by 2030 according to most scenarios (38–40, 43, 46, 47). Electricity share increases modestly from 14% in 2005 to 18% to 29% in 2030.

Policy-intensive alternative scenarios are featured in most studies. These generally fall into categories of (a) high efficiency, (b) high renewable energy, and (c) combined energy efficiency and renewable energy, depending partly on the mix of policies that primarily promote efficiency, renewables, or both. DG-Tren (38, 39) studies consider all three separately, whereas the ITRE study (40) considers two of the three, and most studies only focus on the combined scenario. The high-efficiency scenarios show less energy demand but also smaller shares of renewables, but the opposite is true for the high renewables scenarios. Combined scenarios have lower demand and higher renewables. Stable conditions for investments and technology development and gains in energy intensity result from full implementation of relevant EU directives and policies, along with active national policies, including targets, research and development, market incentives, training, carbon pricing, and international climate policy. These scenarios can be considered high alternatives for renewables with ambitious strategies and policies.

Under the alternative scenarios, renewables reach a primary energy share of 20% to 24% by 2020 in the FORRES (46), WWF

(47), DG-Env 20% (37), and EREC (48) scenarios. By 2030, renewables reach 17% to 21% under the medium European Environment Agency (EEA) (44) and IEA (21) scenarios, and 26% to 39% under the high DG-Tren (38, 39), Vision (43), and ITRE (40) scenarios. By 2050, renewables reach 50% under the Greenpeace (45) scenario. Primary energy demand decreases by 13% to 18% by 2030 in most scenarios and by 36% by 2050 under the Greenpeace scenario.

Electricity share in alternative scenarios increases from 14% in 2005 to 30% to 60% by 2030 in the alternative scenarios. By 2050, renewables' electricity share increases to 45% under the WBCSD (25) scenario (mostly wind and solar power) and to 70% under the Greenpeace & EREC (19) scenario. [Despite the high share, the Greenpeace scenario does not have significantly more total power generation from renewables than some of the other scenarios because total electricity demand is lower in the Greenpeace scenario (see **Figure 2**).]

Studies differ greatly in projected shares of biofuels. There are accounting problems that make some cross-scenario comparisons incompatible, as some studies use share of total transport-sector energy and some use share of road transport fuels. ITRE (40) and Vision (43) reference scenarios give biofuels 6% to 7% of the total transport-sector energy demand by 2030 and 14% to 26% in the alternative scenarios. The WBCSD (25) puts biofuels share at 21% in 2050.

For low-temperature heat production, the current share of renewables in Europe is 6% to 7%, and ~90% of that is from biomass (92). Scenarios do not provide many specific figures for low-temperature heat, but some put the share at 14% to 20% by 2030. Scenarios show that renewables in the heating sector (particularly biomass and solar) are important in achieving high shares of primary energy under alternative scenarios. The European Solar Thermal Technology Platform (41) envisions that 50% of Europe's low-temperature heating, hot water, and cooling needs could be

met by renewables by 2030. One goal of the Platform is a new building standard by 2030 that would require 100% solar heating for new buildings and 50% solar heating retrofits for existing buildings.

The EC's WETO (20) hydrogen carbon-constrained scenario for Europe is different than most other alternative scenarios. A deliberately optimistic series of technology breakthroughs increase the cost-effectiveness of hydrogen technologies and lead to significant hydrogen use in transport. Nuclear energy is used to produce hydrogen starting after 2030 and provides one third of total energy demand by 2050. Renewables produce almost half of the hydrogen by 2050, although renewables' primary energy share by 2050 remains a modest 20%.

Radically different European scenarios also exist in the literature: some focus on the complete phaseout of nuclear power or, conversely, high levels of nuclear; some focus on CO₂ stabilization (e.g., at 450 ppm) or on limits to per capita CO₂ emission (e.g., 3 tons CO₂/person in 2050); some have dramatically higher energy prices; and some have high carbon-market prices. Renewables generally increase with decreasing nuclear under carbon-constrained scenarios and also with higher energy and carbon prices (37, 40, 44, 45).

CO₂ emissions in Europe are 3.8 to 4.5 Gt by 2030 in reference scenarios and 2.1 to 2.6 Gt in alternative scenarios. (In 2005, EU-25 emissions were 3.8 Gt from fossil fuels.) For 2050, Greenpeace & EREC (19) give 5.3 Gt in the reference and 1.2 Gt in the revolution scenario, whereas the WWF (47) gives 4 Gt in the reference and 2.5 Gt in its policies scenario.

COUNTRY-SPECIFIC TARGETS AND SCENARIOS

In addition to the many global and European scenarios, there are a growing number of country-specific scenarios. A sample of these scenarios is reviewed in this section, starting

with country-specific policy targets that can often serve as stepping stones to longer-term scenarios.

Country Policy Targets

By 2006, more than 50 countries and 32 states/provinces around the world had some type of policy target for future shares or amounts of renewable energy (3, 4). Most targets are for 2010 or 2020. Targets exist at national, state/provincial, and municipal levels. Most targets are for shares of primary energy, electricity, and transport fuels (some of these are shown in **Tables 2–4**). Many individual countries are also enacting road maps or strategies in conjunction with targets, such as New Zealand and South Africa (101, 102).

Some countries have opted to target specific amounts of added renewable power capacity by a future year (there is usually no accompanying figure for implied share of renewables). Prime examples in this category are Brazil (3.3 GW to be added by 2006), the Dominican Republic (0.5 GW added by 2015), India (10% of new capacity additions through 2012), and the Philippines (4.7 GW added by 2013). Other countries have policy targets for specific amounts of final energy (electricity and/or heat) from renewables. Examples are Australia (9.5 TWh/year by 2010), New Zealand (8.3 TWh/year by 2012), Norway (7 TWh/year by 2010), South Africa (10 TWh/year by 2013), and Switzerland (3.5 TWh/year by 2010).

Like Europe, China has a comprehensive set of targets. The overall target is 16% of primary energy from renewables by 2020 (up from 7.5% in 2005). There are also targets for individual technologies by 2020, including hydro (300 GW), wind and biomass power (30 GW each), solar PV (1.8 GW), solar hot water (300 million m²), biofuels (15 million liters/year), biogas and biomass gasification (44 million m³/year), and biomass pellets (50 million tons/year) (3, 4). All technology targets reflect threefold to 20-fold increases

from 2005 in the amount of renewable energy or capacity.

United States

The EIA *Annual Energy Outlook* (51) projects primary energy in the United States will increase by 1.1%/year through 2030 in the reference scenario. By 2030, renewables' share will be 8% (10–11 EJ total), compared to 6% in 2004 (6 EJ total). In a “high economic growth” scenario, renewables remain about the same as the reference scenario. Higher amounts of renewables from previous years' projections are the result of higher expected energy prices, more policy action, technology improvements, and lower energy consumption. The 8% share is reached 10 years earlier in the Interlaboratory Working Group's “advanced” scenario (55).

The EIA projected electricity generation share for 2030 remains constant at 9% (560 TWh) in the reference scenario and increases to 11% in a “high renewables” scenario (640 TWh), compared to a 9% share in 2004 (360 TWh). The high renewables scenario projects greater use of wind, biomass, and geothermal. Other scenarios show much higher shares. Both the Interlaboratory Working Group (55) and Clemmer et al. (53) show a 20% share by 2020. A study led by Kutscher (49) says that 50% of electricity from renewables by 2030 is possible with lower demand from energy efficiency, but even a 40% share is possible for the EIA reference scenario. Similarly, the WBCSD (25) shows renewables' electricity share (for both United States and Canada) going from 17% in 2002 to 50% in 2050. Greenpeace & EREC (50) show an 80% share by 2050, as renewables' power capacity grows eightfold from 110 GW in 2004 to 890 GW in 2050.

CO₂ emissions in 2050 in the Greenpeace & EREC (50) study are 8.4 Gt in the reference scenario and 1.6 Gt in the revolution scenario (U.S. emissions in 2003 were 5.6 Gt CO₂). The revolution scenario shows a dramatic reduction in per capita CO₂ emissions from

19.2 tons/person in 2003 to 3.7 tons/person by 2050. The Kutscher study (49) shows about a 2-Gt CO₂ reduction possible by 2030 from greater renewables, plus another 2.5 Gt from efficiency, reducing CO₂ emissions in 2030 to 3.6 Gt, compared to a reference scenario of 8 Gt.

Japan

The Citizens' Open Model Projects for Alternative and Sustainable Scenarios (COMPASS) (56) developed a “revival” scenario, which focuses on economic and environmental sustainability under continued economic growth. Total primary energy in 2030 is only 5% higher than 1990 levels, the primary energy share from renewables reaches 17% (up from 3.4% in 2004), and the electricity share reaches 33% (up from 10% in 2005). Beyond revival, a “switchover” scenario envisions a new paradigm of reduced consumption and community orientation, coupled with local use of renewable energy. In the switchover scenario in 2030, total primary energy is 30% below 1990 levels, the primary energy share from renewables reaches 22%, and the electricity share reaches 41%. This COMPASS reference scenario is almost identical to the *Long-Term Energy Supply and Demand Outlook* of the Ministry of Economy, Trade, and Industry (MITI) (M. Ohbayashi, personal communication). For the reference scenario, primary energy increases by 20% over 1990 levels, primary energy share from renewables is 6%, and the electricity share is 11%. This is similar to the IEA's WEO (21) reference scenario for Japan.

Two other studies also go well beyond the MITI reference scenario. The WBCSD (25) envisions large-scale development of biomass, wind, and distributed solar PV, with 50% of electricity from renewables by 2050. The National Institute for Environmental Studies (57) gives two scenarios for Japan: “Doraemon,” which envisions technology breakthroughs and continued centralized energy production, and “Satsuki and Mei,”

which emphasizes decentralization, community, and self-sufficiency. The first scenario projects mostly nuclear, hydrogen, and carbon capture and storage, with about 25% of primary energy from renewables by 2050. The second scenario projects much greater use of renewables, almost 50% of primary energy by 2050, particularly from biomass and solar PV.

China

The China Energy Research Institute & Lawrence Berkeley Laboratory (62) considered three scenarios to 2020 for China, all with the same GDP growth but differing in urbanization rates, technology development, and policies for energy supply and efficiency, among other factors. The “ordinary effort” scenario shows less priority on environment than implied by ongoing and expected government plans, and the “promoting sustainability” scenario fulfills expectations. A “green growth” scenario represents extra effort in energy efficiency and renewables. By 2020, energy consumption doubles to 90 EJ (from 42 EJ in 2000) under ordinary effort, whereas energy consumption only rises to 67 EJ under green growth. Renewables’ power capacity under green growth is 200 GW of large hydro, 30 GW of wind power, and 40 GW of small hydropower, comparable to actual policy targets enacted.

The Chinese Task Force on Energy Strategies and Technologies’ (59, 61) “advanced technology” scenario relies heavily on coal gasification, which expands from 0% in 2000 to 60% of primary energy by 2050 (accompanied by a reduction in coal combustion to only 8%). At the same time, primary energy share of renewables increases from 7% to 18%. Because of energy intensity improvements, while the economy expands 13-fold by 2050, primary energy only increases 3.5-fold, from 42 EJ in 2000 to 135 EJ in 2050, accompanied by a ninefold increase in renewables from 2.8 EJ to 24 EJ. Similarly, a Tsinghua University scenario shows primary energy from

renewables at 28% by 2050, with economy and energy projections to 2050 updated from the Task Force scenario (58). Although energy use increases 3.5-fold in China, primary energy share increases 4-fold, leading to a 14-fold increase in renewables by 2050. The WBCSD (25) scenario envisions 38% of electricity from renewables by 2050, with 1000 GW of wind capacity. Kroeze et al. (60) show 24% share of electricity by 2020 for a reference scenario and 37% for a policy scenario.

CCS in the IEA’s ETP (21) ACT Map scenario has a significant impact on total Chinese CO₂ emissions from power generation. The carbon intensity of power generation falls from 1100 in 2003 to 800 in 2050 (gCO₂/kWh) under the reference scenario, but it falls to 500 with CCS under the ACT Map scenario.

Other Developing Countries

There are very few energy studies that look at developing countries as a group. One such effort was the “RECIPES” project on renewable energy markets in developing countries, sponsored by the EC Research D-G (63). During 2005–2006, the project collected data on 114 countries and wrote over 2000 pages of project reports. The study constructed future projections on the basis of estimates of market potentials. The “maximum” scenario for the group of 114 countries shows a tripling of primary energy from renewables in these countries by 2020, from 7.7 EJ in 2003 to 23 EJ in 2020, with the primary energy share increasing 3% to 9%; however, the primary energy share increases to 4.5% by 2020 under the reference scenario. The project also studied 15 countries in detail, creating technology-by-technology scenarios to 2020 for Argentina, Brazil, Colombia, Mexico, Peru, Cameroon, Ghana, Niger, South Africa, Uganda, China, Pacific Islands, India, Indonesia, and Thailand. For South Africa, the maximum scenario shows electricity from renewables growing from 1% in 2003 to 5% by 2020. For Brazil, renewables increase, but the share

declines from 74% to 65% as the electricity demand doubles.

Country-specific studies for developing countries tend to be less accessible. An excellent study for Mexico was done by Manzini & Martínez (64), who envision 20% to 30% of primary energy from renewables by 2020, under “conservation” and “sustainability” scenarios. Many country-specific studies have been developed primarily for carbon emissions purposes. For example, Van Buskirk (65) analyzed CO₂ emissions for Eritrea in East Africa through 2050 under different scenarios of efficiency and renewables. By 2100, CO₂ emissions grow 25-fold under the reference scenario but only fivefold under a “very high” renewables’ scenario.

For India, Ghosh et al. (66) show new renewables increasing from less than 1% in 2000 to 5% of power generation by 2035 for the reference case and to 20% for “high mitigation.” Large hydro maintains the same share in 2035 as in 2000—about 20%. With large hydro, the total share of renewables in power generation increases from 20% in 2000 to 40% in 2035. The high mitigation scenario shows a cumulative 530 megatons (Mt) carbon reduction from renewable electricity from 2000 to 2035. Kroeze et al. (60) show an 18% share of electricity by 2020 under a reference scenario and 27% for a policy-intensive scenario that substitutes renewables for coal. A TERI renewables-intensive scenario (68) shows less than 5% primary energy from renewables by 2030.

Some global studies provide regional breakdowns. The GWEC & Greenpeace (23) scenario for 2100 GW of wind power by 2030 shows 200 GW of this in Central and South America, 50 GW in Africa, and 130 GW in South Asia. The Greenpeace & EREC (19) scenario shows renewables’ share of primary energy in Latin America increasing from 28% in 2003 to 70% by 2050 and the share in Africa increasing from 47% to 58%. The IEA’s WEO (21) gives scenario results individually for Brazil, China, and India. The alternative policy scenario shows the share of

electricity from renewables, excluding large hydro, increasing in Brazil from 4% in 2003 to 8% in 2030, in India from 1% to 6%, and remaining stable at 85% in Brazil even as total electricity demand doubles by 2030. Brazil continues to rely on large hydro, building 66 GW of new capacity by 2030, and the share of biofuels in road transport fuel doubles from 14% in 2004 to 30% by 2030 in the alternative policy scenario.

Another multicountry study was done by the Asia-Pacific Energy Research Center (APEREC) for the Asia-Pacific region (which is a mixture of 21 developed and developing economies) with three scenarios for electricity in 2020 and 2050 (69). Under the reference scenario, policy development is slow, and electricity in the Asia-Pacific region increases from 7500 TWh in 2000 to 39,000 TWh in 2050, with 6800 TWh of renewables (17% share). The “accelerated development” scenario envisions vigorous policy development and capital investment prior to 2010, and the “delayed deployment” scenario envisions a 10-year delay, post-2010. In the accelerated development scenario, renewables grow to 50% of power generation by 2050, with 50-year average annual growth rates of 9% for biomass, 11% for solar PV, and 13% for wind.

Country “100% Scenarios”

A number of country-specific scenarios have envisioned a 100% share of energy from renewables, some of these dating back three decades. These include a 1980 scenario by the Union of Concerned Scientists for 100% in the United States by 2050 (103), a 1978 study by a group of research institutes for 100% in France by 2050 (104), a 1977 study by Johansson & Steen for 100% in Sweden by 2015 (105), and a 1981 study by Häfele et al. at the International Institute for Applied Systems Analysis (106) for 100% in Europe by 2100. More recently, the German parliament created a scenario for a 95% share in Germany by 2050 (107). A Japanese study envisions

a 100% future (108). A Netherlands policy-intensive and carbon-constrained study (to 80% of 1990 levels) gives an 80% share (84). The International Network for Sustainable Energy is providing country-based sustainable energy visions for 100% renewables by 2050 (109). And Sørensen (110) based a low-energy zero-carbon global scenario on 100% renewables. Most 100% scenarios give large shares to solar PV, wind, and solar thermal power, and most imply large shares (i.e., 30% to 50%) of distributed generation. A few show very large shares of biomass, such as 60% to 70% shares of primary energy in the Dutch and Swedish studies.

MUNICIPAL POLICY TARGETS AND SCENARIOS

Many cities are adopting future targets of 10% to 20% of electricity from renewables (Table 5). Examples are Adelaide, Australia; Cape Town, South Africa; Freiburg, Germany; and Sacramento (California), United States. Targets typically aim for some year in the 2010–2020 time frame. Some targets are for a share of total energy

consumption, such as Daegu, Korea, with a target of 5% by 2012, and Tokyo, which has proposed a target of 20% of total energy consumption from renewables by 2020 (up from 2.7% today) to be formally adopted by 2008 as part of the city's environmental plan. Other city targets address installed capacity, such as Oxford, United Kingdom, and Cape Town, South Africa, both targeting 10% of homes with solar hot water by 2010 (and solar PV as well in Oxford). Barcelona, Spain, is targeting 100,000 m² of solar hot water by 2010. Some local governments in the United Kingdom are requiring on-site renewables for all new buildings over specific size thresholds (3, 4).

Urban planning that incorporates future clean-energy visions is gaining hold in many cities, often with participation from a variety of stakeholders. Göteborg, Sweden, is an example of a city creating a long-term vision through a project called Göteborg 2050. That project is a collaborative effort between universities, the city government, and the city's energy utility. It includes research, scenario development, strategic planning, dialogue with the public, and demonstration

Table 5 Selected municipal policy targets for renewables^a

City	Share of electricity from renewables	Other types of targets
Adelaide, Australia	15% by 2014	—
Barcelona, Spain	—	100,000 m ² (70 MWth) of solar hot water by 2010
Cape Town, South Africa	10% by 2020	10% of homes with solar hot water by 2010
Chicago, United States	—	20% of city government electricity consumption by 2006
Daegu, Korea	—	5% share of all energy consumption by 2012
Freiburg, Germany	10% by 2010	—
Gwangju, Korea	—	2% share of all energy consumption by 2020
Oxford, United Kingdom	—	10% of homes with solar hot water and/or PV by 2010
Sacramento, United States	20% by 2011	—
Tokyo, Japan	—	20% share of all energy consumption by 2020 (proposed)

^aSource: REN21 Renewable Energy Policy Network for the 21st Century (3–4).

projects. In Japan, where renewable energy policy has been quite active at the local level, 800 local governments have laid out future urban visions over the past 10 years with support from a national government program. These Japanese cities are creating advanced and unique visions taking into consideration their local characteristics and incorporating renewable energy into their visions.

Cities are also establishing CO₂ reduction targets. For example, London announced a target to reduce carbon dioxide emissions by 20% by 2010, relative to 1990 levels, and by 60% by 2050. New York City set a target in 2002 for a 20% reduction by 2010 from 1995 levels; this was supplemented by a “U.S. Mayor’s Climate Protection Agreement” in 2005 targeting a 7% reduction from 1990 levels by 2012. During 2005 and 2006, New York City was joined by more than 200 other U.S. cities, representing a combined population of 41 million people, which made the same agreement.

TECHNOLOGY PATHWAYS

Six themes in energy scenarios related to future technology pathways for renewables recur regularly.

1. Long-term potentials and growth rates of wind, biomass, biofuels, and solar heating
2. Centralized versus distributed electricity supply and particularly the role of distributed solar PV
3. Hydrogen combined with renewables
4. Electric vehicle technology
5. Advanced energy storage technologies
6. Nuclear power and carbon capture and storage

Long-Term Potentials and Growth Rates

Scenarios reveal a wide variation in assessments of long-term technology potentials and growth rates for renewable energy technologies, even for established technologies like

wind and biomass power. Biofuels present the greatest uncertainties. More speculative technologies, such as solar thermal power, are often ignored entirely.

Wind power. Many scenarios show wind power becoming a major source of electricity. GWEC & Greenpeace (23) show wind power becoming 29% of global power generation by 2030 (5200 TWh of wind power) and 34% by 2050 (7900 TWh). Greenpeace & EREC (19) show about the same (7200 TWh) but with a 23% share owing to higher electricity demand. IEA’s ETP (22) ACT Map shows about one third of that amount (2400 TWh), with an 8% share. (In 2005, wind power generated 124 TWh.) European scenarios show shares from 10% to 26% by 2030 (38, 39, 43). High annual growth rates accompany these projections. GWEC & Greenpeace (23) give growth rates above 20% through 2015, becoming 17% through 2020 and 10% through 2025 (and below 5% thereafter). (From 2000–2006, annual growth rates were 25% to 30%.) Some scenarios show wind power becoming constrained by grid-integration issues, although studies show that technical measures exist to strengthen grids and allow high shares (10, 111). Cost reductions and policies play key roles in scenarios. For Europe, the role and share of off-shore wind are also factors, considering technology, siting, acceptance, and cost barriers. Some European scenarios show more than half of all wind power coming from off-shore installations by 2030.

Biomass. Berndes et al. (112) found widely different conclusions in the literature about the possible contribution of biomass to future global energy supply by 2050, ranging from 100 EJ to 400 EJ. (In 2004, traditional biomass was 44 EJ, and modern biomass was 5 EJ.) Fischer & Schrattenholzer (113) give a range of 375 EJ to 450 EJ. Greenpeace & EREC (19) give up to 100 EJ. One reason for different conclusions is that two crucial parameters—land availability and energy crop yields—are subject to widely different

opinions. Availability of land, as well as forest and agricultural residues, relates to the interaction of biomass energy with other land uses (e.g., food production, biodiversity, and soil and nature conservation), and synergies occur between different uses. Berndes et al. (112) conclude that such interactions and synergies need to be better understood and modeled in order to better analyze the prospects for biomass. One of the highest scenarios for biomass use shows 70% of primary energy from biomass in the Netherlands by 2050, mostly for heating (84). European scenarios for 2030 show the share of low-temperature heat from biomass ranging from 3% to 27% (43).

Biofuels. The IEA (14) projects 120 billion liters/year of ethanol production by 2020, or 3% of road transport fuel, and 25 billion liters/year of biodiesel, if policies accelerate. (In 2005, ethanol was 33 billion and biodiesel 4 billion.) The IEA's ETP (22) scenarios show a range of biofuel shares by 2050, from a 3% reference scenario to 13% and 25% for ACT Map and TECH Plus. The WBCSD (25) projects a 15% biofuels share worldwide by 2050, and 25% for the United States and Canada. For Europe, the EC biomass action plan recommended a European target of 10% share by 2020 (95), and a research report envisioned a 25% share by 2030 (114), whereas other scenarios see a marginal contribution of biofuels to primary energy (37). Scenarios also differ on the development of advanced or "second generation" biofuels—such as cellulose to ethanol, biomass to liquids, or biogas. These fuels are expected in many scenarios by 2020, but only with further technology development (32, 37). Enzyme cost reductions and improvements in pretreatment are milestones to commercialization (14). Regulatory limits on biofuel imports are a factor in some European scenarios.

Solar thermal power. Most scenarios ignore this technology or mention it but do not make a distinction between solar ther-

mal power and solar PV when presenting shares of solar power. Some scenarios do show large increases after 2020 or 2030 explicitly for solar thermal power. The Greenpeace & EREC (19) revolution scenario shows 10% of world electricity from solar thermal power by 2050 (2900 TWh). Several European scenarios show shares of solar thermal power comparable to wind power by 2030 (40, 46, 47).

Solar heating and cooling. There are very few policy targets or scenarios that specifically address solar heating and cooling. The IEA's ETP (22) scenarios do not distinguish renewable heating (they only show heat from traditional renewables as part of the buildings sector). The ESTTP (41) "solar thermal vision" sets a goal of 50% of all low-temperature heating and cooling coming from solar in Europe by 2030, led by the "active solar building," which is 100% heated and cooled by solar thermal energy—envisioned as the new building standard by 2030. That vision also includes technologies for seasonal heat storage, commercial use of solar-assisted cooling (which is not yet in widespread commercial use), solar district-heating systems serving groups of buildings, and an array of architectural innovations and practices. China's target of 300 million m² of solar hot water by 2020 represents a quadrupling of capacity and could lead to more than a third of China's households with solar hot water by 2020.

Distributed Power Generation

Most scenarios assume that the electricity system will remain highly centralized or do not address the issue of distributed power generation. However, most advanced scenarios for Europe and some global scenarios do envision distributed generation becoming a prominent part of power systems (19, 25, 32, 49). And a survey of European experts found a large consensus about the trend toward a more decentralized electricity supply, estimating a 30% share of decentralized power by 2020 (42). Many scenarios

envision solar PV as a primary form of distributed generation from renewables, although European scenarios also include large shares of biomass (in combined-heat-and-power plants) and geothermal power. Thus the share of distributed generation from renewables depends on solar PV technology advances and cost reductions.

Bradford (115) argues that the share from solar PV also depends on fairer cost comparisons and that solar PV is much closer to being competitive with conventional power if compared on the basis of delivered electricity or peak power costs. Under a decentralized paradigm, renewables have an advantage because they compete with the end-user cost of power rather than centralized generation costs, avoiding transmission and distribution costs.

Bradford presents a radical distributed solar PV future in the following three phases (which are based on these advantages and an extrapolation of technology cost curves): (a) rapid growth from 2005 to 2020 when installed costs (per watt) decline to \$2.50 (from \$7 in 2005) and solar PV capacity rises to 240 GW (from 5 GW in 2005), (b) “displacement” from 2020 to 2040 when costs further decline to \$1.60 and capacity increases to 6900 GW, and (c) dominance beyond 2040 when costs decline to \$1 and solar PV provides 35% of global electricity. An EC research report envisions a similar trajectory with 1000 GW of solar PV by 2030 (116).

Many studies offer visions and details of decentralized systems using a combination of small-scale renewables along with microturbines, fuel cells, stirling engines, and other emerging technologies, many providing both power and heat (11, 49, 72, 117–123). Also included in this category is the literature on “building-integrated PV” that merges energy and architecture (124–126). In a distributed future, central power grids become more limited, and more users produce their own power. Distributed sources become connected through “intelligent grids” that optimize flows and make least-cost decisions. A

three-stage transition to distributed generation was suggested by the IEA, according to share of total power generation (127). At first, marginal shares pose few issues other than interconnection. Later, increasing shares require utilities to monitor and control generation sources and conduct real-time optimization. Finally, a majority share means that microgrids and community energy systems dominate, with local distribution utilities becoming coordination agents rather than controllers.

Hydrogen Combined with Renewables

McDowall & Eames (75, p. 1245) review the hydrogen futures literature and conclude that “most studies see the ultimate hydrogen economy as fuelled entirely by renewables, with electricity and hydrogen as the dominant, and largely interchangeable energy carriers.” But transitionally at least, until 2030–2050, studies envision hydrogen from nuclear and fossil fuels (some with carbon sequestration). Shell’s “spirit of the coming age” (32) shows hydrogen infrastructure emerging after 2030 with natural gas as “bridge” to hydrogen from renewables after 2050. Some scenarios limit renewables-produced hydrogen because of high projected electricity demand that requires the renewable electricity (40). Others show hydrogen from renewables emerging only after power grids are strengthened to accommodate intermittent and distributed renewables (28). Many European and global scenarios do not show significant hydrogen production until after 2030 (129).

Scenarios show hydrogen primarily used as a transport fuel and reflect high uncertainty or variation depending on factors such as commercial viability of fuel-cell technology, hydrogen distribution options, hydrogen storage media, and gaseous versus liquid fuel. The IEA’s ETP (22) ACT Map scenario shows a minimal contribution from hydrogen, whereas TECH Plus envisions cost reductions in fuel cells and other technology

breakthroughs making hydrogen 9% of transport energy by 2050. The EC's WETO (20) hydrogen scenario shows 13% of world final energy from hydrogen by 2050, produced from nuclear (40%) and renewables (50%). The WBCSD (25) scenario shows widespread use of fuel-cell vehicles by 2050 and 25% of world transport energy from hydrogen (including 17% in China, 27% in the United States/Canada, 32% in Europe, and 100% in Japan), with renewables-produced hydrogen in some countries.

Hydrogen infrastructures could be centralized or decentralized, employing local renewable electricity and biomass for decentralized hydrogen production or large-scale renewables, e.g., wind and solar thermal power, for centralized production (130). Hoffman (131) ponders whether hydrogen is inherently a centralizing technology. In some scenarios, such as Shell's spirit of the coming age (32), hydrogen supports a continued centralized energy paradigm. Others, such as Rifkin (132), envision hydrogen as a decentralizing technology that promotes community energy systems. But neither centralized nor decentralized hydrogen visions are practical or desirable, according to some, who question and even denounce the current hydrogen "fashion" (121, 133–135). They claim that visions of hydrogen combined with renewables deceptively hide an agenda—hydrogen from nuclear and fossil fuels—or that such visions force renewables into current energy paradigms rather than create new paradigms better suited to renewables.

Electric Vehicle Technology

Beyond long-term visions of renewables-produced hydrogen for transport, most scenarios only discuss the contribution of biofuels to the transport sector. A relative "blind spot" in the literature is the direct contribution of renewable electricity for transport. There has been growing interest in hybrid gasoline-electric vehicles, including so-called "plug-in hybrids" in which the battery can be

recharged from an external source such as renewable electricity. Plug-in hybrids could allow shorter trips to be made entirely on renewables, with stored gasoline used for longer trips. There has also been a resurgence of interest in electric-only vehicles, following the demise of earlier models in the 1990s.

A growing number of authors envision a future with transport technology closely tied to electric power and renewable electricity rather than liquid or gaseous fuels (49, 121, 135). This future also includes potential use of electric vehicle batteries as mediums for electricity storage, for example charging a car at night and then using the power during the day or selling it for peak power prices. Wind power is a ideal match for electric vehicle technologies, argue several authors, because vehicles can be charged with cheap off-peak wind power, and because battery charging is ideally suited to intermittent wind power. Automatic control of battery charging and discharging through the grid also fits into "smart grid" or "virtual power station" visions (19, 117–119, 122, 123). The key barrier remains battery technology. Ongoing technology developments may accelerate beyond what some prognoses have suggested (5).

Advanced Storage Technologies

Energy storage is a key enabling technology for integration of renewables, concluded the European Commission (136). The survey of experts by European Energy Delphi (42) shows that many believe energy storage will be used widely by the early 2020s to support renewables. But very few energy scenarios address the storage issue specifically. An optimization model by Wuppertal (137) shows that high amounts of renewables can be integrated into electricity systems if sufficient storage/balancing options are available. A number of energy storage technologies have the potential to shape the use of renewable energy, including centralized storage to stabilize power grids containing large shares of intermittent renewables, local distributed storage,

and storage onboard vehicles. Some scenarios envision advanced battery storage in homes to compliment local solar PV generation (25, 49).

Presently, pumped hydro is the main commercial form of large-scale electricity storage, and some studies consider expanded use of pumped hydro in conjunction with wind turbines (10, 138). Conventional battery technologies (e.g., lead-acid, nickel-cadmium, and nickel-metal-hydride batteries) offer inadequate performance, but new technologies show promise, including those with lithium (e.g., lithium-ion, lithium-polymer, lithium-metal-polymer, and lithium-sulfur batteries), those for high temperatures (e.g., sodium-sulfur and sodium-nickel-chloride batteries), and flow batteries (e.g., vanadium-redox and zinc-bromine batteries). Other forms of energy storage include flywheels, electric capacitors, compressed air storage, and thermal heat storage. Different storage timescales (seconds, minutes, hours, and days) achieve different purposes: smoothing wind power output, load following, peak power dispatch, averaging of hourly and daily variations in wind and solar, and vehicle energy storage (49, 137, 139–141).

Nuclear Power and Carbon Capture and Storage

For carbon-constrained scenarios, the degree of nuclear power and carbon capture and storage (CCS) technologies used also determines how much renewables are needed to reduce carbon emissions. European scenarios show widely diverging futures for nuclear. Reference scenarios show some EU countries phasing out nuclear but others making new nuclear investments, depending on technology costs and policies, with electricity share from nuclear decreasing to 17%–19% by 2030 (compared to 28% in 2005) (38). Alternative scenarios show a complete nuclear phaseout in Europe, with no new plants built and its electricity share falling to 4%–9% in 2030

and zero in 2050 (43, 45, 47). Highest is a EC's WETO (20) scenario showing 45% of European electricity from nuclear by 2050, along with CCS for half of all power plants.

Many global scenarios envision nuclear retaining roughly the same electricity share as today (15%), which means increasing at the same rate of world electricity demand, and at the same time showing large increases in CCS (22, 25). The IEA's ETP (22) ACT Map scenario, which leaves nuclear at a 17% share by 2050, shows CCS for half of all coal-fired power plants worldwide. An alternative "ACT no CSS" scenario, which assumes CSS never becomes commercially available, compensates with higher levels of renewables and nuclear. Similarly, the WBCSD (25) scenario shows a 12% share for nuclear along with CCS for half of all coal power capacity worldwide by 2050, and CCS plants start to become widespread by 2025. Some scenarios show an even higher share for nuclear, 30% or more (84, 142). Highest is a EC's WETO (20) scenario showing 38% electricity share for nuclear along with CCS for two thirds of power generation globally (compared to its reference scenario of 25% nuclear and 12% CCS). At the other extreme, some global scenarios envision the complete elimination of nuclear power by 2050 and, consequently, high levels of renewables (19, 28). Saddler et al. (143) show that it is possible to achieve a 50% reduction in CO₂ emissions by 2040 in Australia without nuclear or CCS.

CONCLUSIONS

Globally, low or reference scenarios show the share of primary energy from renewables in the range of 10% to 15% by 2040–2050, medium scenarios show a 25% to 30% share, and high scenarios show a 40% to 50% share. Total energy consumption in 2050 varies significantly among the scenarios, from 600 EJ to 1600 EJ. The amount of primary energy from renewables ranges from 100 EJ to 450 EJ for most scenarios, or an increase of

1.2-fold to sixfold from 80 EJ in 2004. Reference scenarios show the share of electricity from renewables is about 15% by 2040–2050, medium scenarios show a 30% to 40% share, and high scenarios show a 50% to 80% share, compared to 19% in 2005. The few scenarios giving share of transport energy from biofuels in 2050 show a wide range, from 3% to 25%.

For Europe, low or reference scenarios show primary energy share higher and sooner than global scenarios, at 15% to 20% by 2030, with policy-intensive scenarios showing a 30% to 40% share by 2030 and up to 50% by 2050. (These compare to 6.5% actual in 2004, a 12% target by 2010, and a 20% proposed target by 2020.) Electricity share is 20% to 25% in low or reference scenarios and 45% to 60% in policy-intensive scenarios by 2030, and up to 70% by 2050. (These compare to 14% actual in 2005 and a 21% target by 2010.) Transport fuel share is 6% to 7% in low or reference scenarios and 25% in policy-intensive scenarios by 2030. (These compare to an EU-wide target of 5.75% by 2010.)

For individual countries and states/provinces, there are many targets and scenarios for a 15% to 25% share of primary energy and a 20% to 35% share of electricity by 2020. Scenarios for 2050 show up to a 50% share of primary energy and a 50% to 80% share of electricity under policy-intensive or advanced scenarios. China's target for 16% share of primary energy by 2020 (up from 7.5% in 2005) represents the largest amount of renewables for any individual country.

Factors affecting scenario outcomes include aggressiveness of policy action, cost competitiveness driven by technology development and fuel price changes, and aggregate energy demand. Other factors include carbon prices, speed of capital stock replacement, and business strategies. Reference scenarios envision partial implementation of existing policies, continued reliance on traditional fuels, and stable to modestly increasing fuel prices. Policy-intensive or advanced scenarios envi-

sion aggressive policies and targets, significant technology cost reductions, increased social motivation, higher fuel prices, and high growth rates for renewables over decades. Many scenarios show large reductions in aggregate energy demand from energy efficiency that allows renewables to supply nearly a majority share. In many scenarios, factors affecting biofuels tend to differ from those cited above, with resource constraints, uncertainties about commercial viability of cellulose-to-ethanol technologies, and oil prices influencing scenarios.

Carbon-constrained scenarios depict trade-offs between renewables, nuclear, and carbon capture and storage, along with increases in energy efficiency. With carbon constraints added to scenarios, technology development, social acceptability of nuclear, and relative costs become overriding factors affecting renewables' shares. Some scenarios manage to satisfy carbon constraints with large amounts of renewables and no nuclear or carbon capture. Hydrogen for transport is envisioned in some scenarios—produced from fossil fuels or nuclear starting around 2030 and then later from renewables—but still may only account for modest (10% to 30%) shares of transport fuel by 2050.

Distributed generation from renewables, especially solar PV, plays an important role in some scenarios. Three different visions for the future of power generation might be characterized as (a) continued centralized electric power with bulk renewables feeding into grids; (b) coexisting centralized and decentralized electricity, with smart power grids and two-way power transfer with electric vehicles or other storage devices to take advantage of peak-demand pricing and to smooth intermittent renewables; and (c) radical decentralization with community energy systems predominating.

The future of renewables appears promising to many. Scenarios attempt to show possible futures and implications of different choices and conditions. Cost reduction

and technology development—from method-
ical incremental improvements to paradigm-
shifting surprises—will be important, but ul-

timately, the decisions of business managers,
policy makers, and households will determine
those futures.

SUMMARY POINTS

1. Common indicators of renewable energy futures are shares of primary energy and electricity, but shares of final energy, low-temperature heating, and road transport energy are also important.
2. Global renewable energy scenarios show a 10% to 50% share of primary energy by 2050, with many policy-intensive scenarios projecting 40% to 50%. European policy-intensive scenarios project 45% to 60% by 2030.
3. Wind and biomass power feature strongly in most advanced scenarios, but there are large differences in projections for distributed solar PV, solar thermal power, solar and biomass heating, advanced biofuels, and the role of energy storage and electric vehicle technologies.
4. The IEA's *World Energy Outlook* (21) shows the lowest shares of renewables, whereas the EC and private-sector scenarios show significantly larger shares, and advocacy groups and industry associations show the highest shares.
5. Carbon-constrained scenarios work backward from atmospheric stabilization of CO₂ at 450–550 ppm by 2050 and depict trade-offs between renewables, nuclear power, and carbon capture and storage. Global CO₂ emissions vary from 10 to 100 Gt by 2050 across the range of scenarios reviewed.
6. Scenarios differ in treatment of renewables depending on degree of future policy action, fuel prices, carbon prices, technology cost reductions, aggregate energy demand, feasible power grid integration, and modeling approach, with resource constraints mostly significant only for biomass and biofuels.

FUTURE ISSUES

1. The indicator “share of primary energy” suffers from multiple definitions that make comparisons across countries and studies difficult; better transparency and dual-method reporting are needed.
2. More understanding and transparency are needed to explain how different modeling approaches and assumptions affect data requirements and scenario results, including the quantitative effects of policies.
3. Scenarios should more explicitly cover the role of low-temperature heating and cooling from renewables, including solar hot water and heating, advanced biomass technologies, geothermal heat pumps, and integrated “green building” architecture.
4. Scenario research should better explore the role of distributed generation and particularly distributed solar PV as well as the potential of electric vehicle technology and advanced energy storage to affect renewable futures.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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