100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World

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Note: this is a draft – not the final version – modifications are expected

By

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Abstract

We develop roadmaps to transform the all-purpose energy (electricity, transportation, heating/cooling, industry, agriculture/forestry/fishing) infrastructures of 139 countries to ones powered by wind, water, and sunlight (WWS). The roadmaps envision 80% conversion by 2030 and 100% by 2050. WWS not only replaces business-as-usual (BAU) power, but also reduces it ~42.5% because the work:energy ratio of WWS electricity exceeds that of combustion (23.0%), WWS requires no mining, transporting, or processing of fuels (12.6%), and WWS end-use efficiency exceeds BAU's (6.9%). Converting creates ~24.2 million more 35-year jobs than lost. It eliminates ~4.6 million/yr premature air pollution deaths today, ~3.5 million/yr in 2050, ~$22.8 trillion/yr (12.7 ¢/kWh-BAU-all-energy) in 2050 health costs, and ~$26.9 trillion/yr (14.9 ¢/kWh-BAU-all-energy) in 2050 climate costs. Transitioning reduces and stabilizes energy prices because fuel costs are zero, reduces conflict by creating energy-independent countries, reduces energy poverty, reduces power disruption by decentralizing power, and may avoid 1.5 ºC global warming.

Nations are increasingly striving for 100% clean, renewable energy in all sectors to meet air pollution, climate, and energy security goals. This study provides roadmaps for 139 countries to address this need. The roadmaps describe a future where all energy sectors are electrified or use heat directly with existing technology, energy demand is lower due to several factors, and electricity is generated with 100% clean, renewable WWS. Each roadmap is developed with a consistent methodology (Methods and Supplemental Information, *SI*) to quantify an example of what a 2050 100% WWS versus BAU all-sector energy infrastructure can look like in terms of

(1) Future end-use demand (load) in each energy sector in the WWS and BAU cases;
(2) Needed numbers of WWS generators and their footprint and spacing areas;
(3) WWS raw resources and potential, including solar photovoltaic (PV) rooftop potential;
(4) Costs of energy, transmission, and distribution in the BAU and WWS cases;
(5) Avoided air-pollution mortality and morbidity and their costs due to WWS;
(6) Avoided carbon emissions and global-warming costs due to WWS;
(7) Changes in job numbers and earnings due to WWS; and
(8) Policy measures to implement the roadmaps and a transition timeline.

This work builds upon earlier general world roadmaps[1-3] and 50 U.S. state roadmaps[4]. Other clean-energy plans have been groundbreaking but limited to individual countries or regions, selected sectors, partial carbon emission reductions, and/or emission reductions of carbon only rather than air pollution and carbon (e.g., for the UK[5], Europe and North Africa[6], Australia[7], Europe[8,9], Great Britain[10], Hungary[11], Ireland[12], UK[13], Denmark[14], France[15], several world regions[16], and 16 countries[17]).

Demand Reduction upon Conversion to WWS

Tables 1 and S6 (for all countries) project 139-country BAU and WWS end-use power demand (load) to 2050. End-use load is the power in delivered electricity or fuel that is actually used to provide services such as heating, cooling, lighting, and transportation. It excludes losses during electricity or fuel production and transmission but includes industry self-energy-use for mining, transporting, and refining fossil fuels. All end uses that can be electrified use WWS power directly; however, some transportation is run on hydrogen produced from WWS electricity (Methods).

Table 1. 2012 BAU, 2050 BAU, and 2050 100% WWS end-use loads (GW) by sector, summed among 139 countries The last column shows the total percent reduction in 2050 BAU end-use load due to switching to WWS, including the effects of reduced energy use due to (a) the higher work to energy ratio of electricity over combustion, (b) eliminating energy industry self-use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (c) policy-driven increases in end-use energy efficiency beyond those in the BAU case.

Scenario	Total end-use load (GW)	Resid-ential % of total	Com-mercial % of total	Indus-trial % of total	Trans-port % of total	Ag/for-estry/fishing % of total	Other % of total	(a) 2050 Δ load (%) due to higher work: energy ratio of WWS	(b) 2050 Δ load (%) due to eliminat-ing upstream w/WWS	(c) 2050 Δ load (%) due to effic-iency beyond BAU w/WWS	Total 2050 Δ load (%) w/WWS
BAU 2012	**12,105**	**22.35**	**8.10**	**38.70**	**27.35**	**2.13**	**1.37**				
BAU 2050	**20,604**	**20.40**	**8.08**	**37.30**	**31.00**	**1.87**	**1.34**				
WWS 2050	**11,840**	**25.71**	**11.21**	**42.05**	**16.04**	**2.85**	**2.15**	**-23.00**	**-12.65**	**-6.89**	**-42.54**

SI Section S3 describes the methodology; Table S6 contains individual country values.

In 2012, the 139-country all-purpose, end-use load was ~12.1 TW. Of this, 2.4 TW (19.6%) was electricity demand. Under BAU, all-purpose end-use load may grow to 20.6 TW in 2050. Transitioning to 100% WWS by 2050 reduces the 139-country load by ~42.5%, to 11.8 TW (Table 1), with the greatest percentage reduction in transportation. While electricity use increases with WWS, conventional fuel use decreases to zero. The increase in electric energy is much less than the decrease in energy in the gas, liquid, and solid fuels that the electricity replaces for three major reasons:

(a) The higher energy-to-work conversion efficiency of electricity used for heating, heat pumps, and electric motors and of electrolytic hydrogen in hydrogen fuel cells for transportation, than of fossil fuels (Table S4);

(b) The elimination of energy needed to mine, transport, and refine coal, oil, gas, biofuels, bioenergy, and uranium;

(c) Modest additional policy-driven energy efficiency measures beyond those under BAU.

These factors decrease average demand ~23.0%, 12.6%, and 6.9%, respectively, for a total of 42.5%. Thus, WWS not only replaces fossil-fuel electricity directly but is also an energy efficiency measure, reducing demand.

<u>**Numbers of Electric Power Generators and Their Land Required**</u>

Table 2 summarizes the numbers of WWS generators needed to power all 139 countries in 2050 for all energy purposes assuming the end-use loads by country in Table S6 and the percent of each country's load met by each generator in Table S8. Table 2 accounts for power loss during energy transmission and distribution, generator maintenance, and competition among wind turbines for limited kinetic energy (array losses).

Table 2. Number, capacity, footprint area, and spacing area of WWS power plants or devices needed to meet total annually-averaged end-use all-purpose load, summed over 139 countries.

Energy Technology	Rated power of one plant or device (MW)	[a]Percent of 2050 all-purpose load met by plant/device	Name-plate capacity, existing plus new plants or devices (GW)	Percent name-plate capacity already installed 2015	Number of new plants or devices needed for 139 countries	[b]Percent of 139-country land area for footprint of new plants or devices	Percent of 139-country area for spacing of new plants or devices
Annual power							
Onshore wind	5	23.52	8,332	5.04	1,582,345	0.00002	0.9238
Offshore wind	5	13.62	4,688	0.26	935,150	0.00001	0.5460
Wave device	0.75	0.58	307	0.00	409,517	0.00018	0.0086
Geothermal plant	100	0.67	96	13.05	839	0.00023	0.0000
Hydropower plant [c]	1300	4.00	1,058	100.00	0	0.00000	0.0000
Tidal turbine	1	0.06	31	1.79	30,050	0.00001	0.00009
Res. roof PV	0.005	14.89	9,277	0.76	1,841,306,023	0.04026	0.0000
Com/gov roof PV [d]	0.1	11.58	7,586	1.16	74,981,706	0.03279	0.0000
Solar PV plant [d]	50	21.36	12,629	0.53	251,230	0.12832	0.0000
Utility CSP plant [d]	100	9.72	2,153	0.23	21,485	0.05270	0.0000
Total for annual power		**100**	**46,157**	**3.76**	**1,919,518,345**	**0.255**	**1.478**
New land annual power[e]						0.181	0.924
For peaking/storage							
Additional CSP [f]	100	5.83	1,292	0.00	12,921	0.032	0.000
Solar thermal [f]	50		4,639	8.98	84,448	0.005	0.000
Geothermal heat [f]	50		70	100.00	0	0.000	0.000
Total all			**52,159**	**4.26**	**1,919,615,713**	**0.291**	**1.478**
Total new land[e]						0.218	0.924

All values are summed over 139 countries. Ref. (*19*) provides values for individual countries.

[a]Total end-use load in 2050 with 100% WWS is from Table 1.

[b]Total land area for each country is given in Ref. (*19*). 139-country land area is 119,651,632 km^2.

[c]The average capacity factors of hydropower plants are assumed to increase from their current world average values of ~42% to 50.0%.

[d]The solar PV panels used for this calculation are Sun Power E20 panels. For footprint calculations alone, the CSP mirror sizes are set to those at Ivanpah. CSP is assumed to have storage with a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1. See Table S7 footnote for more details.

[e]The footprint area requiring new land equals the sum of footprints for new onshore wind, geothermal, hydropower, and utility solar PV. Offshore wind, wave and tidal generators are in water, thus do not require new land. Similarly, rooftop solar PV does not use new land. Only onshore wind requires new land for spacing area. See Table S7 footnote for more details.

[f]The installed capacities for peaking power/storage are estimated from Ref. (*20*). Additional CSP is CSP plus storage needed beyond that for annual power generation to firm the grid across all countries. Additional solar thermal and geothermal are used for direct heat or heat storage in soil. Ref. (*20*) also uses other types of storage.

Table S22 summarizes projected 2050 rooftop areas, supportable PV capacity, and installed rooftop PV used by country. Rooftop PV will go on rooftops or elevated canopies above parking lots, highways, and structures without requiring additional land. In 2050, residential rooftops (including garages and carports) among the 139 countries may support up to 26.6 $TW_{dc\text{-}peak}$ of installed power, of which 34.9% is proposed for use. Commercial/government rooftops (including parking lots and parking structures) may support 11.1 $TW_{dc\text{-}peak}$, of which

68.2% is proposed for use. Low-latitude and high GDP-per-capita countries are expected to adopt PV the fastest.

While utility-scale PV can operate in any country because it can use direct and diffuse sunlight, CSP is viable only where significant direct sunlight exists. Thus, CSP penetration in several countries is limited (Section S5.2).

Onshore wind is available in every country but assumed to be viable in high penetrations primarily in countries with good wind resources and sufficient land (Section S5.1). Offshore wind is assumed viable in countries with either ocean or lake coastline (Section S5.1).

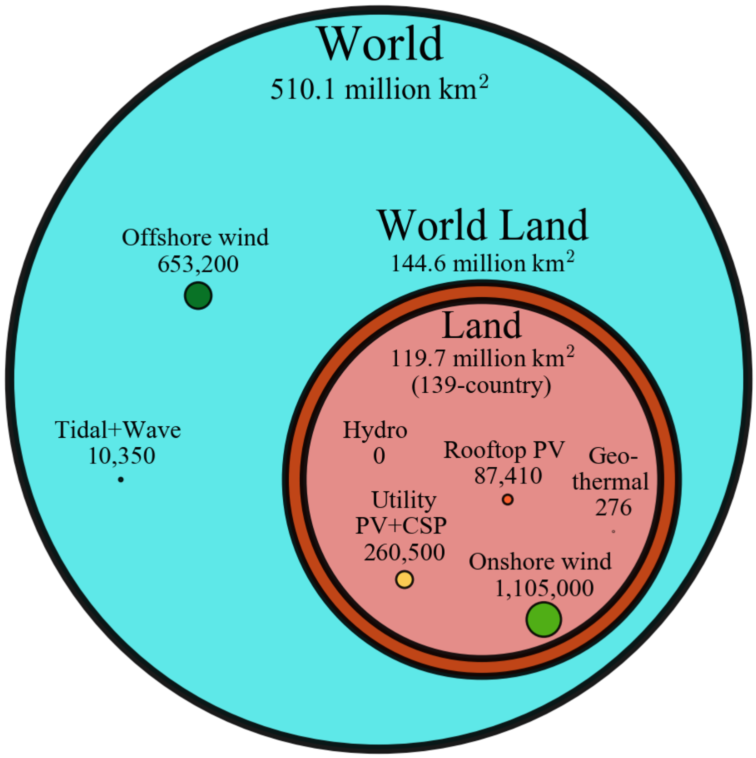
The 2050 nameplate capacity of hydropower is assumed to be the same as in 2015. However, existing dams are assumed to run more frequently for producing peaking power, thus their capacity factors are assumed to increase slightly (Section S5.4). Geothermal, tidal, and wave power are limited by each country's technical potentials (Sections S5.3, S5.5, S5.6).

Table 2 also lists needed installed capacities of additional CSP with storage, solar thermal collectors, and existing geothermal. These collectors are needed to provide electricity or heat that is stored then used later to provide peaking power and to account for power losses into and out of such storage (Section S6).

Table 2 indicates that 4.26% of the 2050 nameplate capacity required for a 100% all-purpose WWS system among the 139 countries was already installed as of the end of 2015. The countries closest to 100% installation are Tajikistan (76.0%), Paraguay (58.9%), Norway (35.8%), Sweden (20.7%), Costa Rica (19.1%), Switzerland (19.0%), Georgia (18.7%), Montenegro (18.4%), and Iceland (17.3%). China (5.8%) ranks 39th and the United States (4.2%) ranks 52nd (Figure S2).

Footprint is the physical area on the top surface of soil or water needed for each energy device. It does not include areas of underground structures. Spacing is the area between some devices, such as wind, tidal, and wave turbines, needed to minimize interference of the wake of one turbine with others downwind. The total new land footprint required for the 139 countries is ~0.22% of the 139-country land area (Table 2), mostly for utility PV. This does not account for the decrease in footprint from eliminating the current energy infrastructure, which includes footprints for mining, transporting, and refining fossil fuels and uranium and for growing, transporting, and refining biocrops. The only spacing over land needed is between onshore wind turbines and requires ~0.92% of the 139-country land area (Figure 1).

Figure 1. Footprint plus spacing areas (km^2) required from Table 2, beyond existing 2015 installations, to repower the 139 countries for all purposes in 2050 with WWS. For hydropower, the new footprint plus spacing area is zero since no new installations are proposed. For rooftop PV, the circle represents the additional area of 2050 rooftops that needs to be covered (thus does not represent new land).



Matching Electric Power Supply with Demand and Costs

The numbers of generators of each type needed to power each country are calculated here based on the 2050 annually-averaged WWS load in the country after all sectors have been electrified but before considering grid reliability and neglecting energy imports and exports. However, results from a grid reliability study[20] for the continental U.S. are used to estimate some additional electricity and heat generators needed in each country to help ensure a reliable electric power grid by region (Table 2, bottom).

Ref. (*20*) estimated the quantities and costs of storage devices needed to ensure that a 100% WWS system, when integrated across the 48 contiguous U.S. states, matched load every 30 s for 6 years (2050-2055) while accounting for the variability and uncertainty of WWS resources. Wind and solar time-series were derived from global model simulations that accounted for extreme events, competition among wind turbines for kinetic energy, and the feedback of extracted solar radiation to roof and surface temperatures. Solutions included the use of demand response to shave periods of excess demand over supply, storage for excess heat (in rocks and water) and electricity (in ice, water, phase-change material tied to CSP, pumped hydro, and hydrogen), and hydropower only as a last resort. No stationary storage batteries, biomass, nuclear power, carbon capture, or natural gas was needed. Multiple low-cost stable solutions were obtained accounting for generation, storage, transmission, distribution, and maintenance (~10.6 ¢/kWh-WWS-electricity, ~11.4 ¢/kWh-WWS-all-energy, 2013 USD).

Here, current and future full social costs (including capital, land, operating, maintenance, storage, fuel, transmission, and externalities) of WWS electric power generators versus non-

WWS conventional fuel generators are estimated. These costs include the costs of CSP storage, solar collectors for heat storage, and all transmission/distribution costs, including additional transmission lines needed to wield more power and long distance high-voltage direct current lines. They do not include costs of pumped hydro storage, underground storage in rocks, heat and cold storage in water and ice, or the costs of hydrogen fuel cells. From (*20*), such costs are estimated roughly as ~0.8 ¢/kWh-WWS-all-energy.

The total up-front capital cost of the 2050 WWS system (for average annual power plus peaking storage in Table 2) for the 139 countries is ~$124.7 trillion for the 49.9 TW of new installed capacity needed (~$2.5 million/MW). Although WWS capital costs exceed BAU's, WWS has zero fuel costs. To account for these factors plus operation/maintenance, transmission/distribution, and storage costs, the levelized cost of energy (LCOE) is needed.

The 2050 LCOEs, weighted among all electricity generators and countries in the BAU and WWS cases, are 9.73 ¢/kWh-BAU-electricity and 8.86 ¢/kWh-WWS-all-energy, respectively (Table S34). Taking the product of the first number and the kWh-BAU in the retail electricity sector, subtracting the product of the second number and the kWh-WWS-electricity replacing BAU retail electricity, and subtracting the amortized cost of energy efficiency improvements beyond BAU improvements in the WWS case, gives a 2050 business cost savings due to switching from BAU to WWS electricity of ~$113/yr per capita ($2013 USD). Adding 0.8 ¢/kWh-WWS-all-energy for additional storage gives a WWS business cost of ~9.66 ¢/kWh-WWS-all-energy, still providing ~$85/yr per capita savings for WWS relative to just BAU's retail electricity sector.

However, a major benefit of WWS over BAU is avoided health and climate costs, which average ~27.5 (10.7-70) ¢/kWh-BAU-all-energy, or $5,700/yr per person, over 139 countries, as separated next.

Air Pollution Cost Reductions due to WWS

The avoided costs due to reducing air pollution mortality in each country are quantified as follows. Global 3-D modeled concentrations of $PM_{2.5}$ and O_3 in each of 139 countries are combined with the relative risk of mortality as a function of concentration and population in a health-effects equation[21]. Results are then extrapolated to 2050 accounting for increasing population, emission sources, emission controls, and a nonlinear relationship between exposure and population (Section S8.1).

Figure S12 gives resulting present-day premature outdoor plus indoor mortalities by country. Over all 139 countries, mortalities sum to ~4.28 (1.2-7.6) million/yr for $PM_{2.5}$, ~0.28 (0.14-0.42) million/yr for O_3, and ~4.56 (1.33-7.98) million/yr for both, which compares with 4-7 million/yr premature outdoor plus indoor air pollution mortalities worldwide from other studies[23-26]. Premature mortalities projected to 2050 here are ~3.5 (0.84-7.4) million/yr (Table S36).

The air pollution damage cost due to fossil fuel and biofuel combustion and evaporative emissions in a country is the sum of mortality, morbidity, and non-health costs such as lost visibility and agricultural output. Mortality cost equals mortalities multiplied by the value of statistical life (VSL). Morbidity plus non-health costs are estimated as in Section S8.1. The resulting 139-country 2050 cost of air pollution is ~\$23 (\$4.1-\$69) trillion/yr, or ~12.7 (2.3-38) ¢/kWh-BAU-all-energy, ~7.6 (1.4-23)% of the 2050 global annual GDP on a purchasing power parity (PPP) basis, and \$2,600/yr per person (in 2013 USD). Our air pollution mean cost, which applies across all BAU sectors, is well within the 1.4-17 ¢/kWh-BAU-electricity range of another study for the retail electricity sector[22].

Global-Warming Damage Costs Eliminated

Global warming costs include costs due to coastal flooding and real estate damage; agricultural loss; water shortages and flooding; health problems due to heat stress and stroke, influenza, malaria, and dengue fever; famine; ocean acidification; drought and wildfires; severe weather; and increased air pollution damage. In some regions, these costs are partly offset by fewer extreme cold events, associated reductions in illness and mortality, and gains in agriculture. Net costs due to global-warming-relevant emissions are embodied in the social cost of carbon dioxide, which is estimated for 2050 from recent studies as \$500 (282-1,063)/metric tonne-CO_2e in 2013 USD[4]. Applying this range to projected 2050 CO_2e emissions suggests that 139-country emissions may cause \$26.9 (15.1-57.2) trillion/yr in climate damage to the world by 2050, or 14.9 (8.4-32) ¢/kWh-BAU-all-energy and ~\$3,100/yr per person (in 2013 USD) (Table S34 and Section S8.2).

Impacts of WWS on Jobs and Earnings in the Power Generation Sector

Changes in job numbers and earnings resulting from building out 100% of the WWS electricity generation and transmission system needed by 2050 are estimated with NREL's Jobs and Economic Development Impact (JEDI) models[27]. The models incorporate three levels of impacts: project development and onsite labor impacts, local revenue and supply chain impacts, and induced impacts.

The build-out of the WWS generation and transmission infrastructure requires construction and operation jobs. While operation jobs are long-term, construction jobs are temporary but are reported as 35-year jobs, where one person works on separate 1-year, 2,080 hours/yr full-time equivalent (FTE) construction jobs for 35 years. Job estimates do not include job changes in industries outside of electric power generation (e.g., the manufacture of electric vehicles, fuel cells or electricity storage), as it is uncertain where those jobs will be located and the extent to which they will be offset by losses in BAU-equivalent industries.

Results indicate that 100% conversion to WWS across 139 countries can create ~25.4 million new 35-year construction jobs and ~26.6 million new 35-year operation and maintenance jobs, totaling 52.0 million 35-year jobs for WWS generators and transmission (Table S39). These numbers do not include all external jobs created in areas such as research and development, storage development, and local economy improvement.

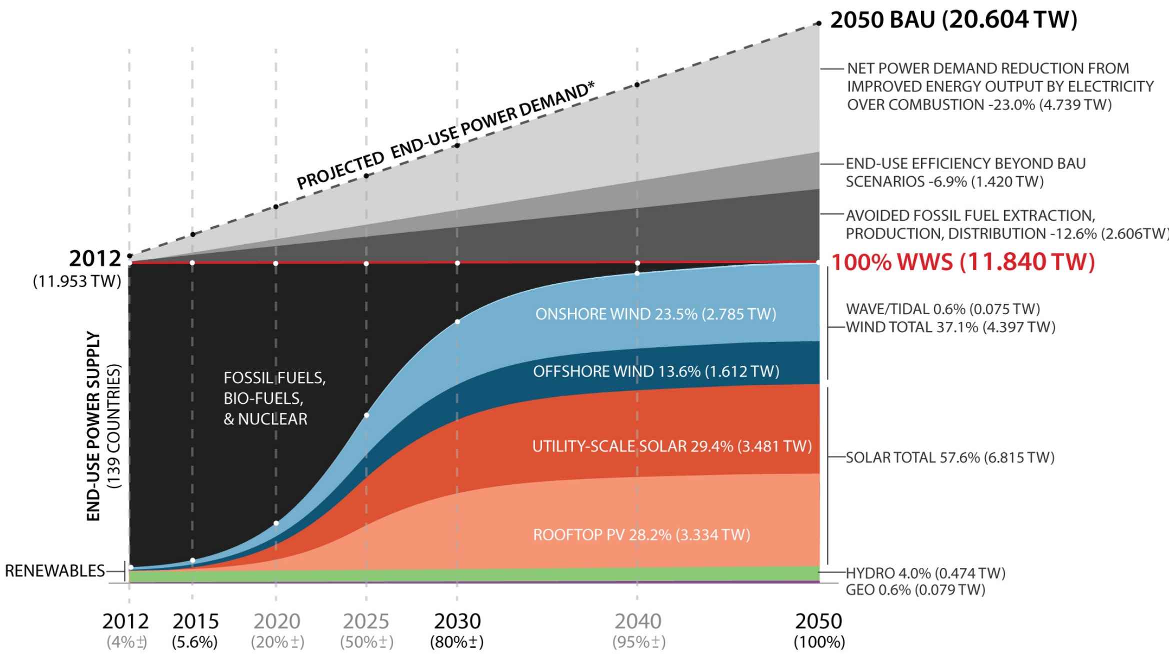
Tables S39 and S42 summarize the resulting 139-country job loss in the oil, gas, coal, nuclear, and bioenergy industries. Because WWS plants replace future fossil, nuclear, and bioenergy plants, jobs lost from the construction of these plants are included. Jobs associated with replacing existing conventional plants are not included to maintain consistency with the exclusion of jobs from WWS plant replacements. Shifting to WWS is estimated to result in ~27.7 million jobs lost in the current fossil fuel, biofuel, and nuclear industries, representing ~0.97% of the 139-country workforce.

In sum, WWS may create a *net* of ~24.2 million 35-year jobs across the 139 countries. Individually, countries that currently extract significant fossil fuels (e.g., Algeria, Angola, Iraq, Kuwait, Libya, Nigeria, Qatar, and Saudi Arabia) may experience net job loss in the energy production sector. Though not included here, these losses can be offset by the manufacture and service of technologies associated with WWS energy (e.g., liquid hydrogen production and storage, electric vehicles, electric heating and cooling, etc.). Collectively, the direct and indirect earnings from producing WWS electricity/transmission across 139 countries amount to ~$1.86 trillion/yr during construction and ~$2.06 trillion/yr during operation. The annual fossil-fuel earnings loss totals ~$2.06 trillion/yr yielding a net ~$1.86 trillion/yr gain.

Timeline

Figure 2 is a proposed WWS transformation timeline for the 139 countries. It assumes 80% conversion to WWS by 2030 and 100% by 2050. Section S12 lists proposed transformation milestones for each energy sector. Whereas, much new infrastructure can be installed upon natural retirement of existing infrastructure, new policies are needed to force remaining existing infrastructure to retire early to allow the complete conversion to WWS. Because the avoided health and climate costs resulting from shutting conventional plants, as quantified here, far exceed the remaining asset value of such plants (as approximately embodied in their LCOEs), shuttering these plants does not result in stranded assets from a social cost point of view. While this study does not advocate specific policies to transition any country, Section S11 identifies several potential policies.

Figure 2. Mean change in 139-country end-use power demand for all purposes (electricity, transportation, heating/cooling, industry, agriculture/fishing/forestry, and other) and its supply by conventional fuels and WWS generators over time based on the 139-country roadmaps. Total power demand decreases upon converting to WWS. The percentages next to each WWS source are final (2050) estimated percent supply of end-use power by the source. The 100% demarcation in 2050 indicates that 100% of all-purpose power is provided by WWS technologies by 2050, and the power demand by that time has decreased.



Impacts on Temperatures

Friedlingstein et al.[28] estimate that, for the globally-averaged temperature change since 1870 to increase by less than 2 ºC with a 67% or 50% probability, cumulative CO_2 emissions since 1870 must stay below 3200 (2900-3600) Gt-CO_2 or 3500 (3100-3900) Gt-CO_2, respectively. This accounts for non-CO_2 forcing agents affecting the temperature response as well. Matthews[29] further estimates the emission limits to keeping temperature increases under 1.5 ºC with probabilities of 67% and 50% as 2400 Gt-CO_2 and 2625 Gt-CO_2, respectively. As of 2015 end, ~2050 Gt-CO_2 from fossil-fuel combustion, cement manufacturing, and land use change had been emitted cumulatively since 1870[29], suggesting no more than 350-575 Gt-CO_2 can be emitted for a 67-50% probability of keeping post-1870 warming under 1.5ºC. The results here suggest that policies that strive to transition 80% of energy but also eliminate 80% of land use change and other emissions by 2030 and 100% by 2050 can limit warming to 1.5 ºC with a probability of between 50% and 67% (Section S10).

Conclusion

Transitioning to 100% WWS may (1) avoid ~4.6 (1.3-8.0) million premature air pollution mortalities/yr today and 3.5 (0.84-7.4) million/yr in 2050, thus avoid ~$23 ($4.1-$69) trillion/yr in 2050 air-pollution damage costs (2013 USD), (2) avoid ~$26.9 (15.1-57.2) trillion/yr in 2050 global warming costs (2013 USD), (3) save ~$85/person/yr in BAU-electricity-sector fuel costs, ~2,600/person/yr in all-sector air-pollution-damage cost, and ~$3,100/person/yr in all-sector climate costs in 2050 (2013 USD), (4) create ~24.2 million net new 35-year jobs, (5) stabilize energy prices, (6) use minimal new land (0.22% of 139-country land for new footprint and 0.92% for new spacing), (6) reduce international conflict over energy because each country will be largely energy independent, (7) enable countries to become largely energy independent, thus reducing international conflict over resources, (8) reduce energy poverty for 4 billion people worldwide by increasing access to distributed energy, and (9) decentralize much of the world power supply, thereby reducing the risk of large-scale system disruptions from power outages or terrorism. Finally, the aggressive worldwide conversion to WWS proposed here will help avoid global temperature rising more than 1.5 °C since 1870. This study concludes that while social and political barriers exist, converting to 100% WWS using existing technologies is technically and economically feasible.

Methods

Quantifying the number of WWS generators in each country begins with 2012 energy use data[18] in each energy sector of 139 countries for which data are available. Energy use in each sector of each country is then projected to 2050 in a BAU scenario (SI, Section S3.2). The projections account for increasing demand; modest shifts from coal to natural gas, biofuels, bioenergy, and some WWS; and some end-use energy efficiency improvements.

All energy-consuming processes in each sector are then electrified, and the resulting end-use energy required for a fully electrified all-purpose energy infrastructure is estimated (Section S3.3). Some end-use electricity is used to produce hydrogen for long-distance ground, ship, and air transportation. Modest additional end-use energy efficiency improvements are then applied. The remaining power demand is supplied with a combination of different WWS technologies determined by available natural resources and the rooftop, land, and water areas in that country.

The WWS electricity generation technologies include onshore and offshore wind turbines, concentrated solar power (CSP), geothermal heat and electricity, rooftop and utility-scale solar photovoltaics, tidal and wave power devices, and hydropower. These are existing technologies found to minimize health and climate impacts compared with other technologies, while also minimizing land and water use[30].

Technologies for ground transportation include battery electric vehicles (BEVs) and BEV-hydrogen fuel cell (HFC) hybrids, where the hydrogen is electrolytic (produced by electrolysis, or passing electricity through water). BEVs with fast charging dominate short- and long-distance, light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance trains, short-distance boats and ships (e.g., ferries, speedboats), and aircraft traveling less than 1000 km. BEV-HFCV hybrids dominate medium- and heavy-duty trucks and long-distance trains, ships, and aircraft. HFCs are not be used to generate electricity due to the relative inefficiency and associated costs. In this study, ~7.0% of all 2050 WWS electricity (43.6% of the transportation load) is for producing, storing, and using hydrogen.

Air heating and cooling are powered by ground-, air-, or water-source electric heat pumps. Water heat is generated by heat pumps with an electric resistance element for low temperatures and/or solar hot water preheating. Cook stoves are electric induction.

Electric arc furnaces, induction furnaces, and dielectric heaters power high-temperature industrial processes.

The roadmaps assume the adoption of new energy-efficiency measures but exclude the use of nuclear power, carbon capture, liquid and solid biofuels, and natural gas primarily because they all increase air pollution and climate-warming emissions more than do WWS technologies[2].

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Supplemental Information for

100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World

October 15, 2016

Note: this is a draft – not the final version – modifications are expected

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Introduction

This document provides additional descriptions and data by country supporting the 100% clean, renewable all-sector energy roadmaps described in the main paper. Our general objective in this document is to examine what a 100% wind, water, and solar (WWS) all-sector energy system in each of 139 countries can look like in 2050 and the costs and benefits of a "business-as-usual" (BAU) infrastructure compared with the WWS infrastructure.

Many of the methods used here are analogous to those used in Jacobson et al. (2015a) to estimate the 100% WWS systems in the 50 U.S. states, so where appropriate we refer to that study rather than re-publish the same methods. The spreadsheets containing all the derivations of the numbers for this analysis can be found in Delucchi et al. (2016).

The topics covered in this document include the following:

Section S1. Defining "Low" and "High" Cost Scenarios

In order to unify our presentation, we report costs and other results for two general cases: one based on low costs and high benefits (i.e., low net costs or high net benefits) for the 100% WWS scenario, and one based on the reverse, high costs and low benefits (i.e., high net costs or low net benefits) for the 100% WWS scenario. For ease of exposition we use the following abbreviations:

LCHB = low cost, high benefits for 100% WWS
HCLB = high cost, low benefits for 100% WWS

For each case, all component costs and benefits summed to make the total have the same underlying explicit or implicit assumptions regarding the discount rate and other parameters. This means, for example, that in either case we do not add a cost estimate based on a low discount rate to a benefit estimate based on a high-discount rate. See the Supplemental Information of Jacobson et al. (2015a) for further discussion.

Section S2. WWS Technologies Considered for each Energy Sector

Quantifying end-use energy requirements and the numbers of WWS generators needed in 2050 by country begins with 2012 energy use data in each energy sector of 139 countries for which data are available (Section S3.1). 2012 energy use in each sector of each country is projected to 2050 in a business-as-usual (BAU) scenario (Section S3.2). The BAU projections account for increasing demand; modest shifts from coal to gas, biofuels, bioenergy, some WWS; and some end use energy efficiency improvements.

All energy-consuming processes in each sector are then electrified, and the resulting end-use energy required for a fully electrified all-purpose energy infrastructure is estimated (Section S3.3). Some end-use electricity in each country is used to produce hydrogen for some transportation and industrial applications. Modest additional end-use energy efficiency improvements are then applied. Finally, the remaining power demand is supplied by a set of WWS technologies, the mix of which varies by country with available resources and rooftop, land, and water areas.

The WWS electricity generation technologies include wind, concentrated solar power (CSP), geothermal, solar PV, tidal, wave, and hydropower. These are existing technologies found to reduce health and climate impacts the most among several technologies while minimizing land and water use and other impacts (Jacobson, 2009).

Vehicles for transportation include battery electric vehicles (BEVs) and BEV-hydrogen fuel cell vehicle (HFCV) hybrids, where the hydrogen is electrolytic (produced by passing electricity through water). BEVs with fast charging dominate 2- and 3-wheel vehicles, short- and long-distance light-duty passenger vehicles and trucks, construction machines, agricultural equipment, short- and moderate-distance trains, short-distance boats and ships (e.g., ferries, speedboats), and aircraft traveling less than 1000 km. BEV-HFCV hybrids dominate medium- and heavy-duty trucks and long-distance trains, ships, and aircraft. Of all commercial aircraft flight distances traveled worldwide, 53.9% are short- haul (<3 hours in duration, with a mean distance of 783 km) (Wilkerson et al., 2010). As such, approximately half the aircraft flights may be electrified with batteries.

In this study, ~7.0% of all 2050 WWS electricity (43.6% of the transportation load) is needed for producing, storing, and using hydrogen. None is used for stationary hydrogen fuel cells to generate electricity because of the relative inefficiency and cost of this process.

Air heating and cooling are accomplished with ground-, air-, or water-source electric heat pumps. Water heat is generated by heat pumps with an electric resistance element for low temperatures and/or solar hot water preheating. Cook stoves use electric induction technology. Dryers are all electric.

Electric arc furnaces, induction furnaces, dielectric heaters, and some resistance heaters are used to power high-temperature industrial processes.

The roadmaps assume the adoption of new energy-efficiency measures but exclude the use of nuclear power, coal with carbon capture, liquid or solid biofuels, or natural gas because all result in more air pollution and climate-relevant emissions than do WWS technologies, in addition to other issues (IPCC, 2014a, Executive Summary, p. 517; Jacobson, 2009; Jacobson and Delucchi, 2011; Jacobson et al., 2013).

This study calculates the numbers of generators of each type needed to power each country based on the 2050 power demand in the country after all sectors have been electrified but before considering grid reliability and neglecting energy imports and exports. However, results from a grid reliability study for the continental U.S. (Jacobson et al., 2015b) are used to estimate the additional electric power generators needed and some of the additional storage needed by country to ensure a reliable electric power grid. An estimate of the full storage needed will be provided in a separate study.

For purposes of calculating the baseline number of energy generators needed in each country, we assume each country is energy independent thus can generate all its annually averaged end-use energy. In reality, energy exchanges among countries will occur in 2050 as they currently do because it will be more profitable for countries with higher-grade WWS resources to produce more power than they need for their own use and export the rest. As such, the real system cost will likely be less than that modeled here since the costs of, for example solar, are higher in low-sunlight countries than in countries that might export solar electricity.

Section S3. Reduction in Load upon Conversion to WWS

Our main objective in this section is to estimate energy end-use in a 2050 100% WWS world relative to a 2050 reference BAU scenario. We proceed in three steps:

S3.1) We start with estimates of actual end-use energy consumption, from the International Energy Agency (IEA), for each country in 2012.

S3.2) We then estimate BAU end-use energy consumption in a future target year (2050) based primarily on the energy end-use projections by the Energy Information Administration (EIA) for 16 regions of the world, assuming that the change in energy use for each country between 2012 and the target year is the same as the EIA-projected change over the period for the region containing the country.

S3.3) To estimate energy use in the future WWS scenario, relative to the future BAU scenario, we adjust the EIA/IEA-based BAU end-use energy estimates by differences between the BAU and the WWS scenarios due to

i) Changes in energy requirements resulting from electrification of end uses in the WWS scenario;
ii) The absence in the WWS scenario of "energy sector own use" (ESOU), which is the energy used to process and transport non-WWS energy (mainly fossil-fuel);
iii) Changes in the amount of capital-intensive energy infrastructure; and
iv) Extra end-use energy efficiency measures in the WWS scenario beyond those assumed in the BAU scenario.

Because our main objectives is to estimate energy consumption in the WWS scenario *relative* to consumption in the BAU scenario, we want to estimate energy consumption for all end-use categories (combinations of demand sectors [e.g., the residential sector] and fuel types [e.g., liquid fuels]) where consumption is likely to differ in the WWS vs. the BAU scenario. The energy-use categories in the original IEA data and EIA projections (see discussion below and Table S1) cover most but not all of the end uses that are likely to differ between the BAU and WWS scenarios (for example, ESOU is only partially covered in the IEA data and not covered at all in the EIA projections), so we adjust the IEA energy-data and EIA energy-projection categories as needed to have estimates of all energy end uses that are likely to differ between the WWS and the BAU scenarios.

S3.1. End-Use energy Consumption by Country, Sector, and Fuel in 2012
We start with the IEA's *World Energy Balances* reports "final consumption," in thousands of tons of oil-equivalent (KTOE), for the year 2012 by country, end-use sector, and fuel (IEA, 2015c). The IEA's energy balance framework shows for each country:

Total final consumption (TFC) (end-use) = Total Primary Energy Supply (TPES) + Transformation Processes (TP).

TPES is originally equal to production + imports – exports – energy for international aviation and marine bunkers. For each country, we add back in energy for international aviation and marine bunkers as described shortly.

Transformation Processes (TP) include for example "energy industry own use;" transformation losses at electricity plants, combined heat-and-power (CHP) plants, and heat-only plants (these are negative values); and transformation-process output from electricity plants, CHP, and heat plants (these are positive values).

TFC is then distributed to end-use sectors and fuel types as shown in Table S1. For the most part, our end-use sectors and end-use fuel types are based on the IEA's categories.

We make three adjustments to the original IEA data to make them suitable for our purposes:

i) The IEA reports energy used for "international marine bunkers" and "international aviation bunkers" as negative TPES rather than as final consumption in the "transport" sector for each country. We want to include this international fuel use in our "transportation" sector for each country, so end-use energy in our transportation sector (in the "oil" fuel category) is equal to the IEA's reported transportation-sector energy use plus the IEA's reported energy use for international marine and air transport.

ii) The IEA estimates "energy industry own use"[1] (EIOU) of fossil fuels but as mentioned above counts it as a negative transformation process and deducts it from primary TPES. Thus, EIOU is not in the industrial sector or any other final demand sector. (EIOU is the industry-sector part of our general category "energy-sector own use" [ESOU]). We include EIOU as a part of our industrial-sector end use, although as discussed later we project EIOU differently from the way we project the energy use in the rest of the industrial sector.

As mentioned above, in the WWS scenario we deduct most EIOU. This gives rise to the question: given that the IEA excludes EIOU from final its final consumption estimates to begin with, why should we add it to industrial-sector consumption, only to subtract it later in the WWS scenario? There are four reasons. First, as just mentioned, we deduct most *but not all* EIOU: the portion of EIOU that pertains to non-energy fuels not replaceable by WWS is retained in the WWS scenario. We explicitly estimate this retained portion, as discussed later. Second, we think that for the purposes of estimating changes in end-use energy as a result of converting to WWS, it is most informative and natural to treat EIOU as end-use energy and show the benefit of reducing it in the WWS scenario. Third (and related to the second), EIOU as a fraction of total consumption is likely to increase as a result of increases in energy intensity (due for example to declining quality of crude oil) and a shift towards more energy-intensive products (such as refined petroleum). We account for this explicitly. Fourth, the IEA does *not* distinguish transportation-sector ESOU (e.g., liquid fuel used by tanker trucks distributing petroleum products), so in any case we have to estimate this separately, and deduct it in the WWS scenario. Given that, it makes more sense to distinguish EIOU (industrial-sector ESOU in our terminology) and provide an explicit, complete accounting of all ESOU.

iii) The IEA reports "non-energy use"[2] of fossil fuels but does not include it in the industrial sector or any other final demand sector. ("Non-energy use" refers to the use fossil fuels to make

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[1] "*Energy industry own use* contains the primary and secondary energy consumed by transformation industries for heating, pumping, traction and lighting purposes... Included here are, for example, own use of energy in coal mines, own consumption in power plants (which includes net electricity consumed for pumped storage) and energy used for oil and gas extraction" (IEA, 2015b, p. 1.12). In its detailed documentation, the IEA (2015a) defines total energy industry own-use as the sum of own use for coal mines, oil and gas extraction, blast furnaces, gas works, gasification plants, coke ovens, patent fuel plants, peat/briquette plants, oil refineries, coal liquefaction plants, LNG plants, Gas-to-liquids plants, electricity and CHP plants, pumped hydro storage, the nuclear industry, charcoal production plants, non-specified energy sectors, and distribution losses. It thus appears that "own-use" for transport of fuels is not included.

[2] "*Non-energy use* covers those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel. Non-energy use is shown separately in final consumption under the heading non-energy use.

non-energy product, such as the use of crude oil to make asphalt.) We include as industrial-sector energy use the fraction of non-energy use of fossil fuels that potentially is replaceable by WWS energy. (The fraction of non-energy use of fossil fuels that is *not* replaceable by WWS energy remains the same in the WWS scenario and the BAU scenario, and hence is outside the scope of our analysis, which is concerned with energy.) We assume that only 10% of non-energy use of coal, oil, and natural gas can be replaced directly by WWS energy.

Table S1 shows the relationships between our end-use sectors and end-use fuel types and those of the IEA.

Table S1. End-use sectors and fuel types in our analysis, the IEA, and the EIA.

A. End-use sectors.

Our analysis	**IEA *World Energy Balances***	**EIA *IEO***
Residential	Residential	Residential
Commercial	Commercial and public services	Commercial
Industrial	Industry + non-energy use[a] + energy industry own use	Industrial
Transportation	Transport, including world marine bunkers and world aviation bunkers	Transportation
Agriculture/forestry/fishing	Agriculture/forestry + fishing	Industrial
other	other, non-specified	Industrial

B. End-use fuel types.

Our analysis	**IEA *World Energy Balances***	**EIA *IEO***
Oil	Oil products + crude oil	Liquids
Natural gas	Natural gas	Natural gas
Coal	Coal + peat + oil shale	Coal
Electricity	Electricity	Electricity
Heat	Heat	N.S. (assume natural gas)
Biofuels and waste	Biofuels and waste	Renewables
Other renewables (excluding electricity, biofuels)	Geothermal + solar/wind/other[b]	Renewables

Source: IEA (2015a), EIA (2016a). IEO = International Energy Outlook; n.s. = not specified.

[a] The portion of non-energy use that is potentially replaceable by WWS. See the discussion in the text.

[b] Final consumption of solar thermal and non-electricity-producing geothermal energy

Note that for biofuels, only the amounts of biomass specifically used for energy purposes (a small part of the total) are included in the energy statistics. Therefore, the non-energy use of biomass is not taken into consideration and the quantities are null by definition" (IEA, 2015b, p. 1.13).

S3.2. Projected End-Use Energy Consumption by Country, Sector, and Fuel in 2050, BAU

The EIA's *International Energy Outlook (IEO)* projects end-use energy consumption by sector (residential, commercial, industrial, and transportation) and fuel (liquids, natural gas, coal, electricity, and renewables) for 16 world regions, through the year 2040 (EIA, 2016a). We start with the EIA's "reference" case for our BAU scenario, and extend their projections to the year 2075 using a 10-year moving linear extrapolation.[3]

In order to apply the EIA projections to the IEA's base-year data, we line up the EIA's energy sector and fuel categories with ours and IEA's. The EIA has fewer fuel and sector categories than does the IEA: EIA does not have the fuel categories "heat" and "biofuels and waste" or the sectors "agricultural/fishing/forestry" and "other". We handle these as follows:

Heat. In the IEA's *Balances*, "heat shows the disposition of heat produced for sale" (IEA, 2015b, p. 1.10), primarily by combined heat-and-power (CHP) plants and heat-only plants. The actual fuels used to produce this purchased heat are included as negative values, and the actual heat produced is included as a positive value, under "transformation processes" (TP).[4] The heat produced in TP is then distributed to different sectors of final consumption. (Thus, in the IEA data, heat is treated in the same way as is electricity.) This means that the end-use consumption of heat is *not* counted elsewhere as is end-use consumption in the EIA data, and so needs to be included in our projections of BAU end-use energy.

The EIA does not have a separate end-use fuel category for "heat," so we need a proxy. In the IEA's *Balances*, CHP and heat-only plants use more NG than any other fuel (IEA, 2015a). Therefore, for the purpose of projecting future BAU energy use, we assume that *X* energy units of heat, as reported by the IEA, are effectively *X* energy units of natural gas end use, and apply the EIA's projected change rates for NG use.

Biofuels and waste. The IEA's "Biofuels and waste" fuel category includes any bio-energy used for fuel purposes; amounts used for *non*-energy purposes are not included (IEA, 2015b, pp. 1.9-1.10). The majority of biofuel use appears to be wood fuel used by households. For the purpose

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[3]In most cases, the EIA's model bases the start of its projections on the same IEA *World Energy Balance* data that we use.

[4]In the IEA's discussion of transformation and losses: "Heat plants refers to plants (including heat pumps and electric boilers) designed to produce heat only, which is sold to a third party under the provisions of a contract… Columns 1 through 8 show the use of primary and secondary fuels in a heating system that transmits and distributes heat from one or more energy sources to, among others, residential, industrial and commercial consumers, for space heating, cooking, hot water and industrial processes" (IEA, 2015b, pp. I.11-I.12).

"Note that for autoproducer CHP plants, all fuel inputs to electricity production are taken into account, while only the part of fuel inputs to heat sold is shown. Fuel inputs for the production of heat consumed within the autoproducer's establishment are not included here but are included with figures for the final consumption of fuels in the appropriate consuming sector" (IEA, 2015b, pp. I.11).

of projecting future BAU energy use, we assume that *X* energy units of "biofuel and waste", as reported by the IEA, are *X* energy units of generic "renewable fuels," and apply the EIA's projected change rates for renewable fuels.

Agricultural/fishing/forestry sector, and "other" sector. The EIA's "industry" sector comprises the end uses in the IEA's "agricultural/fishing/forestry" and "other" sectors, so we project energy use in these IEA sectors on the basis of the EIA's projected change rates for the "industry" sector (Table S1).

We then project future energy use by sector and fuel for each country on the basis of the EIA-projected change in energy use for the region of which the country is a part. (The method is analogous to that used in Jacobson et al. (2015a) to project energy use for the 50 U.S. states.) The general method is

$$E_{i,X,C,TY,BAU} = E_{i,X,C,BY} \cdot \frac{E_{i'\to i,X'\to X,R:C\in R,TY,BAU}}{E_{i'\to i,X'\to X,R:C\in R,BY}}$$

where

$E_{i,X,C,TY,BAU}$ = Use of fuel *i* in sector *X* of country *C* in target-year *TY* in the BAU scenario

$E_{i,X,C,BY}$ = Use of fuel *i* in sector *X* of country *C* in the base-year *BY* scenario (IEA, 2015c; see discussion above)

$E_{i'\to i,X'\to X,R:C\in R,TY,BAU}$ = Use of EIA-fuel category *i' (*mapped to IEA fuel category *i*, as discussed above) in EIA-sector *X'* (mapped to EIA sector X, as discussed above) in region *R* (containing country *C)* in target-year *TY* in the BAU scenario (EIA, 2016a; see discussion above)

$E_{i'\to i,X'\to X,R:C\in R,BY}$ = Use of EIA-fuel category *i' (*mapped to IEA fuel category *i*, as discussed above) in EIA-sector *X'* (mapped to EIA sector X, as discussed above) in region *R* (containing country *C)* in base-year *BY* (EIA, 2016a; see discussion above)

Subscripts

i = IEA fuel categories (discussed above)
i' = EIA fuel categories (discussed above)
X = IEA energy sectors (discussed above)
X' = EIA energy sectors (discussed above)
C = country
TY = Target year of the analysis
BY = Base year of data
WWS = 100% WWS scenario
BAU = Business-as-usual scenario

This general method applies to the residential sector, the commercial sector, the transportation sector, and the industrial sector apart from ESOU and non-energy use of fossil fuels. As discussed next, we treat ESOU and non-energy use of fossil fuels differently from energy use in the rest of the industrial sector.

Projections of end-use energy consumption in the BAU industrial sector

Energy use in the industrial sector in the BAU in the target year is the sum of energy use in the original IEA industrial sector, ESOU, and non-energy use of fossil fuels that is potentially replaceable by WWS. (For our purposes, non-energy use of fossil fuels that is not replaceable by WWS is not counted as energy use.) Formally,

$$E_{i,industrial,C,TY,BAU} = E_{i,industrial*,C,TY,BAU} + ESOU_{i,industrial,C,TY,BAU} + RF_{NE,i} \cdot E_{NE,i,industrial,C,TY,BAU}$$

where

$E_{i,industrial,C,TY,BAU}$ = End use consumption of fuel i in the industrial sector of country C in year TY, in the BAU scenario

$E_{i,industrial*,C,TY,BAU}$ = End use consumption of fuel i in the industrial sector of country C in year TY in the BAU, based on IEA estimates for its original industrial sector, which exclude ESOU and non-energy use of products i

$ESOU_{i,industrial,C,TY,BAU}$ = Own-use of fuel i in the industrial sector of country C in year TY in the BAU

$E_{NE,i,industrial,C,TY,BAU}$ = Non-energy use of i in the industrial sector of country C in year TY in the BAU

$RF_{NE,i}$ = The fraction of non-energy use of i that is potentially replaceable by WWS (we assume that 10% of non-energy use of oil, natural gas, coal, and biofuels, and 100% of non-energy use of electricity, renewables and heat can be replaced by WWS)

Subscript NE = non-energy use of fuel or product

Subscript E = energy use of fuel or product

$E^*_{i,industrial,C,TY,BAU}$ and $E_{NE,i,industrial,C,TY,BAU}$ are estimated as described above, by multiplying IEA base-year estimates by EIA *IEO* projections of the change in energy use in the industrial sector between the base year and the target year (see the formula for $E_{i,X,C,TY,BAU}$).[5]

Industrial ESOU in the target year is the product of reported ESOU in the base year and an all-countries, all-fuels scalar that accounts for: i) changes in the *quantity* of fuels produced, ii) changes in the *mix* of fuel products (because some fuel products require more processing energy than others), and iii) changes in the industrial sector own-use *energy intensity* of fuel production:

[5]Note that we apply the EIA's projection of energy use for the entire industrial sector to the IEA's estimate of energy use in the industrial sector *excluding* EIOU, which we are treating separately. This is a potential problem if the EIA estimates EIOU or any component of it separately, and if the projected rate of change in energy use for EIOU (or its component) is likely to be different from the projected rate of change for the entire industrial sector. The EIA's industrial-sector model does not explicitly treat industrial-sector energy "own use" (EIOU). It does estimate changes in the energy intensity of production in different industries, based on exogenous trend and vintaging factors and endogenous effects of price on efficiency, but it does not estimate increases in energy intensity in fuel-producing industries due to shifts in fuel product mixes or decreasing quality of feedstocks (EIA, 2011b). Thus, it appears that we reasonably may apply the EIA's projection of energy use for the entire industrial sector to the IEA's industrial sector *excluding* EIOU.

$$ESOU_{i,industrial,C,TY,BAU} = ESOU_{i,industrial,C,BY_{IEA}} \cdot K_{ESOU,all-i(p),world,TY/BY}$$

$$K_{ESOU,all-i(p),world,TY/BY} = \frac{\sum_{i(p)} EI_{NE,i(p),industrial,world,TY,BAU} \cdot E_{NE,i(p),all-X,world,TY,BAU} + \sum_{i(p)} EI_{E,i(p),industrial,world,TY,BAU} \cdot E_{E,i(p),all-X,world,TY,BAU}}{ESOU_{all-i,industrial,world,BY_{IEA}}}$$

$$E_{E,i(p),all-X,world,TY,BAU} = E_{Total,i(p),all-X,world,TY,BAU} - E_{NE,i(p),all-X,world,TY,BAU}$$

where

$ESOU_{i,industrial,C,BY_{IEA}}$ = Own-use of fuel *i* in the industrial sector of country *C* in IEA base year *BY* (see IEA data discussed above)

$K_{ESOU,all-i(p),world,TY/BY}$ = Scalar for industrial ESOU in the target year vs. the base year, for all own-use fuels and countries

$EI_{NE,i(p),industrial,world,TY,BAU}$ = The global-average industrial-sector energy intensity of producing *NE* product *i(p)* in year *TY* in the BAU scenario (BTU-own use/BTU-*i*) (discussed below)

$EI_{E,i(p),industrial,world,TY,BAU}$ = The global-average industrial-sector energy intensity of producing *E* product *i(p)* (used for energy purposes) in year *TY* in the BAU (BTU-own use/BTU-*i*) (discussed below)

$E_{NE,i(p),all-X,world,TY,BAU}$ = Total all-sector, all-country (global) energy use of *NE* product *i(p)* in year *TY* in the BAU

$E_{E,i(p),all-X,world,TY,BAU}$ = Total all-sector, all-country (global) energy use of *E* product *i(p)* in year *TY* in the BAU

$E_{Total,i(p),all-X,world,TY,BAU}$ = Total all-sector, all-country (global) energy use of *i(p)* for all purposes (energy and non-energy) in year *TY* in the BAU

$ESOU_{all-i,industrial,world,BY_{IEA}}$ = Total industrial ESOU of all fuels in all countries IEA base year *BY* (see IEA data discussed above)

Subscript *i(p)* refers to the *production* of fuel *i,* as distinguished from *consumption* or end-use of fuel *i*, which is designated just *i* (the actual fuel/product categories are the same for *i* and *i(p))*

Note that this calculation is circular, because the total quantity of energy used includes the total amount of own-use fuels, but as just noted the scalar that gives the total amount of own-use fuels depends on the total quantity of all fuels produced. This circularity is resolved satisfactorily by iterative calculations until trials and results converge.

Note also that we could have applied the calculated energy intensities (by end-use fuel product category) to each country's mix of end-use fuel products, but this would have resulted in unreasonable estimates of ESOU because in fact for many countries industrial ESOU is not related to that country's mix of end-use fuel products. (We verified this by testing this method against the IEA-reported ESOU by country for 2012, and found that in many cases the estimated country ESOU was quite different from the reported ESOU.)

Note that the energy-intensity term captures total industrial-sector own use energy – mainly energy for feedstock production (e.g., coal mining) and fuel processing (e.g., oil refining), but *not* including energy for transporting fuels – per energy unit of fuel *i.* That is, the numerator of the energy intensity term includes all own-use energy as defined for the IEA's *World Energy Balances*, described above, but it does not include non-industrial sector "own use" – e.g., fuel used by trucks transporting fuels. We account separately for this transportation-sector ESOU.

Finally, note that we use different notation to distinguish the production of fuel *i* (*i(p))* from the consumption of fuel *i.*

The energy intensity *EI* is equal to the intensity calculated for the IEA base year multiplied by an assumed annual rate of change through the target year:

$$EI_{E,i(p),global,TY,BAU} = EI_{E,i(p),global,BY_{IEA}} \cdot e^{r_{EI,E,i(p)} \cdot (TY - BY_{IEA})}$$

$$EI_{NE,i(p),gloal,TY,BAU} = EI_{NE,i(p),global,BY_{IEA}} \cdot e^{r_{EI,NE,i(p)} \cdot (TY - BY_{IEA})}$$

where

$EI_{NE,i(p),global,BY_{IEA}}$ = The globally-average energy intensity of producing *NE* product *i(p)* in base-year BY (BTU-own use/BTU-*i(p)*) (discussed below)

$EI_{E,i(p),global,BY_{IEA}}$ = The globally-average energy intensity of producing *E* product *i(p)* in base-year BY (BTU-own use/BTU-*i(p)*) (discussed below)

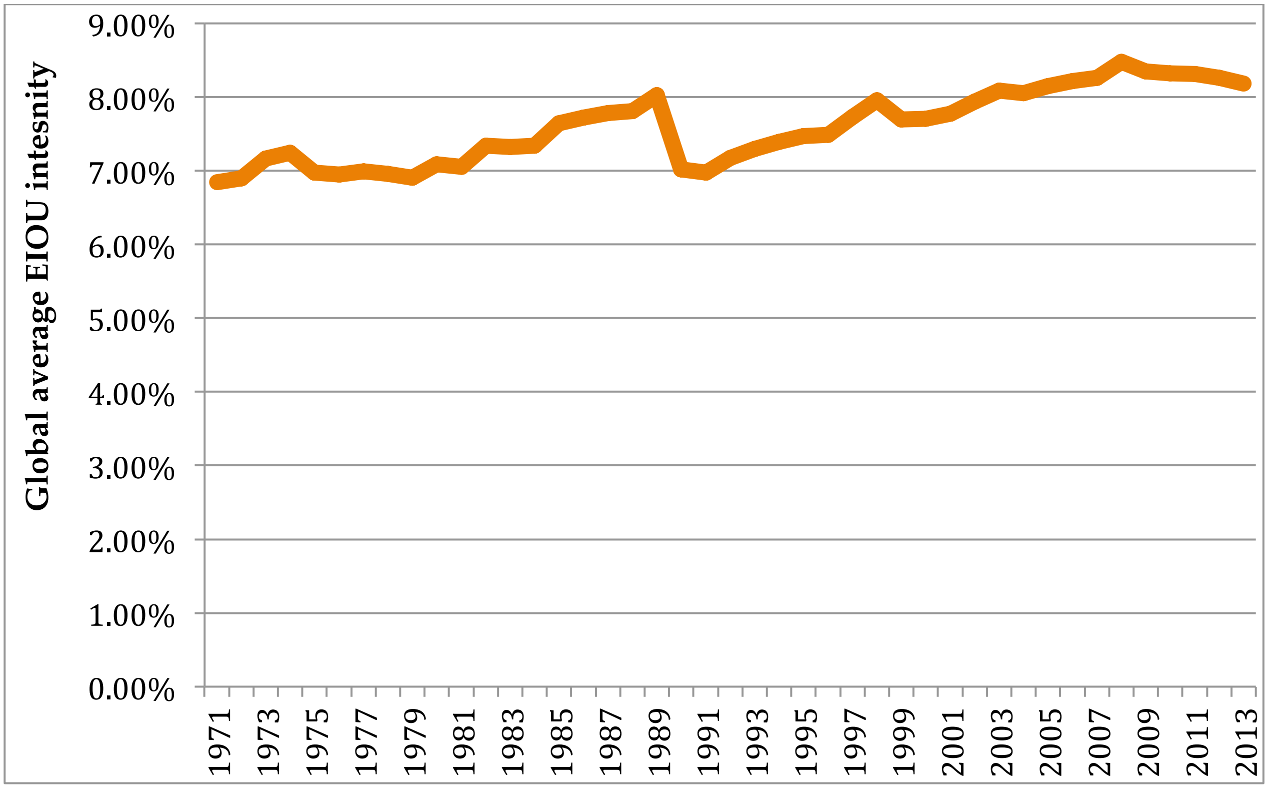
$r_{EI,NE,i(p)}$ = The annual rate of change in the energy intensity of producing *NE* product *i(p)* (Table S2)

$r_{EI,E,i(p)}$ = The annual rate of change in energy intensity of producing *E* product *i*(p) (Table S2)

We assume that decreasing quality of crude oil and raw natural gas, along with increasingly stringent specifications for liquid fuels, will result in slight increases in the industrial-sector energy intensity of extracting and processing liquid fuels and natural gas. This appears to have been the case historically: the global all-product average energy intensity, estimated from the IEA data and shown in Figure S1, generally has increased over time, although since 2008 it has declined. The annual rates of change in the data of Figure S1 are

1971 to 2013: 0.43%/yr
1990 to 2013: 0.67%/yr
2000 to 2013: 0.47%/yr
2003 to 2013: 0.12%/yr
2008 to 2013: -0.70%/yr

Figure S1. Global-average EIOU energy intensity, 1971-2013.



Source: IEA (2015c). The global-average intensity is equal to total EIOU reported by the IEA divided by total final consumption plus EIOU.

Note, though, that the global all-product average intensity also reflects shifts in the product mix, probably towards more energy intensive products, whereas our parameters $r_{EI,F,i(p)}$ and $r_{EI,NF,i(p)}$ represent the rate of change in the energy intensity of producing each fuel product *i*. In any event, consideration of the historical trend of Figure S1, along with our general knowledge of the energy intensity of producing different fuels (Delucchi et al., 2003) leads us to the assumptions of Table S2.

Table S2. Assumed annual rate of change in energy intensity of producing different products.

Fuel type	$r_{EI,NF,i(p)}$	$r_{EI,F,i(p)}$
Oil	0.15%	0.20%
Natural gas	0.10%	0.15%
Coal	0.00%	0.00%
Electricity	0.00%	0.00%
Heat	0.00%	0.00%
Renewables	0.00%	0.00%
Bio Fuels and Waste	0.00%	0.00%

The industrial-sector energy intensity to produce energy (*E*) or non-energy (*NE*) product *i(p)* in the base year is equal to the average intensity over all products multiplied by the intensity of energy or non-energy product *i(p)* relative to the average the base year. We use this formulation because we can estimate the base-year sector-wide average intensity directly from the IEA data. Formally,

$$EI_{E,i(p),global,BY_{IEA}} = EI_{all-i(p),global,BY_{IEA}} \cdot R_{E,i(p),BY_{IEA}}$$

$$EI_{NE,i(p),global,BY_{IEA}} = EI_{all-i(p),global,BY_{IEA}} \cdot R_{NE,i(p),BY_{IEA}}$$

$$EI_{all-i(p),global,BY_{IEA}} = \frac{ESOU_{all-i,industrial,world,BY_{IEA}}}{E_{all-i,TFC,world,BY_{IEA}} + ESOU_{all-i,industrial,world,BY_{IEA}}}$$

where

$EI_{all-i(p),global,BY_{IEA}}$ = The average energy intensity of producing all products (*E* and *NE*), in the IEA data base year (BTU/BTU)

$R_{E,i(p),BY_{IEA}}$ = The industrial *ESOU* energy-intensity of producing *E* product *i(p)*, relative to the average intensity, in IEA base year *BY* (discussed below)

$R_{NE,i(p),BY_{IEA}}$ = The industrial *ESOU* energy-intensity of producing *NE* product *i(p)*, relative to the average intensity, in IEA base year *BY* (discussed below)

$ESOU_{all-i,industrial,world,BY_{IEA}}$ = Industrial sector "own use" of all fuels *i*, worldwide, in IEA base year *BY* (IEA *World Energy Balances*)

$E_{all-i,TFC,world,BY_{IEA}}$ = Total final (all-sector) consumption of all fuels *i* worldwide in IEA base year *BY* (IEA *World Energy Balances*)

The relative intensity parameters *R* must be specified such that the product of the relative intensity, the average intensity, and production, summed over all products, equals the actual reported industrial *ESOU*. To accomplish this, we specify *R* for all product categories except one, which we solve for using the equality constraint just described. The product categories for which we specify *R* are designated *i(p')* and the solved-for product category is designated *i(p*)*. We first develop our equality constraint,

$$ESOU_{all-i,industrial,world,BY} = ESOU_{NE,i,industrial,world,BY} + ESOU_{E,i,industrial,world,BY} =$$

$$\sum_{i(p)} \left[EI_{all-i(p),global,BY_{IEA}} \cdot R_{NE,i(p),BY_{IEA}} \cdot E_{NE,i(p),all-X,world,BY} + EI_{all-i(p),global,BY_{IEA}} \cdot R_{E,i(p),BY_{IEA}} \cdot E_{E,i(p),all-X,world,BY} \right]$$

$$= EI_{all-i(p),global,BY_{IEA}} \cdot \sum_{i(p)} \left[R_{NE,i(p),BY_{IEA}} \cdot E_{NE,i(p),all-X,world,BY} + R_{E,i(p),BY_{IEA}} \cdot E_{E,i(p),all-X,world,BY} \right]$$

Substituting for $ESOU_{all-i,industrial,world,BY}$ gives

$$ESOU_{all-i,industrial,world,BY_{IEA}} = \frac{ESOU_{all-i,industrial,world,BY_{IEA}}}{E_{all-i,TFC,world,BY_{IEA}} + ESOU_{all-i,industrial,world,BY_{IEA}}}$$

$$\cdot \sum_{i(p)} \left[R_{NE,i(p),BY_{IEA}} \cdot E_{NE,i(p),all-X,world,BY} + R_{E,i(p),BY_{IEA}} \cdot E_{E,i(p),all-X,world,BY} \right]$$

Define

$$Efr_{NE,i(p),all-X,industrial,world,BY_{IEA}} \equiv \frac{E_{NE,i(p),all-X,world,BY}}{E_{all-i,TFC,world,BY_{IEA}} + ESOU_{all-i,industrial,world,BY_{IEA}}}$$

$$Efr_{E,i(p),all-X,industrial,world,BY_{IEA}} \equiv \frac{E_{E,i(p),all-X,world,BY}}{E_{all-i,TFC,world,BY_{IEA}} + ESOU_{all-i,industrial,world,BY_{IEA}}}$$

Then we have

$$ESOU_{all-i,industrial,world,BY_{IEA}} = ESOU_{all-i,industrial,world,BY_{IEA}} \cdot$$
$$\sum_{i(p)} \left[R_{NE,i(p),BY_{IEA}} \cdot Efr_{NE,i(p),all-X,industrial,world,BY_{IEA}} + R_{E,i(p),BY_{IEA}} \cdot Efr_{E,i(p),all-X,industrial,world,BY_{IEA}} \right]$$

And finally,

$$1 = \sum_{i(p)} \left[R_{NE,i(p),BY_{IEA}} \cdot Efr_{NE,i(p),all-X,industrial,world,BY_{IEA}} + R_{E,i(p),BY_{IEA}} \cdot Efr_{E,i(p),all-X,industrial,world,BY_{IEA}} \right]$$

Distinguishing between the specified categories *i(p')* and the solved-for category *i(p*)*, we have

$$1 = R_{E,i(p^*),BY_{IEA}} \cdot Efr_{E,i(p^*),all-X,industrial,world,BY_{IEA}} + \sum_{i(p')} \left[R_{NE,i(p'),BY_{IEA}} \cdot Efr_{NE,i(p'),all-X,industrial,world,BY_{IEA}} + R_{E,i(p'),BY_{IEA}} \cdot Efr_{E,i(p'),all-X,industrial,world,BY_{IEA}} \right]$$

Our final solution for the category *i(p*)* is

$$R_{E,i(p^*),BY_{IEA}} = \frac{1 - \sum_{i(p')} \left[R_{NE,i(p'),BY_{IEA}} \cdot Efr_{NE,i(p'),all-X,industrial,world,BY_{IEA}} + R_{E,i(p'),BY_{IEA}} \cdot Efr_{E,i(p'),all-X,industrial,world,BY_{IEA}} \right]}{Efr_{E,i(p^*),all-X,industrial,world,BY_{IEA}}}$$

We pick values for $R_{NE,i(p'),BY_{IEA}}$ and $R_{E,i(p'),BY_{IEA}}$ so that they and the resultant $R_{E,i(p^*),BY_{IEA}}$ are consistent with our general knowledge of the relative energy intensity of producing different products (Table S3). Note that here we use global rather than country-specific values.

Table S3. Assumed relative energy intensity of producing different products.

Fuel type	$R_{NE,i(p'),BY_{IEA}}$	$R_{E,i(p'),BY_{IEA}}$
Oil	0.40	1.22*
Natural gas	0.30	1.10
Coal	0.20	0.70
Electricity	1.00	1.00
Heat	0.40	0.50
Renewables	0.40	1.00
Bio Fuels and Waste	0.40	1.10

Source: Based on Delucchi et al. (2003). * = R_{F,p^*}

S3.3. Projected End-Use Energy Consumption by Country, Sector, and Fuel in 2050, WWS

Energy use in the future WWS scenario is equal to energy use in the future BAU multiplied by an overall adjustment factor that accounts for the effects of electrification, the elimination of ESOU (energy-sector own-use), and extra energy efficiency measures.

Formally,

$$E_{i,X,C,TY,WWS} = E_{i,X,C,TY,BAU} \cdot AF_{i,X,C,TY,WWS/BAU}$$

where

$E_{i,X,C,TY,WWS}$ = Energy use in (the original BAU) fuel-type category *i* in sector *X* in country *C* in year *TY* in the WWS scenario
$E_{i,X,C,TY,BAU}$ = Projected end-use of fuel *i* in sector *X* in country *C* in year *TY* in the BAU scenario (discussed above)
$AF_{i,X,C,TY,WWS/BAU}$ = Adjustment factor for fuel-type category *i* in sector *X* in country *C* in year *TY*, for the WWS vs. the BAU scenario

The overall adjustment factor accounts for the effects on energy use of:

- Extra efficiency measures in the WWS scenario;
- Elimination of energy use for processing and transporting non-WWS energy products in the BAU (energy-sector own-use);
- The use of electricity or hydrogen rather than fossil fuels for combustion; considering effects upstream in the WWS system as well as end-use effects.

Formally,

$$AF_{i,X,C,TY,WWS/BAU} = EFF_{i,X,C,WWS/BAU} \cdot ESOUF_{i,X,C,TY,WWS/BAU} \cdot \left(ElF_{i,X,C,WWS} \cdot ElE_{eu,i,X,WWS/BAU} \cdot ElE_{up,i,X,WWS} + \left(1 - ElF_{i,X,C,WWS}\right) \cdot H2E_{eu,i,X,WWS/BAU} \cdot H2E_{up,i,X,WWS}\right)$$

where

$EFF_{i,X,C,WWS/BAU}$ = The effect of extra end-use efficiency measures in the WWS scenario: the ratio of energy use after the measure to energy use before the measure, for fuel-type category *i* in end-use sector *X* in country *C*
$ESOUF_{i,X,C,TY,WWS/BAU}$ = Factor to account for the elimination of (most) energy used for processing and transporting non-WWS energy products (mainly fossil fuels) in the BAU, for fuel-type *i* in sector *X* in country *C* in year *TY*
$ElF_{i,X,C,WWS}$ = Of end-use energy demand in fuel category *i* in sector *X* in country *C* in the BAU, the fraction that is met by direct use of electricity (as opposed to use of electrolytic hydrogen) in the WWS scenario
$ElE_{eu,i,X,WWS/BAU}$ = The ratio of end-use (*eu*) electrical energy in the WWS scenario to end-use fuel energy in the BAU scenario (holding energy services constant), for fuel category *i* in sector *X* (same for all countries and years)
$ElE_{up,i,X,WWS}$ = Factor to account for any upstream (*up*) energy needed to produce the direct electricity used in fuel category *i* in sector *X* in the WWS scenario (same for all countries and years)
$H2E_{eu,i,X,WWS/BAU}$ = The ratio of end-use (*eu)* hydrogen energy in the WWS scenario to end-use fuel energy in the BAU scenario (holding energy services constant), for fuel category *i* in sector *X* (same for all countries and years)

$H2E_{up,i,X,WWS}$ = Factor to account for any upstream (*up*) energy needed to produce the hydrogen used in fuel category *i* in sector *X* in the WWS scenario (same for all countries and years)

Table S4 shows most of the key parameter values in the analysis, for all sectors.

Table S4. Parameter values in the calculation of WWS energy use relative to the BAU**.**

Sector, *fuel*	**Extra efficiency measures** $EFF_{i,X,C,WWS/BA}$	**Electricity: fuel ratio (end use)** $ElE_{eu,i,X,WWS/BAU}$	**Hydrogen : fuel ratio (end use)** $H2E_{eu,i,X,WWS/BAU}$	**Electricity upstream factor** $ElE_{up,i,X,WWS}$	**Hydrogen upstream factor** $H2E_{up,i,X,WWS}$
Residential					
Oil	0.84	0.82	1.43	1.00	1.00
Natural gas	0.81	0.82	1.43	1.00	1.00
Coal	0.00	0.82	1.43	1.00	1.00
Electricity	0.77	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	0.87	0.82	1.43	1.00	1.00
Biofuels/waste	0.87	0.82	1.43	1.00	1.00
Commercial					
Oil	0.95	0.82	1.43	1.00	1.00
Natural gas	1.01	0.82	1.43	1.00	1.00
Coal	1.00	0.82	1.43	1.00	1.00
Electricity	0.78	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	1.00	0.82	1.43	1.00	1.00
Biofuels/waste	1.00	0.82	1.43	1.00	1.00
Industrial					
Oil	0.98	0.82	1.43	1.00	1.00
Natural gas	0.98	0.82	1.43	1.00	1.00
Coal	0.97	0.82	1.43	1.00	1.00
Electricity	0.92	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	1.14	0.82	1.43	1.00	1.00
Biofuels/waste	1.00	0.82	1.43	1.00	1.00
Transportation					
Oil	0.96	0.19	0.64	1.00	1.18
Natural gas	0.88	0.82	1.43	1.00	1.00
Coal	0.00	1.00	1.43	1.00	1.00
Electricity	1.07	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	1.00	1.00	1.43	1.00	1.00
Biofuels/waste	1.00	1.00	1.43	1.00	1.00
Agriculture/ forestry/fishing					
Oil	1.00	0.82	1.43	1.00	1.00
Natural gas	1.00	0.82	1.43	1.00	1.00
Coal	1.00	0.82	1.43	1.00	1.00
Electricity	1.00	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	1.00	0.82	1.43	1.00	1.00
Biofuels/waste	1.00	0.82	1.43	1.00	1.00
Other					

Oil	1.00	0.82	1.43	1.00	1.00
Natural gas	1.00	0.82	1.43	1.00	1.00
Coal	1.00	0.82	1.43	1.00	1.00
Electricity	1.00	1.00	1.00	1.00	1.00
Heat	1.00	1.00	1.00	1.00	1.00
Renewables	1.00	0.82	1.43	1.00	1.00
Biofuels/waste	1.00	0.82	1.43	1.00	1.00

Extra energy efficiency measures in the WWS scenario (parameter $EFF_{i,X,C,WWS/BAU}$)

Our assumptions, shown in Table S4 are adapted from the analysis of Jacobson et al. (2015a) for the 50 U.S. states. See for comparison Table S4 from the Supplemental Information of Jacobson et al. (2015a). Although the extra-efficiency-measures parameter $EFF_{i,X,C,WWS/BAU}$ can be specified to be different for different countries, we have assumed here the same values for all countries.

Fraction of end-use energy demand met by electricity (parameter $ElF_{i,X,C,WWS}$)

We assume that all energy end uses can be 100% directly electrified except for in the transportation sector. Any end-use demand not directly electrified is met by electrolytic hydrogen (produced by WWS power). Although the electrification-fraction parameter $ElF_{i,X,C,WWS}$ can be specified to be different for different countries, we have assumed here the same values for all countries.

Ratio of WWS energy to BAU fuel use in end use, and WWS upstream factors (parameters $ElE_{eu,i,X,WWS/BAU}$, $H2E_{eu,i,X,WWS/BAU}$, $ElE_{up,i,X,WWS}$, and $H2E_{up,i,X,WWS}$)

The parameters $ElE_{eu,i,X,WWS/BAU}$ and $H2E_{eu,i,X,WWS/BAU}$ express the end-use energy requirements of using electricity or hydrogen relative to the requirements of using BAU fuels, holding constant the service provided (e.g., heat for cooking or miles of travel). For example, in the case of heat for cooking, the parameter $ElE_{eu,i,X,WWS/BAU}$ can be BTUs of electricity, measured at the meter, per unit of heat transferred to the cooking object, relative to BTUs of natural gas, measured at the meter, per unit of heat transferred to the cooking object. In the case of transportation, these parameters are BTU/mi for electric vehicles (EVs) relative to BTU/mi for gasoline internal-combustion-engine vehicles (ICEVs), where the BTUs for the EV are measured at the electricity meter, going into the EV charger, and BTUs for the ICEV are measured at the gasoline pump nozzle. For hydrogen fuel-cell vehicles (FCVs), the BTUs are measured at the hydrogen dispenser outlet, going into the vehicle.

The values shown in Table S4 are adapted from Jacobson et al. (2015a). The values for hydrogen end-use ($H2E_{eu,i,X,WWS/BAU}$) assume that electrolytic hydrogen is produced with an electrolyzer at the site of end-use and therefore start with the energy content of the input electricity (rather than the energy content of the output hydrogen). The upstream adjustment for hydrogen (

$H2E_{up,i,X,WWS}$) accounts for the electricity generated "upstream" for hydrogen compression or liquefaction.[6]

The original definitions of these are given in section A.2.8 and A.2.9, p. 1166 of Jacobson and Delucchi (2011). In that paper we included electrolysis in the e-H2: fuel ratio, and compression or liquefaction energy in the upstream-H2 factor. For the end result, it doesn't really matter what goes where, but I think it's more natural to now use these definitions:

Electricity:fuel ratio
BTU/mi for EVs divided by BTU/mi for ICEVs, where BTUs for EVs are measured at the wall plug (going into the charger) and BTUs for ICEVs are measured at the gasoline pump going into the tank. This is the same as the definition you write below.

e-H_2:fuel ratio
BTU/mi for FCVs divided by BTU/mi for ICEVs, where BTUs for FCVs are measured at the hydrogen pump going into the tank and BTUs for ICEVs are measured at the gasoline pump going into the tank. This now would exclude electrolysis. We need these ratios for all of the modes for which we have BAU energy use. These are

domestic marine freight
international marine freight
rail freight
rail passenger
heavy trucks
medium truck
light trucks
light-duty automobiles
2 and 3 wheelers
bus
air

The *upstream factors* are meant to account for any process/system energy that is not included in either vehicle end-use or electricity generation or distribution to end users. In the case of direct use of electricity, the end-use system begins where the generation and distribution system ends — at the end-user's plug — so by construction there is no additional process/system energy, and the upstream factor always is 1.00. In the case of hydrogen, the upstream factor accounts for all of the energy required to convert delivered electricity to delivered hydrogen. In general there are three possible energy processes here: conversion of electricity to hydrogen, transport of hydrogen, and further processing of hydrogen for end use (e.g., compression or liquefaction).

We assume that hydrogen is used by some transportation modes, but not for energy in any other

[6] Note that because the factors $H2E_{eu,i,X}$ and $H2E_{up,i,X}$ are multiplicative it doesn't matter whether we show one under "end use" and one under "upstream", and then multiply them together, or multiply them together and show the result under "upstream." We have chosen to classify and show them separately, even though the distinction between "upstream" and "end use" in this case is arbitrary, because it makes the individual assumptions explicit.

sector. As such, all hydrogen can be produced by electrolysis at the site of end-use, without any transportation of hydrogen. The efficiency of electrolysis depends on the technology and scale, so we make general assumptions about the size and technology of electrolyzers at refueling stations and then get appropriate efficiency figures.

Elimination of energy-sector own-use: energy to process and transport BAU energy products other than wind, water, and solar power (parameter $ESOUF_{i,X,C,TY,WWS/BAU}$)

In the 100% WWS scenario, no end-use energy will be needed to produce and transport fossil-fuels, nuclear energy, or bioenergy. For example, the 100% WWS scenario will eliminate energy used by petroleum refineries, natural-gas pipelines, and oil tankers. Here we estimate the adjustment-factor components that account for own-use energy in the industrial sector to produce fossil fuels, and own-use energy in the transport sector to transport fossil fuels.

Own-use energy eliminated in the industrial sector ($ESOUF_{i,industrial,C,TY,WWS/BAU}$ *)*

The BAU industrial sector uses energy to produce different kinds of fossil-fuel based products *i(p)* for energy (*E*) and non-energy (*NE*) purposes. This use of energy is referred to as "own use" in the industrial sector. As discussed above, the IEA reports total (all-purpose) $ESOUF_{industrial}$ for each country. (The IEA also breaks out $ESOUF_{industrial}$ by type of own-use fuel, but for our purposes in this section this breakout is not relevant.) In a WWS world, all of the products used for energy (*E)* purposes will be replaced by WWS energy, but only some (presumably small) fraction of the products used for *NE* purposes will be replaced by WWS energy. This means that in the WWS energy-use scenario, we must subtract all $ESOUF_{industrial}$ for *E* products, but only some fraction of the $ESOUF_{industrial}$ for *NE* products. Designating the final amount of energy-industry own-use to be subtracted as *EIOU**, we have

$$ESOUF_{i,industrial,C,TY,WWS/BAU} = \frac{E_{i,industrial,C,TY,BAU} - ESOU^*_{i,industrial,C,TY,BAU}}{E_{i,industrial,C,TY,BAU}} = 1 - \frac{ESOU^*_{i,industrial,C,TY}}{E_{i,industrial,C,TY,BAU}}$$

where

$ESOUF_{i,industrial,C,TY,WWS/BAU}$ = Factor to account for the elimination of (most) energy used in the industrial sector to process non-WWS energy products (mainly fossil fuels): the ratio of industrial-sector energy use of *i* in country *C* in year *TY* in the *WWS* scenario to industrial-sector energy use of *i* in country *C* in year *TY* in the *BAU*

$E_{i,industrial,C,TY,BAU}$ = Use of fuel *i* in the industrial sector of country *C* in year *TY* in the *BAU* (includes all industrial *ESOU* and all use of replaceable non-energy products as well as all other industrial-sector energy use) (estimated as described above)

$ESOU^*_{i,industrial,C,TY,BAU}$ = Industrial energy-sector own-use of *i* in country *C* in year *TY* in the BAU, to produce products that will be replaced by WWS power: all energy *(E)* products and the replaceable portion of non-energy *(NE)* products

The industrial-sector own use, $ESOU^*_{i,industrial,C,TY,BAU}$, is the product of the industrial-sector energy intensity of fuel production and total fuel production, for *E* and replaceable *NE* products:

$$ESOU^*_{i,industrial,C,TY,BAU} = \sum_{i(p)} EI_{NE,i(p),industrial,world,TY,BAU} \cdot E_{NE,i(p),all-X,world,TY,BAU} \cdot RF_{NE,i(p)}$$
$$+\sum_{i(p)} EI_{E,i(p),industrial,world,TY,BAU} \cdot E_{E,i(p),all-X,world,TY,BAU}$$

where all terms are defined and specified above in the subsection "Projections of end-use energy consumption in the BAU industrial sector."

Own-use energy eliminated in the transport sector ($ESOUF_{i,transport,C,TY,WWS/BAU}$)

As discussed next, a small but nontrivial amount of petroleum end-use in the transport sector is for shipment of coal and petroleum products. This "own use" will be eliminated in the 100% WWS scenario. As noted above, the IEA does not include transport-sector energy "own-use" in its estimates of EIOU, so we must estimate it ourselves.

Table S5 shows ton-miles of movement of coal and petroleum products by truck, rail, water, and pipeline transport (*2012 Commodity Flow Survey [CFS]*, U. S. Bureau of Transportation Statistics and U. S. Census Bureau, 2015). The *CFS* data indicate that in 2012 transport of coal and petroleum products accounted for 55% of ton-miles by rail, 24% of ton-miles by water, 8% of ton-miles by truck, and 95% of ton-miles by pipeline. (Note that the *CFS* excludes shipment of crude oil and natural gas, which if included would increase the fossil-fuel share of total ton-miles by water and pipeline, but also excludes shipment of forestry and some agricultural commodities, which if included would decrease the fossil-fuel share of ton-miles by truck.) In the U. S. in 2012, medium and heavy trucks used 21.6% of all petroleum used in transport, freight ships used 3.3%, and freight rail used 1.9% (Davis et al., 2015). Combining these shares of transport petroleum use with the ton-mile shares from Table S5, we estimate that shipment of fossil fuels accounted for about 4% of all petroleum end use in the transport sector in the U. S. in 2012.

Table S5. Transport of fossil fuels by mode (ton-miles).

Rail	**Ton-miles**	**% of total**
All commodities	1,211,481	100.0%
Coal	609,335	50.3%
Petroleum products	19,682	1.6%
Fuel oil	3,187	0.3%
Other coal & oil	29,582	2.4%
Coal+petroleum	*661,786*	*54.6%*
Water	**Ton-miles**	**% of total**
All commodities	192,866	100.0%
Coal	1,075	0.6%
Petroleum products	19,779	10.3%
Fuel oil	8,888	4.6%
Other coal & oil	16,884	8.8%
Coal+petroleum	46,626	24.2%

Truck	Ton-miles	% of total
All commodities	1,247,717	100.0%
Coal	9,848	0.8%
Petroleum products	28,183	2.3%
Fuel oil	20,530	1.6%
Other coal & oil	47,539	3.8%
Coal+petroleum	*106,100*	*8.5%*
Pipeline	**Tons**	**% of total**
All commodities	635,975	100.0%
Coal	0	0.0%
Petroleum products	342,839	53.9%
Fuel oil	233,424	36.7%
Other coal & oil	29,950	4.7%
Coal+petroleum	*606,213*	*95.3%*

Source: U. S. Bureau of Transportation Statistics and U. S. Census Bureau (2015).

Following the method established for own-use energy eliminated in the industrial sector, we have

$$ESOUF_{i,transport,C,TY,WWS/BAU} = 1 - \frac{ESOU^*_{i,transport,C,TY}}{E_{i,transport,C,TY,BAU}}$$

$$ESOUF_{i,transport,C} = \frac{E_{i,X,C} - ESOU^*_{i,transport,C}}{E_{i,transport,C}} = 1 - \frac{ESOU^*_{i,transport,C}}{E_{i,transport,C}}$$

where

$ESOUF_{i,transport,C,TY,WWS/BAU}$ = Factor to account for the elimination of (most) energy used in the transport sector to transport non-WWS energy products (mainly fossil fuels): the ratio of transport-sector energy use of *i* in country *C* in year *TY* in the *WWS* scenario to transport-sector energy use of *i* in country *C* in year *TY* in the *BAU*

$E_{i,transport,C,TY,BAU}$ = Use of fuel *i* in the transport sector of country *C* in year *TY* in the *BAU* (includes all transport *ESOU* and transport of replaceable non-energy products as well as all other transport-sector energy use) (estimated as described above)

$ESOU^*_{i,transport,C,TY,BAU}$ = Transport energy-sector own-use of *i* in country *C* in year *TY* in the BAU, to transport products that will be replaced by WWS power: all energy *(E)* products and the replaceable portion of non-energy *(NE)* products

For simplicity we define:

$$\frac{ESOU^*_{i,transport,C}}{E_{i,transport,C}} \equiv ESOUF^*_{i,transport,C}$$

and hence

$$ESOUF_{i,transport,C} = 1 - ESOUF^*_{i,transport,C}$$

where

$ESOUF^*_{i,transport,C}$ = Of total use of fuel *i* in the transport sector in country *C*, the fraction that is used to transport fossil fuels, nuclear materials, and biofuels used for energy purposes.

The Lifecycle Emissions Model (Delucchi et al., 2003) provides results that allow us to estimate *ESOUF**.

$$ESOUF^*_{liquids,transport} = 0.02$$
$$ESOUF^*_{NG,transport} = 0.75$$
$$ESOUF^*_{El,transport} = 0.50$$

(Note that in the accompanying spreadsheet, the quantity entered is *ESOUF*, not *ESOUF**.)

The EIA's *IEO* projects freight ton-miles and ton-miles per BTU by mode (heavy trucks, other trucks, rail, domestic water, and international water), fuel (gasoline, diesel, LPG, coal, electricity, natural gas, and renewables), and region (EIA, 2011c). Demand for freight service is projected as a function of GDP, fuel price, and, in some cases, a trend factor representing exogenous effects of, for example, improvements in efficiency (EIA, 2011c). Shares of different fuels are held fixed at the base-year values. Base-year data in the model are from the IEA's *World Energy Balances*.

S3.4. Summary of BAU and WWS Loads for Each of 139 Countries

Table S6 projects 139-country BAU and WWS end-use power demands to 2050. Table 1 of the main text summarizes results over all countries. End-use power is the power in delivered electricity or fuel (e.g., gasoline) that is actually used to provide services such as heating, cooling, lighting, and transportation. It excludes losses during the production and transmission of the electricity or fuel but includes industry self-energy-use for mining, transporting, and refining fossil fuels. All end uses that feasibly can be electrified use WWS electricity directly, but WWS electricity is also used to produce electrolytic hydrogen for some transportation.

Table S6. 1st row of each country: estimated 2050 total end-use load (GW) and percent of the total load by sector if conventional fossil-fuel, nuclear, and biofuel use continue from today to 2050 under a BAU trajectory. 2nd row of each country: estimated 2050 total end-use load (GW) and percent of total load by sector if 100% of BAU end-use all-purpose delivered load in 2050 is instead provided by WWS. The last column shows the percent reductions in total 2050 BAU load due to switching from BAU to WWS, including the effects of (a) energy use reduction due to the higher work to energy ratio of electricity over combustion, (b) eliminating energy use for the upstream mining, transporting, and/or refining of coal, oil, gas, biofuels, bioenergy, and uranium, and (c) policy-driven increases in end-use efficiency beyond those in the BAU case.

Country	Scen-ario	2050 Total end-use load (GW)	Resid-ential per-cent of total	Com-mercial per-cent of total	Indus-trial per-cent of total	Trans-port per-cent of total	Ag/For/Fish-ing per-cent of total	Other percent of total	(a) Percent change end-use load w/WWS due to higher work: energy ratio	(b) Percent change end-use load w/WWS due to eliminat-ing upstream	(c) Percent change end-use load w/WWS due to effic-iency beyond BAU	Overall percent change in end-use load with WWS
Albania	BAU	4.1	33.5	11.9	13.8	37.4	3.3	0.2				
	WWS	2.1	47.9	17.7	7.0	21.7	5.4	0.3	-28.94	-8.82	-9.77	-47.53
Algeria	BAU	144.4	15.1	0.0	20.8	59.5	0.3	4.2				
	WWS	53.8	28.3	0.0	24.2	36.6	0.8	10.0	-29.29	-26.79	-6.70	-62.77
Angola	BAU	29.8	43.6	7.1	13.2	35.9	0.1	0.1				
	WWS	15.1	61.9	10.9	5.3	21.6	0.1	0.1	-32.83	-9.28	-7.25	-49.35
Argentina	BAU	166.3	21.0	6.0	28.5	41.7	2.9	0.0				
	WWS	79.8	30.3	9.8	32.1	22.8	5.0	0.0	-24.34	-20.12	-7.56	-52.01
Armenia	BAU	4.9	37.1	7.9	11.9	33.2	0.3	9.6				
	WWS	2.4	52.5	12.6	4.5	13.3	0.6	16.5	-16.02	-24.10	-10.52	-50.64
Australia	BAU	212.3	11.6	12.4	40.9	33.3	1.8	0.1				
	WWS	118.9	15.1	17.2	46.6	18.2	2.7	0.2	-26.25	-10.71	-7.04	-43.99
Austria	BAU	50.5	22.9	10.7	31.8	33.0	1.5	0.0				
	WWS	29.8	28.9	15.3	32.5	21.1	2.2	0.0	-21.22	-13.08	-6.70	-41.01
Azerbaijan	BAU	19.4	37.1	9.3	22.8	27.8	3.0	0.0				
	WWS	10.8	46.6	13.3	19.7	15.8	4.6	0.0	-26.11	-8.79	-9.41	-44.31
Bahrain	BAU	15.4	15.5	9.0	48.2	27.3	0.1	0.0				
	WWS	9.3	19.6	11.6	54.8	13.8	0.1	0.0	-23.32	-8.61	-7.83	-39.76
Bangladesh	BAU	70.9	36.7	2.1	24.8	31.7	4.5	0.2				
	WWS	37.7	49.2	3.1	27.7	12.4	7.1	0.5	-18.93	-19.41	-8.45	-46.79
Belarus	BAU	40.9	30.9	14.8	29.6	21.1	3.6	0.0				
	WWS	27.5	37.6	19.5	28.6	9.7	4.7	0.0	-17.07	-9.32	-6.34	-32.73
Belgium	BAU	68.2	20.8	12.8	29.8	35.1	1.4	0.1				
	WWS	37.6	26.2	18.5	31.3	21.7	2.1	0.2	-27.87	-9.85	-7.20	-44.92
Benin	BAU	9.0	37.0	10.3	2.0	50.8	0.0	0.0				
	WWS	3.9	60.6	19.1	-15.3	35.6	0.0	0.0	-40.11	-9.64	-6.67	-56.42
Bolivia	BAU	16.1	11.7	2.8	23.7	51.7	6.0	4.1				
	WWS	6.7	20.2	5.2	26.5	28.0	12.1	8.0	-27.23	-24.92	-5.91	-58.06
Bosnia and	BAU	6.6	34.1	0.0	23.5	32.5	0.2	9.8				
Herzegovina	WWS	3.8	44.1	0.0	22.6	17.8	0.3	15.2	-25.79	-7.97	-9.21	-42.97
Botswana	BAU	5.9	21.9	5.4	21.9	44.0	1.5	5.4				
	WWS	3.0	31.4	8.3	22.4	26.4	2.7	8.8	-34.72	-7.94	-6.44	-49.10
Brazil	BAU	550.6	8.9	5.2	42.8	39.0	3.8	0.2				
	WWS	315.9	11.6	7.1	48.4	27.0	5.7	0.2	-27.06	-10.56	-5.00	-42.62
Brunei	BAU	6.2	8.6	10.7	48.3	32.3	0.0	0.0				
Darussalam	WWS	3.5	11.7	14.9	55.8	17.7	0.0	0.0	-29.09	-9.03	-6.03	-44.15
Bulgaria	BAU	22.3	27.4	14.4	27.1	30.0	1.2	0.0				
	WWS	13.1	34.9	19.6	28.0	15.8	1.7	0.0	-21.30	-10.67	-9.38	-41.35
Cambodia	BAU	12.3	44.1	2.7	17.8	33.0	0.0	2.4				
	WWS	6.5	60.4	4.0	12.7	19.1	0.0	3.8	-31.18	-9.06	-7.18	-47.42
Cameroon	BAU	25.4	31.3	47.9	6.0	14.8	0.1	0.0				
	WWS	17.6	32.4	56.6	4.4	6.5	0.1	0.0	-22.86	-2.69	-5.21	-30.76
Canada	BAU	389.5	14.5	12.0	45.0	23.9	2.5	2.2				
	WWS	240.3	16.9	15.2	47.6	13.3	3.4	3.5	-21.55	-10.22	-6.55	-38.32
Chile	BAU	78.0	16.6	8.6	30.8	43.2	0.8	0.0				
	WWS	37.3	25.1	14.1	38.2	21.3	1.3	0.0	-22.87	-21.90	-7.44	-52.20
China	BAU	5404.1	19.2	3.5	47.4	26.5	1.4	2.0				
	WWS	3291.6	22.7	4.6	56.8	10.8	2.0	3.1	-15.63	-16.42	-7.04	-39.09
Chinese Taipei	BAU	167.1	10.9	8.5	45.6	31.4	0.9	2.8				

	WWS	99.8	13.7	11.1	52.3	17.0	1.4	4.6	-25.13	-8.47	-6.70	-40.30
Colombia	BAU	67.4	16.1	6.2	28.8	44.5	4.3	0.1				
	WWS	32.6	24.0	10.1	32.1	26.2	7.4	0.2	-32.06	-13.21	-6.36	-51.64
Congo	BAU	4.7	48.2	0.8	4.0	44.6	0.0	2.3				
	WWS	2.3	69.9	1.3	-2.6	27.5	0.0	3.9	-36.66	-6.06	-7.74	-50.46
Congo, Dem.	BAU	43.8	61.7	0.2	31.0	7.1	0.0	0.0				
Republic of	WWS	28.3	68.4	0.2	28.0	3.4	0.0	0.0	-19.35	-8.31	-7.69	-35.35
Costa Rica	BAU	7.7	15.1	11.8	18.0	53.2	1.4	0.5				
	WWS	3.5	25.2	20.3	14.9	36.0	2.8	0.9	-38.19	-9.52	-7.13	-54.85
Cote d'Ivoire	BAU	16.2	57.2	12.7	9.9	18.5	1.5	0.0				
	WWS	10.2	65.2	16.2	7.6	9.0	2.0	0.0	-23.85	-4.09	-8.86	-36.81
Croatia	BAU	14.3	32.0	15.8	21.8	28.2	2.1	0.0				
	WWS	8.2	41.5	21.9	17.6	16.0	3.0	0.0	-24.86	-8.72	-9.08	-42.66
Cuba	BAU	11.7	21.6	6.0	52.2	12.5	2.0	5.7				
	WWS	7.7	24.3	7.0	52.1	6.9	2.6	7.0	-17.88	-8.96	-6.85	-33.69
Cyprus	BAU	4.2	19.6	16.9	6.3	55.5	1.3	0.5				
	WWS	1.8	33.2	29.9	-6.6	39.9	2.6	1.0	-38.41	-9.29	-8.47	-56.17
Czech Republic	BAU	43.4	25.2	13.7	34.2	24.1	1.9	0.9				
	WWS	27.6	28.1	17.7	35.0	15.3	2.5	1.4	-18.93	-9.52	-7.94	-36.39
Denmark	BAU	26.9	29.4	14.7	22.6	28.7	4.5	0.1				
	WWS	16.8	38.8	20.1	18.5	16.3	6.3	0.1	-22.86	-8.34	-6.45	-37.64
Dominican	BAU	12.6	19.9	7.1	20.6	50.9	1.5	0.0				
Republic	WWS	5.8	31.6	12.0	20.1	33.3	3.1	0.0	-36.65	-9.96	-7.16	-53.77
Ecuador	BAU	27.0	11.1	3.9	27.4	55.3	0.6	1.6				
	WWS	11.9	18.5	6.8	31.7	38.5	1.2	3.3	-40.54	-10.10	-5.43	-56.06
Egypt	BAU	214.4	17.1	6.4	27.0	44.5	3.7	1.2				
	WWS	102.3	26.7	10.4	29.9	24.2	6.7	2.1	-27.66	-17.27	-7.35	-52.28
El Salvador	BAU	5.4	22.7	3.4	22.0	50.0	0.2	1.7				
	WWS	2.5	35.6	5.7	21.9	32.8	0.5	3.5	-37.30	-9.65	-6.52	-53.47
Eritrea	BAU	1.1	71.1	8.5	3.4	17.0	0.0	0.0				
	WWS	0.7	80.6	10.7	0.5	8.2	0.0	0.0	-23.27	-3.13	-10.20	-36.61
Estonia	BAU	5.9	30.2	14.8	23.2	29.1	2.7	0.0				
	WWS	3.6	40.1	19.9	20.8	15.5	3.7	0.0	-23.38	-8.21	-7.03	-38.62
Ethiopia	BAU	71.4	86.8	1.9	3.4	7.1	0.4	0.5				
	WWS	48.7	91.1	2.3	2.4	3.2	0.4	0.6	-19.63	-1.42	-10.77	-31.82
Finland	BAU	43.4	23.5	14.2	41.6	17.3	2.5	0.9				
	WWS	29.9	27.8	17.2	41.6	9.2	3.2	1.0	-16.03	-8.30	-6.60	-30.93
France	BAU	267.2	28.6	17.5	20.9	29.8	2.3	0.9				
	WWS	158.0	35.0	23.5	16.7	20.1	3.3	1.4	-23.09	-9.10	-8.66	-40.85
Gabon	BAU	5.7	39.2	2.8	29.6	27.4	0.6	0.4				
	WWS	3.2	50.6	3.9	28.8	15.0	0.9	0.7	-28.03	-9.09	-6.87	-43.99
Georgia	BAU	6.4	41.8	8.5	17.6	28.6	3.2	0.5				
	WWS	3.6	52.6	11.9	13.4	16.5	4.8	0.7	-24.99	-8.67	-9.88	-43.54
Germany	BAU	379.2	25.9	16.6	29.7	27.7	0.0	0.1				
	WWS	226.3	31.0	22.4	29.6	16.9	0.0	0.1	-21.97	-10.33	-8.03	-40.33
Ghana	BAU	18.9	25.0	4.3	22.0	46.8	1.9	0.0				
	WWS	9.0	38.2	7.2	21.3	30.1	3.2	0.0	-36.60	-9.57	-6.34	-52.51
Gibraltar	BAU	6.0	0.0	0.0	0.1	99.6	0.0	0.3				
	WWS	1.3	0.0	0.1	-39.9	138.2	0.0	1.6	-63.13	-11.17	-3.72	-78.01
Greece	BAU	35.5	24.4	12.9	24.8	34.8	1.3	1.7				
	WWS	19.3	32.8	18.5	23.5	20.3	2.3	2.6	-27.81	-9.63	-8.33	-45.78
Guatemala	BAU	15.0	51.4	4.8	9.5	34.3	0.0	0.0				
	WWS	8.2	67.6	6.9	6.2	19.2	0.0	0.0	-31.22	-5.58	-8.62	-45.42
Haiti	BAU	4.4	70.8	2.2	7.3	19.7	0.0	0.0				
	WWS	2.5	89.5	3.1	-3.2	10.6	0.0	0.0	-25.80	-8.63	-8.94	-43.38
Honduras	BAU	8.1	36.5	5.3	23.2	33.0	0.0	2.0				
	WWS	4.3	49.6	7.8	20.6	18.9	0.0	3.1	-30.26	-9.06	-7.40	-46.72
Hong Kong,	BAU	76.9	5.9	15.8	7.6	70.7	0.0	0.0				
China	WWS	27.5	11.3	34.4	-6.1	60.3	0.0	0.1	-47.23	-9.81	-7.15	-64.19
Hungary	BAU	27.1	34.5	19.8	21.4	22.3	2.1	0.0				

	WWS	16.8	39.6	25.9	17.3	14.3	2.9	0.0	-20.83	-8.36	-8.78	-37.97
Iceland	BAU	4.5	16.5	13.6	47.1	15.2	7.4	0.3				
	WWS	3.4	20.4	16.2	48.3	6.5	8.3	0.3	-11.98	-6.89	-5.85	-24.73
India	BAU	1709.4	24.2	4.1	37.3	27.9	4.1	2.4				
	WWS	996.0	30.0	5.6	40.0	14.4	6.6	3.6	-24.59	-10.77	-6.37	-41.73
Indonesia	BAU	427.6	27.5	4.6	30.5	35.6	1.6	0.2				
	WWS	226.7	37.5	6.7	31.9	21.0	2.5	0.3	-31.23	-9.29	-6.46	-46.98
Iran, Islamic	BAU	434.6	21.6	4.9	37.3	32.0	4.1	0.2				
Republic of	WWS	231.4	27.9	7.3	42.1	15.4	6.9	0.4	-24.42	-15.55	-6.78	-46.75
Iraq	BAU	60.5	17.4	1.3	22.7	49.5	0.0	9.2				
	WWS	29.0	26.4	2.0	20.9	31.5	0.0	19.1	-36.52	-9.87	-5.69	-52.08
Ireland	BAU	16.9	25.9	14.9	22.4	34.8	2.0	0.0				
	WWS	8.7	31.5	22.8	21.0	21.4	3.4	0.0	-29.18	-8.93	-10.15	-48.26
Israel	BAU	27.3	22.1	14.7	21.7	28.7	0.9	12.0				
	WWS	15.9	28.0	19.5	18.7	15.0	1.5	17.2	-24.82	-8.41	-8.52	-41.75
Italy	BAU	240.8	25.8	13.5	25.7	33.3	1.7	0.1				
	WWS	134.9	32.3	19.2	25.5	20.4	2.5	0.1	-22.65	-13.44	-7.87	-43.96
Jamaica	BAU	4.1	9.5	9.6	30.8	47.5	2.4	0.1				
	WWS	2.0	14.8	15.7	34.9	30.3	4.2	0.2	-36.73	-9.81	-5.59	-52.13
Japan	BAU	411.8	16.8	24.6	33.2	24.3	0.8	0.2				
	WWS	250.8	20.1	32.0	32.6	13.9	1.1	0.3	-21.80	-9.52	-7.77	-39.09
Jordan	BAU	14.7	21.4	7.3	21.5	44.0	3.2	2.7				
	WWS	7.4	31.7	11.3	19.5	26.7	6.3	4.4	-33.11	-9.18	-7.44	-49.73
Kazakhstan	BAU	114.1	13.2	4.9	69.0	9.6	0.9	2.4				
	WWS	81.1	13.7	6.0	71.6	4.6	1.2	2.9	-16.23	-7.68	-4.99	-28.90
Kenya	BAU	31.2	62.1	1.3	9.7	26.3	0.2	0.4				
	WWS	18.3	76.0	1.7	7.8	13.7	0.2	0.5	-28.03	-4.36	-9.01	-41.40
Korea, Dem.	BAU	32.3	0.8	0.0	65.5	4.6	0.0	29.2				
People's Rep.	WWS	24.2	0.8	0.0	64.2	1.9	0.0	33.2	-17.09	-5.72	-2.23	-25.04
Korea,	BAU	326.8	11.9	17.4	41.0	27.5	1.6	0.6				
Republic of	WWS	193.9	14.3	23.0	46.2	13.2	2.5	0.8	-21.17	-11.66	-7.82	-40.65
Kosovo	BAU	3.0	48.2	10.7	16.8	23.4	0.9	0.0				
	WWS	1.7	60.8	14.3	11.2	12.3	1.3	0.0	-21.98	-8.49	-11.52	-41.98
Kuwait	BAU	60.0	15.9	7.0	52.4	24.7	0.0	0.0				
	WWS	35.9	20.3	9.1	58.0	12.6	0.0	0.0	-24.56	-8.91	-6.73	-40.19
Kyrgyzstan	BAU	7.5	31.4	10.1	13.2	36.8	1.6	6.8				
	WWS	4.2	45.2	14.7	7.3	20.2	2.5	10.0	-27.57	-8.28	-8.51	-44.36
Latvia	BAU	8.8	34.2	19.1	14.8	29.6	2.2	0.0				
	WWS	5.3	45.9	26.5	8.4	16.0	3.1	0.0	-24.86	-8.33	-7.00	-40.19
Lebanon	BAU	11.3	28.6	6.3	14.5	44.7	0.0	5.8				
	WWS	5.6	42.3	9.8	8.9	27.4	0.0	11.6	-32.68	-9.00	-8.46	-50.14
Libya	BAU	36.0	9.3	6.1	14.7	59.6	1.0	9.4				
	WWS	15.7	15.6	10.7	8.2	41.6	2.4	21.4	-41.07	-9.80	-5.39	-56.26
Lithuania	BAU	11.8	29.6	14.5	25.4	29.2	1.2	0.0				
	WWS	7.1	39.1	20.2	23.2	15.8	1.7	0.0	-23.46	-8.82	-7.01	-39.29
Luxembourg	BAU	6.5	12.0	15.8	14.4	57.2	0.5	0.0				
	WWS	2.9	18.7	28.7	9.1	42.5	1.0	0.0	-39.31	-9.63	-6.32	-55.26
Macedonia,	BAU	4.0	36.9	16.4	22.9	23.0	0.8	0.0				
Republic of	WWS	2.4	46.7	21.4	19.2	11.7	1.1	0.0	-20.66	-8.31	-10.48	-39.46
Malaysia	BAU	158.0	8.0	11.1	40.2	39.0	1.7	0.0				
	WWS	83.9	11.3	16.2	47.8	22.1	2.6	0.0	-29.82	-10.84	-6.22	-46.88
Malta	BAU	3.6	6.8	7.0	2.2	83.8	0.2	0.1				
	WWS	1.1	17.1	18.2	-22.4	86.2	0.5	0.4	-54.13	-10.47	-5.57	-70.18
Mexico	BAU	326.4	13.0	5.3	39.7	38.6	2.7	0.8				
	WWS	173.2	18.0	7.8	46.7	21.6	4.3	1.5	-30.08	-11.14	-5.71	-46.94
Moldova,	BAU	4.4	44.0	15.3	21.7	17.1	1.5	0.5				
Republic of	WWS	2.8	50.9	20.4	17.5	8.5	1.9	0.8	-18.84	-8.21	-10.01	-37.06
Mongolia	BAU	9.0	19.5	6.1	35.7	26.3	2.2	10.3				
	WWS	5.8	21.1	9.5	38.6	14.2	2.9	13.8	-21.54	-7.35	-7.43	-36.32
Montenegro	BAU	1.5	48.6	1.4	19.2	30.0	0.4	0.5				

	WWS	0.8	64.0	2.1	16.3	16.4	0.5	0.7	-24.67	-8.55	-10.47	-43.68
Morocco	BAU	45.2	15.8	8.4	23.0	41.7	11.0	0.0				
	WWS	23.2	22.6	13.1	21.1	25.3	17.9	0.0	-33.15	-9.68	-5.90	-48.73
Mozambique	BAU	20.9	59.9	0.7	26.7	12.5	0.1	0.0				
	WWS	13.1	68.7	0.9	24.4	5.8	0.1	0.0	-19.87	-9.05	-8.48	-37.41
Myanmar	BAU	33.6	59.9	2.0	16.3	17.4	1.2	3.3				
	WWS	19.5	74.3	2.6	9.7	7.0	1.6	4.8	-19.61	-13.70	-8.76	-42.07
Namibia	BAU	4.6	4.1	0.1	11.4	47.5	17.2	19.7				
	WWS	2.4	5.6	0.1	2.2	28.0	27.3	36.7	-35.48	-10.08	-2.74	-48.31
Nepal	BAU	20.6	75.1	2.3	7.5	13.3	1.6	0.1				
	WWS	12.3	90.1	3.1	-2.3	6.9	2.2	0.2	-22.40	-8.27	-9.54	-40.21
Netherlands	BAU	114.7	16.6	14.7	28.8	35.6	4.3	0.0				
	WWS	63.3	21.0	21.6	29.4	21.3	6.7	0.0	-29.34	-9.25	-6.25	-44.84
Netherlands	BAU	6.8	0.9	0.0	29.8	68.6	0.0	0.7				
Antilles	WWS	2.5	1.7	0.0	40.6	55.9	0.0	1.8	-48.41	-10.76	-3.40	-62.57
New Zealand	BAU	31.1	11.6	13.5	35.9	34.0	4.7	0.3				
	WWS	17.6	15.4	18.6	39.6	18.5	7.4	0.5	-27.71	-8.94	-6.91	-43.56
Nicaragua	BAU	4.0	36.5	11.0	15.4	35.3	1.8	0.0				
	WWS	2.1	50.6	16.4	9.3	20.6	3.0	0.1	-30.94	-9.16	-7.71	-47.82
Nigeria	BAU	260.2	64.0	4.1	17.2	12.4	0.0	2.3				
	WWS	159.3	75.0	5.4	10.3	6.2	0.0	3.1	-22.09	-8.49	-8.22	-38.80
Norway	BAU	46.4	18.5	14.0	44.6	20.0	2.6	0.3				
	WWS	29.7	22.1	17.4	46.6	10.1	3.5	0.3	-16.94	-10.71	-8.45	-36.10
Oman	BAU	54.6	6.9	4.0	64.6	21.9	0.1	2.5				
	WWS	33.5	8.6	5.1	71.9	10.9	0.2	3.3	-25.20	-9.15	-4.29	-38.64
Pakistan	BAU	206.0	36.8	3.4	24.4	34.3	0.9	0.1				
	WWS	103.2	52.4	5.4	24.4	15.8	1.8	0.2	-22.95	-18.95	-8.01	-49.91
Panama	BAU	15.5	7.6	7.2	10.1	74.9	0.2	0.0				
	WWS	5.2	16.6	16.6	-1.2	67.6	0.4	0.0	-50.34	-10.33	-5.52	-66.19
Paraguay	BAU	8.7	25.8	8.1	23.2	42.9	0.0	0.0				
	WWS	4.5	37.1	12.3	22.1	28.5	0.0	0.0	-32.52	-9.16	-7.23	-48.91
Peru	BAU	40.8	14.5	5.8	27.9	50.0	1.8	0.0				
	WWS	18.9	22.9	9.8	32.5	31.5	3.3	0.0	-30.77	-16.60	-6.28	-53.65
Philippines	BAU	76.8	19.1	12.7	24.8	42.3	1.1	0.0				
	WWS	39.6	27.4	19.1	24.8	26.8	1.9	0.0	-32.14	-9.12	-7.23	-48.49
Poland	BAU	119.5	27.7	13.7	29.1	25.4	4.2	0.0				
	WWS	68.9	28.7	19.2	30.7	15.3	6.0	0.0	-20.10	-10.46	-11.75	-42.32
Portugal	BAU	29.6	16.9	14.2	32.1	34.8	2.0	0.1				
	WWS	16.8	21.9	19.7	34.2	21.1	3.0	0.1	-26.72	-9.44	-7.26	-43.42
Qatar	BAU	68.6	5.1	1.8	71.1	19.6	0.0	2.4				
	WWS	43.5	6.1	2.3	78.4	9.4	0.0	3.8	-23.84	-9.10	-3.67	-36.61
Romania	BAU	50.7	36.3	9.8	29.9	22.0	1.3	0.7				
	WWS	31.4	43.5	13.0	28.6	12.3	1.8	0.9	-21.85	-8.50	-7.69	-38.04
Russian	BAU	725.5	24.2	8.5	40.3	25.4	1.6	0.0				
Federation	WWS	473.3	31.1	11.0	44.9	10.7	2.3	0.0	-13.74	-14.98	-6.04	-34.76
Saudi Arabia	BAU	337.5	13.5	6.7	46.8	32.7	0.3	0.0				
	WWS	187.6	18.5	9.3	53.6	18.0	0.5	0.1	-28.90	-9.24	-6.29	-44.42
Senegal	BAU	7.9	36.6	5.0	14.9	42.5	0.3	0.7				
	WWS	3.8	54.5	8.0	8.8	26.8	0.5	1.4	-34.98	-9.07	-7.49	-51.54
Serbia	BAU	18.9	43.2	12.1	24.1	19.3	1.3	0.0				
	WWS	11.8	51.8	15.6	21.0	9.9	1.7	0.0	-18.45	-8.04	-10.97	-37.46
Singapore	BAU	203.2	1.2	3.6	10.5	84.7	0.0	0.1				
	WWS	61.6	3.0	9.1	0.0	87.6	0.0	0.2	-54.63	-10.78	-4.30	-69.71
Slovak Republic	BAU	22.1	17.2	12.6	36.2	33.0	0.9	0.0				
	WWS	12.4	23.2	18.4	41.5	15.5	1.4	0.0	-16.85	-20.04	-7.08	-43.97
Slovenia	BAU	8.1	25.9	12.0	24.9	35.4	1.3	0.4				
	WWS	4.6	34.2	17.0	24.6	21.8	1.9	0.6	-27.22	-8.94	-7.69	-43.85
South Africa	BAU	246.8	15.6	6.9	42.6	30.4	2.2	2.4				
	WWS	142.4	17.6	9.4	49.3	16.8	3.3	3.5	-26.68	-8.19	-7.43	-42.30
Spain	BAU	168.9	17.0	13.1	29.9	37.1	2.3	0.6				

	WWS	93.2	22.2	18.6	30.3	24.3	3.5	1.0	-27.54	-10.05	-7.24	-44.83
Sri Lanka	BAU WWS	26.9 13.7	32.0 45.5	5.2 8.1	22.3 20.5	38.9 23.3	0.0 0.0	1.6 2.6	-33.28	-9.22	-6.63	-49.14
Sudan	BAU WWS	27.6 14.1	30.9 43.9	14.7 23.2	14.5 7.3	38.4 22.9	0.9 1.5	0.7 1.1	-33.33	-9.31	-6.32	-48.96
Sweden	BAU WWS	60.1 39.2	24.0 30.8	16.0 20.3	32.2 31.1	26.8 16.5	1.0 1.4	0.0 0.0	-18.26	-9.27	-7.26	-34.79
Switzerland	BAU WWS	36.0 20.5	27.1 34.5	18.7 26.1	18.0 13.0	35.0 24.5	0.6 0.9	0.6 0.9	-24.83	-10.14	-8.20	-43.17
Syrian Arab Republic	BAU WWS	24.7 13.5	21.7 29.7	4.8 6.8	31.9 33.8	35.6 19.9	3.5 5.2	2.5 4.5	-28.90	-9.31	-7.21	-45.42
Tajikistan	BAU WWS	3.5 2.6	24.3 25.6	7.3 7.7	20.6 16.1	8.7 3.6	11.9 16.3	27.1 30.6	-10.28	-8.21	-8.55	-27.05
Tanzania, United	BAU WWS	44.3 27.2	55.9 65.1	0.9 1.2	19.6 13.6	13.7 6.8	5.9 7.9	4.0 5.3	-22.71	-8.52	-7.26	-38.48
Republic of Thailand	BAU WWS	282.3 143.4	9.7 14.1	8.9 13.7	36.5 43.8	41.3 22.6	3.5 5.6	0.1 0.2	-26.50	-16.57	-6.13	-49.20
Togo	BAU WWS	5.0 2.5	50.1 70.9	10.3 16.5	4.0 -9.2	35.4 21.3	0.0 0.0	0.3 0.6	-32.47	-9.09	-7.65	-49.21
Trinidad and Tobago	BAU WWS	19.4 12.2	4.8 5.6	1.2 1.5	73.9 83.2	20.0 9.7	0.0 0.0	0.0 0.0	-24.78	-8.66	-3.51	-36.95
Tunisia	BAU WWS	42.5 13.8	10.8 24.2	5.2 12.5	16.7 17.7	64.7 38.5	2.7 7.1	0.0 0.0	-23.71	-36.28	-7.56	-67.55
Turkey	BAU WWS	140.6 82.2	26.4 27.1	13.7 18.6	33.9 36.8	21.4 10.9	4.6 6.6	0.0 0.0	-21.39	-9.58	-10.55	-41.51
Turkmenistan	BAU WWS	40.5 25.3	2.1 2.5	40.9 54.4	21.8 15.7	20.1 7.0	0.8 1.3	14.4 19.1	-18.30	-17.19	-2.05	-37.54
Ukraine	BAU WWS	148.8 96.3	39.6 45.2	9.5 12.7	31.0 30.8	18.0 8.6	1.9 2.6	0.0 0.0	-15.86	-10.54	-8.86	-35.27
United Arab Emirates	BAU WWS	196.8 108.0	6.3 8.7	5.1 7.2	51.6 61.3	35.3 19.7	0.0 0.0	1.7 3.1	-31.17	-9.35	-4.63	-45.16
United Kingdom	BAU WWS	251.6 140.4	29.2 36.1	14.0 20.1	25.2 23.6	30.3 18.4	0.5 0.8	0.7 1.0	-26.55	-8.86	-8.78	-44.20
United States of America	BAU WWS	2360.6 1291.4	14.6 19.3	14.7 21.5	31.8 33.9	36.6 21.6	1.4 2.2	0.9 1.6	-27.58	-10.93	-6.78	-45.29
Uruguay	BAU WWS	8.6 4.4	18.4 26.5	10.0 15.1	26.0 26.0	41.4 25.4	4.0 6.6	0.2 0.3	-32.28	-9.31	-6.84	-48.43
Uzbekistan	BAU WWS	73.5 45.7	49.2 52.9	10.5 13.9	21.3 16.2	10.6 4.1	3.3 4.9	5.0 7.9	-15.85	-12.10	-9.88	-37.83
Venezuela	BAU WWS	131.0 71.6	7.8 10.5	5.2 7.4	52.0 62.3	34.9 19.6	0.1 0.1	0.0 0.0	-30.82	-9.64	-4.90	-45.36
Vietnam	BAU WWS	131.1 75.5	28.0 34.4	4.5 6.1	38.7 43.1	27.5 14.6	1.2 1.8	0.0 0.0	-26.23	-8.32	-7.88	-42.43
Yemen	BAU WWS	10.4 5.0	19.1 28.9	3.4 5.5	24.3 23.4	46.3 29.5	3.8 6.5	3.1 6.1	-36.45	-9.77	-5.93	-52.15
Zambia	BAU WWS	17.0 11.2	57.1 62.7	1.9 2.3	32.3 29.8	7.4 3.5	0.8 1.1	0.5 0.6	-17.32	-8.30	-8.63	-34.26
Zimbabwe	BAU WWS	23.0 14.5	53.5 61.1	5.8 7.3	13.2 5.9	12.6 6.0	13.5 17.7	1.5 2.0	-20.86	-8.07	-8.00	-36.93
All countries	**BAU** **WWS**	**20,604** **11,840**	**20.40** **25.71**	**8.08** **11.21**	**37.30** **42.05**	**31.00** **16.04**	**1.87** **2.85**	**1.34** **2.15**	**-23.00**	**-12.65**	**-6.89**	**-42.54**

BAU values are extrapolated from IEA (2015c) data for 2012 to 2050 as described in Section S3.2. Briefly, EIA's International Energy Outlook (IEO) projects energy use by end-use sector, fuel, and world region out to 2040 (EIA, 2015). This is extended to 2075 using a ten-year moving linear extrapolation. EIA sectors and fuels are then mapped to IEA sectors and fuels, and each country's 2012 energy consumption by sector and fuel is scaled by the ratio of EIA's 2050/2012 energy consumption by sector and fuel for each region. The transportation load includes, among other loads, energy produced in each country for international transportation and shipping. 2050 WWS values are estimated from 2050 BAU values assuming electrification of end-uses and effects of additional energy-efficiency measures.

In 2012, the 139-country all-purpose, end-use load was ~12.1 TW. Of this, 2.4 TW (20.1%) was electricity demand. Under the BAU trajectory, all-purpose end-use load may grow to 20.6 TW in 2050. Conversion to WWS by 2050 reduces the 139-country load by ~42.5%, to 11.8 TW (Table S6), with the greatest percentage reduction in transportation.

While electricity use increases with WWS, conventional fuel use decreases to zero. The increase in electric energy is much less than the decrease in energy in the gas, liquid, and solid fuels that the electricity replaces, for three major reasons:

(a) The higher energy-to-work conversion efficiency of electricity used for heating, heat pumps, and electric motors than of fossil fuel equivalents and the higher energy-to-work conversion efficiency of electrolytic hydrogen used for hydrogen fuel cells than of liquid fuels used for transportation (Table S4).

(b) The elimination of energy needed to mine, transport, and refine coal, oil, gas, biofuels, bioenergy, and uranium;

(c) Modest additional policy-driven energy efficiency measures beyond those in the BAU case.

These three factors decrease 139-country-averaged demand ~23.0%, 12.6%, and 6.9%, respectively. Thus, electrification of all energy sectors reduces demand 42.5%. This result implies that WWS not only replaces fossil-fuel electricity directly but is also an energy efficiency measure, reducing demand.

The percent decreases in load upon conversion to WWS in Table S6 are greater in some countries than in others. The reason is that the transportation-energy share of total energy is greater in some countries than in others. This trend is shown in Table S6, where countries with a higher fraction of load in the transportation sector exhibit a greater reduction in power demand.

Section S4. Numbers of WWS Generators, Footprint Areas, and Spacing Areas

Table S7 summarizes the number of WWS power plants or devices needed to power the sum of all 139 countries in 2050 for all purposes assuming the end use power requirements in Table S6 and the percent mixes of end-use power generation by country in Table S8. Table S7 accounts for power losses during energy transmission and distribution, generator maintenance, and competition among wind turbines for limited kinetic energy (array losses).

Table S7. Number, capacity, footprint area, and spacing area of WWS power plants or devices needed to provide total annually averaged end-use all-purpose load over all 139 countries examined. Derivations for individual countries are in Delucchi et al. (2016).

Energy Technology	Rated power one plant or device (MW)	[a]Percent of 2050 all-purpose load met by plant/device	Name-plate capacity, existing plus new plants or devices (GW)	Percent name-plate capacity already installed 2015	Number of new plants or devices needed for 139 countries	[b]Percent of 139-country land area for footprint of new plants or devices	Percent of 139-country area for spacing of new plants or devices
Annual power							

Onshore wind	5	23.52	8,332	5.04	1,582,345	0.00002	0.9238
Offshore wind	5	13.62	4,688	0.26	935,150	0.00001	0.5460
Wave device	0.75	0.58	307	0.00	409,517	0.00018	0.0086
Geothermal plant	100	0.67	96	13.05	839	0.00023	0.0000
Hydropower plant [c]	1300	4.00	1,058	100.00	0	0.00000	0.0000
Tidal turbine	1	0.06	31	1.79	30,050	0.00001	0.00009
Res. roof PV	0.005	14.89	9,277	0.76	1,841,306,023	0.04026	0.0000
Com/gov roof PV [d]	0.1	11.58	7,586	1.16	74,981,706	0.03279	0.0000
Solar PV plant [d]	50	21.36	12,629	0.53	251,230	0.12832	0.0000
Utility CSP plant [d]	100	9.72	2,153	0.23	21,485	0.05270	0.0000
Total for annual power		**100**	**46,157**	**3.76**	**1,919,518,345**	**0.255**	**1.478**
New land annual power[e]						0.181	0.924
For peaking/storage							
Additional CSP [f]	100	5.83	1,292	0.00	12,921	0.032	0.000
Solar thermal [f]	50		4,639	8.98	84,448	0.005	0.000
Geothermal heat [f]	50		70	100.00	0	0.000	0.000
Total all			**52,159**	**4.26**	**1,919,615,713**	**0.291**	**1.478**
Total new land[e]						0.218	0.924

The total number of each device is the sum among all countries. The number of devices in each country is the end-use load in 2050 in each country to be supplied by WWS (Table S6) multiplied by the fraction of load satisfied by each WWS device in each country (Table S8) and divided by the annual power output from each device. The annual output by device equals the rated power in the first column (same for all countries) multiplied by the country-specific annual capacity factor of the device, diminished by transmission, distribution, maintenance, and array losses. The capacity factors, given in Delucchi et al. (2016), before transmission, distribution, and maintenance losses for onshore and offshore wind turbines at 100-m hub height in 2050, are calculated country by country from global model simulations of winds and wind power (Figure S3) that account for competition among wind turbines for available kinetic energy based on the approximate number of turbines needed per country as determined iteratively from Tables S7 and S8. Wind array losses due to competition among turbines for the same energy are calculated here to be ~8.5%. Footprint and spacing areas are calculated in Delucchi et al. (2016). Footprint is the area on the top surface of soil covered by an energy technology, thus does not include underground structures.

[a]Total end-use power demand in 2050 with 100% WWS is from Table S6.

[b]Total land area for each country is given in Delucchi et al. (2016). 139-country land area is 119,651,632 km^2. The world land area is 510,072,000 km^2.

[c]The average capacity factors of hydropower plants are assumed to increase from their current values to 50%.

[d]The solar PV panels used for this calculation are Sun Power E20 panels. For footprint calculations alone, the CSP mirror sizes are set to those at Ivanpah. CSP is assumed to have storage with a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1 (Jacobson et al., 2015b). The capacity factors used for residential PV, commercial/government rooftop PV, utility scale PV, and CSP are calculated as discussed in Section S5.2. For utility solar PV plants, "spacing" between panels is included in the plant footprint area.

[e]The footprint area requiring new land equals the sum of the footprint areas for new onshore wind, geothermal, hydropower, and utility solar PV. Offshore wind, wave and tidal generators are in water and thus do not require new land. Similarly, rooftop solar PV does not use new land because the rooftops already exist. Only onshore wind requires new land for spacing area. Spacing area is for onshore and offshore wind is calculated as $44D^2$, where D=rotor diameter. The 5-MW Senvion (RePower) turbine is assumed here, where D=126 m. The other energy sources either are in water or on rooftops, or do not use new land for spacing. Note that the spacing area for onshore wind can be used for multiple purposes, such as open space, agriculture, grazing, etc.

[f]The installed capacities for peaking power/storage are estimated from Jacobson et al. (2015b). Additional CSP is CSP plus storage needed beyond that for annual power generation to firm the grid across all countries. Additional solar thermal and geothermal are used for direct heat or heat storage in underground rocks. Other types of storage are also used in Jacobson et al. (2015b).

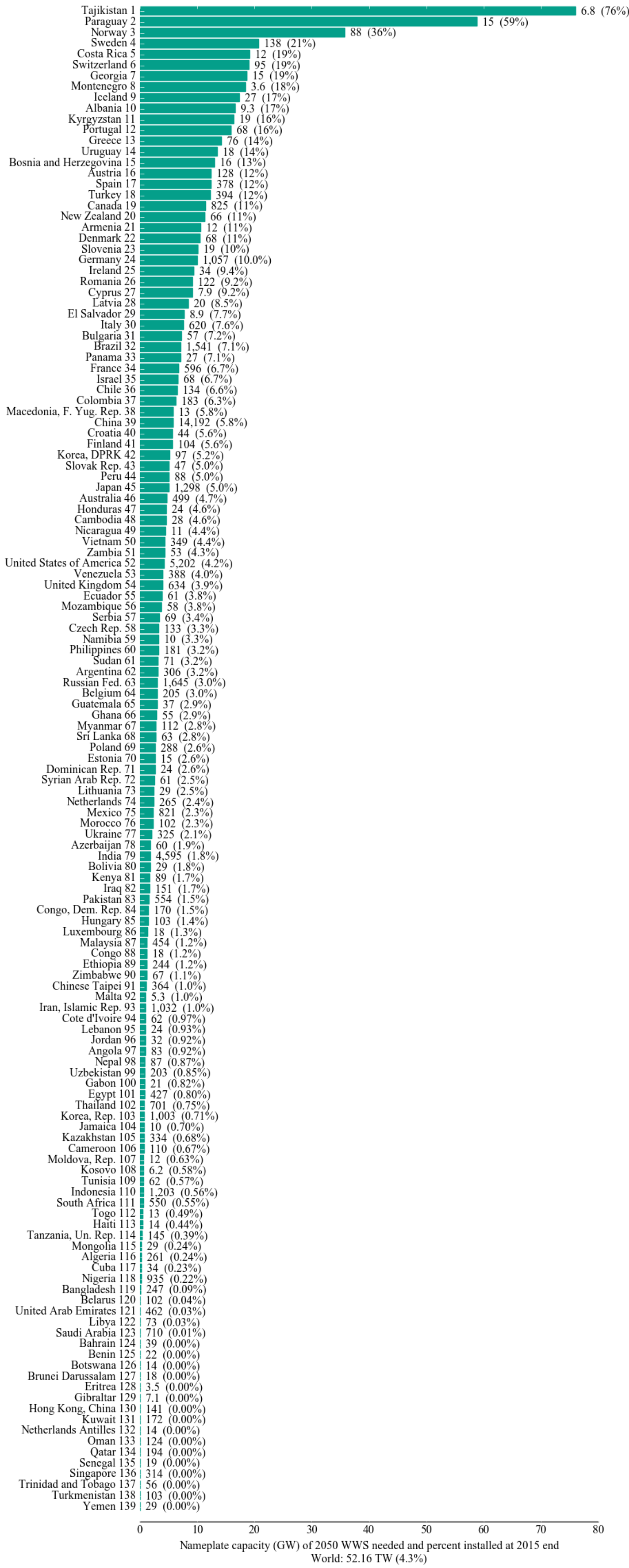
Rooftop PV in Table S7 is divided into residential (5-kW systems on average) and commercial/government (100-kW systems on average). Rooftop PV can be placed on existing rooftops or on elevated canopies above parking lots, highways, and structures without taking up additional undeveloped land. Table S22 (Section S5.2) summarizes projected 2050 rooftop areas by country usable for solar PV on residential and commercial/government buildings, carports, garages, parking structures, and parking lot canopies. The rooftop areas in Table S22 are used to calculate potential rooftop generation, which in turn limits the penetration of PV on residential and commercial/government buildings in Table S8. Utility-scale PV power plants are sized, on average, relatively small (50 MW) to allow optimal placement in available locations. While utility-scale PV can operate in any country because it can take advantage of both direct and diffuse solar radiation, CSP is assumed to be viable only in countries with significant direct solar radiation, and its penetration in each country is limited to less than its technical potential.

Onshore wind is available to some extent in every country but assumed to be viable in high penetrations primarily in countries with good wind resources (Section S5.1). Offshore wind is assumed to be viable in any country with either ocean or lake coastline (Section S5.1). Wind and solar are the only two sources of electric power with sufficient resource to power the world independently on their own. Averaged over the 139 countries, wind (~37.1%) and solar (57.6%) are the largest generators of annually averaged end-use electric power under these plans. The ratio of solar to wind end-use power is 1.55:1.

Under the roadmaps, the 2050 nameplate capacity of hydropower in each country is assumed to be exactly the same as in 2015. However, existing dams in most countries are assumed to run more efficiently for producing peaking power, thus the capacity factor of dams is assumed to increase (Section S5.4). Geothermal, tidal, and wave energy expansions are limited in each country by their technical potentials (Sections S5.3 and S5.5).

Table S7 indicates that 4.26% of the summed nameplate capacity required for a 100% WWS system for 2050 all-purpose, annually averaged power over the 139 countries was already installed as of the end of 2015. Figure S2 shows that the countries closest to 100% 2050 all-purpose WWS installations as of the end of 2015 are Tajikistan (76.0%), Paraguay (58.9%), Norway (35.8%), Sweden (20.7%), Costa Rica (19.1%), Switzerland (19.0%), Georgia (18.7%), Montenegro (18.4%), and Iceland (17.3%). China (5.8%) ranks 39th and the United States (4.2%) ranks 52nd. The high penetrations in Tajikistan, Paraguay, and several other countries are due to their significant hydroelectric power capacity already installed plus their ability to obtain higher capacity factors from the same facilities without building more dams.

Figure S2. Countries ranked in order of how close they are at the end of 2015 to reaching 100% WWS power for all purposes in 2050. The first number is existing plus new nameplate capacity needed in 2050 (GW); percentages are of 2050 WWS total installed capacity (summed over all WWS technologies) needed that was already installed as of the end of 2015. The 139-country existing plus new installed capacity needed is 52.16 TW; of this, 4.26% is already installed.



Tajikistan 1 6.8 (76%)
Paraguay 2 15 (59%)
Norway 3 88 (36%)
Sweden 4 138 (21%)
Costa Rica 5 12 (19%)
Switzerland 6 95 (19%)
Georgia 7 15 (19%)
Montenegro 8 3.6 (18%)
Iceland 9 27 (17%)
Albania 10 9.3 (17%)
Kyrgyzstan 11 19 (16%)
Portugal 12 68 (16%)
Greece 13 76 (14%)
Uruguay 14 18 (14%)
Bosnia and Herzegovina 15 16 (13%)
Austria 16 128 (12%)
Spain 17 378 (12%)
Turkey 18 394 (12%)
Canada 19 825 (11%)
New Zealand 20 66 (11%)
Armenia 21 12 (11%)
Denmark 22 68 (11%)
Slovenia 23 19 (10%)
Germany 24 1,057 (10.0%)
Ireland 25 34 (9.4%)
Romania 26 122 (9.2%)
Cyprus 27 7.9 (9.2%)
Latvia 28 20 (8.5%)
El Salvador 29 8.9 (7.7%)
Italy 30 620 (7.6%)
Bulgaria 31 57 (7.2%)
Brazil 32 1,541 (7.1%)
Panama 33 27 (7.1%)
France 34 596 (6.7%)
Israel 35 68 (6.7%)
Chile 36 134 (6.6%)
Colombia 37 183 (6.3%)
Macedonia, F. Yug. Rep. 38 13 (5.8%)
China 39 14,192 (5.8%)
Croatia 40 44 (5.6%)
Finland 41 104 (5.6%)
Korea, DPRK 42 97 (5.2%)
Slovak Rep. 43 47 (5.0%)
Peru 44 88 (5.0%)
Japan 45 1,298 (5.0%)
Australia 46 499 (4.7%)
Honduras 47 24 (4.6%)
Cambodia 48 28 (4.6%)
Nicaragua 49 11 (4.4%)
Vietnam 50 349 (4.4%)
Zambia 51 53 (4.3%)
United States of America 52 5,202 (4.2%)
Venezuela 53 388 (4.0%)
United Kingdom 54 634 (3.9%)
Ecuador 55 61 (3.8%)
Mozambique 56 58 (3.8%)
Serbia 57 69 (3.4%)
Czech Rep. 58 133 (3.3%)
Namibia 59 10 (3.3%)
Philippines 60 181 (3.2%)
Sudan 61 71 (3.2%)
Argentina 62 306 (3.2%)
Russian Fed. 63 1,645 (3.0%)
Belgium 64 205 (3.0%)
Guatemala 65 37 (2.9%)
Ghana 66 55 (2.9%)
Myanmar 67 112 (2.8%)
Sri Lanka 68 63 (2.8%)
Poland 69 288 (2.6%)
Estonia 70 15 (2.6%)
Dominican Rep. 71 24 (2.6%)
Syrian Arab Rep. 72 61 (2.5%)
Lithuania 73 29 (2.5%)
Netherlands 74 265 (2.4%)
Mexico 75 821 (2.3%)
Morocco 76 102 (2.3%)
Ukraine 77 325 (2.1%)
Azerbaijan 78 60 (1.9%)
India 79 4,595 (1.8%)
Bolivia 80 29 (1.8%)
Kenya 81 89 (1.7%)
Iraq 82 151 (1.7%)
Pakistan 83 554 (1.5%)
Congo, Dem. Rep. 84 170 (1.5%)
Hungary 85 103 (1.4%)
Luxembourg 86 18 (1.3%)
Malaysia 87 454 (1.2%)
Congo 88 18 (1.2%)
Ethiopia 89 244 (1.2%)
Zimbabwe 90 67 (1.1%)
Chinese Taipei 91 364 (1.0%)
Malta 92 5.3 (1.0%)
Iran, Islamic Rep. 93 1,032 (1.0%)
Cote d'Ivoire 94 62 (0.97%)
Lebanon 95 24 (0.93%)
Jordan 96 32 (0.92%)
Angola 97 83 (0.92%)
Nepal 98 87 (0.87%)
Uzbekistan 99 203 (0.85%)
Gabon 100 21 (0.82%)
Egypt 101 427 (0.80%)
Thailand 102 701 (0.75%)
Korea, Rep. 103 1,003 (0.71%)
Jamaica 104 10 (0.70%)
Kazakhstan 105 334 (0.68%)
Cameroon 106 110 (0.67%)
Moldova, Rep. 107 12 (0.63%)
Kosovo 108 6.2 (0.58%)
Tunisia 109 62 (0.57%)
Indonesia 110 1,203 (0.56%)
South Africa 111 550 (0.55%)
Togo 112 13 (0.49%)
Haiti 113 14 (0.44%)
Tanzania, Un. Rep. 114 145 (0.39%)
Mongolia 115 29 (0.24%)
Algeria 116 261 (0.24%)
Cuba 117 34 (0.23%)
Nigeria 118 935 (0.22%)
Bangladesh 119 247 (0.09%)
Belarus 120 102 (0.04%)
United Arab Emirates 121 462 (0.03%)
Libya 122 73 (0.03%)
Saudi Arabia 123 710 (0.01%)
Bahrain 124 39 (0.00%)
Benin 125 22 (0.00%)
Botswana 126 14 (0.00%)
Brunei Darussalam 127 18 (0.00%)
Eritrea 128 3.5 (0.00%)
Gibraltar 129 7.1 (0.00%)
Hong Kong, China 130 141 (0.00%)
Kuwait 131 172 (0.00%)
Netherlands Antilles 132 14 (0.00%)
Oman 133 124 (0.00%)
Qatar 134 194 (0.00%)
Senegal 135 19 (0.00%)
Singapore 136 314 (0.00%)
Trinidad and Tobago 137 56 (0.00%)
Turkmenistan 138 103 (0.00%)
Yemen 139 29 (0.00%)
0
10
20
30
40
50
60
70
80
Nameplate capacity (GW) of 2050 WWS needed and percent installed at 2015 end
World: 52.16 TW (4.3%)

Table S7 also lists needed installed capacities of 1) additional CSP with storage, 2) solar thermal collectors, and 3) existing geothermal for heat. These collectors are needed to provide electricity or heat that is stored and used later to provide peaking power and to account for power losses into and out of such storage (Section S6).

Table S8. Percent of the annually averaged 2050 country-specific all-purpose end-use load (not installed capacity) in Table S6 in a WWS world that we propose to meet with the given electric power generator. All rows add up to 100%.

Country	On-shore wind	Offshore wind	Wave	Geo-thermal	Hydro-electric	Tidal	Res PV	Comm/gov PV	Utility PV	CSP
Albania	18.71	0.31	0.00	0.00	30.84	0.10	12.76	24.31	4.68	8.29
Algeria	32.64	0.02	0.07	0.00	0.17	0.01	21.98	24.97	8.16	11.97
Angola	24.14	1.38	5.74	0.00	2.27	0.04	16.99	32.37	6.04	11.03
Argentina	19.10	15.92	0.00	1.02	5.14	0.02	21.43	21.34	4.77	11.26
Armenia	19.17	0.00	0.00	0.81	22.41	0.00	18.79	13.88	15.72	9.21
Australia	20.07	16.73	5.79	0.28	3.13	0.10	13.73	11.17	18.11	10.88
Austria	44.67	0.00	0.00	0.00	12.44	0.00	7.93	6.36	28.33	0.25
Azerbaijan	14.95	0.00	0.00	0.00	4.46	0.00	21.42	22.87	24.83	11.46
Bahrain	0.38	16.89	0.00	0.00	0.00	0.02	3.70	1.74	65.28	12.00
Bangladesh	5.77	5.80	0.50	0.00	0.26	0.08	27.81	7.81	40.06	11.90
Belarus	64.55	0.00	0.00	0.03	0.06	0.00	3.83	3.41	16.14	11.99
Belgium	4.80	17.80	0.00	0.00	0.15	0.00	1.43	1.27	74.56	0.00
Benin	22.63	18.86	0.85	0.00	0.01	0.03	25.39	14.69	5.66	11.89
Bolivia	22.33	0.00	0.00	15.34	3.34	0.00	15.03	28.63	5.58	9.76
Bosnia and Herzegovina	20.12	4.32	0.00	0.00	25.15	0.01	16.21	19.54	5.67	8.98
Botswana	27.46	0.00	0.00	0.00	0.00	0.00	18.48	35.20	6.86	12.00
Brazil	17.24	14.37	0.89	0.00	13.03	0.01	19.34	20.48	4.31	10.33
Brunei Darussalam	1.04	21.11	1.24	0.00	0.00	0.04	18.85	8.25	37.62	11.85
Bulgaria	44.14	10.34	0.00	0.00	7.80	0.02	13.34	13.33	11.04	0.00
Cambodia	15.02	12.51	0.00	0.00	8.81	0.04	16.85	32.09	3.75	10.94
Cameroon	16.52	0.92	0.69	0.00	1.91	0.01	25.79	12.01	30.46	11.69
Canada	27.49	22.90	2.24	1.65	14.51	0.18	5.30	9.09	6.87	9.77
Chile	18.70	15.59	5.28	3.65	8.22	0.06	20.22	13.67	4.68	9.93
China	24.08	11.77	0.03	0.05	4.13	0.01	14.08	9.14	25.23	11.49
Chinese Taipei	2.08	21.73	0.14	28.64	0.98	0.01	10.83	5.09	30.51	0.00
Colombia	13.70	11.42	0.81	0.00	15.68	0.34	15.37	29.28	3.43	9.98
Congo	17.81	14.85	1.59	0.00	3.20	0.05	19.98	38.07	4.45	0.00
Congo, Dem. Republic	38.00	0.54	0.04	0.00	4.11	0.00	25.87	10.44	9.50	11.50
Costa Rica	5.70	1.23	2.88	28.23	23.63	0.15	8.34	15.88	8.55	5.41
Cote d'Ivoire	18.42	15.41	1.18	0.00	2.39	0.03	20.75	25.56	4.70	11.57
Croatia	9.73	0.00	0.00	0.00	10.20	0.18	15.38	12.01	41.75	10.75
Cuba	15.41	12.84	5.97	0.00	0.36	0.13	17.29	32.93	3.85	11.22
Cyprus	8.33	16.67	1.70	0.00	0.00	0.19	22.44	22.21	16.68	11.77
Czech Republic	41.64	0.00	0.00	0.00	1.76	0.00	6.17	5.89	44.54	0.00
Denmark	26.51	37.29	1.08	0.00	0.02	0.10	3.66	1.92	29.43	0.00
Dominican Republic	8.13	12.76	0.00	9.50	4.21	0.09	17.18	26.76	11.01	10.34
Ecuador	21.69	2.27	5.10	0.27	8.56	0.46	15.82	30.14	5.42	10.27
Egypt	30.28	0.24	0.00	0.00	1.23	0.01	20.51	28.32	7.57	11.85
El Salvador	9.14	7.62	2.32	33.46	8.64	0.08	10.25	19.53	2.29	6.66
Eritrea	16.31	13.59	0.00	0.00	0.00	1.00	18.29	34.85	4.08	11.88
Estonia	43.85	36.54	0.00	0.00	0.10	0.28	4.83	3.43	10.96	0.00
Ethiopia	39.58	0.00	0.00	2.47	2.05	0.00	26.64	7.90	9.90	11.46
Finland	43.58	36.31	0.00	0.00	5.05	0.02	2.86	1.29	10.89	0.00
France	31.12	25.94	0.49	0.02	5.25	0.14	9.57	8.40	7.78	11.29
Gabon	17.19	14.32	5.86	0.00	2.20	0.12	19.28	36.73	4.30	0.00
Georgia	14.96	12.47	0.00	0.00	33.71	0.06	16.79	18.27	3.74	0.00

Germany	22.08	22.95	0.07	0.01	0.92	0.00	5.49	5.76	42.72	0.00
Ghana	17.78	14.81	1.37	0.00	6.98	0.03	19.94	23.65	4.44	11.00
Gibraltar	0.00	98.10	0.18	0.00	0.00	0.02	0.10	0.05	0.00	1.55
Greece	35.20	3.52	2.74	2.00	6.66	0.13	16.06	14.27	8.80	10.62
Guatemala	17.33	2.82	1.10	22.14	5.39	0.03	13.18	25.11	4.33	8.56
Haiti	10.79	10.61	0.00	0.00	0.91	0.21	26.00	12.72	26.89	11.87
Honduras	13.90	11.58	2.85	9.55	5.02	0.08	15.59	28.06	3.47	9.90
Hong Kong, China	0.00	98.17	0.15	0.00	0.00	0.01	1.15	0.52	0.00	0.00
Hungary	11.55	0.00	0.00	1.79	0.15	0.00	12.36	10.82	63.33	0.00
Iceland	22.04	18.37	2.93	22.66	28.09	0.39	0.00	0.00	5.51	0.00
India	34.73	2.67	0.05	0.02	2.09	0.02	24.92	14.89	8.88	11.74
Indonesia	12.25	12.88	3.71	3.45	1.03	0.03	17.33	31.25	7.06	11.01
Iran, Islamic Republic	21.85	9.49	0.00	0.00	1.91	0.00	18.17	11.04	25.77	11.77
Iraq	26.02	0.67	0.00	0.00	3.28	0.00	17.87	34.05	6.51	11.61
Ireland	36.74	30.62	5.92	0.00	1.22	0.06	12.93	3.31	9.19	0.00
Israel	6.84	12.60	0.00	0.00	0.02	0.01	17.48	9.03	42.02	12.00
Italy	25.15	1.13	0.22	0.61	4.85	0.01	16.38	5.72	34.62	11.32
Jamaica	6.36	16.49	0.00	0.00	0.47	0.20	22.20	23.99	18.37	11.92
Japan	1.74	7.02	0.74	0.49	4.14	0.20	5.52	3.35	76.79	0.00
Jordan	30.79	1.37	0.00	0.00	0.07	0.01	21.46	26.61	7.70	11.99
Kazakhstan	45.75	0.00	0.00	0.00	1.30	0.00	16.62	13.04	11.44	11.84
Kenya	23.14	6.28	0.49	7.42	1.86	0.01	18.96	25.23	5.78	10.83
Korea, Dem. People's Rep.	52.42	13.50	0.00	0.00	8.43	0.83	9.59	1.93	13.10	0.21
Korea, Republic of	3.15	11.56	0.00	0.00	0.43	0.12	5.62	3.47	63.73	11.93
Kosovo	24.21	0.00	0.00	35.94	0.90	0.00	16.47	8.52	6.38	7.58
Kuwait	1.19	11.68	0.00	0.00	0.00	0.01	2.70	1.58	70.85	12.00
Kyrgyzstan	24.97	0.00	0.00	0.00	29.14	0.00	16.81	14.34	6.24	8.50
Latvia	35.88	29.90	0.00	0.00	14.01	0.06	6.98	4.21	8.97	0.00
Lebanon	2.74	24.57	0.00	0.00	1.82	0.03	16.29	8.66	34.11	11.78
Libya	29.10	3.02	0.00	0.00	0.00	0.04	21.21	27.36	7.27	12.00
Lithuania	38.22	31.85	0.00	0.00	0.76	0.01	10.24	9.36	9.55	0.00
Luxembourg	3.86	0.00	0.00	0.00	0.56	0.00	1.35	1.42	92.82	0.00
Macedonia, Republic of	15.38	0.00	0.00	0.00	12.03	0.00	24.22	18.76	29.61	0.00
Malaysia	2.47	18.54	0.18	0.00	2.99	0.01	24.96	13.88	25.34	11.62
Malta	1.36	0.00	0.75	0.00	0.00	0.17	4.54	2.24	79.04	11.89
Mexico	19.16	15.97	0.71	2.20	2.94	0.01	21.49	21.44	4.79	11.30
Moldova, Republic of	58.40	0.00	0.00	0.00	1.15	0.00	18.70	7.14	14.60	0.00
Mongolia	34.44	0.00	0.00	0.00	0.00	0.00	23.18	21.77	8.61	12.00
Montenegro	12.97	10.81	0.00	0.00	33.31	0.22	14.55	16.91	3.24	7.98
Morocco	16.24	13.53	2.07	0.00	2.53	0.03	18.22	31.87	4.06	11.44
Mozambique	19.92	16.60	4.29	0.00	7.08	1.59	22.35	12.74	4.98	10.44
Myanmar	15.37	12.81	0.64	0.00	5.87	0.18	17.24	32.84	3.84	11.20
Namibia	21.33	3.43	5.60	0.00	6.47	0.25	16.20	30.87	5.33	10.52
Nepal	16.07	0.00	0.00	0.00	2.23	0.00	28.63	4.25	37.09	11.73
Netherlands	5.73	41.32	0.00	0.00	0.03	0.00	1.07	0.81	39.04	12.00
Netherlands Antilles	0.71	6.71	0.00	0.00	0.00	0.09	2.90	1.27	76.33	11.99
New Zealand	19.04	15.86	4.61	9.29	13.55	0.25	13.85	10.11	4.76	8.68
Nicaragua	12.45	10.37	4.82	16.90	2.54	0.19	13.96	26.59	3.11	9.07
Nigeria	6.31	0.00	0.14	0.00	0.59	0.00	22.24	23.80	35.00	11.91
Norway	22.90	19.08	3.32	0.00	44.47	0.26	3.63	0.61	5.73	0.00
Oman	47.44	3.52	0.63	0.00	0.00	0.02	15.27	9.33	11.86	11.92
Pakistan	19.14	8.42	0.19	0.00	2.83	0.00	24.77	14.56	18.45	11.64
Panama	17.02	6.18	5.11	0.00	14.06	0.84	14.78	28.16	4.26	9.60
Paraguay	6.48	0.00	0.00	0.00	76.41	0.00	4.36	8.30	1.62	2.83
Peru	21.50	0.00	5.00	6.28	10.37	0.04	14.47	27.56	5.37	9.40
Philippines	7.66	11.54	0.59	11.22	3.86	0.27	15.53	29.59	9.65	10.09
Poland	42.62	23.38	0.00	0.13	0.37	0.00	8.64	14.19	10.66	0.00
Portugal	18.45	15.37	4.18	0.48	12.03	0.65	20.69	13.61	4.61	9.92
Qatar	0.32	11.82	0.00	0.00	0.00	0.01	1.30	0.74	73.82	12.00

Romania	32.73	27.28	0.00	0.26	9.41	0.01	15.54	6.60	8.18	0.00
Russian Federation	39.13	32.61	0.25	0.08	4.62	0.02	5.55	5.86	9.78	2.12
Saudi Arabia	41.77	0.00	0.00	0.00	0.00	0.00	22.26	13.52	10.44	12.00
Senegal	17.16	14.30	1.56	0.00	0.00	0.07	19.25	31.56	4.29	11.80
Serbia	10.41	0.00	0.00	0.00	8.11	0.00	15.93	15.40	50.13	0.00
Singapore	0.00	92.93	0.00	5.49	0.00	0.00	1.22	0.35	0.00	0.00
Slovak Republic	61.78	0.00	0.00	0.00	6.05	0.00	10.12	6.60	15.44	0.00
Slovenia	43.31	7.70	0.00	1.81	13.05	0.01	11.95	11.33	10.83	0.00
South Africa	42.00	6.17	3.19	0.00	0.22	0.01	17.22	9.11	10.50	11.59
Spain	33.49	13.55	1.47	0.04	6.29	0.23	17.18	8.34	8.37	11.04
Sri Lanka	15.55	12.95	1.38	0.00	5.19	0.04	17.44	32.36	3.89	11.21
Sudan	15.38	12.82	0.00	0.00	6.61	0.03	17.25	32.86	3.85	11.20
Sweden	36.42	30.35	0.00	0.00	18.69	0.06	3.70	1.67	9.11	0.00
Switzerland	20.70	0.00	0.00	0.00	30.49	0.00	11.27	9.25	28.18	0.11
Syrian Arab Republic	17.57	10.70	0.00	0.00	4.81	0.01	17.59	33.50	4.39	11.42
Tajikistan	3.26	0.00	0.00	0.00	88.11	0.00	2.20	4.18	0.82	1.43
Tanzania, United Republic	33.10	5.42	0.60	0.00	0.85	0.37	25.20	14.38	8.28	11.78
Thailand	3.24	16.27	0.00	0.07	1.13	0.01	25.68	13.55	28.18	11.85
Togo	19.84	17.99	0.66	0.00	1.19	0.03	26.77	9.87	11.88	11.77
Trinidad and Tobago	0.27	29.05	0.30	0.00	0.00	0.02	12.24	2.85	43.31	11.96
Tunisia	21.76	18.14	0.00	0.00	0.21	0.03	24.41	18.04	5.44	11.97
Turkey	26.66	0.06	0.00	0.67	12.93	0.02	17.98	24.66	6.66	10.37
Turkmenistan	49.92	0.00	0.00	0.00	0.00	0.00	15.50	10.10	12.48	12.00
Ukraine	41.47	34.55	0.00	0.00	2.55	0.01	7.32	3.73	10.37	0.00
United Arab Emirates	7.01	11.88	0.00	0.00	0.00	0.01	4.21	2.40	62.50	12.00
United Kingdom	13.13	35.57	2.49	0.00	0.54	1.80	3.50	2.76	40.22	0.00
United States of America	21.32	17.09	1.08	0.41	2.80	0.01	14.48	11.79	19.53	11.48
Uruguay	16.36	13.63	1.45	0.00	15.82	0.08	18.35	20.31	4.09	9.92
Uzbekistan	29.45	0.00	0.00	0.00	1.75	0.00	26.33	11.23	19.45	11.79
Venezuela	20.98	17.49	0.10	0.00	8.98	0.01	23.54	12.75	5.25	10.91
Vietnam	0.88	16.25	0.69	0.00	8.93	0.01	21.88	17.01	23.50	10.84
Yemen	5.71	12.83	5.06	1.35	0.00	0.11	17.28	32.91	13.54	11.22
Zambia	24.70	0.00	0.00	0.67	9.37	0.00	16.62	31.66	6.17	10.79
Zimbabwe	41.17	0.00	0.00	0.00	2.26	0.00	27.71	6.82	10.29	11.73
World average	**23.52**	**13.62**	**0.58**	**0.67**	**4.00**	**0.06**	**14.89**	**11.58**	**21.36**	**9.72**

Footprint area is the physical area on the top surface of the ground or water needed for each energy device. Spacing area is the area between some devices, such as wind, tidal, and wave turbines, needed to minimize interference of the wake of one turbine with downwind turbines.

Only onshore wind, geothermal, additional hydropower (none of which is proposed here), utility PV plants, and CSP plants require new footprint on land. Rooftop PV does not take up new land. Table S7 indicates that the total new land footprint required for the plans, averaged over the 139 countries is ~0.22% of the land area of the countries, mostly for utility PV and CSP plants. This does not account for the decrease in footprint from eliminating the current energy infrastructure, which includes the footprint for mining, transporting, and refining fossil fuels and uranium and for growing, transporting, and refining biofuels and bioenergy. The only spacing over land needed for the WWS system is between onshore wind turbines and requires ~0.92% of the 139-country land area.

For several reasons, the footprint and spacing areas of additional transmission lines is neglected here. Transmission systems have virtually no footprint on the ground because transmission towers are four metal supports connected to small foundations, allowing grass to grow under the towers. Further, the rights-of-way under transmission lines can typically accommodate many uses; more than can the rights-of-way under gas and oil pipelines and other conventional infrastructure that new transmission lines will replace. Finally, in the WWS roadmaps, as much additional transmission capacity as possible will be placed along existing pathways but with enhanced lines.

Section S5. WWS Resource Availability and Technical Potential

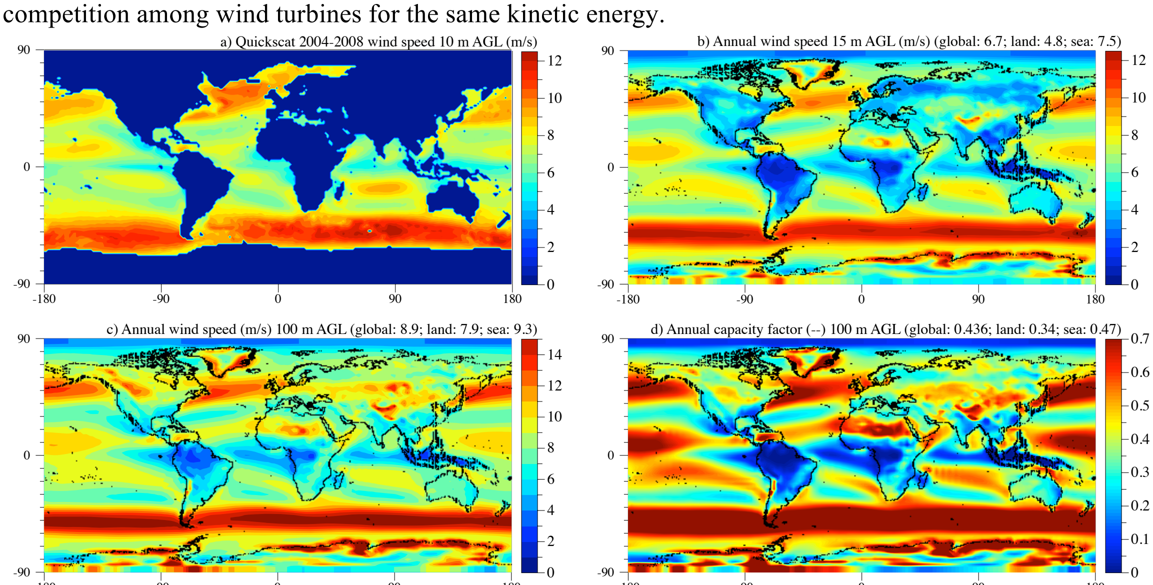
This section evaluates the raw resource availability and technical potential in each of the 139 countries for each energy technology

S5.1. Onshore and Offshore Wind

Raw Resources. Figure S3 shows three-dimensional computer model estimates, derived for this study, of the world annually averaged wind speed and capacity factor at the 100-m hub height above the topographical surface of a modern 5-MW wind turbine. The figure also compares near-surface modeled wind speeds with QuikSCAT data over the oceans, suggesting model predictions and data are similar at that height and giving confidence in the 100-m values.

Locations of strong onshore wind resources include the Great Plains of the U.S. and Canada, the Sahara desert, the Gobi desert, much of Australia, the south of Argentina, South Africa, and northern Europe among other locations. Strong offshore wind resources occur off the east and west coasts of North America, over the Great Lakes, the North Sea, the west coast of Europe and the east coast of Asia, offshore of Peru and Argentina, Australia, South Africa, India, Saudi Arabia, and west Africa.

Figure S3. (a) QuikSCAT 10-m above ground level (AGL) wind speed at 1.5^o x 1.5^o resolution (JPL, 2010), (b) GATOR-GCMOM (Jacobson, 2010b) 4-year-average modeled annual 15-m AGL wind speed at 2.5^o W-E x 2.0^o S-N resolution, (c) Same as (b) but at 100 m AGL, (d) Same as (c) but showing capacity factors assuming a Senvion (RePower) 5 MW turbine with 126-m rotor diameter. In all cases, wind speeds are determined before accounting for competition among wind turbines for the same kinetic energy.



Technical and Economic Potential. Our estimates of the nameplate capacity of onshore and offshore wind to be installed in each country (Tables S7 and S8) are limited by the country's power demand and the wind's technical potential capacity, as described next.

Technical potential of onshore wind

The technical potential capacity of onshore wind is set equal to the areal power density of onshore wind systems multiplied by the lesser of: i) the maximum allowable land area for wind power, and ii) the total onshore land area with a wind resource that can provide what we designate as the minimum acceptable capacity factor, where the capacity factor and the areal power density are a function of the hub height of the turbines. We also assume that the technical potential is at least as great as either some multiple of the capacity actually installed in a base year BY, or some fixed minimum capacity. Formally,

$$C_{TP,ONW,h,C,TY} = \max\begin{bmatrix} C_{ONW,C,BY} \cdot M_{TP,ONW}, C_{\min,ONW}, \\ C_{PD,ONW,h} \cdot \min\left[LA_{\max,ONW,C,TY}, LA_{CF_{ONW,h} \geq CF_{ONW,\min},C}\right] \end{bmatrix}$$

$$C_{PD,ONW,h} = \frac{CAP_{ONW,h}}{A_{ONW,h}}$$

where

$C_{TP,ONW,h,C,TY}$ = Total technical potential (TP) capacity of onshore wind power with a hub height of h in country C in year TY (MW)

$C_{ONW,C,BY}$ = Capacity of onshore wind installed in country C in year BY (use year 2015 data)

$M_{TP,ONW}$ = Multiplier on capacity installed as of year BY (we assume 3.0)

$C_{\min,ONW,}$ = The minimum onshore wind capacity in any country (we assume 100 MW)

$C_{PD,ONW,h}$= The capacity of onshore wind systems, as areal power density, for a hub height of h (MW/km^2)

$LA_{\max,ONW,C,TY}$ = The maximum allowable land area devoted to onshore wind power in country C in year TY (km^2) (see discussion below)

$LA_{CF_{ONW,h} \geq CF_{ONW,\min},C}$ = The total onshore area of country C with a wind resource that can provide at least the minimum wind capacity factor given a hub height of h ($CF_{ONW,h} \geq CF_{ONW,\min}$) (km^2) (see discussion below)

$CAP_{ONW,h}$ = The rated capacity of an individual offshore wind turbine, with a hub height of h (5 MW for a turbine with a hub height of 100 m above ground).

$A_{ONW,h}$ = The average spacing area per onshore wind turbine with a hub height of h (0.70 km^2 for a turbine with a hub height of 100 m above ground).

$CF_{ONW,h}$ = The wind capacity factor given a hub height of h

$CF_{ONW,\min}$ = The minimum capacity factor for qualifying the resource as potentially "technically" available (see discussion below)

subscript h = Hub height of wind turbine (m) (a variable in our analysis; here, we assume 100 m)

Wind turbine spacing affects not only the capacity factor of installed turbines, but also land acquisition cost and social opposition (Enevoldsen and Sovacool, 2016). Thus, it is important to ensure that the spacing distances chosen for the 2050 WWS scenario is reasonable. A recent study analyzed the spacing of more than 1,000 operating wind turbines of different size covering 44 onshore and offshore wind farms worldwide (Enevoldsen and Valentine, 2016). The study found a median spacing of 4.2 times the rotor diameter, which corresponds to A = 4.2D x 4.2D =0.28 km^2 per 5-MW Senvion (RePower) turbine, where D=turbine rotor diameter (126 m). This compares to a spacing area of 4D x 11D = 0.70 km^2 assumed for the turbines proposed here. Thus, our estimate is conservative compared with data. In other words, a large buildout of wind turbines may in reality take up less space than proposed here. Real wind turbine spacing has decreased over time, due to improved technologies (Enevoldsen and Valentine, 2016).

Maximum allowable land area devoted to wind power. We assume that there is a limit to the amount of land that a country will devote to wind power development. We estimate this limit as a function of population density and non-urban population share, relative to reference points, with the assumption that the greater the population density and the urban population share, the smaller the maximum percentage of land area that can be devoted to wind power:

$$LA_{\max,ONW,C,TY} = LA\%_{\max,ONW,C,TY} \cdot LA_C$$

$$LA\%_{\max,ONW,C,TY} = \min\left[LA\%_{\max,ONW,upper}, \max\left[\begin{array}{l} LA\%_{\max,ONW,lower}, \\ LA\%_{\max,ONW,ref} \cdot \left(\dfrac{PD_{C,TY}}{PD_{ref}}\right)^{\kappa 1} \cdot \left(\dfrac{1-URB\%_{C,TY}}{1-URB\%_{ref}}\right)^{\kappa 2} \end{array} \right]\right]$$

where

$LA\%_{\max,ONW,C,TY}$ = The maximum allowable percent of land area for onshore wind in country C in year TY

$LA\%_{\max,ONW,upper}$ = The upper bound on the maximum allowable percentage (discussed below)

$LA\%_{\max,ONW,lower}$ = The lower bound on the maximum allowable percentage (discussed below)

$LA\%_{\max,ONW,ref}$ = The reference value maximum allowable percent of land area for onshore wind (discussed below)

$PD_{C,TY}$ = Population density of country C in year TY (persons/km^2) (discussed elsewhere)

PD_{ref} = Reference population density (persons/km^2) (discussed below)

$URB\%_{C,TY}$ = The urban population share of country C in year TY (%) (see "Important general parameters")

$URB\%_{ref}$ = The reference urban population share (discussed below)

LA_C = Land area of country C (km^2) (discussed elsewhere)

$\kappa 1$ = Exponent relating change in population density to change in the maximum allowable land percentage (discussed below)

$\kappa 2$ = Exponent relating change in non-urban population share to change in the maximum allowable land percentage (discussed below)

We use the non-urban share, rather than the urban share, because the function behaves more desirably when the non-urban share goes to zero than when the urban share goes to 100%. We set upper and lower bounds on the maximum allowable land percentage to keep it within reasonable bounds; in particular, without a lower bound the formula would evaluate to *LA%* = 0 for countries with zero rural population, and this doesn't seem reasonable. We believe that bounds of 0.5% and 15% are reasonable.

We set the reference values to what we think are reasonable for the U.S. for ca. 2015: 6.5% maximum land area with U. S. population density and urban shares for 2015. Our investigation of the behavior of the function with different values of the exponents suggests that the most reasonable range of results is obtained with $\kappa 1$ = -0.30 and $\kappa 2$ = 0.50. For example, these exponent values result in $LA\%_{\max,ONW,C,TY}$ = 0.5% for a country a population density of 3000 persons/km^2 and an urban population share of 95%, and $LA\%_{\max,ONW,C,TY}$ = 12.6% for a country a population density of 15 persons/km^2 and an urban population share of 50%

<u>Minimum qualifying capacity factor $CF_{ONW,\min}$.</u> If the technical potential capacity is defined without regard to economics, then *any* wind resource can provide technical potential – even, for example, if the resource is so poor that it results in a wind turbine operating at capacity for only one hour a year. However, it does not seem reasonable to count towards technical potential wind resources that provide capacity factors so low as to render wind power uneconomical under *any* conceivable circumstances, anywhere, at any time. Therefore, we count towards the technical potential capacity only those resources that *might* conceivably be exploited economically. Accordingly, we define the minimum qualifying capacity factor $CF_{wind,\min}$ as the capacity factor below which no wind resource ever will be exploited, anywhere, and hence as the lower-bound capacity factor for determining the technical potential. We believe that a reasonable value for $CF_{wind,\min}$ is just below 10%. (We pick a value just below 10% in order to capture a very small fraction of the wind resource in the lowest resource class.)

<u>Total onshore area with minimum acceptable potential resource.</u> This parameter is the sum of the areas in each capacity-factor class above the minimum, using the midpoint of each capacity factor class. The areas by capacity-factor class, for a turbine of height *h,* are based on the NREL estimates of land areas with wind resources of different capacity-factor classes at 50 m above the ground (corresponding to a 50-m turbine-hub height), with the midpoints of the NREL capacity-factor classes adjusted to account for the effects of (hub) heights greater than 50 m. Formally,

$$LA_{CF_{ONW,h} \geq CF_{ONW,\min},C} = \sum_{j_{mid} \geq CF_{ONW,\min}}^{j_{mid} \leq CF_{ONW,\max}} LA_{CF_{j_{mid},ONW,h},C}$$

$$LA_{CF_{j_{mid},ONW,h},C} = LA_{CF_{j_{mid},ONW,50}\left(\rightarrow CF_{j_{mid},ONW,h}\right),C}$$

$$CF_{j_{mid},ONW,h} = \frac{P_{PD,ONW,j_{mid},h}}{C_{PD,ONW,h}}$$

$$CF_{j_{mid},ONW,50} = \frac{P_{PD,ONW,j_{mid},50}}{C_{PD,ONW,50}}$$

$$CF_{j_{mid},ONW,h} = CF_{j_{mid},wind,50} \cdot \frac{\dfrac{P_{PD,ONW,j_{mid},h}}{C_{PD,ONW,h}}}{\dfrac{P_{PD,ONW,j_{mid},50}}{C_{PD,ONW,50}}} = CF_{j_{mid},ONW,50} \cdot \frac{C_{PD,ONW,50}}{C_{PD,ONW,h}} \cdot \frac{P_{PD,ONW,j_{mid},h}}{P_{PD,ONW,j_{mid},50}}$$

where

$LA_{CF_{j_{mid},ONW,h},C}$ = Onshore area of country *C* with a wind resource corresponding to capacity-factor class midpoint $CF_{j_{mid},ONW,h}$ at a height of *h* m (km^2)

$LA_{CF_{j_{mid},ONW,50},C}$ = Onshore area of country *C* with a wind resource corresponding to capacity-factor class midpoint $CF_{j_{mid},ONW,50}$ at a height of 50 m (km^2) (NREL, 2012c)

$CF_{j_{mid},ONW,50}\left(\rightarrow CF_{j_{mid},ONW,h}\right)$ = The capacity-factor midpoints at 50 m height mapped to the capacity-factor midpoints at *h* m height

$CF_{ONW,\max}$ = The maximum capacity-factor class for wind (based on the adjusted maximum capacity-factor class in the NREL estimates)

$CF_{j_{mid},ONW,h}$ = The midpoint of capacity-factor class *j*, for a height of *h* m

$CF_{j_{mid},ONW,50}$ = The midpoint of capacity-factor class *j*, for a height of 50 m

$P_{PD,ONW,j_{mid},h}$ = The average annual power production, as areal density, for onshore wind, at capacity-factor-class midpoint j_{mid}, for a height of *h* (MW/km^2)

$P_{PD,ONW,j_{mid},50}$ = The average annual power production, as areal density, for onshore wind, at capacity-factor-class midpoint j_{mid}, for a height of 50 m (MW/km^2)

$C_{PD,ONW,h}$ = The capacity of onshore wind systems, as areal power density, for a turbine hub-height of *h* (MW/km^2) (5/0.78, for a turbine with a hub height of 100 m)

$C_{PD,ONW,h}$= The capacity of onshore wind systems, as areal power density, for a turbine hub-height of 50 m (MW/km^2)
Subscript j = Capacity-factor classes in the original NREL estimates (5% increments from 0 to over 45%: 0-5%, 5-10%, 10-15%...35-40%, 40-45%, 45%+)

Generally the minimum acceptable wind capacity factor falls between two capacity-factor-class midpoints (i.e., the minimum is almost never *exactly* equal to one of the class midpoints). In these cases, rather than count only wind power above the upper bracketing midpoint, we give a partial weight to the lower bracketing capacity-factor-class midpoint, where the weight is equal to:

$$\frac{CF_{j_{mid}-upper,ONW,h} - CF_{ONW,\min}}{CF_{j_{mid}-upper,ONW,h} - CF_{j_{mid}-lower,ONW,h}}$$

and $CF_{j_{mid}-upper,ONW,h}$ is the capacity-factor -class midpoint immediately above $CF_{ONW,\min}$, and $CF_{j_{mid}-lower,ONW,h}$ is the wave-power-class midpoint immediately below.

The ratio $\frac{P_{PD,ONW,j_{mid},h}}{P_{PD,ONW,j_{mid},50}}$. The published NREL data for $LA_{CF_{j_{mid}},ONW,50,C}$ show land area by capacity-factor-class increments for a hub height of 50 m. Now, for any given area $LA_{WCF_{j_{mid}},50,C}$, if the assumed hub height were increased to h, then generally the wind speed and hence wind power would increase. Therefore, we adjust the NREL capacity-factor classes from their 50m-height basis to our h-height basis. (Note that this matters only because we have assumed some nonzero value of $CF_{ONW,\min}$: increasing $CF_{j_{mid},ONW,50}$ to $CF_{j_{mid},ONW,h}$ increases the land area above the threshold $CF_{ONW,\min}$.)

We define the ratio $\frac{P_{PD,ONW,j_{mid},h}}{P_{PD,ONW,j_{mid},50}} \equiv AF_{CF_{j_{mid}},ONW,h/CF_{j_{mid}},ONW,50}$. We assume that there is a maximum adjustment factor based on the change in power output with height, and a minimum adjustment factor of 1.00 (no adjustment). We assume that the adjustment factor decreases logistically with increasing capacity factor, because in areas with very high wind speeds (and hence high capacity factors) at 50 m, there is less of an increase in wind speed from 50 m to 100 m based on a logarithmic or power-law wind speed profile. Formally,

$$AF_{CF_{j_{mid}},ONW,h/CF_{j_{mid}},ONW,50} = AF_{lower,h/50} + \frac{AF_{upper,h/50} - AF_{lower,h/50}}{1+e^{k\cdot\left(CF_{ONW}-CF_{ONW,ref}\right)}\cdot\left(\frac{AF_{upper,h/50}-AF_{ref,h/50}}{AF_{ref,h/50}-AF_{lower,h/50}}\right)}$$

$$AF_{ref,h/50} = 1 + k1\cdot\left(AF_{upper,h/50} - AF_{lower,h/50}\right)$$

where

$AF_{lower,h/50}$ = The lower bound of the adjustment factor (1.00)
$AF_{upper,h/50}$ = The upper bound of the adjustment factor (see discussion below)
$AF_{ref,h/50}$ = The adjustment factor at the reference wind capacity factor
$CF_{ONW,ref}$ = The reference wind capacity factor (0.325)
CF_{ONW} = The wind capacity factor
k = Exponent that determines steepness of decline from upper to lower limit (20; higher values make steeper declines)
k1 = Reference adjustment factor as a fraction of difference between upper and lower adjustment factors (0.541)

The upper bound of the adjustment factor is assumed to be slightly above the increase in power resulting from increasing the turbine height from 50 m to *h*, where the power varies with the cube of the change in wind speed,

$$AF_{upper,h/50} = k2 \cdot \left(\frac{V_{ONW,h}}{V_{ONW,50}} \right)^3$$

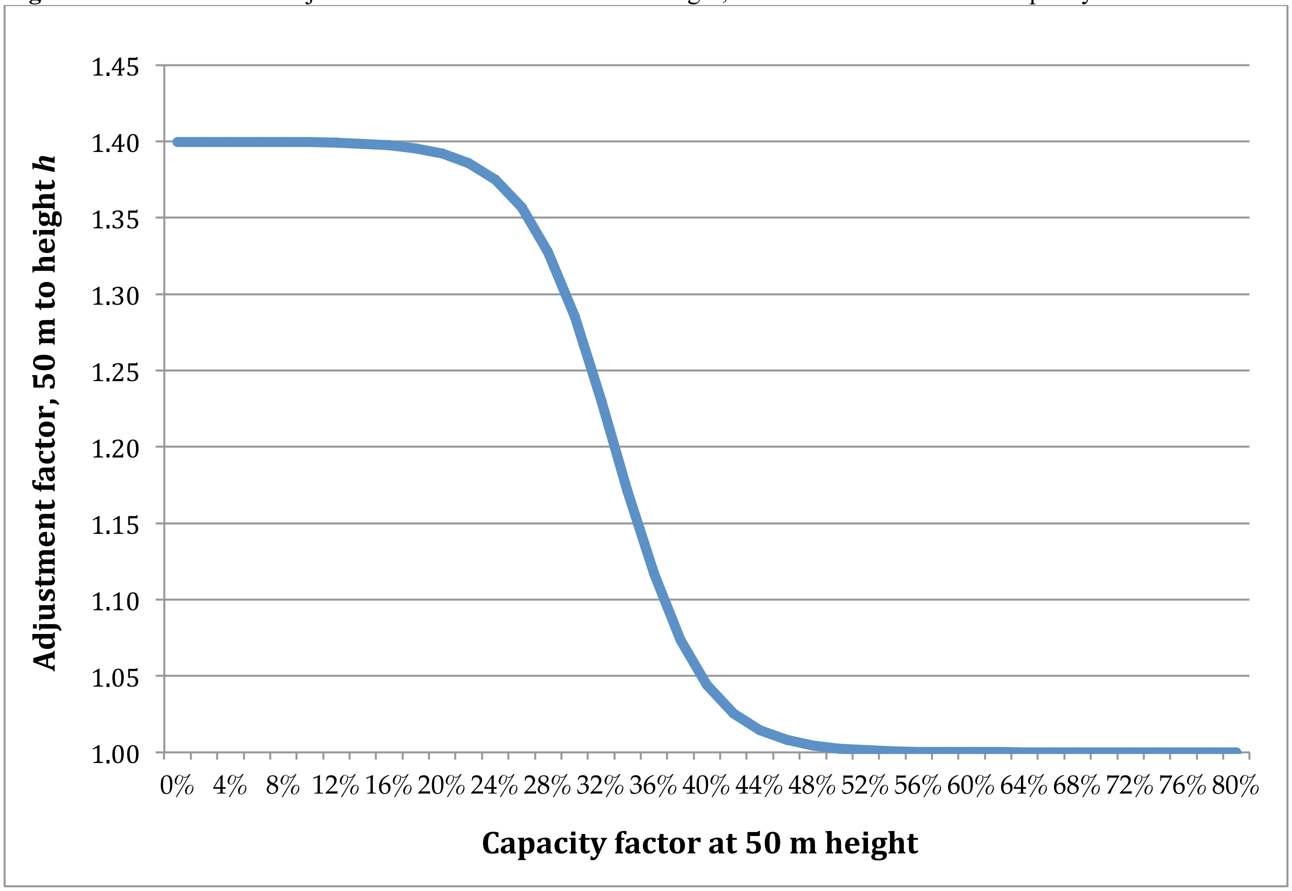
$$\frac{V_{ONW,h}}{V_{ONW,50}} = \left(\frac{h}{50} \right)^{\frac{1}{7}}$$

where

k2 = Upscaling factor (1.04)
$V_{ONW,h}$ = Wind speed at height *h* (m/sec)
$V_{ONW,50}$ = Wind speed at height 50 m (m/sec)
h = Height of turbine (we assume 100 m)

The parameter values shown above result in the logistic relationship shown in Figure S4.

Figure S4. The land-area adjustment factor due to increased height, as a function of the wind capacity factor class.



Technical potential for offshore wind

We use the National Renewable Energy Laboratory (NREL) estimates of technical potential offshore wind capacity by country (Arent et al., 2012), for offshore areas less than 60 meters deep and with a wind resource providing at least a 34% capacity factor. For countries not covered in NREL's analysis, we estimate the technical potential as the product of the areal power density for offshore wind systems and the coastal area suitable for wind power development,

$$C_{TP,OFFW,C} = AP_{OFFW} \cdot CA_C \cdot Sfr_{OFFW}$$

$$AP_{OFFW} = \frac{CAP_{OFFW}}{A_{OFFW}}$$

$$CA_C = CL_C \cdot CLK_{OFFW} \cdot \left(OD_{\max} - OD_{\min}\right)$$

where

$C_{TP,OFFW,C}$ = Total technical potential (*TP*) capacity of offshore wind power in country *C* (MW)

AP_{OFFW} = The areal power density of offshore wind systems (MW/km^2)

CA_C = The total offshore area of country C available for offshore wind farms (km^2)

Sfr_{OFFW} = The fraction of available offshore area technically suitable for offshore wind development (5%; same for all countries)

CAP_{OFFW} = The rated capacity of an individual offshore wind turbine (5 MW)

A_{OFFW} = The average spacing area per offshore wind turbine (0.70 km^2)

CL_C = The reported length of coastline of country C (km) (CIA, 2016a)

CL_C CLK_{OFFW} = The coastline convolution correction factor for offshore wind; equal to the ratio of the coastline length at approximately a 1 km resolution to the reported coastline length (same for all countries; see discussion below)

$OD_{\max}$ = Maximum distance from shore for wind turbines, reflecting economic and siting considerations (km; same for all countries; see discussion below)

$OD_{\max}$ $OD_{\min}$ = Minimum distance from shore for wind turbines, reflecting visual/esthetic considerations (km; same for all countries; see discussion below)

$OD_{\max}$ $OD_{\min}$

Coastline convolution correction factor for offshore wind. Because no coastline is perfectly straight at all scales (levels of resolution), the length of a coastline depends on the scale or level of resolution of the measurement. The smaller the scale, the longer the measured coastline: a measurement taken every cm will count the contours of rocks along the shore; a measurement taken every 100 km will result in straight lines cutting across large-scale features such as bays and peninsulas.

Because offshore wind turbines will be placed on the order of 0.5 to 1.0 km apart, the relevant coast-side length of the available offshore area should be measured at about a 1.0 km scale. It appears to us that the data source we use, the CIA's *World Factbook* (CIA, 2016a), takes measurements at close to this scale. We assume a correction factor of 70%.

Maximum and minimum distance from shore. The ocean coastal area suitable for offshore wind depends mainly on the distance from shore of shallow enough water, although floating turbines are now being commercialized. GWEC (2014) states, "at present, in Europe the average offshore wind turbine size is 3.7 MW, average water depth 22.4 meters and average distance from shore 32.9 km" (p. 53). NREL (Arent et al., 2012) assumes a minimum distance from shore of 5 nautical miles (9.26 km), and a maximum of 50 to 100 nautical miles (92.6 to 185.2 km). The minimum is meant to keep the turbines far enough offshore so that they are not really noticeable from shore; the maximum is based mainly on the need to minimize costs associated with installation in deeper waters.

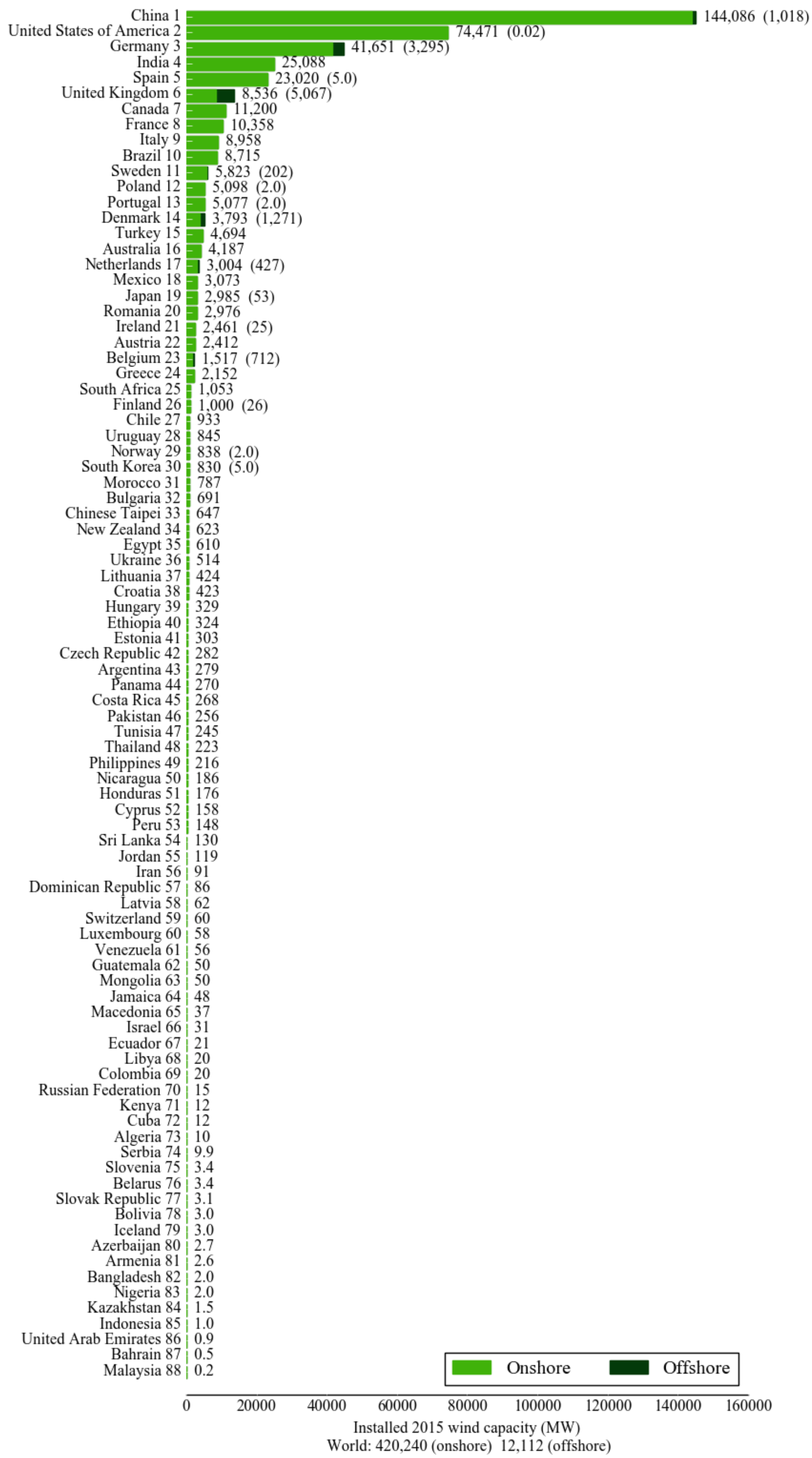
With these considerations, we assume a minimum distance of 10 km and a maximum of 100 km.

As a check on the plausibility of our method, we applied it to estimate the technical potential for the countries covered in NREL's (Arent et al., 2012) analysis. Many of our estimates for particular countries differ considerably from NREL's, but because some of our estimates are higher while some or lower than NREL's, our estimated total potential for *all* countries is very close to NREL's. In any case, the technical potential estimated by this method for the countries not included in the NREL analysis is only 4% of the total potential estimated by NREL.

Results. Only 16.8% of the onshore technical potential and 32.6% of the near-shore offshore technical potential are proposed for use in 2050. Table S7 indicates that the 2050 WWS roadmaps require ~0.92% of the 139-country onshore land area and 0.55% of the 139-country onshore-equivalent land area that is sited offshore for wind-turbine spacing to power 37.1% of all-purpose annually averaged 139-country power in 2015.

As of the end of 2015, 5.04% of the proposed 8.33 TW of 2050 onshore wind nameplate capacity and 0.26% of the 4.69 TW of offshore wind capacity among the 139 countries had been installed. Figure S5 indicates that China, the United States, and Germany have installed the greatest capacity of onshore wind, whereas the United Kingdom, Germany, and Denmark have installed the most offshore wind to date.

Figure S5. Installed onshore and offshore wind power by country as of the end of 2015 from GWEC (2016) and EWEA (2016).

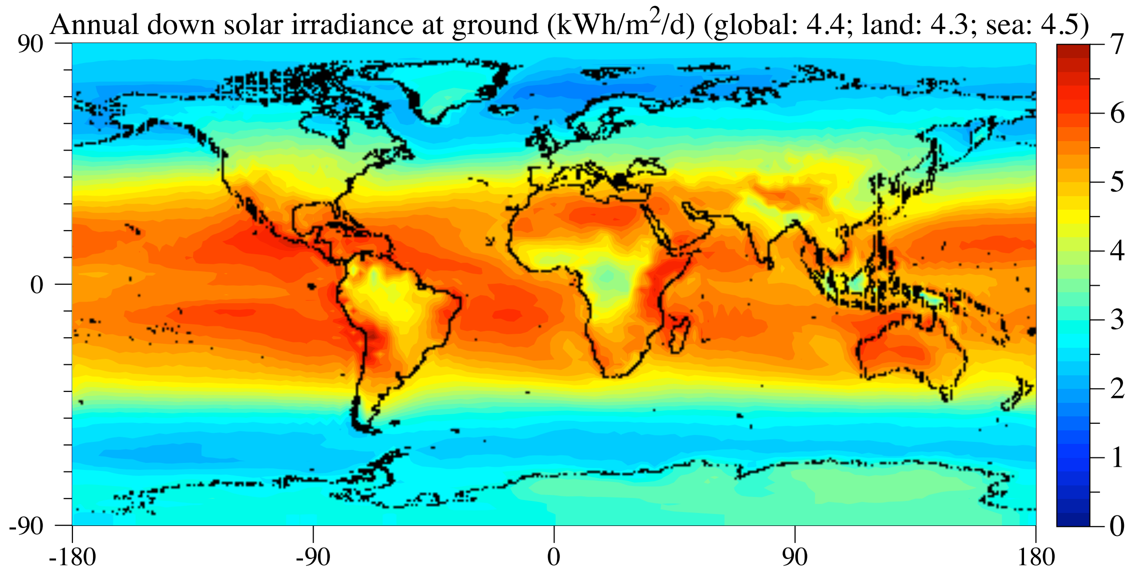

China 1 144,086 (1,018)
United States of America 2 74,471 (0.02)
Germany 3 41,651 (3,295)
India 4 25,088
Spain 5 23,020 (5.0)
United Kingdom 6 8,536 (5,067)
Canada 7 11,200
France 8 10,358
Italy 9 8,958
Brazil 10 8,715
Sweden 11 5,823 (202)
Poland 12 5,098 (2.0)
Portugal 13 5,077 (2.0)
Denmark 14 3,793 (1,271)
Turkey 15 4,694
Australia 16 4,187
Netherlands 17 3,004 (427)
Mexico 18 3,073
Japan 19 2,985 (53)
Romania 20 2,976
Ireland 21 2,461 (25)
Austria 22 2,412
Belgium 23 1,517 (712)
Greece 24 2,152
South Africa 25 1,053
Finland 26 1,000 (26)
Chile 27 933
Uruguay 28 845
Norway 29 838 (2.0)
South Korea 30 830 (5.0)
Morocco 31 787
Bulgaria 32 691
Chinese Taipei 33 647
New Zealand 34 623
Egypt 35 610
Ukraine 36 514
Lithuania 37 424
Croatia 38 423
Hungary 39 329
Ethiopia 40 324
Estonia 41 303
Czech Republic 42 282
Argentina 43 279
Panama 44 270
Costa Rica 45 268
Pakistan 46 256
Tunisia 47 245
Thailand 48 223
Philippines 49 216
Nicaragua 50 186
Honduras 51 176
Cyprus 52 158
Peru 53 148
Sri Lanka 54 130
Jordan 55 119
Iran 56 91
Dominican Republic 57 86
Latvia 58 62
Switzerland 59 60
Luxembourg 60 58
Venezuela 61 56
Guatemala 62 50
Mongolia 63 50
Jamaica 64 48
Macedonia 65 37
Israel 66 31
Ecuador 67 21
Libya 68 20
Colombia 69 20
Russian Federation 70 15
Kenya 71 12
Cuba 72 12
Algeria 73 10
Serbia 74 9.9
Slovenia 75 3.4
Belarus 76 3.4
Slovak Republic 77 3.1
Bolivia 78 3.0
Iceland 79 3.0
Azerbaijan 80 2.7
Armenia 81 2.6
Bangladesh 82 2.0
Nigeria 83 2.0
Kazakhstan 84 1.5
Indonesia 85 1.0
United Arab Emirates 86 0.9
Bahrain 87 0.5
Malaysia 88 0.2
Onshore
Offshore
0
20000
40000
60000
80000
100000
120000
140000
160000
Installed 2015 wind capacity (MW)
World: 420,240 (onshore) 12,112 (offshore)

S5.2. Rooftop and Utility-Scale PV and CSP

Resources

Figure S6 shows annually averaged modeled solar irradiance worldwide accounting for sun angles, day/night, and clouds. The best solar resources are broadly between 40 ^{o}N and 40 ^{o}S. The new land area in 2050 required for non-rooftop solar under the roadmaps here is equivalent to ~0.22% of the 139-country land area (Table S7).

Figure S6. Modeled annually averaged downward direct plus diffuse solar irradiance at the ground (kWh/m^2/day) worldwide. The model used is GATOR-GCMOM (Jacobson, 2010b), which simulates clouds, aerosols gases, weather, radiation fields, and variations in surface albedo over time. The model is run with horizontal resolution of 2.5^o W-E x 2.0^o S-N.



Technical potential of rooftop PV

In this section, we estimate the technical-economic potential and installed capacity of solar PV on the rooftops of residential buildings, residential parking structures, commercial/institutional/government buildings, and industrial/manufacturing facilities. In some instances we report results in two aggregated categories, residential and commercial, where *residential* includes residential parking rooftops and *commercial* includes manufacturing/industrial rooftops. Generally, we build from estimates of floor space to estimates of rooftop area and ultimately to the useable fraction of technical potential capacity.

Installed capacity. The estimated installed capacity of rooftop solar in the target year is equal to the technical potential multiplied by the fraction of the technical potential that we estimate is used:

$$C_{I,PVroof,C,TY} = C_{TP,PVroof,C,TY} \cdot Ufr_{PVroof,C,TY}$$

where

$C_{I,PVroof,C,TY}$ = Total installed capacity of rooftop solar power in country C in target year TY (MW)

$C_{TP,PVroof,C,TY}$ = Total technical-potential capacity of rooftop solar power in country C in target year TY (MW)

$Ufr_{PVroof,C,TY}$ = The fraction of technically suitable rooftop actually used for PVs in country C in target year TY

Technical potential. The technical potential is the product of the PV areal power density, the total rooftop area, the fraction of rooftop area that is technically suitable for PVs.

Formally,

$$C_{TP,PVroof,C,TY} = AP_{PV,TY} \cdot RA_{C,TY} \cdot Sfr_{PVroof,C}$$

$$AP_{PV,TY} = AP_{PV,BY} \cdot e^{\varphi_{PV} \cdot (TY - BY_{PV})}$$

where

$AP_{PV,TY}$ = The areal power density of PV systems in target year TY

$AP_{PV,BY}$ = The areal power density of PV systems in a base year BY_{PV} (discussed below)

φ_{PV} = The annual rate of change in the AP_{PV} (discussed below)

$Sfr_{PVroof,C}$ = The fraction of rooftop area technically suitable for rooftop PV in country C (discussed below)

$RA_{C,TY}$ = The total rooftop area of country C in target year TY (km^2) (discussed below)

Areal power density of PV systems. For all PV systems (commercial, residential, and utility-scale), in all countries, the base-year (2015) panel is a SunPower E20-327, which has a *dc* nameplate rating of 327W for a panel of 1.046m by 1.558m (SunPower, 2016), giving $AP_{PV,2015}$ = 201 W/m^2 in 2015. We assume that the panel efficiency and hence AP_{PV} (power output at constant panel size) increases at 0.5%/year, based in part on estimates in the NREL (2012b).

Total rooftop area in each country. The total rooftop area for residential buildings, commercial/institutional/government buildings, and industrial/manufacturing buildings is the product of the floor area per capita, the population, an overhang multiplier, and a pitch (slope) multiplier, divided by the average number of stories,

$$RA_{C,TY} = \frac{FAC_{C,TY} \cdot P_{C,TY} \cdot OH_{C,TY} \cdot SL_C}{SB_{C,TY} \cdot 10^6}$$

$$SB_{C,TY} \equiv \frac{FA_{C,TY}}{CA_{C,TY}}$$

where

$FAC_{C,TY}$ = floor area per capita in country *C* in target year *TY* (m^2/capita)
$P_{C,TY}$ = the population in country *C* in year *TY* (see "Important general parameters")
$OH_{C,TY}$ = the overhang multiplier covered parking-area roofs in country *C* in year *TY*
SL_C = slope multiplier for pitched roofs in country *C* (assumed to be the same for all years)
$SB_{C,TY}$ = the average number of stories per building in country *C* in year *Y*
$FA_{C,TY}$ = the total (all-stories) floor area in country *C* in year *TY* (m^2)
$CA_{C,TY}$ = the upper ceiling area in country *C* in year *TY* (essentially the flat underside of the roof, excluding any overhang) (m^2)

The method to estimate the rooftop area of residential parking is slightly different, and is presented later.

Floor area per capita (*FAC*) for residential and commercial buildings. For residential buildings (not including residential parking) and commercial/institutional/government buildings (not including industrial/manufacturing facilities), the total floor area per capita (FAC) for each country in year *TY* ($FAC_{C,TY}$) is calculated as a function of GDP per capita (divided by 1000), population density, and urban population percentage in a prior year, on the assumption that floor area per capita is related to construction activity in prior years. The function is calibrated to base-year estimates of FAC for several European countries and the United States, and is constrained to above minimum and below maximum values.

For countries for which we have reported base-year data on FAC (Table S9), we calculate $FAC_{C,TY}$ by scaling the base-year data (Table S9) by the ratio of estimated target-year to base-year FAC; otherwise, we use estimated target-year FAC directly. Formally,

If we have base-year data on FAC for country C, then

$$FAC_{C,TY} = FAC^*_{C,BY} \cdot \frac{F\hat{A}C_{C,TY}}{F\hat{A}C_{C,BY}} \cdot FAC_{correction}$$

Otherwise,

$$FAC_{C,TY} = F\hat{A}C_{C,TY} \cdot FAC_{correction}$$

$$F\hat{A}C_{C,TY} = \min\left[FAC_{\max,TY}, \max\left[\begin{array}{l} FAC_{\min,TY}, \beta 1 \cdot \left(\frac{GDPC_{C,TY-L_{BD}}}{1000}\right)^{\delta 1} + \beta 2 \cdot \left(\frac{GDPC_{C,TY-L_{BD}}}{1000}\right)^{\delta 2} + \\ \beta 3 \cdot \left(\frac{GDPC_{C,TY-L_{BD}}}{1000}\right)^{\delta 3} + \beta 4 \cdot PD_{C,TY-L_{BD}}{}^{\delta 4} + \\ \beta 5 \cdot PD_{C,TY-L_{BD}}{}^{\delta 5} + \beta 6 \cdot URB\%_{C,TY-L_{BD}}{}^{\delta 6} + \beta 7 \end{array}\right]\right]$$

$$PD_{C,TY} = \frac{P_{C,TY}}{LA_C}$$

where

$F\hat{A}C_{C,TY}$ = estimated floor area per capita in country C in target year TY (m^2/capita) (discussed below)

$FAC^*_{C,BY}$ = reported base-year data on floor-area per capita (Table S9)

$FAC_{correction}$ = factor to correct for omissions in the reported base-year data (discussed below)

$\frac{GDPC_{C,TY-L_{BD}}}{1000}$ = GDP per capita in country C in year TY-L , divided by 1000 (constant year-2013 international dollars, PPP basis; see section "Projection of GDP per capita")

$PD_{C,TY-L_{BD}}$ = the population density of country C in year TY-L

LA_C = the total onshore area of country C (km^2) (World Bank, 2016b; except values for Gibraltar, Taiwan (Chinese Taipei), and Netherlands Antilles from Wikipedia, 2016d)

$URB\%_{C,TY-L_{BD}}$ = the percentage of the population in urban areas in country C in year TY-L (see "Important general parameters")

L_{BD} = the effective (average) lag between the target year and the year of the economic and demographic conditions that determine building characteristics in the target year (discussed below)

$\beta 1 ... \beta 7$ and $\delta 1 ... \delta 6$ are estimated parameters (discussed below; Table S10)

$FAC_{\min,TY}$ = the minimum floor space per capita in year TY (m^2/capita), linearly interpolated based on the following assumed points:

2010	*2060*	
7.0	10.5	residential
1.2	1.8	service (commercial/institutional/government)

$FAC_{\max,TY}$ = the maximum floor space per capita in year TY (m^2/capita), linearly interpolated based on the following assumed points:

2010	*2050*	
65.0	81.3	Residential
35.2	43.8	service (commercial/institutional/government)

Table S9. Residential and commercial floor space per capita in selected countries.

Country	**m^2 floorspace/capita**		**Year**	**Source**
	Residential	*Commercial*		
Austria	40.96	13.71	2008	Entranze
Belgium	35.28	9.74	2008	Entranze
Bulgaria	25.87	8.37	2008	Entranze
Cyprus	48.80	9.74	2008	Entranze
Czech Republic	29.68	8.51	2008	Entranze
Denmark	54.36	22.38	2008	Entranze
Estonia	27.87	8.96	2008	Entranze
Finland	37.53	20.11	2008	Entranze
France	38.77	14.19	2008	Entranze
Germany	39.39	13.47	2008	Entranze
Greece	28.77	12.48	2008	Entranze
Hungary	30.22	9.84	2008	Entranze
Ireland	41.75	9.77	2008	Entranze
Italy	42.92	6.93	2008	Entranze
Latvia	28.00	7.60	2008	Entranze
Lithuania	30.90	9.25	2008	Entranze
Luxembourg	33.77	10.03	2008	Entranze
Malta	32.82	9.68	2008	Entranze
Netherlands	38.45	17.97	2008	Entranze
Poland	24.70	10.11	2008	Entranze
Portugal	38.59	9.67	2008	Entranze
Romania	21.23	2.76	2008	Entranze
Slovak Republic	24.51	7.05	2008	Entranze
Slovenia	29.91	13.54	2008	Entranze
Spain	33.97	7.58	2008	Entranze
Sweden	41.75	16.48	2008	Entranze
United Kingdom	31.35	11.99	2008	Entranze
United States	68.88	25.95	2009/12	EIA 2009 RECS, 2012 CBECS
Serbia	22.28	7.43	2008	Entranze
Croatia	25.44	7.26	2008	Entranze

Sources: Entranze = Entranze, 2015; RECS = EIA 2009 *Residential Energy Consumption Survey* (RECS; EIA, 2013a); CBECS = 2012 *Commercial Buildings Energy Consumption Survey* (CBECS; EIA, 2016d). The Entranze data are reported for the residential and the non-residential "service" sectors, with the latter including "office buildings, hospitals, schools and universities, hotels and restaurants, buildings in wholesale and retail trade" (Sebi et al., 2013, p. 11). This is consistent with the EIA's CBECS "commercial" sector and with our "commercial/institutional/government" sector.

The effective lag L_{BD} accounts for the fact that the relevant characteristics (such as floor space) of buildings in any year *Y* presumably were determined by economic and demographic variables (such as GDP per capita) in years prior to *Y*, mainly because most buildings existing in year *Y* were built many years prior to *Y.* If building characteristics were determined by the economic and demographic conditions at the time the buildings were built, then L_{BD} is approximately the average age of buildings. This presumably is the maximum reasonable value of L_{BD}. However, builders are aware that buildings exist for many years and hence ought to accommodate future needs, and thus in some fashion probably build in anticipation of future economic and demographic conditions. If builders have good foresight and do long-range planning with no "discounting," then they build in anticipation of the conditions when the building is roughly at its average age, which results in L_{BD} being about zero (the minimum value, of course).

An analysis of the distribution of building ages from the EIA's *Commercial Buildings Energy Consumption Survey* (CBECS), (EIA, 2016d) and *Residential Energy Consumption Survey* (RECS) (EIA, 2013a) suggests that floor-space weighted average age is about 32 years for commercial buildings and 36 years for residential buildings. (Note that the EIA's definition of "commercial" includes institutional and government buildings.) If we exclude the oldest buildings (60+ years for commercial, 55+ years for residential) on the grounds that buildings today are not built for as long a life, then the average age is 27 commercial buildings an d 28 for residential. Thus, in the U. S., L_{BD} can range from 0 to about 30 years. Without further analysis, we assume a mid-range value of 15 years for L_{BD}. This means, for example, that the average building in the year 2050 was built in about 2020 on the basis of conditions anticipated for the year 2035.

The reported base-year residential data of Table S9 include only the conditioned or living area of permanently occupied dwellings; they do not include areas of vacant homes, second homes, or spaces such as shared hallways in multi-family dwellings (Sebi et al., 2013; country reports from Entranze, 2016). However, these areas are relevant to our analysis because they have roof area that is available for PVs. We assume that this area is 2% of the uncorrected estimated floor space in all countries.

We assume that the reported service (commercial/institutional/government) area data do not include covered (or potentially coverable) parking areas *not* underneath floorspace that is included in the reported data. We assume that this area is 5% of the uncorrected estimated floor space in all countries.

The residential data of Table S9 also presumably do not include areas of residential garages, so we estimate this separately.

Table S10. Parameters in the estimation of *FAC*.

	$\delta1$	$\delta2$	$\delta3$	$\delta4$	$\delta5$	$\delta6$	$\beta1$	$\beta2$	$\beta3$	$\beta4$	$\beta5$	$\beta6$	$\beta7$
$\hat{FAC}_{res,C,Y}$	1.038	0.760	0.517	0.088	0.027	0.000	0.212	-3.749	14.810	-3.264	-4.376	0.375	0.308
$\hat{FAC}_{com,C,Y}$	0.141	0.733	0.404	0.393	0.234	0.425	1.069	-0.408	5.799	2.328	-10.348	1.095	0.776

res. = residential; com = commercial; n.a. = not applicable.

The parameters $\beta1...\beta7$ and $\delta1...\delta6$ are estimated by using a genetic algorithm to find the best (error-minimizing) fit of the polynomial to base-year data on *FAC, GDPC, PD,* and *URB%*, for several European countries. Table S9 shows the base-year (2008) *FAC* data; the other base-year data (*GDPC, PD,* and *URB%*) are estimated as described elsewhere in this documentation. We assume that the "service" category in Tables S9 is the same as our "commercial" category. Table S10 shows the fitted parameters $\beta1...\beta7$ and $\delta1...\delta6$. These parameters, along with the minimum and maximum constraints, give reasonable results for years from 2005 to 2075.

Floor area per capita (*FAC*) for manufacturing/industrial buildings. For manufacturing/industrial buildings, *FAC* is calculated as function of *GDPC, PD, URB%* and a reference value of *FAC* for the U. S.,

$$FAC_{ind,C,TY} = FAC_{ind,US,RY_{ind}} \cdot \min\left[\left|\frac{FAC_{ind,C,TY}}{FAC_{ind,US,RY_{ind}}}\right|_{\max}, \overline{\overline{GDPC}}_{C,\overline{\overline{Y}}} \cdot \overline{\overline{PD}}_{C,\overline{\overline{Y}}} \cdot \overline{\overline{URB\%}}_{C,\overline{\overline{Y}}}\right]$$

where

$FAC_{ind,C,TY}$ = Floor area per capita in the industrial sector in country *C* in year *TY* (m^2/capita)

$FAC_{ind,US,RY_{ind}}$ = $FAC_{ind,C,TY}$ = Floor area per capita in the industrial sector in the U. S. in reference year RY_{ind} (m^2/capita) (discussed below)

$\left|\frac{FAC_{ind,C,TY}}{FAC_{ind,US,RY_{ind}}}\right|_{\max}$ = The maximum value of the ratio of *FAC* for country *C* in year *TY* to *FAC* for the U. S. in year *RY* (assume 2.5)

$\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}}$ = Adjusted relative GDP per capita in country *C,* for $\overline{\overline{Y}}$

$\overline{\overline{PD}}_{C,\overline{\overline{Y}}}$ = Adjusted relative population density in country *C,* for $\overline{\overline{Y}}$

$\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}}$ = Adjusted relative urban population share in country *C,* for $\overline{\overline{Y}}$

The *GDPC, PD,* and *URB%* parameters are a nonlinear function of the parameter for each country relative to that for the U. S., where the exponent (or elasticity) is itself a function of the relative parameter:

$$\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}} = GDPC'_{C,\overline{\overline{Y}}}{}^{\varepsilon_1 \cdot GDPC'_{C,\overline{\overline{Y}}}{}^{\alpha_1}} \qquad \overline{\overline{PD}}_{C,\overline{\overline{Y}}} = PD'_{C,\overline{\overline{Y}}}{}^{\varepsilon_2 \cdot PD'_{C,\overline{\overline{Y}}}{}^{\alpha_2}}$$

$$\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}} = URB\%'_{C,\overline{\overline{Y}}}{}^{\varepsilon_3 \cdot URB\%'_{C,\overline{\overline{Y}}}{}^{\alpha_3}}$$

$$\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}} = \frac{GDPC_{C,TY-L_{ind}}}{GDPC_{US,RY_{ind}-L_{ind}}} \qquad \overline{\overline{PD}}_{C,\overline{\overline{Y}}} = \frac{PD_{C,TY-L_{ind}}}{PD_{US,RY_{ind}-L_{ind}}}$$

$$\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}} = \frac{URB\%_{C,TY-L_{ind}}}{URB\%_{US,RY_{ind}-L_{ind}}}$$

where

$GDPC'_{C,\overline{\overline{Y}}}$ = GDP per capita in country *C* relative to the U. S., for $\overline{\overline{Y}}$

$PD'_{C,\overline{\overline{Y}}}$ = Population density in country *C* relative to the U. S., for $\overline{\overline{Y}}$

$URB\%'_{C,\overline{\overline{Y}}}$ = Urban population share in country *C* relative to the U. S., for $\overline{\overline{Y}}$

$\overline{\overline{Y}}$ = Estimate based on year $TY - L_{ind}$ for country *C* and year $RY_{ind} - L_{ind}$ for the U. S.

$\overline{\overline{Y}}$ $\varepsilon_1, \varepsilon_2, \varepsilon_3, \alpha_1, \alpha_2, \alpha_3$ = Exponents (Table S11)

TY = Target year of the analysis

RY_{ind} = Year of reference value of floorspace per capita in the industrial sector

RY_{ind} L_{ind} = The effective (average) lag between the target or reference year and the year of the economic and demographic conditions that determine industrial-building characteristics in the target or reference year (discussed below)

RY_{ind} L_{ind} $GDPC_{C,Y}$, $PD_{C,Y}$, $URB\%_{C,Y}$ are discussed in the section "Important general parameters"

The EIA's *Manufacturing Energy Consumption Survey* (MECS) reports 11,000 billion square feet of total enclosed floors pace at manufacturing facilities in the U. S. in 2010 (EIA, 2013b). We use this value to calculate $FAC_{ind,US,RY_{ind}}$ for the U. S. for 2010. About half of the square footage is in the food, chemicals, plastics, fabricated-metals, and transportation-equipment industries.

As discussed above in the estimation of *FAC* for residential and non-industrial commercial buildings, the effective lag *L* accounts for the fact that the relevant characteristics (such as floor space) of buildings in any year *Y* presumably were determined by economic and demographic variables (such as GDP per capita) in years prior to *Y*, mainly because most buildings existing in year *Y* were built many years prior to *Y*. On the assumption that industrial buildings generally are older than commercial buildings, we assume that L_{ind} is 20 years, which is larger than L_{BD}.

Table S11. Estimation of the floors pace of industrial buildings.

	α	ε	**Comment**
1. *GDPC*	-0.48	0.2	Makes $\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}}$ much more sensitive to decreases in $GDPC'_{C,\overline{\overline{Y}}}$ than to increases; as $GDPC'_{C,\overline{\overline{Y}}}$ approaches highest values, $\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}}$ is only ~1.15, but as $GDPC'_{C,\overline{\overline{Y}}}$ approaches lowest values, $\overline{\overline{GDPC}}_{C,\overline{\overline{Y}}}$ is close to zero.
2. *PD*	0.34	-0.09	Makes $\overline{\overline{PD}}_{C,\overline{\overline{Y}}}$ much more sensitive to increases in $PD'_{C,\overline{\overline{Y}}}$ than to decreases; as $PD'_{C,\overline{\overline{Y}}}$ approaches highest values, $\overline{\overline{PD}}_{C,\overline{\overline{Y}}}$ approaches zero, but as $PD'_{C,\overline{\overline{Y}}}$ approaches zero, $\overline{\overline{PD}}_{C,\overline{\overline{Y}}}$ increases to only ~1.10.
3. *URB%*	5.00	-0.80	Makes $\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}}$ much more sensitive to increases in $URB\%'_{C,\overline{\overline{Y}}}$ than to decreases; as $URB\%'_{C,\overline{\overline{Y}}}$ approaches 100%, $\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}}$ drops below 0.5, but as $URB\%'_{C,\overline{\overline{Y}}}$ approaches 0%, $\overline{\overline{URB\%}}_{C,\overline{\overline{Y}}}$ actually returns to 1.00

Overhang multiplier *(OH)*. The overhang multiplier accounts for the fact that roofs typically overhang the floor area below. Assuming that the overhang distance does not increase in proportion to floor area, then the multiplier decreases with increasing floor area. Table S12 shows the overhang multiplier for four different building sizes and six roof overhangs. Table S12 shows that the overhang multiplier can range from 1.01 for large industrial buildings with small overhangs, to 1.5 for small houses with large overhangs.

Here we assume a simple nonlinear relationship between the multiplier, upper-ceiling-are per capita, and latitude, around a reference values,

$$OH_{C,TY} = \max\left[OH_{\min}, \min\left[OH_{\max}, OH_{ref} \cdot \left(\frac{CAC_{C,TY}}{CAC_{ref}}\right)^{\varphi 1} \cdot \left(\frac{LAT_{ave,C}}{LAT_{OH,ave,ref}}\right)^{\varphi 2}\right]\right]$$

$$CAC_{C,TY} = \frac{FAC_{C,TY}}{SB_{C,TY}}$$

where

$OH_{\min}$ = the minimum overhang multiplier
$OH_{\max}$ = the minimum overhang multiplier
OH_{ref} = the reference overhang multiplier
CAC_{ref} = the reference upper ceiling area per capita (m^2/capita) (the calculated 139-country average)

$CAC_{C,TY}$ = the upper ceiling area per capita in country C in year TY (essentially the flat underside of the roof, excluding any overhang) (m^2/capita)

$LAT_{OH,ave,ref}$ = the reference average latitude for the overhang-multiplier estimate

$LAT_{ave,C}$ = the average latitude of country C (degrees; determined by GATOR-GCM)

$\varphi 1$ = exponent relating changes in ceiling area to changes in overhang

$\varphi 2$ = exponent relating changes in latitude to changes in overhang

All parameter values are discussed in Table S13. With these assumptions, the overhang multiplier *OH* averages 1.17 for residential buildings, 1.27 for residential parking, 1.05 for commercial/institutional/government buildings, and 1.02 for industrial/manufacturing buildings.

Table S12. Overhang multiplier as a function of building size and overhang.

Type of building	Ceiling area	Feet of overhang					
		0.50	*1.00*	*1.50*	*2.00*	*2.50*	*3.00*
Small residential building	750	1.08	1.16	1.24	1.33	1.42	1.51
Residential buildings, U. S.	1,499	1.06	1.11	1.17	1.23	1.29	1.35
Commercial buildings, U. S.	10,004	1.02	1.04	1.06	1.09	1.11	1.13
Industrial buildings, U. S.	31,996	1.01	1.02	1.04	1.05	1.06	1.07
Residential buildings, world	1,050	1.07	1.13	1.21	1.28	1.35	1.43
Commercial buildings, world	7,003	1.03	1.05	1.08	1.10	1.13	1.16
Industrial buildings, world	22,397	1.01	1.03	1.04	1.06	1.07	1.09

Ceiling area is the "upper ceiling area" as estimated in this section. Average upper ceiling area per building in the U. S. is calculated using U. S. EIA data on number of buildings and total square footage, as reported in the EIA's RECS, CBECS, and MECS, and our estimates of number stories, as described elsewhere in this SI. On the basis of our estimates here, we assume that world-average building areas are 70% of U. S. values. Commercial buildings include institutional and government buildings. We assume that buildings are rectangles with one side twice the other.

Multiplier for sloped roofs *(SL)*. The slope multiplier accounts for the fact that for pitched roofs, the roof area exceeds the floor area, as a function of the slope angle. The slope multiplier is calculated as a function of the percentage of roofs that are pitched (or sloped; as opposed to almost flat) and the average slope:

$$SL_C = 1 - SL\%_C + \frac{SL\%_C}{\cos\left[SL\theta_C\right]}$$

where

$SL\%_C$ = the percentage of pitched (sloped) roofs in country C

$SL\theta_C$ = the average slope of pitched roofs in country C (degrees)

These parameters are estimated as a function of the country latitude, with fewer flat roofs and greater slope with increasing latitude, on the assumptions the further from the equator, the greater average snowfall and the consequent need for steeper roofs for shedding snow. Formally,

$$SL\%_C = \min\left[SL\%_{\max}, \max\left[SL\%_{\min}, SL\%_{ref} \cdot \left(\frac{LAT_{ave,C}}{LAT_{SL,ave,ref}}\right)^{\partial 1}\right]\right]$$

$$SL\theta_C = \min\left[SL\theta_{\max}, \max\left[SL\theta_{\min}, SL\theta_{ref} \cdot \left(\frac{LAT_{ave,C}}{LAT_{SL,ave,ref}}\right)^{\partial 2}\right]\right]$$

where

$SL\%_{\max}$ = The maximum percentage of sloped roofs in a country
$SL\%_{\min}$ = The minimum percentage of sloped roofs in a country
$SL\%_{ref}$ = The percentage of sloped roofs at the reference latitude
$LAT_{SL,ave,ref}$ = The reference average latitude for the slope-multiplier estimate (assume 38 degrees)
$SL\theta_{\max}$ = The maximum average slope of pitched roofs in a country
$SL\theta_{\min}$ = The minimum average slope of pitched roofs in a country
$SL\theta_{ref}$ = The average of slope of pitched roofs at the reference latitude
$\partial 1$ = Exponent relating changes in latitude to changes in percentage of sloped roofs
$\partial 2$ = Exponent relating changes in latitude to changes in slope angle

All parameter values are discussed in S14. Table S14 also shows results statistics for all 139 countries. With these assumptions, the slope correction factor *SL* varies from 1.0 to 1.16 with an average of 1.08 for residential, 1.00 - 1.08 [1.04 avg.] for residential parking, 1.00 - 1.04 [1.02] for commercial/institutional/government, and 1.00 - 1.02 [1.01] for industrial/manufacturing.

<u>Stories per building (*SB*).</u> The average number of stories per commercial/ institutional/government building in country *C* in year *Y*, $SB_{com,C,TY}$, is estimated as a function of GDP per capita, population density, urban percentage, with respect to reference values, fit to synthetic data. Formally,

$$SB_{com,C,TY} = \min\left[SB_{\max,com}, \max\left[\begin{array}{l} SB_{\min,com}, \beta 1 + SB_{com,Cref,RY} \cdot \left(\dfrac{GDPC_{C,Y-L_{BD}}}{GDPC_{Cref,RY-L_{BD}}}\right)^{\delta 1} \cdot \\ \left(\dfrac{PD_{C,Y-L_{BD}}}{PD_{Cref,RY-L_{BD}}}\right)^{\delta 2} \cdot \left(\dfrac{URB\%_{C,Y-L_{BD}}}{URB\%_{Cref,RY-L_{BD}}}\right)^{\delta 3} \end{array}\right]\right]$$

$$SB_{com,Cref,RY} = SB^*_{com,Cref,RY} - \beta 1$$

where

$SB_{\max,com}$ = the maximum allowable value of SB in the commercial sector (30 stories per building)

$SB_{\min,com}$ = the minimum allowable value of SB in the commercial sector (1.02 stories per building)

$SB_{com,Cref,RY}$ = the part of the reference SB that varies with $GDPC$, PD, and $URB\%$

Table S13. Parameters in the estimation of the roof-overhang multiplier.

Parameter	**Residential** *urban*	*non-urban*	**Res. parking** *urban*	*non-urban*	**Com.**	**Ind.**	**Comment**
$OH_{\min}$	1.05	1.05	1.06	1.06	1.01	1.00	See Table S12. Overhang multiplier is larger for buildings with smaller ceiling area, and we assume buildings are smaller in urban areas. However, we also assume buildings in urban areas, and commercial and industrial buildings, have smaller overhangs.
$OH_{\max}$	1.35	1.35	1.45	1.45	1.15	1.08	
OH_{ref}	1.16	1.16	1.20	1.20	1.025	1.015	See Table S12. The reference values here apply to the 139-country averages ceilin areas.
$\varphi 1$	-0.10	-0.10	-0.10	-0.10	-0.10	-0.10	The overhang decreases slightly with increasing ceiling area.
$LAT_{OH,ave,ref}$	38	38	38	38	38	38	Our assumption.
$\varphi 2$	0.00	0.00	0.00	0.00	0.00	0.00	Presently we assume that *OH* does not vary by latitude.

Res. parking = residential parking; Com. = commercial/institutional/government*; Ind. = industrial/manufacturing.*

Table S14. Parameters in the estimation of the rooftop slope adjustment factor.

	Residential		Res. Park.		Commercial		Industrial		Comment
	SL%	*SLθ*	*SL%*	*SLθ*	*SL%*	*SLθ*	*SL%*	*SLθ*	
Min.	20%	10	15%	5	15%	5	5%	5	We believe that most countries will have at least 15-20% pitched roofs. We assume characteristics of res. parking are between those of residential and commercial. Assume industrial buildings generally have flat roofs.
Max.	99%	65	95%	65	95%	65	50%	45	Our judgment.
Ref.	90%	26	25%	23	25%	23	15%	20	Residential, commercial based on values for cool regions of Californi (Jacobson et al., 2014). See also Melius et al. (2013). Assume industria buildings generally have flat roofs.
Exp. ∂	-0.30	-0.30	-0.35	-0.35	-0.35	-0.35	-0.30	-0.30	Our judgment, assuming small deviations away from ref values.
Results									
Min.	22%	10	15%	5	15%	5	5%	5	
Max.	99%	31	30%	28	30%	28	18%	23	
Ave.	79%	23	22%	20	22%	20	13%	18	
SD	18%	5.1	5%	5.1	5%	5.1	3%	4.1	

Res. Park. = residential parking; Commercial includes commercial/institutional/government *Min. = minimum; Max. = maximum; Ref. = reference value; Exp. = exponent; Ave. = average; SD = standard deviation.*

$SB^*_{com,Cref,RY}$ = The reference level of SB: stories per building in the commercial sector in reference country *Cref* in reference year RY (discussed below)

$GDPC_{Cref,RY-L_{BD}}$ = The reference level of *GDPC*: GDP per capita in the commercial sector in reference country *Cref* in reference year RY (discussed below)

$PD_{Cref,RY-L_{BD}}$ = The reference level of *PD*: population density in the commercial sector in reference country *Cref* in reference year RY (discussed below)

$URB\%_{Cref,RY-L_{BD}}$ = The reference level of *URB%*: the urban percentage in the commercial sector in reference country *Cref* in reference year RY (discussed below)

RY = The year of reference data (discussed below)

Cref = The reference country (U. S.)

$\beta 1$ and $\delta 1 ... \delta 3$ are estimated parameters (dependent on whether *GDPC*, *PD*, or *URB%* are above or below its reference value; Table S15a)

Subscript com = Commercial/institutional/government

Other parameters are discussed in the estimation of FAC

The equation is fit to synthetic data that represent our judgment of how stories per building vary with GDP per capita, population density, and the urban fraction of population. The fit is subject to constraints on the predicted minimum, maximum, and average values for all 139 countries for the year 2020 and the year 2075, as shown in Table S15b.

The reference values are based on data for the U. S. in 2012. The EIA's *Commercial Building Energy Consumption Survey* (CBECS*)* reports floor space and number of floors for all commercial buildings in the U. S. in 2012 (EIA, 2016e). In the CBECS (EIA, 2016f):

> Commercial buildings include all buildings in which at least half of the floorspace is used for a purpose that is not residential, industrial, or agricultural. By this definition, CBECS includes building types that might not traditionally be considered commercial, such as schools, hospitals, correctional institutions, and buildings used for religious worship, in addition to traditional commercial buildings such as stores, restaurants, warehouses, and office buildings.

We assume that buildings in the EIA category "4 to 9 stories" have 6 stories, and that buildings in the category "10 or more stories" have 15 stories. We also assume that the upper floors on 2-story and 3-story buildings cover 95% of the ground area of the first floor. With these assumptions, we calculate the total upper ceiling area, $CA_{com,US,2012}$, and then the average number of stories as $SB_{com,US,2012} = \frac{FA_{com,US,2012}}{CA_{com,US,2012}}$, where $FA_{com,US,2012}$ is provided by the CBECS. The result is 1.57, which seems reasonable. We then use U. S. 2012 values for $GDPC_{Cref,RY-L_{BD}}$, $PD_{Cref,RY-L_{BD}}$, and $URB\%_{Cref,RY-L_{BD}}$.

Table S15. Parameters for estimating stories per building.

S15.a. Exponents and intercept.

	$\delta 1$	$\delta 2$	$\delta 3$	$\beta 1$
Parameter above reference value	0.30	0.33	4.78	1.10
Parameter below reference value	0.34	1.20	0.24	

S15.b. Constraints on estimation of $SB_{com,C,TY}$

	Year 2075, all countries			US 2075	Year 2020, all countries		
	ave *SB*	min *SB*	max *SB*	*SB*	ave *SB*	min *SB*	max *SB*
Lower bound	2.00	1.02	12.00	1.90	1.40	1.00	7.00
Upper bound	2.40	1.30	30.00	2.30	1.90	1.20	30.00

We assume that stories per building in the residential sector is related to stories in the commercial/institutional/government sector:

$$SB_{res,C,TY} = SB_{com,C,TY}{}^{\eta}$$

To estimate η, we compare the average number of stories per building in the residential sector with our estimate of 1.57 stories per commercial/institutional/government building in the U. S. in 2012. Using data from the U. S. EIA's *RECS* (EIA, 2013a), we estimate that all residential buildings in the U. S. averaged 1.32 stories in 2009. This implies that η = ~0.6 for all commercial/institutional/government and residential buildings in the U. S. On the assumption that urban residential buildings have more stories than do non-urban buildings, we assume η is 0.80 for urban areas and 0.50 in non-urban areas.

Finally, we assume that all industrial/manufacturing buildings in all countries and all years are one story.

Rooftop area of residential parking. As mentioned above, the calculation of the rooftop area of residential parking is slightly different:

$$RA_{respark,C,TY} = PCC_{C,TY} \cdot PKC_{C,TY} \cdot PKCV\%_{C,TY} \cdot PKR\%_{C,TY} \cdot PKAC_{C,TY} \cdot OH_{respark,C,TY} \cdot SL_{respark,C}$$

where

$PCC_{C,TY}$ = Passenger cars per capita in country *C* in target year *TY* (discussed below)

$PKC_{C,TY}$ = Residential parking spaces per car in country *C* in year *TY* (discussed below)

$PKCV\%_{C,TY}$ = The percentage of parking spaces that are covered in country *C* in year *TY* (discussed below)

$PKR\%_{C,TY}$ = The percentage of covered parking floor area that has an exposed roof, in country *C* in year *TY* (discussed below)

$PKAC_{C,TY}$ = Floor area per covered space (m^2/space)

$OH_{respark,C,TY}$ $OH_{respark,C}$ = The overhang multiplier covered parking-area roofs in country C in year TY (see discussion of $OH_{C,TY}$ above)

$SL_{respark,C}$ = Slope multiplier for pitched covered parking-area roofs in country C (assumed to be the same for all years; see discussion of SL_C above)

To estimate passenger cars per capita, we start with World Bank estimates for the year 2006 and then project to future years assuming that ownership increases with wealth (GDP per capita) but decreases with population density, with the wealth effect being dominant:

$$PCC_{C,TY} = \max\left[PCC_{\min,C}, \min\left[PCC_{\max}, PCC_{C,BY} \cdot \left(\frac{GDPC_{C,TY-L_{PCC}}}{GDPC_{C,BY-L_{PCC}}}\right)^{\Omega 1} \cdot \left(\frac{PD_{C,TY-L_{PCC}}}{PD_{C,BY-L_{PCC}}}\right)^{\Omega 2}\right]\right]$$

$$PCC_{\min,C} = PCC_{C,BY} \cdot \left(1 - \Delta PCC_{\max}\right)$$

where

$PCC_{C,BY}$ = Passenger cars per capita in country C in base year BY (data from World Bank Development Indicators [World Bank, 2014; note that these data no longer are available], with missing data filled in as described in Delucchi et al., 2016, and with data for reference country [U. S.] from sources for $PCC_{Cref,RY-L_{PK}}$, for internal consistency)

$PCC_{\min,C}$ = Minimum passenger cars per capita in country C

$\Delta PCC_{\max}$ = Maximum fractional decrease in PCC below level in BY in country C (10%)

$PCC_{\max}$ = Maximum passenger cars per capita (we assume 0.60, for all countries)

$\Omega 1$ = Exponent relating changes in GDP per capita to changes in the passenger cars per capita (we assume 0.75)

$\Omega 2$ = Exponent relating changes in population density to changes in the passenger cars per capita (we assume -0.20)

L_{PCC} = The effective (average) lag between the target or base year and the year of the economic an demographic conditions that determine passenger cars per capita in the target or base year (discussed below)

BY = Base year (2006)

Regarding the lag parameter L_{PCC}, see the discussion of L_{BD} in the estimation of floor area per capita. Because cars have a relatively short lifetime, we expect that L_{PCC} is much less than L_{BD}. However, because we do not have data on GDP per capita prior to 2005, we cannot estimate

$GDPC_{C,BY-L_{PCC}}$ for any value of L_{PCC} greater than 1 when BY = 2006. Fortunately in this case it is reasonable to assume that L_{PCC} is zero, because $\frac{GDPC_{C,TY-L_{PCC}}}{GDPC_{C,BY-L_{PCC}}} \approx \frac{GDPC_{C,TY}}{GDPC_{C,BY}}$.

The parameters for residential spaces per car ($PKC_{C,TY}$), percentage of spaces that are covered ($PKCV\%_{C,TY}$), percentage of covered spaces with an exposed roof ($PKR\%_{C,TY}$), and floor area per covered space ($PKAC_{C,TY}$) are estimated as a function of cars per capita, GDP per capita and population density, subject to minimum and maximum values:

$$PRM_{C,TY} = \min\left[PRM_{\max}, \max\left[\begin{array}{l} PRM_{\min}, PRM_{Cref,RY} \cdot \\ \left(\frac{GDPC_{C,TY-L_{PK}}}{GDPC_{Cref,RY-L_{PK}}}\right)^{\varepsilon 1} \cdot \left(\frac{PD_{C,TY-L_{PK}}}{PD_{Cref,RY-L_{PK}}}\right)^{\varepsilon 2} \cdot \left(\frac{PCC_{C,TY-L_{PK}}}{PCC_{Cref,RY-L_{PK}}}\right)^{\varepsilon 3} \end{array}\right]\right]$$

where

$PRM_{C,TY}$ = The value of the parameter ($PKC_{C,TY}$, $PKCV\%_{C,TY}$, $PKR\%_{C,TY}$, $PKAC_{C,TY}$) in country C in year TY

$PRM_{\max}$ = Maximum value of the parameter (Tables S16a – S16d)

$PRM_{\min}$ = Minimum value of the parameter (Tables S16a – S16d)

$PRM_{Cref,RY}$ = The value of the parameter in the reference country *Cref* in the reference year (Tables S16a – S16d)

$GDPC_{Cref,RY-L_{PK}}$ = GDP per capita in the reference country *Cref* in the year $RY - L_{PK}$ (constant year-2013 international dollars per capita, PPP basis) (based on World Bank Development Indicators [World Bank, 2016d])

$PD_{Cref,RY-L_{PK}}$ = Population density in the reference country *Cref* in the year $RY - L_{PK}$ (persons/km^2) (based on U. S. population data (U.S. Census Bureau, 2015))

$PCC_{Cref,RY-L_{PK}}$ = Passenger cars per capita in the reference country *Cref* in the year $RY - L_{PK}$ (based primarily on data from U.S. Bureau of Transportation Statistics (2016))

Cref = Reference country for all parameters (U. S.)

RY = The year of the reference value of the parameters (2012)

L_{PK} = The effective (average) lag between the target or base year and the year of the economic and demographic conditions that determine residential parking in the target or base year (discussed below)

$\varepsilon 1$ = Exponent determining the relationship between changes in GDP per capita and changes in the floor area of covered spaces (Tables S16a – S16d)

$\varepsilon 2$ = Exponent determining the relationship between changes in population density and changes in the floor area of covered spaces (Tables S16a – S16d)

$\varepsilon 3$ = Exponent determining the relationship between changes in passenger cars per capita and changes in the floor area of covered spaces (Tables S16a – S16d)

$GDPC_{C,TY-L}$, $PD_{C,TY-L}$, and $PCC_{C,TY-L}$ are defined elsewhere

Regarding the lag parameter L_{PK} , see the discussion of L_{BD} in the estimation of floor area per capita. We assume that L_{PK} is slightly less than L_{BD} , because we assume that residential parking spaces turnover slightly more quickly than do buildings.

The EIA's *RECS* reports data on residential parking spaces at single-family and mobile homes in the U. S. in 2009. With these data, we calculate 1.3 parking spaces per single family or mobile home. Assuming 0.85 spaces per multi-family housing unit, we calculate a national-average of 1.015 parking spaces per passenger car in the U. S. in 2009. We assume 1.02 for the U. S. for 2012.

Dulac (2013) estimates global land requirements for parking and road infrastructure in 2010 and 2050. He estimates that in 2010, passenger cars in North America, OECD Pacific (except Korea and Japan), China, ASEAN, the Middle East, and Latin America required 18 m^2 per parking space, and that passenger cars in OECD Europe, India, Japan, Korea, and Africa required 15 m^2 per parking space. He assumes that these requirements will remain the same in 2050 unless there are aggressive parking policies and major shifts to smaller, more fuel-efficient vehicles, in which case in all regions passenger cars would require 15 m^2 per parking space in 2050.

We use these estimates as the basis for our assumptions for the minimum, maximum and reference values of floor area per covered space (Table S16d).

Fraction of roof area technically suitable for PV

This parameter limits technical potential to portions of roofs with reasonable orientation (e.g., close to south-facing in the northern hemisphere) and relatively little shading. Melius et al. (2013) review estimates of rooftop suitability for PVs, and find that 10% to 60% of building rooftop area is suitable for PVs, with the higher end pertaining to commercial buildings, larger buildings, or buildings with flat roofs. (Presumably commercial buildings are more suitable mainly because they are larger and tend to have flatter roofs.)

Table S16. Parameters in the estimation of rooftop area for residential parking.

S16a. Residential spaces per passenger car

	Urban	Non-urban	Comment
Min.	0.05	0.07	Our assumptions. Reference values are for U. S. ca. 2012; see discussion of *RECS* data in the text.
Max.	1.50	2.00	
Ref.	1.02	1.02	
$\varepsilon 1$	0.12	0.12	Assume parking spaces per car increases slightly with wealth.
$\varepsilon 2$	-0.16	-0.12	Assume that the number of parking spaces per car decreases with increasing population density.
$\varepsilon 3$	-0.03	-0.02	Assume that as the number of cars per capita increases the number of parking places per car decreases very slightly

S16b. Percentage of spaces that are covered

	Urban	Non-urban	Comment
Min.	35%	20%	Our assumptions. Reference values are for U. S. ca. 2012. Residential parking areas are more likely to be covered in urban areas.
Max.	100%	95%	
Ref.	75%	60%	
$\varepsilon 1$	0.10	0.10	Coverage is costly and hence presumably increases slightly with GDP per capita.
$\varepsilon 2$	0.10	0.07	Coverage presumably increases with increasing population density, especially in urban areas.
$\varepsilon 3$	-0.07	-0.05	Coverage presumably decreases with increasing vehicle ownership, especially in urban areas.

S16c. Percentage of covered parking spaces with an exposed roof

	Urban	Non-urban	Comment
Min.	15%	40%	Our assumptions. Reference values are for U. S. ca. 2012. Residential parking areas are more likely to have an exposed roof in non-urban areas because buildings in non-urban areas generally have fewer stories.
Max.	75%	95%	
Ref.	40%	70%	
$\varepsilon 1$	-0.10	-0.08	Assume that increasing wealth increases building on top of residential parking structures, with slightly greater effect in urban areas.
$\varepsilon 2$	-0.12	-0.10	Assume that increasing population density increases building on top of residential parking structures, with slightly greater effect in urban areas.
$\varepsilon 3$	0.00	0.00	Assume no effect

S16d. Floor area per covered space

	Urban	Non-urban	Comment
Min.	15.00	15.00	See discussion of Dulac (2013) in text. We assume that covered spaces are slightly larger than the uncovered spaces (Dulac's estimates are for all spaces, covered and uncovered). We also assume that spaces are slightly larger in non-urban than urban areas.
Max.	19.00	19.50	
Ref.	18.50	19.00	
$\varepsilon 1$	0.10	0.12	Floor area per covered space presumably increases slightly with GDP per capita. Assume slightly larger response in non-urban areas, because less s pace constrained
$\varepsilon 2$	-0.12	-0.10	Floor area per covered space presumably decreases with increasing

			population density. Assume less constrained in non-urban areas
$\varepsilon 3$	-0.07	-0.05	Assume that area devoted to vehicles decreases slightly with increasing vehicle ownership

Here we estimate the fraction of rooftop area suitable for PVs as a function of parameters that we are estimating for each country:

- Average building height (the greater the average height, the greater the variation in height, and hence the more likely that buildings shade one-another);
- Average rooftop area (the greater the area, the more likely that some significant portion of it is unshaded);
- The percentage of rooftop area that is flat (all else equal, the entire area of a flat roof is suitable for PVs); and
- The average slope of pitched roofs (the steeper the roof, the less suitable it is for PVs if it is pitched away from the sun).

We estimate this function with respect to reference values for the U. S. Formally,

$$Sfr_{PVroof,C,TY} = \min\left[\begin{array}{l} Sfr_{PVroof,\max}, \\ Sfr_{PVroof,US,RY} \cdot \left(\dfrac{SB_{C,TY}}{SB_{US,RY}}\right)^{\omega 1} \cdot \left(\dfrac{RAC_{C,TY}}{RAC_{US,RY}}\right)^{\omega 2} \cdot \left(\dfrac{FL\%_C}{FL\%_{US}}\right)^{\omega 3} \cdot \left(\dfrac{SL\theta_C}{SL\theta_{US}}\right)^{\omega 4} \end{array}\right]$$

$FL\%_C = 1 - SL\%_C \qquad\qquad FL\%_{US} = 1 - SL\%_{US}$

$$RAC_{C,TY} = \frac{RA_{C,TY}}{P_{C,TY}}$$

where

$Sfr_{PVroof,C}$ = The fraction of rooftop area technically suitable for rooftop PV in country C

$Sfr_{PVroof,\max}$ = The maximum allowable fraction of rooftop area suitable for PVs (Table S17)

$Sfr_{PVroof,US,RY}$ = Fraction of rooftop area technically suitable for rooftop PV in the U. S. in reference year FY (Table S17)

$SB_{US,RY}$ = Average stories per building in the U. S. in reference year RY (see discussion of $SB_{C,TY}$)

$RAC_{C,TY}$ = The rooftop area per capita (m^2/cap)

$RAC_{US,RY}$ = Roof area per capita in the U. S. in reference year RY (m^2/capita) (see discussion of $RA_{C,TY}$)

$FL\%_C$ = The percentage of flat roofs in country C

$SL\%_{US}$ = The percentage of sloped roofs in the U. S. (see discussion of $SL\%_C$)

$SL\theta_{US}$ = The average slope of pitched roofs in the U. S. (degrees) (see discussion of $SL\theta_C$)

$SB_{C,TY}$, $RA_{C,TY}$, $P_{C,TY}$, $SL\%_C$, and $SL\theta_C$ are defined above

$\omega 1 ... \omega 4$ = Exponents determining the relationship between building characteristics relative to those in the U. S. and the suitability fraction *Sfr* (Table S17)

Fraction of technical potential used ($Ufr_{PVroof,C,TY}$).

The estimated fraction of the technical potential actually used – the usability fraction – is a function of the cost of rooftop PV, the structural quality of the building stocks, roof area reserved for fire access, and energy policy. We start with a baseline estimate of the usability fraction as a function of the cost of rooftop PV, and then make adjustments to this baseline for structural quality, fire access requirements, and energy policy:

$$Ufr_{PVroof,C,TY} = MIN\left[\begin{array}{l} Ufr_{PVroof,\max}, Ufr\left(COST\right)_{PVroof,base,C} \cdot \\ STRUCT_{PVroof,C,TY} \cdot FIRE_{PVroof,C,TY} \cdot POL_{PVroof,C} \end{array}\right]$$

where

$Ufr\left(COST\right)_{PVroof,base,C}$ = The baseline usability fraction for rooftop PV in country C as a function of the cost

$Ufr_{PVroof,\max}$ = The maximum usability fraction for rooftop PV (0.90)

$STRUCT_{PVroof,C,TY}$ = The structural-quality adjustment for rooftop PV for country C in target year TY

$FIRE_{PVroof,C,TY}$ = Adjustment for roof area reserved for fire access for rooftop PV for country C in target year TY

$POL_{PVroof,C}$ = The policy adjustment for rooftop PV for country C (assumed to be scalar; e.g., for countries with aggressive PV policies, POL = 3.0)

We estimate the usability fraction for residential rooftops (excluding parking), residential parking rooftops, commercial/government/institutional rooftops (excluding industrial), and industrial rooftops. We then combine the residential and residential parking factors, weighted by technical potential, to estimate an overall usability factor for residential including parking, and combine the commercial and industrial factors, weighted by technical potential, to estimate an overall usability factor for commercial plus industrial.

The baseline usability fraction is estimated as a logistic function of the country-specific capacity factor – a proxy for cost – relative to a reference capacity factor and a reference usability factor. (The capacity factor is a good proxy for cost because the capacity factor is the primary determinant of the LCOE of rooftop PV.) With this formulation, the usability fraction is an S-shaped curve that passes through the reference points and approaches a lower limit of 0 and an upper limit of 1, with a “steepness” determined by an exponent α,

$$Ufr\left(COST\right)_{PVroof,base,C} = \frac{1}{1+e^{\alpha\cdot\left(CF_{PVroof-ave,C}-CF_{PVroof,ref}\right)}\cdot\left(\frac{1-Ufr_{PVroof,ref}}{Ufr_{PVroof,ref}}\right)}$$

$$CF_{PVroof-ave,C} = \frac{1}{ave\left(\frac{1}{CF_{PVroof-low,C}},\frac{1}{CF_{PVroof-high,C}}\right)}$$

where

$Ufr_{PVroof,ref}$ = The usability fraction at the reference capacity factor (discussed below)
$CF_{PVroof-ave,C}$ = The average capacity factor for rooftop PV in country C (same for all years)
$CF_{PVroof-low,C}$, $CF_{PVroof-high,C}$ = Low and high estimates of the capacity factor for rooftop PV in country C (discussed below)
$CF_{PVroof,ref}$ = Reference capacity factor for rooftop PV (discussed below)
α = Steepness exponent (based on results in Table S18; see discussion below)

The baseline usability as a function of cost alone (setting aside the other usability factors) should be very high at typical, economical capacity factors (17% to 19%), very low at the capacity factors of 12% and below, and virtually 100% at capacity factors above 20%. We find that setting $Ufr_{PVroof,ref}$ = 0.35 at $CF_{PVroof,ref}$ = 0.14, along with a high value of α, results in reasonable estimates of $Ufr\left(COST\right)_{PVroof,base,C}$. Table S18 shows the value of $Ufr\left(COST\right)_{PVroof,base,C}$ as a function of the capacity factor and the exponent α. We have highlighted values of $Ufr_{PVroof,ref}$ at very low, low, typical, and high capacity factors. Based on our examination of Table S18, we have chosen α = -86.0.

As a proxy for structural quality we use GDP/capita. We assume that there is a threshold value of GDP/capita at which the building stock is of sufficient quality to support rooftop PVs; at this threshold, $STRUCT_{PVroof,C,TY}$ = 1.0. At lower levels of GDP/capita, $STRUCT_{PVroof,C,TY}$ falls below 1.0, as follows:

$$STRUCT_{PVroof,C,TY} = MIN\left[1.0, \left(\frac{GDPC_{C,TY}}{GDPC_{struct,ref}}\right)^{\gamma_{PV}}\right]$$

where

$GDPC_{C,TY}$ = GDP per capita in country C in target year TY (constant year-2013 international dollars, PPP basis) (see "Important general parameters")
$GDPC_{struct,ref}$ = Reference GDP per capita ($46,000, constant year-2013 international dollars, PPP basis)
γ_{PV} = 0.45 (based on results in Table S19; see discussion below)

Values of exponent parameters α and γ_{PV}

Table S18 shows the usability fraction $Ufr_{PVroof,C,TY}$ as a function of the capacity-factor exponent α and the capacity factor, given the values assumed above for $CF_{PVroof,ref}$, $Ufr_{PVroof,\max}$, and

$Ufr_{PVroof,ref}$, and assuming that the structural-quality adjustment ($STRUCT_{PVroof,C,TY}$) = 1.0. The results for the chosen value of the exponent are highlighted.

Table S19 shows the structural-quality adjustment $STRUCT_{PVroof,C,TY}$ as a function of the GDP-per-capita exponent γ_{PV} and the GDP per capita. The results for the chosen value of the exponent are highlighted.

Adjustment for roof area reserved for fire access ($FIRE_{PVroof,C,TY}$)

We assume that most countries developing rooftop PV systems require (or will require) that a portion of the roof not be covered with PVs to allow access for firefighters. We assume that this reserved roof area is not captured by the parameter *Sfr*, the fraction of rooftop area *technically* suitable for PVs, or by the base-case usability fraction $Ufr_{PVroof,ref}$.

Table S17. Parameters in the estimation of suitable rooftop PV area.

	Com	Residential		Res-park		Ind	Comment
		urb	*n-urb*	*urb*	*n-urb*		
$Sfr_{PVroof,US,RY}$	60%	25%	40%	18%	28%	65%	Com, res, and res-park assumptions based on review in Melius et al. (2013). We assume that residential buildings in non-urban areas have less shading. Ind is our assumption.
$Sfr_{PVroof,\max}$	85%	70%	80%	65%	75%	75%	Our assumptions.
$\omega 1$ (SB)	-0.30	-0.30	-0.30	n.a.	n.a.	-0.30	We assume that this is a relatively important factor, because higher average building heights cause more shading. Not applicable to residential parking because we implicitly assume only one story for residential parking.
$\omega 2$ (RAC)	0.15	0.15	0.15	0.15	0.15	0.15	Our assumptions.
$\omega 3$ $(FL\%)$	0.50	0.45	0.45	0.45	0.45	0.50	We assume that this is a relatively important factor, because flat roofs do not have any areas facing away from the sun. We assume that suitability is slightly more sensitive to this parameter for commercial and industrial buildings.
$\omega 4$ $(SL\theta)$	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15	The steeper the roof, the less suitable it is for PVs if it is pitched away from the sun. This is a relatively minor factor because it is sub-ordinate to the more important orientation factor.

Com. = commercial/institutional/government; Res-park = residential parking; Ind = industrial/manufacturing; urb = urban; n-urb = non-urban; n.a. = not applicable.

Table S18. Usability fraction as a function of the capacity-factor exponent and the reference capacity factor.

CF / α	-70.0	-71.0	-72.0	-73.0	-74.0	-75.0	-76.0	-77.0	-78.0	-79.0	-80.0	-81.0	-82.0	-83.0	-84.0	-85.0	-86.0	-87.0	-88.0	-89.0	-90.0	-91.0
.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.08	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.09	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
.10	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01
.11	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03
.12	0.12	0.12	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08
.13	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.18
.14	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
.15	0.52	0.52	0.53	0.53	0.53	0.53	0.54	0.54	0.54	0.54	0.55	0.55	0.55	0.55	0.56	0.56	0.56	0.56	0.56	0.57	0.57	0.57
.16	0.69	0.69	0.69	0.70	0.70	0.71	0.71	0.72	0.72	0.72	0.73	0.73	0.74	0.74	0.74	0.75	0.75	0.75	0.76	0.76	0.77	0.77
.17	0.81	0.82	0.82	0.83	0.83	0.84	0.84	0.84	0.85	0.85	0.86	0.86	0.86	0.87	0.87	0.87	0.88	0.88	0.88	0.89	0.89	0.89
.18	0.90	0.90	0.91	0.91	0.91	0.92	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.95	0.95	0.95	0.95	0.95
.19	0.95	0.95	0.95	0.95	0.96	0.96	0.96	0.96	0.96	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98
.20	0.97	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
.21	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.22	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.23	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.24	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.26	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.27	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.28	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.29	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.31	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.32	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.33	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.34	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.37	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.38	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.39	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
.40	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table S19. Structural-quality adjustment as a function of the GDP-per-capita exponent and the GDP per capita.

GDPC/ γ	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10
000	0.83	0.68	0.56	0.46	0.38	0.32	0.26	0.22	0.18	0.15	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.01
000	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34	0.29	0.26	0.22	0.19	0.17	0.15	0.13	0.11	0.10	0.09	0.07	0.07	0.06	0.05
000	0.89	0.80	0.72	0.64	0.57	0.51	0.46	0.41	0.37	0.33	0.30	0.26	0.24	0.21	0.19	0.17	0.15	0.14	0.12	0.11	0.10	0.09
000	0.91	0.83	0.75	0.69	0.62	0.57	0.52	0.47	0.43	0.39	0.36	0.32	0.29	0.27	0.24	0.22	0.20	0.18	0.17	0.15	0.14	0.13
000	0.92	0.85	0.78	0.72	0.67	0.61	0.56	0.52	0.48	0.44	0.41	0.38	0.35	0.32	0.29	0.27	0.25	0.23	0.21	0.20	0.18	0.17
1000	0.93	0.87	0.81	0.75	0.70	0.65	0.61	0.56	0.53	0.49	0.46	0.42	0.39	0.37	0.34	0.32	0.30	0.28	0.26	0.24	0.22	0.21
3000	0.94	0.88	0.83	0.78	0.73	0.68	0.64	0.60	0.57	0.53	0.50	0.47	0.44	0.41	0.39	0.36	0.34	0.32	0.30	0.28	0.27	0.25
5000	0.95	0.89	0.85	0.80	0.76	0.71	0.68	0.64	0.60	0.57	0.54	0.51	0.48	0.46	0.43	0.41	0.39	0.36	0.34	0.33	0.31	0.29
7000	0.95	0.91	0.86	0.82	0.78	0.74	0.71	0.67	0.64	0.61	0.58	0.55	0.52	0.50	0.47	0.45	0.43	0.41	0.39	0.37	0.35	0.33
9000	0.96	0.92	0.88	0.84	0.80	0.77	0.73	0.70	0.67	0.64	0.61	0.59	0.56	0.54	0.52	0.49	0.47	0.45	0.43	0.41	0.40	0.38
1000	0.96	0.92	0.89	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65	0.62	0.60	0.58	0.56	0.53	0.51	0.49	0.47	0.46	0.44	0.42
3000	0.97	0.93	0.90	0.87	0.84	0.81	0.78	0.76	0.73	0.71	0.68	0.66	0.64	0.62	0.59	0.57	0.55	0.54	0.52	0.50	0.48	0.47
5000	0.97	0.94	0.91	0.89	0.86	0.83	0.81	0.78	0.76	0.74	0.72	0.69	0.67	0.65	0.63	0.61	0.60	0.58	0.56	0.54	0.53	0.51
7000	0.97	0.95	0.92	0.90	0.88	0.85	0.83	0.81	0.79	0.77	0.75	0.73	0.71	0.69	0.67	0.65	0.64	0.62	0.60	0.59	0.57	0.56
9000	0.98	0.95	0.93	0.91	0.89	0.87	0.85	0.83	0.81	0.79	0.78	0.76	0.74	0.72	0.71	0.69	0.68	0.66	0.65	0.63	0.62	0.60
1000	0.98	0.96	0.94	0.92	0.91	0.89	0.87	0.85	0.84	0.82	0.80	0.79	0.77	0.76	0.74	0.73	0.72	0.70	0.69	0.67	0.66	0.65
3000	0.98	0.97	0.95	0.94	0.92	0.91	0.89	0.88	0.86	0.85	0.83	0.82	0.81	0.79	0.78	0.77	0.75	0.74	0.73	0.72	0.71	0.69
5000	0.99	0.97	0.96	0.95	0.93	0.92	0.91	0.90	0.88	0.87	0.86	0.85	0.84	0.83	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.74
0000	0.99	0.99	0.98	0.97	0.97	0.96	0.95	0.95	0.94	0.93	0.93	0.92	0.91	0.91	0.90	0.89	0.89	0.88	0.88	0.87	0.86	0.86
5000	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
0000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
00000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
80000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
90000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
00000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
40000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
50000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The fraction of roof area reserved for fire access depends on two factors: whether a country has fire-access regulations, and the area reserved for access relative to the total roof area. We assume that the likelihood of a country having fire-access regulations increases sharply with GDP per capita. Regarding access area requirements, the International Fire Code (IFC), Section 605.11.1, "Access and Pathways" (ICC, 2016) specifies that PV systems on rooftops of group R-3 occupancies (in essence, one- and two-family dwelling units) with *more* than a 2:12 slope typically must allow for 3-foot-wide access paths along the eaves and ridge of each slope, although in some cases the panels may go up to the ridge. PV systems on commercial buildings with one axis of 250 feet or less must have at least a 4-foot wide path around the building perimeter; otherwise, a 6-foot wide access is required. Four-foot-wide centerline access pathways also are required. Table S20 shows the fraction of roof area required for these access pathways as a function of building type and size.

Our formal estimation represents these two effects (probability of a regulation, and the impact of regulation) as multiplicative factors, with upper and lower bounds. For the residential sector, the regulations apply only to sloped roofs:

$$FIRE_{PVroof,C,TY} = 1 - SL\%_{res,C} \cdot FRreg_{PVroof,C,TY} \cdot FRfr_{PVroof,C,TY}$$

For all other sectors,

$$FIRE_{PVroof,C,TY} = 1 - FRreg_{PVroof,C,TY} \cdot FRfr_{PVroof,C,TY}$$

$$FRreg_{PVroof,C,TY} = \max\left[FRreg_{PVroof,\min}, \min\left[1.0, FRreg_{PVroof,ref} \cdot \left(\frac{GDPC_{C,TY}}{GDPC_{fire,ref}} \right)^{\phi 1} \right] \right]$$

$$FRfr_{PVroof,C,TY} = \max\left[FRfr_{PVroof,\min}, \min\left[FRfr_{PVroof,\max}, FRfr_{PVroof,ref} \cdot \left(\frac{RAC_{C,TY}}{RAC_{fire,ref}} \right)^{-\phi 2} \right] \right]$$

where

$FRreg_{PVroof,C,TY}$ = The likelihood having fire-access requirements in country *C* in year *TY*

$SL\%_{res,C}$ = The percentage of sloped roofs in the residential sector in country *C* (discussed above)

$FRfr_{PVroof,C,TY}$ = The roof area reserved for fire access in country *C* in year *TY* (fraction of total roof area)

$FRreg_{PVroof,ref}$ = The reference likelihood of having fire-access requirements, at the reference GDP per capita (we assume 80%)

$FRreg_{PVroof,\min}$ = The minimum likelihood (we assume 50%)

$GDPC_{fire,ref}$ = The reference GDP per capita for the fire-access-regulation-likelihood estimate ($45,000, year-2013 PPP; this is the approximate 139-country average in 2050)

$FRfr_{PVroof,\min}$ = The minimum fraction of roof area reserved for fire access (Table S21)

$FRfr_{PVroof,\max}$ = The maximum fraction of roof area reserved for fire access (Table S21)

$FRfr_{PVroof,ref}$ = The reference fraction of roof area reserved for fire access, at the reference floor area per capita (Table S21)

$RAC_{fire,ref}$ = The reference rooftop area per capita for the fire-access-area estimate (we use the 139-country average values in 2050)

$\phi 1$ = Exponent determining the relationship between *FRreg* and changes in *GDPC* (Table S21)

$\phi 2$ = Exponent determining the relationship between *FRfr* and changes in *RAC* (Table S21)

Other terms defined above.

Capacity factor for rooftop PV. We use the 3-D global simulation model GATOR-GCMOM to model the solar irradiance and capacity factor for rooftop PVs, by country (Figure S6).

Table S20. Percent of roof area for access requirements, by building type and size.

Residential buildings, access on three sides				
Side 1	Side 2	Access width	Roof face area (ft^2)	Access % of area
20	10	3	200	51.0%
20	20	3	400	40.5%
35	12	3	420	37.9%
45	20	3	900	26.3%
50	30	3	1500	20.8%
Non-residential buildings, one side <250 ft., access on all sides, centerline pathways				
Side 1	Side 2	Access width	Roof face area (ft^2)	Access % of area
100	100	4	10000	22.7%
320	100	4	32000	15.4%
Large industrial buildings, access on all sides, centerline pathways				
Side 1	Side 2	Access width	Roof face area (ft^2)	Access % of area
260	260	6	67600	12.0%
500	300	6	150000	8.4%

Table S21. Parameters in the estimation of the fire-access component of the useable fraction of the rooftop PV technical potential.

	Res	**Park**	**Com**	**Ind**	**Comment**
$FRfr_{PVroof,ref}$	28%	40%	18%	10%	Based on values in Table S20.
$FRfr_{PVroof,\min}$	15%	20%	8%	5%	Based on values in Table S20.
$FRfr_{PVroof,\max}$	45%	55%	35%	25%	Based on values in Table S20.
$\phi 1$	2.25	2.25	2.25	2.25	Assumptions based on our examination of the relationship between $\phi 1$ and *GDPC*
$\phi 2$	0.50	0.50	0.40	0.40	We show this as a negative exponent because increasing results in decreasing *FRfr* . Assumptions based on our examination of the relationship between $\phi 2$ and *RAC*.

Com. = commercial/institutional/government; Res = residential; Park = residential parking; Ind = industrial/manufacturing

Snow cover. An additional issue related to rooftop solar is the extent to which snow cover may reduce its power output. If snow is not removed from panels, panel output may decrease by ~5-15% in the annual average (Northern Alberta Institute of Technology, 2015). However, this is more than compensated for by the fact that at minus 43^{o}C ambient temperature, which often occurs in the presence of snow, a PV system provides 29% more power than its rated power (Dodge and Thompson, 2016). We conservatively assume these two factors offset each other so don't modify the number of panels needed due to snow cover.

Results. Table S22 provides estimates of each country's maximum rooftop PV nameplate capacity and the percent of maximum capacity actually installed under the roadmaps proposed here. Rooftops considered include those on residential, commercial, and governmental buildings, and garages, carports, parking lots, and parking structures associated with these buildings. Commercial and governmental buildings include all non-residential buildings except manufacturing, industrial, and military buildings. Commercial buildings include schools.

Based on the foregoing analysis, 2050 residential rooftop areas (including garages and carports) are estimated to support up to 26.6 $TW_{dc\text{-}peak}$ of installed power, of which 34.9% is proposed for use. In 2050, commercial/government rooftops (including parking lots and parking structures) may support 11.1 $TW_{dc\text{-}peak}$ of installed power, of which 68.2% is proposed for use. Low-latitude and high GDP-per-capita countries are expected to adopt PV the fastest.

Table S22. Rooftop areas suitable for PV panels, potential capacity of suitable rooftop areas, and proposed installed capacity for both residential and commercial/government buildings, by country. See Delucchi et al. (2016) for calculations.

	Residential rooftop PV				Commercial/government rooftop PV			
Country	Rooftop area suitable for PVs in 2012 (km^2)	Potential capacity of suitable area in 2050 ($MW_{dc\text{-}peak}$)	Proposed installed capacity in 2050 ($MW_{dc\text{-}peak}$)	Percent of potential capacity installed	Rooftop area suitable for PVs in 2012 (km^2)	Potential capacity of suitable area in 2050 ($MW_{dc\text{-}peak}$)	Proposed installed capacity in 2050 ($MW_{dc\text{-}peak}$)	Percent of potential capacity installed

Albania	25	6,007	1,480	24.6	17	4,183	3,163	75.6
Algeria	688	164,609	65,461	39.8	387	92,540	77,064	83.3
Angola	856	204,819	13,924	6.8	272	65,100	26,060	40.0
Argentina	593	141,758	75,219	53.1	412	98,605	81,465	82.6
Armenia	29	6,831	2,767	40.5	16	3,813	2,276	59.7
Australia	872	208,451	86,335	41.4	529	126,438	72,216	57.1
Austria	79	18,833	12,885	68.4	66	15,743	12,167	77.3
Azerbaijan	141	33,659	13,104	38.9	85	20,367	15,577	76.5
Bahrain	11	2,610	1,496	57.3	4	1,021	722	70.7
Bangladesh	1,373	328,403	66,637	20.3	193	46,183	19,026	41.2
Belarus	37	8,858	5,963	67.3	62	14,927	6,545	43.8
Belgium	22	5,291	3,064	57.9	19	4,625	3,266	70.6
Benin	281	67,115	6,513	9.7	41	9,764	3,697	37.9
Bolivia	267	63,887	4,859	7.6	105	25,151	9,184	36.5
Bosnia and Herzegovina	43	10,250	3,281	32.0	24	5,851	4,519	77.2
Botswana	70	16,671	2,726	16.4	33	7,980	5,254	65.8
Brazil	3,729	891,827	309,645	34.7	1,641	392,587	324,096	82.6
Brunei Darussalam	19	4,657	3,190	68.5	7	1,776	1,380	77.7
Bulgaria	54	12,993	8,807	67.8	53	12,750	9,947	78.0
Cambodia	364	86,993	5,027	5.8	56	13,422	9,422	70.2
Cameroon	508	121,415	26,662	22.0	114	27,171	12,199	44.9
Canada	376	90,040	64,960	72.1	729	174,304	138,318	79.4
Chile	212	50,724	35,457	69.9	140	33,547	25,788	76.9
China	15,170	3,628,387	2,407,007	66.3	9,221	2,205,373	1,678,213	76.1
Chinese Taipei	329	78,632	52,613	66.9	138	33,059	25,147	76.1
Colombia	1,075	257,160	31,041	12.1	401	95,991	58,448	60.9
Congo	203	48,486	3,009	6.2	66	15,667	5,712	36.5
Congo, Dem. Republic	2,173	519,751	41,128	7.9	257	61,434	16,440	26.8
Costa Rica	63	15,041	1,389	9.2	26	6,316	2,597	41.1
Cote d'Ivoire	504	120,542	12,802	10.6	116	27,650	15,482	56.0
Croatia	43	10,344	6,940	67.1	35	8,255	6,204	75.2
Cuba	139	33,251	6,286	18.9	66	15,866	12,078	76.1
Cyprus	31	7,367	1,739	23.6	10	2,425	1,855	76.5
Czech Republic	60	14,321	9,561	66.8	60	14,333	10,947	76.4
Denmark	23	5,509	3,685	66.9	40	9,628	2,438	25.3
Dominican Republic	81	19,435	4,714	24.3	38	9,088	7,339	80.8
Ecuador	433	103,595	8,729	8.4	140	33,523	16,554	49.4
Egypt	1,945	465,278	95,806	20.6	694	166,024	136,356	82.1
El Salvador	67	16,074	1,277	7.9	22	5,331	2,401	45.0
Eritrea	152	36,427	733	2.0	15	3,667	1,381	37.7
Estonia	6	1,456	1,026	70.5	11	2,662	938	35.2
Ethiopia	3,856	922,271	83,788	9.1	272	65,042	24,371	37.5
Finland	30	7,097	4,926	69.4	75	17,911	2,971	16.6
France	558	133,371	87,718	65.8	488	116,637	89,126	76.4
Gabon	95	22,814	3,281	14.4	41	9,739	6,228	63.9
Georgia	40	9,649	3,409	35.3	25	5,885	4,192	71.2
Germany	452	108,151	72,159	66.7	500	119,623	91,363	76.4
Ghana	524	125,366	12,294	9.8	124	29,613	14,301	48.3
Gibraltar	0	12	6	49.3	0	6	4	64.7
Greece	85	20,365	14,219	69.8	74	17,642	13,847	78.5
Guatemala	292	69,778	5,519	7.9	88	21,022	10,419	49.6
Haiti	84	20,155	3,695	18.3	15	3,665	1,807	49.3
Honduras	160	38,369	4,053	10.6	46	10,979	7,215	65.7
Hong Kong, China	13	3,202	1,581	49.4	5	1,140	732	64.2
Hungary	69	16,525	11,795	71.4	72	17,158	12,102	70.5
Iceland	3	730	0	0.0	6	1,406	0	0.0
India	19,366	4,631,873	1,448,982	31.3	5,069	1,212,271	874,466	72.1
Indonesia	5,914	1,414,390	207,220	14.7	1,888	451,444	371,066	82.2
Iran, Islamic Republic	1,212	289,992	224,773	77.5	728	174,208	144,638	83.0

Iraq	661	158,075	28,509	18.0	363	86,809	57,880	66.7
Ireland	48	11,389	7,292	64.0	55	13,260	2,312	17.4
Israel	80	19,162	11,838	61.8	37	8,827	6,452	73.1
Italy	737	176,202	117,941	66.9	259	61,871	46,128	74.6
Jamaica	42	10,032	2,307	23.0	13	3,065	2,487	81.1
Japan	496	118,566	72,125	60.8	274	65,470	46,846	71.6
Jordan	90	21,471	7,246	33.7	48	11,571	9,475	81.9
Kazakhstan	415	99,308	71,226	71.7	363	86,701	65,048	75.0
Kenya	1,240	296,518	19,390	6.5	192	45,927	25,727	56.0
Korea, Dem. People's Rep.	145	34,772	13,825	39.8	39	9,233	3,090	33.5
Korea, Republic of	372	88,927	56,158	63.2	210	50,126	37,411	74.6
Kosovo	11	2,747	1,609	58.6	7	1,605	954	59.4
Kuwait	31	7,322	4,595	62.8	16	3,777	2,804	74.2
Kyrgyzstan	78	18,674	4,247	22.7	30	7,277	4,064	55.8
Latvia	12	2,968	2,099	70.7	22	5,189	1,605	30.9
Lebanon	23	5,467	4,027	73.7	12	2,829	2,288	80.9
Libya	208	49,642	17,293	34.8	115	27,460	22,939	83.5
Lithuania	24	5,685	4,051	71.3	43	10,346	4,631	44.8
Luxembourg	2	384	218	56.8	2	382	276	72.3
Macedonia, Republic of	23	5,555	3,163	56.9	15	3,472	2,757	79.4
Malaysia	846	202,325	107,404	53.1	326	77,871	59,124	75.9
Malta	2	387	222	57.3	1	170	118	69.6
Mexico	1,966	470,201	190,185	40.4	983	235,059	192,907	82.1
Moldova, Republic of	16	3,824	2,917	76.3	9	2,195	1,306	59.5
Mongolia	45	10,659	7,479	70.2	46	10,963	8,161	74.4
Montenegro	7	1,627	702	43.2	5	1,209	931	77.0
Morocco	452	108,126	20,817	19.3	193	46,186	37,817	81.9
Mozambique	751	179,509	15,638	8.7	92	22,054	8,905	40.4
Myanmar	946	226,163	20,955	9.3	235	56,105	39,922	71.2
Namibia	44	10,493	1,932	18.4	21	4,943	3,733	75.5
Nepal	433	103,598	27,064	26.1	54	12,935	4,180	32.3
Netherlands	29	6,916	3,941	57.0	46	10,961	3,621	33.0
Netherlands Antilles	2	519	374	72.1	1	213	163	76.3
New Zealand	83	19,813	13,842	69.9	63	14,986	11,235	75.0
Nicaragua	107	25,683	1,594	6.2	33	7,824	2,991	38.2
Nigeria	5,037	1,204,827	199,558	16.6	1,326	317,029	209,444	66.1
Norway	45	10,741	6,974	64.9	82	19,581	1,566	8.0
Oman	143	34,231	23,978	70.0	79	18,815	14,772	78.5
Pakistan	2,566	613,659	160,703	26.2	736	175,967	99,053	56.3
Panama	111	26,638	3,717	14.0	44	10,439	6,945	66.5
Paraguay	139	33,230	1,065	3.2	59	14,026	2,061	14.7
Peru	638	152,477	12,583	8.3	255	60,989	23,516	38.6
Philippines	2,292	548,258	31,658	5.8	523	125,122	59,393	47.5
Poland	202	48,290	34,173	70.8	357	85,359	68,035	79.7
Portugal	140	33,519	18,012	53.7	71	16,878	12,918	76.5
Qatar	17	4,114	2,487	60.4	8	1,990	1,458	73.3
Romania	176	42,030	27,775	66.1	89	21,188	13,720	64.8
Russian Federation	891	213,014	150,920	70.8	1,633	390,500	197,192	50.5
Saudi Arabia	1,104	264,110	187,210	70.9	614	146,955	115,777	78.8
Senegal	336	80,383	4,174	5.2	58	13,956	6,759	48.4
Serbia	61	14,701	10,655	72.5	61	14,630	11,744	80.3
Singapore	28	6,804	3,357	49.3	6	1,531	964	62.9
Slovak Republic	43	10,320	6,936	67.2	39	9,447	5,371	56.9
Slovenia	18	4,373	2,970	67.9	19	4,517	3,267	72.3
South Africa	672	160,822	124,205	77.2	344	82,302	68,233	82.9
Spain	566	135,450	88,008	65.0	257	61,369	46,052	75.0
Sri Lanka	559	133,722	11,907	8.9	111	26,622	21,674	81.4
Sudan	1,683	402,505	14,596	3.6	365	87,200	27,412	31.4
Sweden	53	12,629	8,739	69.2	97	23,149	5,139	22.2

Switzerland	79	18,937	13,051	68.9	68	16,156	12,518	77.5
Syrian Arab Republic	300	71,701	11,450	16.0	140	33,481	23,477	70.1
Tajikistan	115	27,487	320	1.2	32	7,700	674	8.8
Tanzania, United Republic	1,074	256,993	39,484	15.4	176	42,197	22,179	52.6
Thailand	1,217	291,009	183,457	63.0	486	116,139	95,411	82.2
Togo	195	46,672	3,998	8.6	20	4,717	1,446	30.7
Trinidad and Tobago	38	9,094	6,951	76.4	9	2,091	1,593	76.1
Tunisia	132	31,542	17,243	54.7	69	16,512	13,621	82.5
Turkey	908	217,268	81,284	37.4	624	149,303	123,085	82.4
Turkmenistan	125	29,832	20,737	69.5	80	19,101	14,892	78.0
Ukraine	218	52,251	40,183	76.9	191	45,800	24,196	52.8
United Arab Emirates	125	29,949	20,114	67.2	64	15,194	11,680	76.9
United Kingdom	196	46,864	29,057	62.0	334	79,790	28,506	35.7
United States of America	8,424	2,014,777	837,961	41.6	5,783	1,383,123	759,644	54.9
Uruguay	37	8,758	3,764	43.0	22	5,345	4,417	82.6
Uzbekistan	353	84,429	59,813	70.8	160	38,172	28,635	75.0
Venezuela	641	153,204	92,002	60.1	249	59,528	49,052	82.4
Vietnam	1,367	326,834	81,172	24.8	325	77,824	62,549	80.4
Yemen	666	159,196	5,198	3.3	157	37,610	9,806	26.1
Zambia	603	144,128	9,503	6.6	143	34,092	17,839	52.3
Zimbabwe	347	83,007	21,168	25.5	46	10,971	5,214	47.5
World total or average	**111,046**	**26,559,354**	**9,276,861**	**34.9**	**46,505**	**11,122,804**	**7,585,920**	**68.2**

Technical potential of utility-scale PV

Utility-scale PV technical potential by country is determined with the NREL Global Solar Opportunity Tool (NREL, 2012a), which gives the utility PV potential (in GW of rated capacity) by country for different resource thresholds. We define the utility-scale PV potential as the potential calculated from the tool in locations exceeding 4 $kWh/m^2/day$. Values used here are provided in Delucchi et al. (2016).

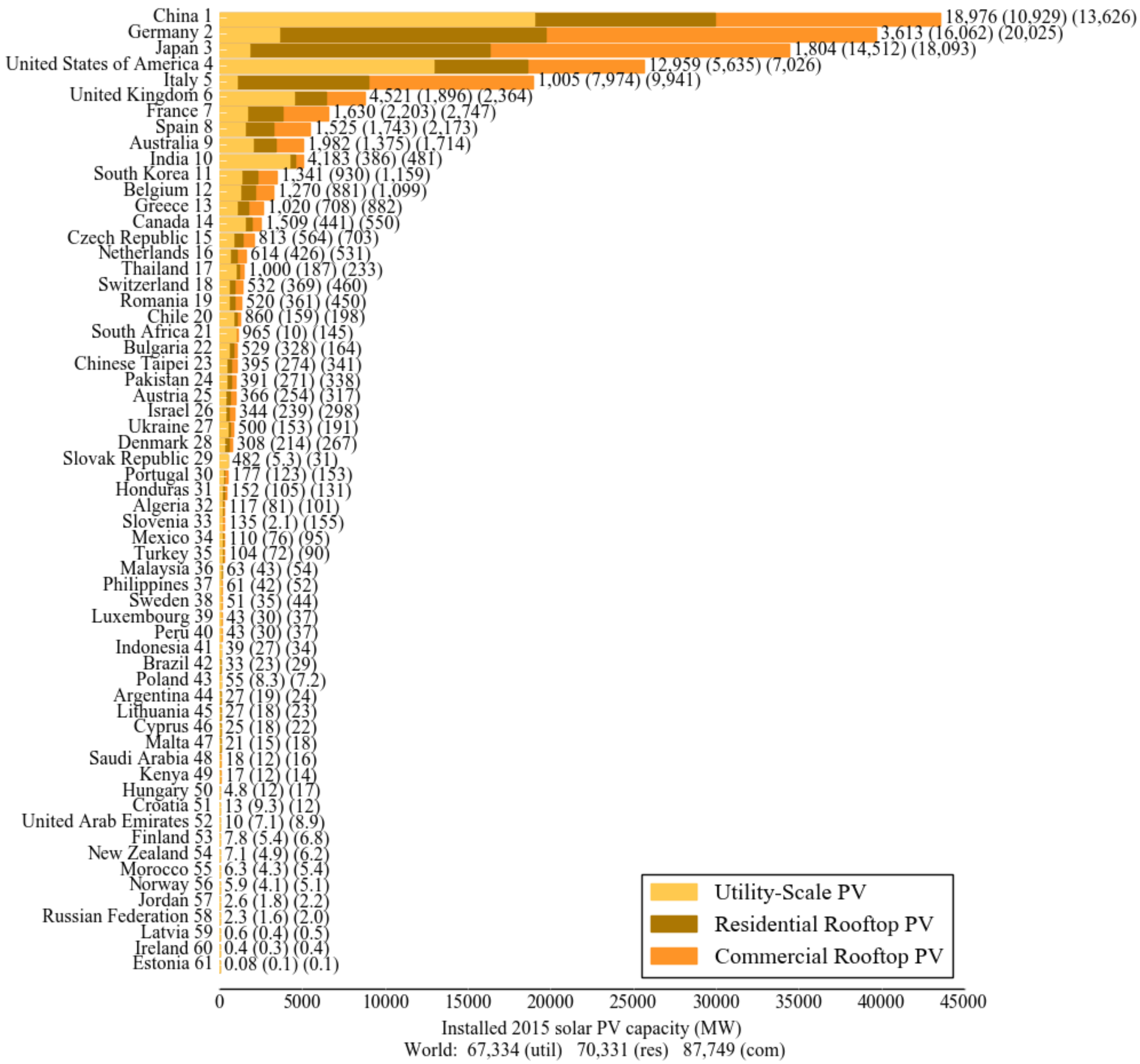
Technical potential of CSP

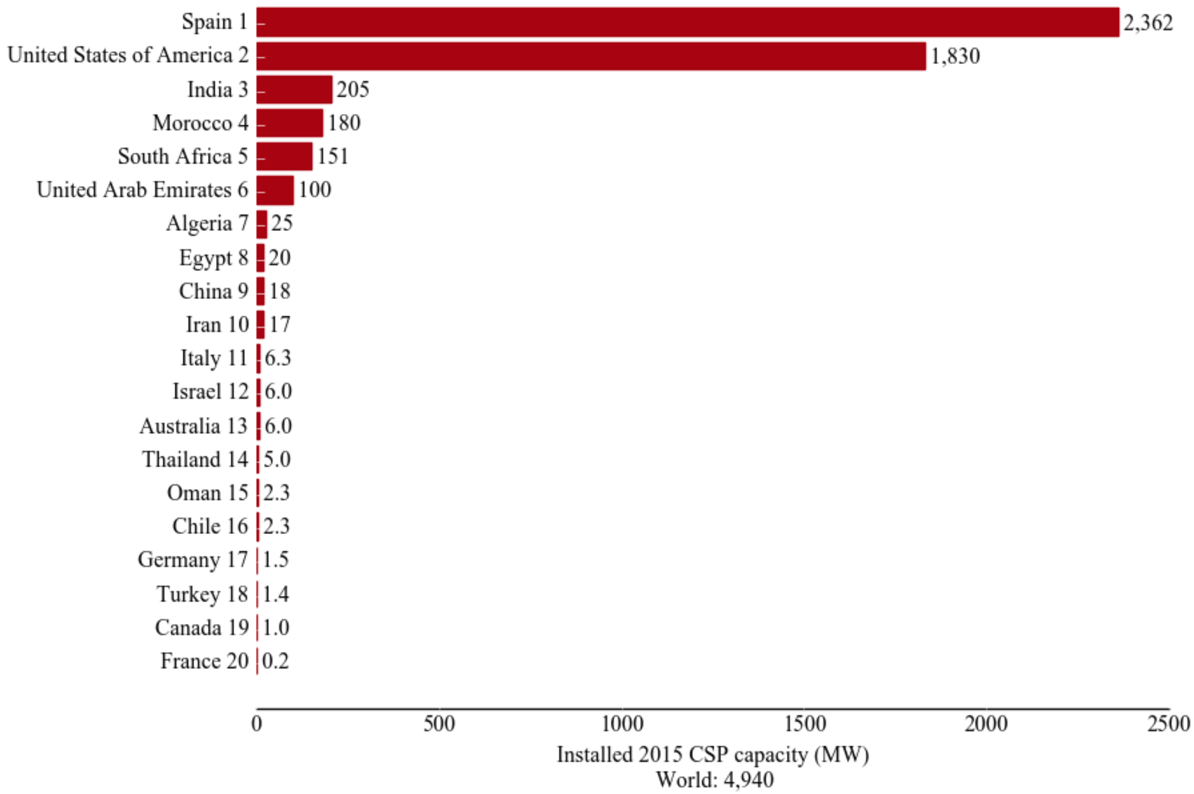
Concentrated solar power (CSP) technical potential by country is obtained by estimating the land area exposed to 5 $kWh/m^2/day$, as determined from the NREL (2012a) Global Solar Opportunity Tool. Values used here are provided in Delucchi et al. (2016).

Existing PV and CSP installations

As of the end of 2015, 0.76% of the proposed 2050 PV (residential rooftop, commercial/government rooftop, and utility scale) capacity and 0.14% of the CSP capacity among the 139 countries from Table S8 had been installed. Figure S7 indicates that Germany, China, Japan, and Italy have installed the most PV. Spain, the United States, and India have installed the most CSP.

Figure S7. (a) Installed residential, commercial/government, plus utility PV by country and (b) installed CSP by country as of the end of 2015. Total PV is determined first from IEA (2016); the ratios of residential : commercial/government : utility PV for 20 European countries and global averages used on the remaining countries are from EPIA (2014). CSP by country is from CSP Plaza (2016).


China 1 18,976 (10,929) (13,626)
Germany 2 3,613 (16,062) (20,025)
Japan 3 1,804 (14,512) (18,093)
United States of America 4 12,959 (5,635) (7,026)
Italy 5 1,005 (7,974) (9,941)
United Kingdom 6 4,521 (1,896) (2,364)
France 7 1,630 (2,203) (2,747)
Spain 8 1,525 (1,743) (2,173)
Australia 9 1,982 (1,375) (1,714)
India 10 4,183 (386) (481)
South Korea 11 1,341 (930) (1,159)
Belgium 12 1,270 (881) (1,099)
Greece 13 1,020 (708) (882)
Canada 14 1,509 (441) (550)
Czech Republic 15 813 (564) (703)
Netherlands 16 614 (426) (531)
Thailand 17 1,000 (187) (233)
Switzerland 18 532 (369) (460)
Romania 19 520 (361) (450)
Chile 20 860 (159) (198)
South Africa 21 965 (10) (145)
Bulgaria 22 529 (328) (164)
Chinese Taipei 23 395 (274) (341)
Pakistan 24 391 (271) (338)
Austria 25 366 (254) (317)
Israel 26 344 (239) (298)
Ukraine 27 500 (153) (191)
Denmark 28 308 (214) (267)
Slovak Republic 29 482 (5.3) (31)
Portugal 30 177 (123) (153)
Honduras 31 152 (105) (131)
Algeria 32 117 (81) (101)
Slovenia 33 135 (2.1) (155)
Mexico 34 110 (76) (95)
Turkey 35 104 (72) (90)
Malaysia 36 63 (43) (54)
Philippines 37 61 (42) (52)
Sweden 38 51 (35) (44)
Luxembourg 39 43 (30) (37)
Peru 40 43 (30) (37)
Indonesia 41 39 (27) (34)
Brazil 42 33 (23) (29)
Poland 43 55 (8.3) (7.2)
Argentina 44 27 (19) (24)
Lithuania 45 27 (18) (23)
Cyprus 46 25 (18) (22)
Malta 47 21 (15) (18)
Saudi Arabia 48 18 (12) (16)
Kenya 49 17 (12) (14)
Hungary 50 4.8 (12) (17)
Croatia 51 13 (9.3) (12)
United Arab Emirates 52 10 (7.1) (8.9)
Finland 53 7.8 (5.4) (6.8)
New Zealand 54 7.1 (4.9) (6.2)
Morocco 55 6.3 (4.3) (5.4)
Norway 56 5.9 (4.1) (5.1)
Jordan 57 2.6 (1.8) (2.2)
Russian Federation 58 2.3 (1.6) (2.0)
Latvia 59 0.6 (0.4) (0.5)
Ireland 60 0.4 (0.3) (0.4)
Estonia 61 0.08 (0.1) (0.1)
Utility-Scale PV
Residential Rooftop PV
Commercial Rooftop PV
0 5000 10000 15000 20000 25000 30000 35000 40000 45000
Installed 2015 solar PV capacity (MW)
World: 67,334 (util) 70,331 (res) 87,749 (com)

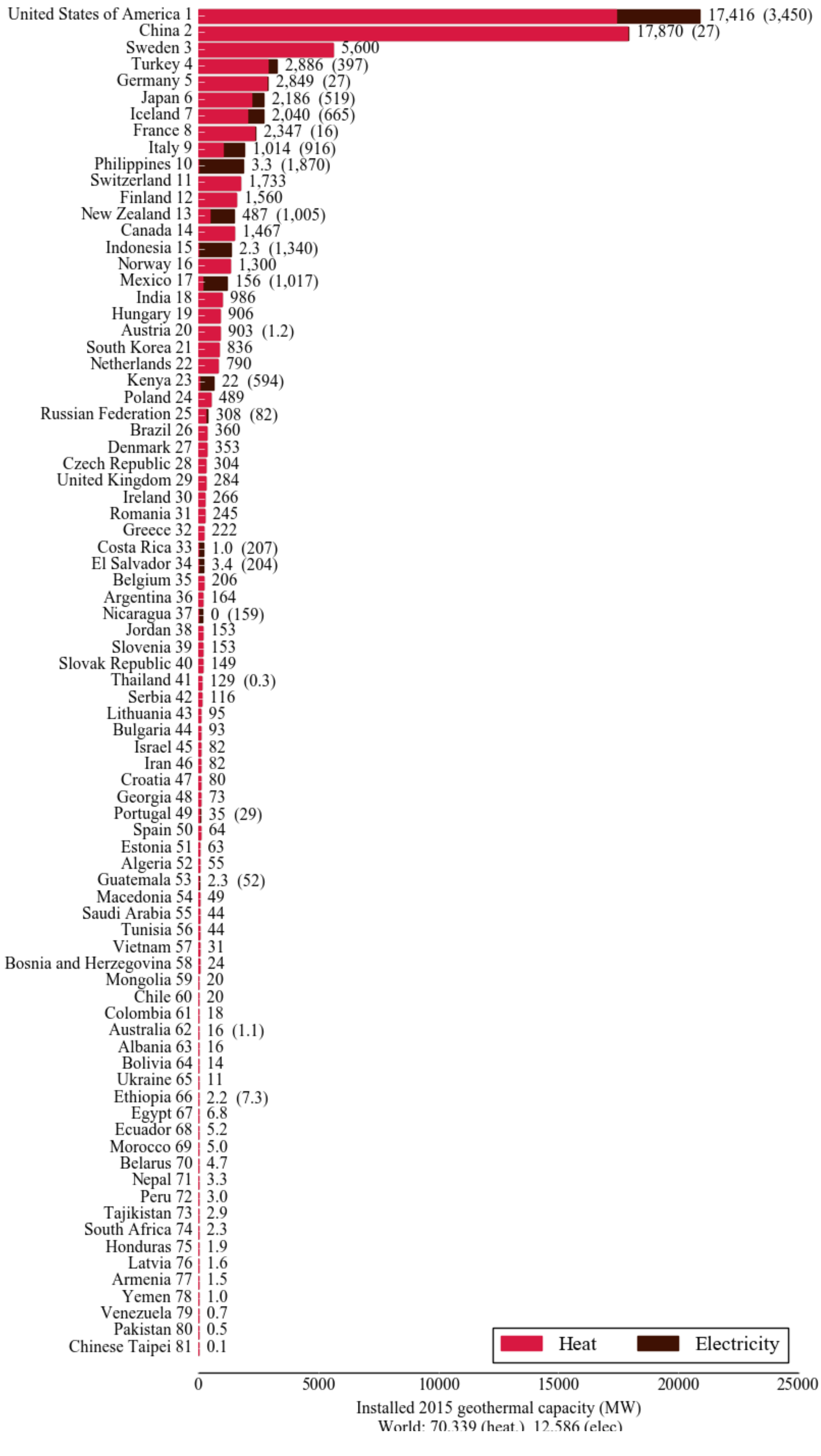


S5.3. Geothermal

Geothermal heat from volcanos, geysers, hot springs, conduction from the interior of the Earth, and solar radiation absorbed by the ground can be used to generate electricity or produce heat, depending on the temperature of the resource. All countries can extract heat from the ground for direct heating or use in heat pumps.

As of the end of 2015, 12.586 GW of geothermal has been installed for electric power and 70.339 GW has been installed for heat worldwide. The United States, Philippines, and Indonesia lead electric power installations, whereas China, the United States, and Sweden lead heat installations (Figure S8). The installed geothermal for electricity represents 13.1% of the nameplate capacity of geothermal needed for electric power generation under the plans proposed here (Table S7). The geothermal for heat already installed is 100% of the nameplate capacity of geothermal needed for heat storage under these plans (Table S7).

Figure S8. Installed geothermal power used for electricity and heat by country in 2015 (IRENA, 2016a).



United States of America 1
17,416 (3,450)
China 2
17,870 (27)
Sweden 3
5,600
Turkey 4
2,886 (397)
Germany 5
2,849 (27)
Japan 6
2,186 (519)
Iceland 7
2,040 (665)
France 8
2,347 (16)
Italy 9
1,014 (916)
Philippines 10
3.3 (1,870)
Switzerland 11
1,733
Finland 12
1,560
New Zealand 13
487 (1,005)
Canada 14
1,467
Indonesia 15
2.3 (1,340)
Norway 16
1,300
Mexico 17
156 (1,017)
India 18
986
Hungary 19
906
Austria 20
903 (1.2)
South Korea 21
836
Netherlands 22
790
Kenya 23
22 (594)
Poland 24
489
Russian Federation 25
308 (82)
Brazil 26
360
Denmark 27
353
Czech Republic 28
304
United Kingdom 29
284
Ireland 30
266
Romania 31
245
Greece 32
222
Costa Rica 33
1.0 (207)
El Salvador 34
3.4 (204)
Belgium 35
206
Argentina 36
164
Nicaragua 37
0 (159)
Jordan 38
153
Slovenia 39
153
Slovak Republic 40
149
Thailand 41
129 (0.3)
Serbia 42
116
Lithuania 43
95
Bulgaria 44
93
Israel 45
82
Iran 46
82
Croatia 47
80
Georgia 48
73
Portugal 49
35 (29)
Spain 50
64
Estonia 51
63
Algeria 52
55
Guatemala 53
2.3 (52)
Macedonia 54
49
Saudi Arabia 55
44
Tunisia 56
44
Vietnam 57
31
Bosnia and Herzegovina 58
24
Mongolia 59
20
Chile 60
20
Colombia 61
18
Australia 62
16 (1.1)
Albania 63
16
Bolivia 64
14
Ukraine 65
11
Ethiopia 66
2.2 (7.3)
Egypt 67
6.8
Ecuador 68
5.2
Morocco 69
5.0
Belarus 70
4.7
Nepal 71
3.3
Peru 72
3.0
Tajikistan 73
2.9
South Africa 74
2.3
Honduras 75
1.9
Latvia 76
1.6
Armenia 77
1.5
Yemen 78
1.0
Venezuela 79
0.7
Pakistan 80
0.5
Chinese Taipei 81
0.1
Heat
Electricity
0
5000
10000
15000
20000
25000
Installed 2015 geothermal capacity (MW)
World: 70,339 (heat.) 12,586 (elec)

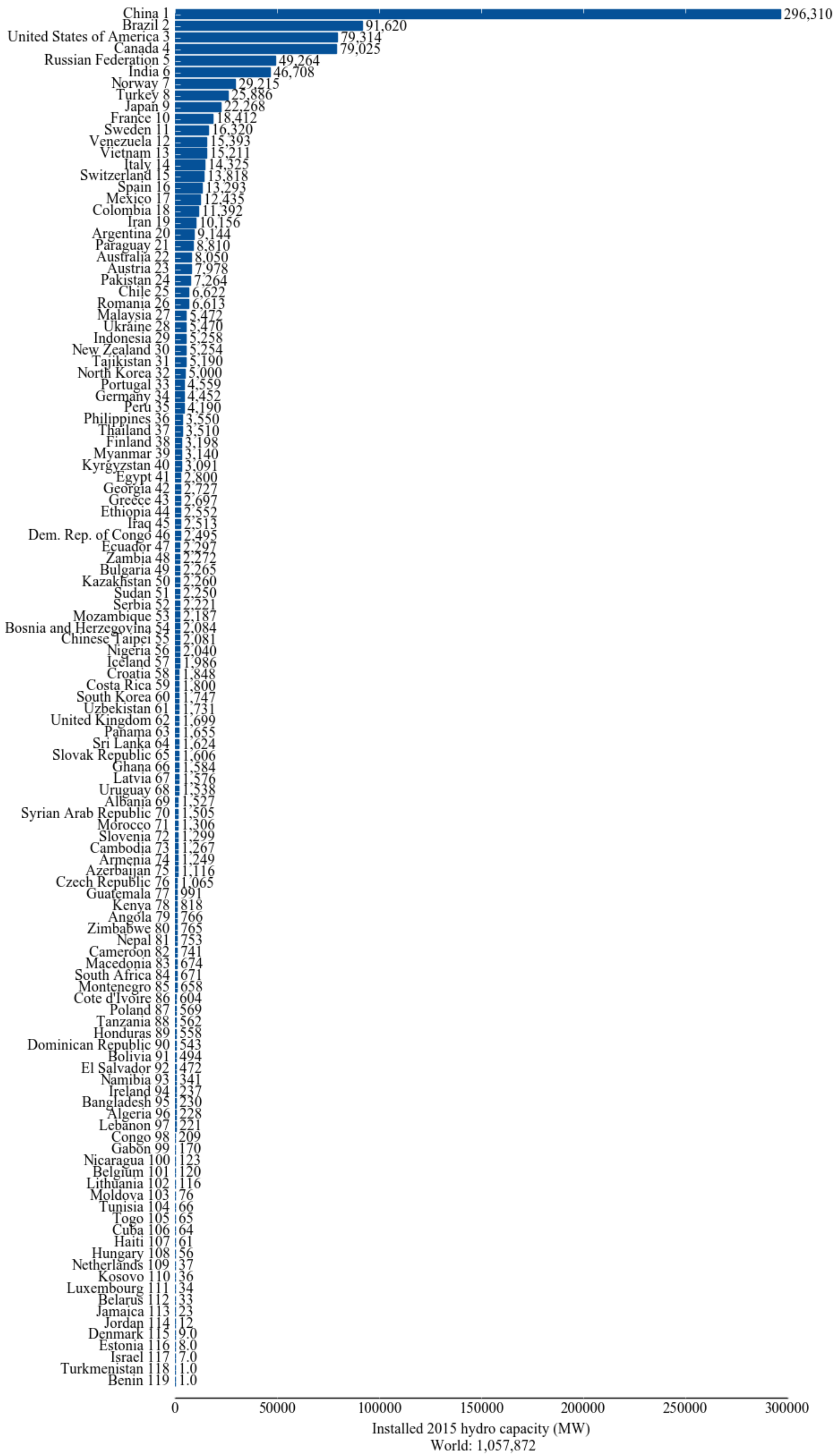
The average capacity factor of installed geothermal for electricity worldwide based on 2012 data is ~70.3% (IEA, 2015c). However, this is not a technical or economic limit, and in a 100% WWS system the capacity factor for geothermal could be higher than this. Therefore, the roadmaps here assume that the capacity factor of geothermal will increase to 90.0% by 2050. This results in a 139-country-total requirement of 96.5 GW of installed geothermal for electricity, producing 86.9 GW of actual power and 78.8 GW of delivered power after transmission, distribution, and downtime losses in 2050.

S5.4. Hydropower

In 2013, conventional (small and large) hydropower provided ~16.3% of the world electric power supply (IEA, 2015d). 2015 installations of hydropower (excluding pumped hydroelectric) were ~1.058 TW (Figure S9). Given the world-averaged capacity factor for hydropower of ~42.0% in 2013 (IEA, 2015c), this implies hydropower generated ~444.0 GW (3,889 TWh/yr) of electricity in 2015.

Figure S9 shows the distribution of installed conventional hydropower by country in 2015. China, Brazil, the United States, and Canada lead in installations. However, the countries of the world with the greatest percentage of their electric power production from hydropower in 2013 include, in order: Albania (100%), Paraguay (100%), Zambia (99.7%), Tajikistan (99.7%), Nepal (99.7%), Democratic Republic of the Congo (99.6%), Mozambique (97.7%), Norway (96.1%), Ethiopia (95.6%), Namibia (95.6%), and the Kyrgyz Republic (93.5%) (World Bank, 2016a). Thus, 6 countries already produce 99-100% of their electricity (but not total energy) from WWS hydropower. Further, ~22 countries produce more than 70% of all their electricity from hydropower and 36, of which 28 are developing countries, produce more than 50%.

Figure S9. Installed conventional hydropower by country in 2015 (IHA, 2016).


China 1 296,310
Brazil 2 91,620
United States of America 3 79,314
Canada 4 79,025
Russian Federation 5 49,264
India 6 46,708
Norway 7 29,215
Turkey 8 25,886
Japan 9 22,268
France 10 18,412
Sweden 11 16,320
Venezuela 12 15,393
Vietnam 13 15,211
Italy 14 14,325
Switzerland 15 13,818
Spain 16 13,293
Mexico 17 12,435
Colombia 18 11,392
Iran 19 10,156
Argentina 20 9,144
Paraguay 21 8,810
Australia 22 8,050
Austria 23 7,978
Pakistan 24 7,264
Chile 25 6,622
Romania 26 6,613
Malaysia 27 5,472
Ukraine 28 5,470
Indonesia 29 5,258
New Zealand 30 5,254
Tajikistan 31 5,190
North Korea 32 5,000
Portugal 33 4,559
Germany 34 4,452
Peru 35 4,190
Philippines 36 3,550
Thailand 37 3,510
Finland 38 3,198
Myanmar 39 3,140
Kyrgyzstan 40 3,091
Egypt 41 2,800
Georgia 42 2,727
Greece 43 2,697
Ethiopia 44 2,552
Iraq 45 2,513
Dem. Rep. of Congo 46 2,495
Ecuador 47 2,297
Zambia 48 2,272
Bulgaria 49 2,265
Kazakhstan 50 2,260
Sudan 51 2,250
Serbia 52 2,221
Mozambique 53 2,187
Bosnia and Herzegovina 54 2,084
Chinese Taipei 55 2,081
Nigeria 56 2,040
Iceland 57 1,986
Croatia 58 1,848
Costa Rica 59 1,800
South Korea 60 1,747
Uzbekistan 61 1,731
United Kingdom 62 1,699
Panama 63 1,655
Sri Lanka 64 1,624
Slovak Republic 65 1,606
Ghana 66 1,584
Latvia 67 1,576
Uruguay 68 1,538
Albania 69 1,527
Syrian Arab Republic 70 1,505
Morocco 71 1,306
Slovenia 72 1,299
Cambodia 73 1,267
Armenia 74 1,249
Azerbaijan 75 1,116
Czech Republic 76 1,065
Guatemala 77 991
Kenya 78 818
Angola 79 766
Zimbabwe 80 765
Nepal 81 753
Cameroon 82 741
Macedonia 83 674
South Africa 84 671
Montenegro 85 658
Cote d'Ivoire 86 604
Poland 87 569
Tanzania 88 562
Honduras 89 558
Dominican Republic 90 543
Bolivia 91 494
El Salvador 92 472
Namibia 93 341
Ireland 94 237
Bangladesh 95 230
Algeria 96 228
Lebanon 97 221
Congo 98 209
Gabon 99 170
Nicaragua 100 123
Belgium 101 120
Lithuania 102 116
Moldova 103 76
Tunisia 104 66
Togo 105 65
Cuba 106 64
Haiti 107 61
Hungary 108 56
Netherlands 109 37
Kosovo 110 36
Luxembourg 111 34
Belarus 112 33
Jamaica 113 23
Jordan 114 12
Denmark 115 9.0
Estonia 116 8.0
Israel 117 7.0
Turkmenistan 118 1.0
Benin 119 1.0
0
50000
100000
150000
200000
250000
300000
Installed 2015 hydro capacity (MW)
World: 1,057,872

Under the roadmaps proposed here, conventional hydropower will supply ~4.004% (474.1 GW) of the 139-country 2050 end-use power demand for all purposes (Table S7). However, no new hydropower dams are proposed for installation. Instead, the capacity factor of hydropower will be increased from a 139-country average of ~42.0% to 50% by 2050. Increasing the capacity factor is feasible because existing dams currently produce less than their maximum capacity, mainly since many other dispatchable sources of electricity exist in the current energy system, greatly reducing the need for hydropower to balance supply and demand. Also, in some cases, hydropower is not used to its full extent because other priorities affect water use, and in a 100% WWS system, these other priorities will remain.

Whereas, increasing hydropower capacity factors should be possible, if it is not, additional hydropower capacity can be obtained by powering presently non-powered dams. The U.S., for example, has over 80,000 dams that are not powered at present. Although only a small fraction of these dams can feasibly be powered, DOE (2012) estimates that the potential amounts to ~12 GW of capacity in the contiguous 48 states.

S5.5. Tidal

Technical Potential

Atlantis Resources Ltd. (2014) provide estimates of the technical potential for tidal power in 28 countries with relatively favorable conditions. For all other countries we estimate the technical potential as a nonlinear function of the length of coastline according to the following formula:

$$C_{TP,TIDE,C} = \left(\frac{CL_C \cdot CLK_{TIDAL}}{k} \right)^{\varphi}$$

where

CL_C = the length of coastline of country C (km) (see discussion of offshore wind technical potential)

CLK_{TIDAL} = coastline convolution correction factor for tidal power (1.00, on the assumption that the resolution of the coastline-length data matches the resolution appropriate for estimating tidal power resources; see discussion of offshore wind technical potential)

k, φ = we assume values of k = 10 and φ = 0.65, which generate the following seemingly reasonable results:

CL_C	10	50	100	500	1,000	2,000	5,000	20,000	50,000	100,000	200,000
$C_{TP,TIDE,C}$	1.0	2.8	4.5	13	20	31	57	140	254	398	625

These results indicate that this formulation results in relatively low technical potential (by comparison, countries with favorable conditions have 1000s of MW of potential), which is appropriate because the feasible technical potential for tidal power is a function not just of the length of coastline but of the characteristics of the tides, and presumably the estimates in the literature of the technical potential for tidal power in 28 countries (mentioned above) are for places with the most favorable tide characteristics.

For all countries, we assume that the actual installed capacity of tidal power equals its technical potential,

$$C_{I,TIDE,C} = C_{TP,TIDE,C}$$

where

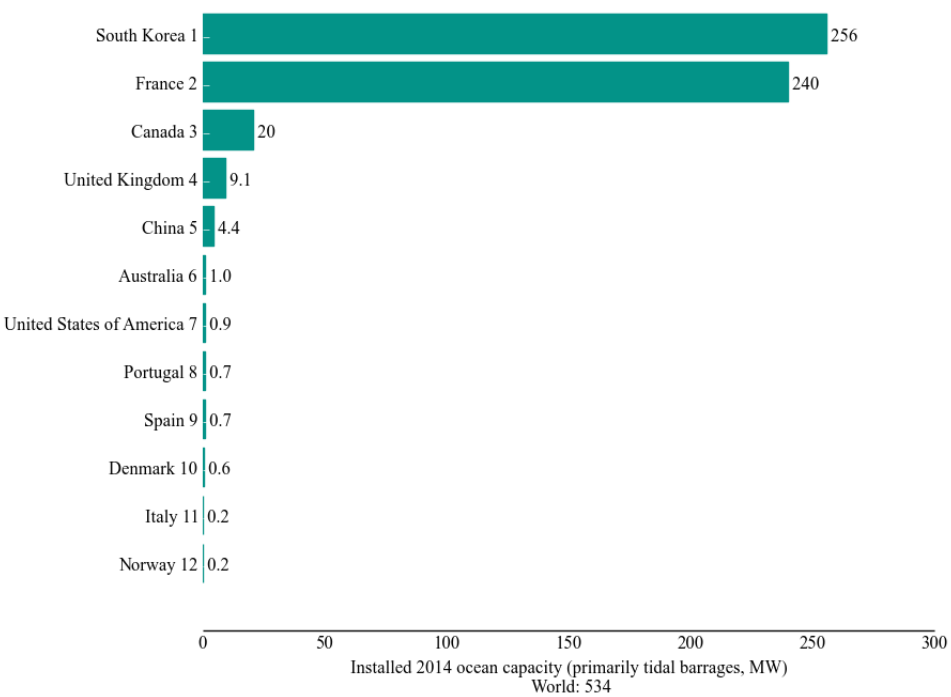
$C_{I,TIDE,C}$ = Total installed capacity of tidal power in country C (MW)

$C_{TP,TIDE,C}$ = Total technical-potential capacity of tidal power in country C (MW) (discussed below)

Current installations of tidal

Worldwide by the end of 2015, a total of ~534 MW of ocean devices (mostly tidal barrages) had been installed (Figure S10). This capacity is mostly from two large plants in South Korea and France and smaller plants in Canada and the United Kingdom.

Figure S10. Installed ocean power by country in 2015 (IRENA, 2016a). Ocean power includes tidal rise and fall, ocean and tidal currents, wave power, ocean thermal energy conversion, and salinity gradients. Nearly all the existing capacity in the figure arises from tidal barrages.



Proposed tidal installations in 100% WWS roadmaps

Under the roadmaps here, tidal is proposed to contribute ~0.057%, or ~6.73 GW, of the 139-country end-use delivered power in 2050 (Table S7). This requires a nameplate capacity of ~30.6

GW installed of which ~1.8% has been installed as of the end of 2015. The needed nameplate capacity is much less than the estimated world technical potential of ~556 GW installed (1200 TWh/yr or 137 GW delivered power) (Marine Renewables Canada, 2013). Some countries with significant tidal potential include Australia (3.8 GW nameplate capacity), Canada (171 GW), France (16 GW), Ireland (107 GW), Japan (3 GW), United Kingdom (8 GW), and the United States (116 GW) (Marine Renewables Canada, 2013).

S5.6. Wave

Technical Potential

The technical potential capacity for wave power is a function of the wave power available per unit of coastline, the fraction of the coastline that can be exploited for wave power, the wave-energy/electrical-energy conversion efficiency of the wave-energy converter (WEC), and the overall "gross" capacity factor for the WEC (a function of the wave power flux per unit coastline), where "gross" means without consideration of the *availability* of the WEC. [See Falcão (2010) and López et al. (2013) for a review of WEC technologies.] We consider several classes of wave-power resources, and sum over all classes with a midpoint greater than a minimum acceptable value,

$$C_{TP,WAVE,C} = CL_C \cdot CLK_{WAVE} \cdot \cos\theta_{WAVE,C} \cdot CE_{MECH,WAVE} \cdot CE_{ELEC,WAVE} \cdot$$

$$\sum_{p \geq Pcl_{WAVE,\min}} \frac{Pcl_{WAVE,p} \cdot Frcl_{p,C} \cdot Frcle_{p,C} \cdot CE_{ABS,WAVE,p}}{CF_{WAVE,gross,p}}$$

$$CF_{WAVE,gross,p} = CF_{WAVE,gross,ref} \cdot \left(\frac{Pcl_{WAVE,p}}{Pcl_{WAVE,ref}} \right)^{\varphi}$$

where

$Pcl_{WAVE,p}$ = The wave power impinging on the coastline (i.e., perpendicular to the coastline) per unit of coastline in wave-power-resource class *p* (MW/km) (discussed below)

CL_C = The length of coastline of country *C* (km) (discussed below)

CLK_{WAVE} = Coastline convolution correction factor for wave power (discussed below)

$\theta_{WAVE,C}$ = The angle between the prevailing wave direction and the perpendicular to the shoreline (degrees)

$Frcl_{p,C}$ = The fraction of the coastline in country *C* with wave-power-resource class *p* (discussed below)

$Frcle_{p,C}$ = The fraction of the coastline in country *C* that can be exploited for wave power, in wave-power-resource class *p* (discussed below)

$CE_{MECH,WAVE}$ = The efficiency of conversion of absorbed power to mechanical power (ratio of power at mechanical/electrical system junction to power at point that waves impinge upon the mechanical system of the WEC) (discussed below)

$CE_{ELEC,WAVE}$ = The efficiency of conversion of mechanical power to electrical power (ratio of power out of the WEC into the electrical grid to power input to the electrical system at the mechanical/electrical system junction (discussed below)

$CE_{ABS,WAVE,p}$ = The efficiency of absorption (or capture) of wave power in wave-power-resource class p (the ratio of absorbed power, impinging upon the mechanical system of the WEC, to the incident wave-front power; also referred to as the "capture width" fraction or ratio: the power captured by the WEC as a fraction of the incident wavefront power [Yemm et al., 2012; Barbarit et al., 2012]) (discussed below)

$CF_{WAVE,gross,p}$ = The gross capacity factor for the wave-power device in wave-power-resource class p (discussed below)

$CF_{WAVE,gross,ref}$ = Reference gross capacity factor (at reference wave power)

$Pcl_{WAVE,ref}$ = Reference wave power (discussed below)

φ = Exponent (discussed below)

φ Subscript p = The midpoint of the wave-power classes (MW/km) (0, 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, 90-100, 100-110, 110-120)

$Pcl_{WAVE,\min}$ = The minimum acceptable wave power (MW/km) (discussed below)

Generally the minimum acceptable wave power falls between two wave-power-class midpoints (i.e., the minimum is almost never *exactly* equal to one of the class midpoints). In these cases, rather than count only wave power above the upper bracketing midpoint, we give a partial weight to the lower bracketing wave-power-class midpoint, where the weight equals

$$\frac{Pcl_{WAVE,p-upper} - Pcl_{WAVE,\min}}{Pcl_{WAVE,p-upper} - Pcl_{WAVE,p-lower}}$$

and $Pcl_{WAVE,p-upper}$ is the wave-power-class midpoint immediately above $Pcl_{WAVE,\min}$, and $Pcl_{WAVE,p-lower}$ is the wave-power-class midpoint immediately below.

<u>Wave power per unit of coastline, by country ($Pcl_{WAVE,p}$, $Frcl_{p,C}$, $\theta_{WAVE,C}$, $Frcle_{p,C}$)</u>

The global wave power resource near shore, defined as the energy flux per unit of wave crest length, ranges between ~10 and 100+ MW/km, depending on the latitude, orientation of the coastline, and season, with the highest values occurring at times and places receiving the heaviest storms (winter months at high north or low south latitudes on west-facing shores; e.g., western Australia in July; Pacific coast of North America in December) (López et al. 2013; Arinaga and Cheung, 2012; Reguero et al., 2011; Ocean Energy Systems, 2011; Gunn and Stock-Williams, 2012) (The mean annual exploitable energy resource (excluding extremely high-energy and hence un-exploitable sea states) in the best near-shore locations is in the range of 30 to 70 MW/km (Reguero et al., 2011; Gunn and Stock-Williams, 2012). Wave power plants need a resource of at least 20 MW/km annual median wave power to be viable (Arinaga and Cheung, 2012).

Gunn and Stock-Williams (2012) show wave-power classes, prevailing wave directions, and coastline buffer areas around the globe. We use their map to estimate $Pcl_{WAVE,p}$, $\theta_{WAVE,C}$, and $Frcl_{p,C}$. Gunn and Stock-Williams (2012) also provide estimates of the total wave-power resource for Australia, the U. S., Chile, New Zealand, Canada, South Africa, United Kingdom, Ireland, Norway, Spain, Portugal, and France; we calibrate our parameter inputs so that our estimated wave-power resources for these countries match theirs.

Gunn and Stock-Willams (2012) do not estimate resources for the Mediterranean sea; for this, we use the estimates of López et al. (2013), calibrating our assumptions to reproduce the López et al. (2013) estimate of 75 GW for the Mediterranean.

We assume that only 30% of the coastline can be used for wave power, in every country and wave-power class. (If we do get better data, we can specify $Frcle_{p,C}$ by country and wave-power class.)

Minimum acceptable wave power ($Pcl_{WAVE,\min}$)

The minimum acceptable wave power is calculated from the specified minimum acceptable gross capacity factor,

$$\frac{CF_{WAVE,gross,\min}}{CF_{WAVE,gross,ref}} = \cdot \left(\frac{Pcl_{WAVE,\min}}{Pcl_{WAVE,ref}} \right)^{\varphi}$$

$$Pcl_{WAVE,\min,low} = Pcl_{WAVE,ref} \cdot \left(\frac{CF_{WAVE,gross,\min,low}}{CF_{WAVE,gross,ref,low}} \right)^{\frac{1}{\varphi}}$$

$$Pcl_{WAVE,\min,high} = Pcl_{WAVE,ref} \cdot \left(\frac{CF_{WAVE,gross,\min,high}}{CF_{WAVE,gross,ref,high}} \right)^{\frac{1}{\varphi}}$$

where

$CF_{WAVE,gross,ref}$ = The reference gross capacity factor (discussed below)

$CF_{WAVE,gross,\min}$ = The minimum acceptable capacity factor

Low refers to the low-cost, high-benefits case (high capacity factor, high resource availability)

High refers to the high-cost, low-benefits case (low capacity factor, low resource availability)

“Gross” refers to the capacity factor without considering availability; i.e., the ratio of actual output if availability were 100% to maximum potential output at 100% availability

Based on our analysis of the relationship between the capacity factor and the LCOE for wave power, we assume that $CF_{WAVE,gross,\min,low}$ = 24% and $CF_{WAVE,gross,\min,high}$ = 30%.[7] This results in $Pcl_{WAVE,\min,low}$ = 15.5 MW/km and $Pcl_{WAVE,\min,high}$ = 42 MW/km. For comparison, Arinaga and Cheung (2012) assume that $Pcl_{WAVE,\min}$ = 20 MW/km.

Coastline length and coastline correction factor CL_C , CLK_{WAVE})

To define the world's coastlines, Gunn and Stock-Williams (2012) use the Natural Earth 1:50,000,000 coastline dataset (Natural Earth, 2016) which, in turn, is derived primarily from the CIA's World Data Bank II. Our estimates of coastline lengths are from the CIA's *World Factbook* (CIA, 2016a). On the assumption that the coastline lengths in the CIA's *World Factbook* are the same as the lengths in the CIA's World Data Bank II, the correction factor to apply to our coastline length data, for the purpose of having it match the coastline length used by Gunn and Stock-Williams (2012), is 1.00

Wave power conversion efficiency ($CE_{MECH,WAVE}$, $CE_{ELEC,WAVE}$, $CE_{ABS,WAVE,p}$)

So et al. (2015) model a hydraulic power-take off WEC given a wave height of 3 meters and a dominant period of 11 seconds, and find $CE_{ELEC,WAVE}$ = 82% and $CE_{MECH,WAVE}$ = 74%., giving a "wave to wire" efficiency of ~ 60%. Similarly, Carballo and Iglesias (2012) assume that the product of $CE_{MECH,WAVE}$ and $CE_{ELEC,WAVE}$ is 60%.

Yemm et al. (2012) show a graph that indicates that $CE_{ELEC,WAVE}$ ~ 90%, and write that for the Pelamis P2 line-absorber WEC, "the total combined conversion efficiency (from wave to wire) is typically approximately 70%" (p. 378), which implies that $CE_{MECH,WAVE}$ ~ 80%. We assume $CE_{ELEC,WAVE}$ = 85% (high-cost case) to 90% (low-cost case) and $CE_{MECH,WAVE}$ = 70% (high-cost case) to 80% (low-cost case)

The absorption efficiency $CE_{ABS,WAVE,p}$ depends on the incident wave power and on the design and operation of the wave-energy converter system. Yemm et al. (2012) show that the *theoretical* maximum capture efficiency can be as high as 73% for line absorber with a length of twice the wave front.

The absorption efficiency $CE_{ABS,WAVE,p}$ typically is estimated using a WEC "power matrix," which shows the power generated by the device as a function of the significant wave height and the power period. Babarit et al. (2012) use numerical models to estimate the power matrix, the wave energy absorption and the "capture width ratio" (our parameter $CE_{ABS,WAVE}$) for 8 different

[7] Note that in the analysis of cost, a higher capacity factor results in a lower cost, but in the analysis of resource availability, a higher minimally acceptable capacity factor results in a lower resource availability. Thus, it is coherent and correct to have a high actual capacity factor but low minimally acceptable capacity factor in the low-cost, high-benefits (i.e., high resource availability) case.

WECs at five different sites along the Atlantic coast of Europe (Table S23). The parameter $CE_{ABS,WAVE}$ varies from a low of 2.1% for small bottom-referenced heavy buoy at the site with the highest wave-power resource to a high of 72% for a bottom-fixed oscillating flap at a site with mid-range wave-power resource. As shown in Table S23, the wave-capture efficiency depends much more heavily on the WEC technology than on the wave-power flux.

Table S23. Wave capture efficiency for 8 WECs and 5 coastal sites.

Wave MW/km	**WEC** *1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
14	3.6	9.0	27.0	14.0	11.0	61.0	14.0	41.0
20	4.2	13.0	29.0	16.0	11.0	68.0	20.0	50.0
25	4.1	13.0	36.0	17.0	11.0	72.0	20.0	52.0
35	3.1	8.0	27.0	12.0	6.4	58.0	11.0	41.0
75	2.1	6.0	23.0	12.0	3.9	52.0	7.0	38.0

Source: Barbarit et al. (2012). The 8 WECs are 1= small bottom-referenced heaving buoy; 2 = bottom-referenced submerged heave-buoy; 3 = floating two-body heaving converter; 4 = bottom-fixed heave-buoy array; 5 = floating heave-buoy array; 6 = bottom-fixed oscillating flap; 7 = floating three-body oscillating flap device; 8 = floating oscillating water column. The MW/km values shown are in between the deep-water and shallow-water values for each of the 5 sites.

The estimates of Babarit et al. (2012) can be fit to a quadratic equation. We use linear extrapolation to extend the values of Table S23 to 5 MW/km and 100 MW/km, convert all values to a fraction of the value at 25 MW/km, and then fit the results to a quadratic, subject to minimum and maximum values w.r.t to the value at 25 MW/km:

$$CE_{ABS,WAVE,p} = CE_{ABS,WAVE,p=25} \cdot \max\left\langle CEfr_{ABS,WAVE,\min}, \min\begin{bmatrix} CEfr_{ABS,WAVE,\max}, \\ b1 + b2 \cdot p_{mid} + b3 \cdot p_{mid}^2 \end{bmatrix}\right\rangle$$

where

$CE_{ABS,WAVE,p=25}$ = The wave absorption efficiency at a wave flux of 25 MW/km (we assume a low-cost case (high capacity factor) estimate of 55% and a high-cost case 35%)
$CEfr_{ABS,WAVE,\min}$ = The minimum wave absorption efficiency w.r.t the efficiency at 25 MW/km (0.20)
$CEfr_{ABS,WAVE,\max}$ = The maximum wave absorption efficiency w.r.t the efficiency at 25 MW/km (0.95)
b1, b2, b3 = Coefficients from quadratic fit to Babarit et al. (2012) data (b1=0.800, b2 = 0.0128, b3 = -0.000193)

The resultant overall efficiency, the product of our three efficiency parameters, is in the range of 7% to 35%, which is consistent with other estimates of the overall efficiency. McCormick and Ertekin (2009) assume an overall conversion efficiency of 25%. Bedard et al. (2007) assume that efficiency of converting wave energy to mechanical energy is 15%, and the efficiency of converting mechanical energy to electrical energy is 90%, giving an overall conversion efficiency of 13.5%. Ocean Energy Systems (2014) report overall wave-energy-to-electrical-energy conversion efficiencies of 14%, 17%, and 55% for three different systems.

Gross capacity factor for wave-power devices ($CF_{WAVE,gross,p}$ and associated parameters)

The gross capacity factor generally will increase with increasing wave-power resources. Ocean Energy Systems (2015) plots estimates of the gross capacity factor (assuming 100% availability) as a function of the wave resource (in MW/km). The following values provide an acceptable fit to their plots:

$CF_{WAVE,gross,ref,low}$ = 34%

$CF_{WAVE,gross,ref,high}$ = 30%

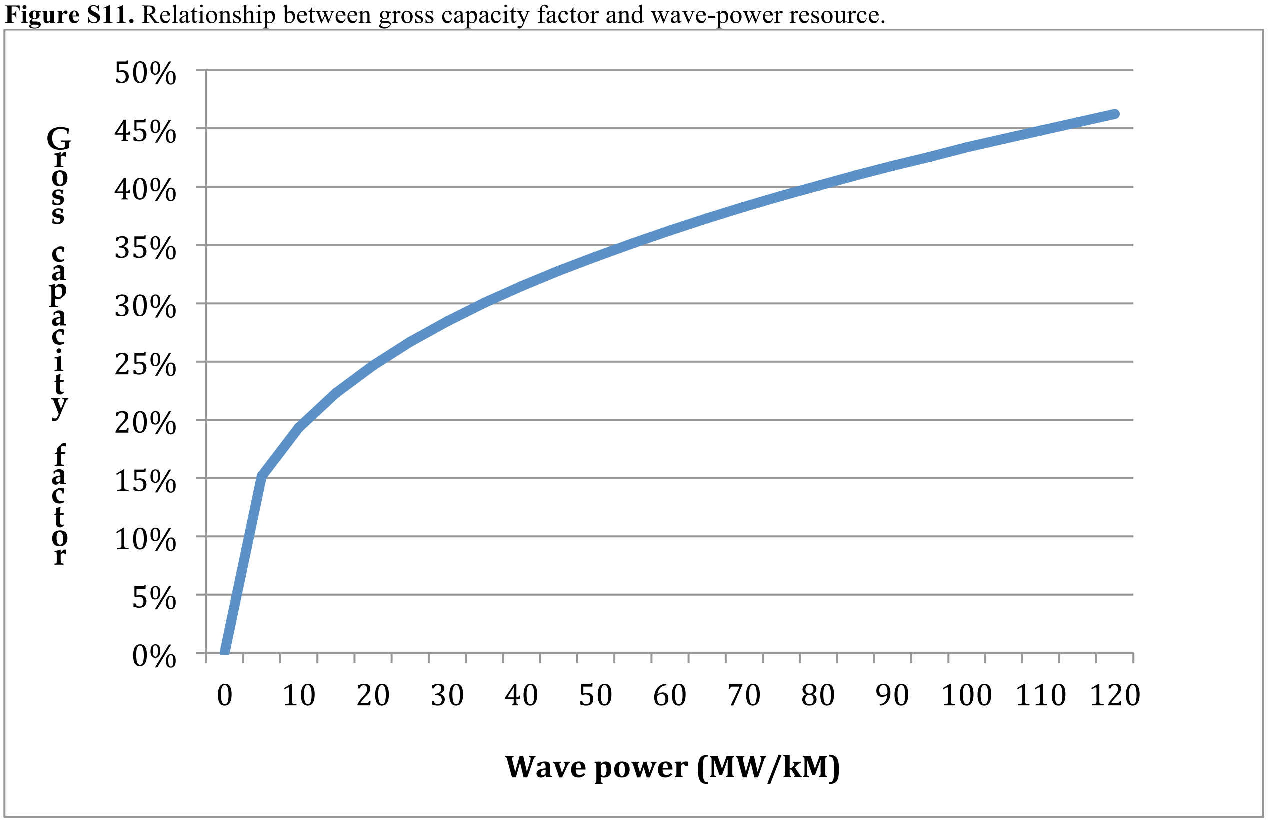
$Pcl_{WAVE,ref}$ = 42 MW/km

φ = 0.35

φ "Low" refers to low cost, high benefits and "high" refers to high cost, low benefits

These values result in the relationship shown in Figure S11.

Figure S11. Relationship between gross capacity factor and wave-power resource.



Note: based on the average of the low-cost (high-capacity-factor) and high-cost parameter values shown above.

The results shown in Figure S11 are broadly consistent with other estimates. Marine Renewables Canada (2013) estimates technical potential TWh per year from wave power in Australia, Canada, France, Japan, Ireland, Norway, the United Kingdom, and the U.S.; we back-calculate the installed capacity assuming an average capacity factor of 23.16% (Jacobson, 2009). The EOEA (2010) remarks that 188 GW of installed capacity can produce 645 TWh/year, implying a capacity factor of 39%. Yemm et al. (2012) write that the target capacity factor for the Pelamis P2 wave energy converter is "25-40% depending on the conditions at the chosen wave farm site" (P. 366). Similarly, Folley and Whittaker (2009) suggest that WECs will have a "load factor" of between 25% and 40%.

Calculation of net capacity factor

We used the "gross" capacity factor (at 100% availability) to estimate installed capacity because the reference that provided information on the relationship between capacity factor and wave resource used the "gross" capacity factor. However, for the purpose of calculating actual power output and the associated LCOE, we must account for the availability of the WEC. We refer to this as the capacity factor without the subscript "gross". Formally,

$$CF_{WAVE,C} = \frac{AP_{WAVE,C}}{C_{TP,WAVE,C}}$$

$$AP_{WAVE,C} = CL_C \cdot CLK_{WAVE} \cdot \cos\theta_{WAVE,C} \cdot CE_{MECH,WAVE} \cdot CE_{ELEC,WAVE} \cdot AV_{WAVE}$$

$$\sum_{p \geq Pcl_{WAVE,\min}} Pcl_{WAVE,p} \cdot Frcl_{p,C} \cdot Frcle_{p,C} \cdot CE_{ABS,WAVE,p}$$

where

$CF_{WAVE,C}$ = the actual overall capacity factor for wave power in country *C*

$AP_{WAVE,C}$ = the actual continuous power output from wave power in country *C* (MW)

AV_{WAVE} = the availability factor for wave power (98% low cost case, 96% high cost case; Ocean Energy Systems, 2015)

other terms defined above

For all countries, we assume that the actual installed capacity equals the technical potential (because we estimate what might be called a technical "economic" potential):

$$C_{I,WAVE,C} = C_{TP,WAVE,C}$$

where

$C_{I,WAVE,C}$ = total installed capacity of wave power in country *C* (MW)

$C_{TP,WAVE,C}$ = total technical potential capacity of wave power in country *C* (MW)

Proposed wave power installations in 100% WWS roadmaps

Wave power is proposed here to contribute ~0.58%, or ~68.5 GW, of the 139-country end-use power demand in 2050 (Table S7). This requires a nameplate installation of ~307 GW, which is much less than the world technical potential for the 139 countries considered of ~4.362 GW installed (8,850 TWh/yr, or 1010 GW delivered) (Marine Renewables Canada, 2013 but assuming 70% exclusion zones). Some of countries with significant wave potential include Australia (192 GW installed), Canada (275 GW), France (14 GW), Japan (13 GW), Ireland (3 GW), Norway (59 GW), United Kingdom (6 GW), and the United States (263 GW) (Marine Renewables Canada, 2013).

Section S6. Matching Electric Power Supply with Demand

An important requirement for 100% WWS roadmaps is that the grid remains reliable. To that end, Jacobson et al. (2015b) developed and applied a grid integration model to determine the quantities and costs of storage devices needed to ensure that a 100% WWS system developed for each of the 48 contiguous U.S. states, when integrated across all such states, could match load without loss every 30 s for 6 years (2050-2055) while accounting for the variability and uncertainty of WWS resources.

Wind and solar time-series are derived from 3-D GATOR-GCMOM global model simulations that accounted for extreme events and competition among wind turbines for kinetic energy and the feedback of extracted solar radiation to roof and surface temperatures. Solutions are obtained by prioritizing storage for excess heat (in underground rocks and water) and electricity (in ice, water, phase-change material tied to CSP, pumped hydro, and hydrogen), using hydropower only as a last resort, and using demand response to shave periods of excess demand over supply. Additional simulations show that grid reliability is maintained even without demand response by increasing electricity generation, but at a slightly higher cost.

No stationary storage batteries, biomass, nuclear power, or natural gas are needed in these roadmaps. Frequency regulation of the grid is provided by ramping up/down hydropower, stored CSP or pumped hydro; ramping down other WWS generators and storing the electricity in heat, cold, or hydrogen instead of curtailment; and using demand response.

Multiple low-cost stable solutions to the grid integration problem across the 48 contiguous U.S. states were obtained, suggesting that maintaining grid reliability upon 100% conversion to WWS in that region is a solvable problem. The mean U.S.-averaged levelized cost of energy in that study, accounting for storage transmission, distribution, maintenance, and array losses, is ~10.6 ¢/kWh-WWS-electricity and ~11.4 ¢/kWh-WWS-all-energy (2013 USD).

Here, current and future full social costs (including capital, land, operating, maintenance, storage, fuel, transmission, and externality costs) of WWS electric power generators versus non-WWS conventional fuel generators are estimated. These costs include the costs of CSP storage, existing hydroelectric power used for storage, solar collectors used to collect heat for storage, and all transmission/distribution costs. They do not include costs of pumped hydro storage, underground storage in rocks, heat and cold storage in water and ice, or the costs of hydrogen fuel cells. Such costs are estimated here simplistically as < 0.8 ¢/kWh-WWS-all-energy from Jacobson et al. (2015b) but will be estimated more precisely as part of a separate study.

Section S7. Costs of BAU and WWS Energy

In this section, current and future full social costs (including capital, land, operating, maintenance, storage, fuel, transmission, distribution, and externality costs) of WWS electric power generators versus non-WWS conventional fuel generators are estimated. These costs do not include the costs of storage necessary to keep the grid stable aside from the cost associated with CSP storage and existing conventional hydroelectric power. Such additional storage costs are discussed in Jacobson et al. (2015b).

First, we update and adapt the U.S.-baseline cost estimates of Jacobson et al. (2015a) using recent analyses by IRENA (2015a), Lazard (2015), and other sources.

S7.1. Levelized Cost of Electricity From IRENA and Lazard

IRENA (2015a) provides a comprehensive review of the costs of unsubsidized and subsidized renewable electricity-generating technologies around the world. Table S24a presents their estimates for the year 2013/14, and Table S24b presents their projections for the year 2025.

IRENA (2015a) notes that costs are lower in China and India in part because of lower costs of materials (e.g., cement and steel) and labor. Costs for CSP with 6 to 9 hours of storage tend to be somewhat higher than the average shown in Table S24a.

IRENA (2015a) also provides information on O&M costs. Their Figure 4-15 shows that full-service O&M pricing for wind projects fell from above $40/kW/year in 2008-2009 to under $30/kW/year in 2012-2013. Elsewhere, IRENA (2015e) reports that its cost database indicates that O&M costs for utility-scale wind projects are $20-$40/kW/yr.

Table S24a. IRENA estimates of weighted-average total installed cost of utility-scale renewable power generation technologies, by region, 2013/2014 (year-2014 USD/kW).

	China and India	OECD	ROW
Biomass	1,200	4,200	2,700
Geothermal	n.e.	3,900	2,700
Hydro	1,250	2,400	1,700
Solar PV	1,600	2,200	2,650
CSP (w and w/out storage)	4,400	6,700	4,00
Offshore wind	1,400	4,400	n.e.
Onshore wind	1,300	2,000	2,250

Source: IRENA (2015a; their Figure 2.8). OECD = Organization for Economic Cooperation and Development; ROW = rest of world. Offshore wind costs include grid connection.

Table S24b. IRENA projections of cost reduction for renewable power generation technologies (year-2014 USD/kW or % change 2025 vs. 2014).

	China and India	US or OECD
Biomass	-10% to -15%	
Solar PV utility	n.e.	1,100 to 1,200
Solar PV rooftop	n.e.	1,600 to 2,000
CSP	-20% to -45%	
Onshore wind	no change (costs already competitive; move to larger turbines will offset any cost reductions)	1,400 to 1,600

Source: IRENA (2015a). OECD = Organization for Economic Cooperation and Development; ROW = rest of world. N.e. = not estimated.

IRENA (2015a) assumes that hydro and geothermal are mature technologies and that technology-related costs will not decline significantly in the future. However, according to IRENA (2015a) the installed capital cost of hydropower might increase in the future as smaller, more remote projects are built.

Jacobson et al. (2015a) relied heavily on Lazard's (2014) "version 8.0" analysis of the cost of electricity-generating technologies; since then, Lazard (2015) has published version 9.0. Tables S25a and S25b show Lazard's (2015) version 9.0 low-cost and high-cost estimates, and Tables S25c and S25d show the difference between Lazard (2015) version 9.0 and Lazard (2014) version 8.0.

Table S25a. Lazard (2015) version 9.0 low-cost-case estimates.

	CC ($/kW)	Build (yrs)	CF	Life (years)	VOM ($/MWh)	FOM ($/kW/yr)	Fuel ($/10^6-BTU)	Fuel efficiency
Advanced pulv. Coal	3000	5.0	93%	40	2.0	40	1.96	39%
IGCC coal	4000	4.8	75%	40	7.0	62.25	1.46	39%
Gas peaking	800	2.1	10%	20	4.7	5	3.45	33%
Gas combined cycle	1000	3.0	70%	20	3.5	6.2	3.45	51%
Diesel generator	500	0.3	95%	20	15.0	15	18.23	34%
Nuclear	5400	5.8	90%	40	0.5	135	0.50	33%
Geothermal	4500	3.0	90%	25	30.0	0	0.00	100%
Microturbine	2500	0.3	95%	20	7.0	6.85	3.45	31%
Biomass direct	3000	3.0	85%	25	15.0	95	1.00	24%
Wind	1250	1.0	55%	20	0.0	35	0.00	100%
Off-shore wind	3100	1.0	45%	20	13.0	60	0.00	100%
Fuel cell	3800	0.3	95%	20	30.0	0	3.45	47%
Solar thermal w/18-hr storage	10300	3.0	85%	35	0.0	115	0.00	100%
Utility PV crystalline tracking	1750	1.0	30%	30	0.0	13	0.00	100%
Utility PV thin film tracking	1600	1.0	32%	30	0.0	13	0.00	100%
Rooftop comm. Ind. PV	2600	0.3	25%	25	0.0	15	0.00	100%
Rooftop residential PV	4100	0.3	25%	20	0.0	17.5	0.00	100%

Table S25b. Lazard (2015) version 9.0 high-cost-case estimates.

	CC ($/kW)	Build (yrs)	CF	Life (years)	VOM ($/MWh)	FOM ($/kW/yr)	Fuel ($/10^6-BTU)	Fuel efficiency
Advanced pulv. Coal w/CC	8400	5.5	93%	40	5.0	80	1.96	28%
IGCC coal w/CC	9800	5.3	75%	40	8.5	73	0.65	29%
Gas peaking	1000	2.1	10%	20	7.5	25	3.45	38%
Gas combined cycle	1300	3.0	40%	20	2.0	5.5	3.45	49%
Diesel generator (intermittent)	800	0.3	10%	20	15.0	15	18.23	34%
Nuclear	8200	5.8	90%	40	0.8	135	0.75	33%
Geothermal	6400	3.0	85%	25	40.0	0	0.00	100%
Microturbine	2700	0.3	95%	20	10.0	9.12	3.45	28%
Biomass direct	4000	3.0	85%	25	15.0	95	2.00	24%
Wind	1700	1.0	30%	20	0.0	40	0.00	100%
Off-shore wind	5500	1.0	40%	20	18.0	100	0.00	100%
Fuel cell	7500	0.3	95%	20	50.0	0	3.45	52%
Solar thermal w/10-hr storage	10000	3.0	52%	35	0.0	80	0.00	100%
Utility PV crystalline fixed	1500	1.0	21%	30	0.0	10	0.00	100%
Utility PV thin film fixed	1400	1.0	23%	30	0.0	10	0.00	100%
Rooftop comm. Ind. PV	3750	0.3	20%	20	25.0	20	0.00	100%
Rooftop residential PV	5300	0.3	20%	20	0.0	22.5	0.00	100%

Table S25c. Lazard (2015) version 9.0 vs. Lazard (2014) version 8.0, low-cost case.

	CC ($/kW)	Build (yrs)	CF	Life (years)	VOM ($/MWh)	FOM ($/kW/yr)	Fuel ($/10^6-BTU)	Fuel efficiency
Advanced pulv. Coal w/CC	100%	100%	100%	100%	100%	100%	98%	100%
IGCC coal w/CC	100%	100%	100%	100%	100%	100%	73%	99%
Gas peaking	100%	100%	100%	100%	100%	100%	77%	100%
Gas combined cycle	99%	100%	100%	100%	100%	100%	77%	100%
Diesel generator (intermittent)	100%	100%	100%	100%	n.e. 2014	100%	63%	100%
Nuclear	100%	100%	100%	100%	167%	142%	71%	99%
Geothermal	98%	100%	100%	125%	100%	n.e.	n.e.	100%
Microturbine	109%	100%	100%	100%	39%	n.e. 2014	77%	91%
Biomass direct	100%	100%	100%	125%	100%	100%	100%	98%
Wind	89%	100%	106%	100%	n.e.	100%	n.e.	100%
Off-shore wind	100%	100%	105%	100%	100%	100%	n.e.	100%
Fuel cell	100%	100%	100%	100%	100%	n.e.	77%	100%
Solar thermal w/10-hr storage	105%	120%	106%	88%	n.e.	100%	n.e.	100%
Utility PV crystalline fixed	100%	100%	100%	150%	n.e.	65%	n.e.	100%
Utility PV thin film fixed	91%	100%	107%	150%	n.e.	65%	n.e.	100%
Rooftop comm. Ind. PV	104%	100%	109%	125%	n.e.	115%	n.e.	100%
Rooftop residential PV	117%	100%	109%	100%	n.e.	70%	n.e.	100%

Table S25d. Lazard (2015) version 9.0 vs. Lazard (2014) version 8.0, high-cost case.

	CC ($/kW)	Build (yrs)	CF	Life (years)	VOM ($/MWh)	FOM ($/kW/yr)	Fuel ($/10^6-BTU)	Fuel efficiency
Advanced pulv. Coal w/CC	100%	100%	100%	100%	100%	100%	98%	102%
IGCC coal w/CC	123%	100%	100%	100%	100%	100%	33%	91%
Gas peaking	100%	100%	100%	100%	100%	100%	77%	100%
Gas combined cycle	99%	100%	100%	100%	100%	100%	77%	101%
Diesel generator (intermittent)	100%	100%	33%	100%	n.e. 2014	100%	63%	100%
Nuclear	100%	100%	100%	100%	94%	117%	107%	99%
Geothermal	88%	100%	106%	125%	100%	n.e.	n.e.	100%
Microturbine	71%	100%	100%	100%	45%	n.e. 2014	77%	102%
Biomass direct	100%	100%	100%	125%	100%	100%	100%	98%
Wind	94%	100%	100%	100%	n.e.	100%	n.e.	100%
Off-shore wind	100%	100%	108%	100%	100%	100%	n.e.	100%
Fuel cell	100%	100%	100%	100%	100%	n.e.	77%	100%
Solar thermal w/10-hr storage	143%	120%	100%	88%	n.e.	100%	n.e.	100%
Utility PV crystalline fixed	100%	100%	100%	150%	n.e.	77%	n.e.	100%
Utility PV thin film fixed	93%	100%	110%	150%	n.e.	77%	n.e.	100%
Rooftop comm. Ind. PV	125%	100%	100%	100%	n.e. 2014	100%	n.e.	100%
Rooftop residential PV	118%	100%	100%	100%	n.e.	75%	n.e.	100%

Notes for Tables S26a-S26d. CC = Capital cost; Build = build time; CF = capacity factor; VOM = variable operations and maintenance; FOM = fixed operations and maintenance; Fuel = fuel cost; n.e. = not estimated; n.e. 2014 = not estimated in Lazard (2014).

As shown in Tables S25c and S25d, Lazard (2015), compared with Lazard (2014), estimates higher capital costs for residential and commercial PV, solar thermal, and IGCC coal; lower capital costs for geothermal, onshore wind, and utility-scale thin-film PV; higher capacity factors for wind and PV; longer lifetimes for geothermal, biomass, and PVs; higher O&M costs for nuclear; and lower O&M costs for most PVs.

S7.2. Levelized Cost of Electricity From Other studies

Recent work suggests that in the long run, CSP and ocean power may be economical. N'Tsoukpoe et al. (2016) present an analysis of a small-scale (10-kWe), low-cost CSP plant for developing countries. They expect that the use of local materials and relatively simple design and construction can result in an affordable LCOE.

Xu et al. (2015) review recent developments in CSP technologies using phase-change materials. They estimate that latent-heat thermal-energy storage systems (60 Mwe system, 35% thermal efficiency, 6-to-8-hour charge) costs about $350/kWe.

SolarReserve's recently completed "Crescent Dunes" 110-MW CSP project in Nevada, with 10 hours of full-load molten-salt thermal-energy storage, had a private capital cost investment "in excess" of $750 million (SolarReserve, 2016), giving a unit capital cost of at least $6800/kW. SolarReserve states that construction cost for its "Redstone" 100-MW CSP project under development in South Africa, with 12 hours of full-load storage, is about 30% below the cost for Crescent Dunes (Grikas, 2016), implying a capital cost of at least $4800/kW. The O&M cost for the Crescent Dunes plant is at least $100/kW-yr.

Shirawasa et al. (2016) propose a new marine-current turbine that uses to the middle layer of marine currents, to avoid the influence of wind and waves. Their design has relatively few parts, which they believe will make it reliable and relatively inexpensive.

Ocean Energy Systems (2015) provides estimates of cost parameters for tidal and wave power technologies, for current technologies (Table S26). The cost values generally are lower than in Jacobson et al. (2015a).

On the basis of information in Koomey and Hultman (2007) and a reconsideration of the studies cited in Jacobson et al. (2015a) we have changed the build time for APWR nuclear power to 6 to 11 years. We assume that build times for SMRs are 70% of this. Finally, upon reconsideration of the studies cited in Jacobson et al. (2015a) we have slightly increased the high-end overnight capital and lower-limit cost % for nuclear power.

Table S26. Cost parameters for tidal and wave power ~100 MW projects with current technology and commercial-scale production.

	Tidal power		**Wave power**	
	low-cost	*high-cost*	*low-cost*	*high-cost*
Capital cost ($/kW)	$3,400	$6,000	$3,000	$7,000
Operating costs ($/kW/year)	$120	$260	$60	$200
Capacity factor[a]	40%	35%	50%	25%
Long term LCOE w.r.t to current[b]	~25%		~10%	

Source: Ocean Energy Systems (OES) (2015). LCOE = levelized cost of energy

[a] The capacity factor as we define it here is the product of the "gross" capacity factor and the "availability" factor in the OES (2015) analysis. The OES estimates for tidal power account, qualitatively, for the reduction with increasing number of rows in the array, on account of the first rows extracting tidal energy and reducing the available energy for the rows behind. The OES estimates for wave power depend strongly on wave resource (MW/km), ranging from about 25% to what likely is the poorest exploitable resource to about 50% for the best wave resources.

[b] For tidal power: the ratio of the LCOE at a cumulative industry deployment of 10,000 MW to the LCOE at 1 MW. For wave power: the ratio of the LCOE at a cumulative industry deployment of 100,000 MW to the LCOE at 10 MW.

In light of the recent estimates from IRENA (2015a), Lazard (2015), and the other studies summarized above, we have revised the baseline U.S. estimates of Jacobson et al. (2015a). The revisions are most significant for wave power and tidal power.

S7.3. Levelized Cost of Transmission and Distribution

The cost of electricity transmission and distribution (T&D) is a significant fraction of the total levelized cost of delivered electricity: Jacobson et al. (2015a) estimate that in 2013, the cost of T&D was 37% of the average total delivered cost of electricity in the U. S. Because T&D is so costly, and because the development of a 100% WWS energy system will change some aspects of and expand the BAU T&D system, the T&D-system differences between the BAU and the 100% WWS might have a non-trivial impact on the estimated total levelized cost of delivered power. Therefore, in this section we
estimate the levelized cost of electricity transmission and distribution for a BAU scenario and for a 100% WWS scenario that satisfies that same end-use demand for energy services.

For the BAU scenario, we estimate the total levelized cost of the T&D system as the sum of the costs of three parts:

• The conventional high-voltage (mainly AC) transmission and sub-transmission network, which connects the step-up transformers at large central generating stations with the substation step-down transformers at the "start" of the distribution system;

• The distribution system, including the substations connected to the transmission network, primary distribution feeder lines, secondary (lower-voltage) lateral lines, and the utility's service lines connecting the secondary lines to the end-user's pole drop; and

• The end-user's pole drop and service panel.

(See Willis [2004] for an extensive discussion of the components of electricity T&D systems.)

For the 100% WWS scenario, we estimate the total levelized cost of the T&D system as the sum of the cost of the three parts above plus the cost of:

• A high-voltage, direct-current (HVDC) "super-grid" connecting generators and end-users over very large distances (above and beyond any HVDC lines in the BAU scenario).

We have distinguished the customer-side pole drop and service panel from the utility's distribution service lines because the differences in the cost and power of end-user equipment between the BAU scenario and the 100% WWS scenario will not be the same as the differences in the cost and power of utility-side equipment between the BAU and the 100% WWS scenario.

Substations in the T&D network generally have transformer, switches, and protection and control equipment, and may have capacitors and other equipment for regulating voltage. We assume that the T&D system will include any new monitoring and control equipment for a "smart" grid. (See also the section on "ancillary services" in the power sector.)

For each part of the T&D system, the total levelized cost per unit of electricity delivered to end users is a function of the capital cost of the equipment, the life of the equipment, the operating and maintenance (O&M) cost, the amount of energy delivered relative to the full delivery capacity of the system (the capacity factor, generally referred to in this context as the "load" factor), and the energy-delivery efficiency of the T&D system. The capital cost, in turn, is a function of the type, size (capacity), and amount (or length) of equipment, and the life of the equipment and the energy-delivery efficiency are a function of the capacity factor. All of these cost factors will be different in the 100% WWS scenario than in the BAU scenario.

Capital cost as a function of equipment size or length

For all of the parts of the T&D system, we estimate the capital cost as a function of the average power flow relative to a reference power flow. This allows us to estimate the impact on cost of differences in average power flows, due either to differences between the BAU scenario and the 100% WWS scenario (in the case of AC transmission, distribution, and end-user service costs), or to different configurations of the WWS HVDC super-grid. For conventional AC transmission and HVDC super-grid transmission, we estimate capital cost as a function of transmission distance relative to a reference distance.

Formal methods

Electricity distribution system

The cost of electricity distribution (ED), per kWh delivered to end users, is a function of the amortized capital cost per kW, operations and maintenance (O&M) costs, the overall ED-system capacity factor, and the efficiency of the ED system. The overall ED-system capacity factor is the ratio of total end-use electricity to the maximum potential output from the distribution system. Total end-use electricity includes power from distributed generation (DG) technologies, such as rooftop PV, which might not always send power through the ED system, because the size and cost of the ED system is a function of the size of and power flows from DG technologies.

Formally,

$$C_{TOT,ED,C,Y,S} = \frac{C_{ACC,ED,C,Y,S} + C_{FOM,ED,C,Y,S}}{CF_{ED,C,Y,S} \cdot 8760 \cdot eff_{ED,C,Y,S}} + C_{VOM,ED,C,Y,S}$$

$$C_{ACC,ED,C,Y,S} = \frac{r \cdot C_{CC,ED,C,Y,S}}{1 - e^{-r \cdot t_{life,ED}}}$$

Let

$$C_{FOM,ED,C,Y,S} \equiv C_{CC,ED,C,Y,S} \cdot Fr_{FOM/CC}$$

then

$$C_{TOT,ED,C,Y,S} = \frac{\frac{r \cdot C_{CC,ED,C,Y,S}}{1-e^{-r \cdot t_{life,ED}}} + C_{CC,ED,C,Y,S} \cdot Fr_{FOM/CC}}{CF_{ED,C,Y,S} \cdot 8760 \cdot eff_{ED,C,Y,S}} + C_{VOM,ED,C,Y,S}$$

$$= \frac{C_{CC,ED,C,Y,S} \cdot \left(\frac{r}{1-e^{-r \cdot t_{life,ED}}} + Fr_{FOM/CC} \right)}{CF_{ED,C,Y,S} \cdot 8760 \cdot eff_{ED,C,Y,S}} + C_{VOM,ED,C,Y,S}$$

where

$C_{TOT,ED,C,Y,S}$ = the total annualized cost of the ED system in country *C* in year *Y* in scenario *S* ($/kWh-end-use)
$C_{ACC,ED,C,Y,S}$ = the annualized capital cost of the ED system in country *C* in year *Y* in scenario *S* ($/kW/year)
$C_{FOM,ED,C,Y,S}$ = fixed O&M costs of the ED system in country *C* in year *Y* in scenario *S* ($/kW/year)
$C_{VOM,ED,C,Y,S}$ = variable O&M costs of the ED system in country *C* in year *Y* in scenario *S* ($/kWh-end-use)
$CF_{ED,C,Y,S}$ = the capacity factor for the ED system in country *C* in year *Y* in scenario *S* ($/kWh-end-use)
8760 = hours per year
$eff_{ED,C,Y,S}$ = efficiency of ED in country *C* in year *Y* in scenario *S* (see discussion in subsection "Transmission and distribution efficiency")
$C_{CC,ED,C,Y,S}$ = the capital cost of the ED system in country *C* in year *Y* in scenario *S* ($/kW)
r = the annual discount rate
$t_{life,ED}$ = the lifetime of the ED system before replacement or major upgrade (years)
$Fr_{FOM/CC}$ = fixed O&M as a fraction of the initial capital cost ($/kW/yr per $/kW)
subscript *ED* = electricity distribution
subscript *C* = country
subscript *Y* = year
subscript *S* = scenario (BAU or 100% WWS)

Willis (2004) notes that upgrades are more expensive than original installations, in $/kW terms, mainly because of the need to remove and replace old equipment. (We also would add that in the case of upgrades, one-time costs of mobilizing manpower and construction equipment are spread out over a smaller total installed kW base, and hence are larger in terms of $/kW.) Therefore, we decompose the overall average $/kW capital cost of expanding and upgrading the electricity-distribution system into a cost of adding new capacity and a cost of upgrading existing capacity.

Formally, the capital cost of the electricity-distribution system, in $/kW, at a particular time in a particular place, is a function of the capital cost of new expansion, the capital cost of replacing or upgrading old equipment, and the amount of capacity added or upgraded:

$$C_{CC,ED,C,Y,S} = \frac{CAP_{ED,NEW,C,Y,S} \cdot C_{CC,ED,NEW,C,Y,S} + CAP_{ED,UP,C,Y,S} \cdot C_{CC,ED,UP,C,Y,S}}{CAP_{ED,NEW,C,Y,S} + CAP_{ED,UP,C,Y,S}}$$

where

$C_{CC,ED,C,Y,S}$ = the ongoing average capital cost of expanding and upgrading the electricity-distribution system in country *C* in year *Y* in scenario *S* (BAU or 100% WWS) ($/kW)

$CAP_{ED,NEW,C,Y,S}$ = new electricity-distribution-system capacity in country *C* in year *Y* in scenario *S* (kW)

$C_{CC-NEW,ED,C,Y,S}$ = the average capital cost of newly expanding the electricity-distribution system in country *C* in year *Y* in scenario *S* ($/kW)

$CAP_{ED,UP,C,Y,S}$ = upgraded electricity-distribution-system capacity in country *C* in year *Y* in scenario *S* (kW)

$C_{CC-UP,ED,C,Y,S}$ = the average cost per kW of upgrading the electricity-distribution system in country *C* in year *Y* in scenario *S* ($/kW)

We define

$$CAPfr_{ED,NEW,C,Y,S} \equiv \frac{CAP_{ED,NEW,C,Y,S}}{CAP_{ED,NEW,C,Y,S} + CAP_{ED,UP,C,Y,S}}$$

$$RCC_{ED,UP/NEW} = \frac{C_{CC,ED,UP,C,Y,S}}{C_{CC,ED,NEW,C,Y,S}}$$

where

$CAPfr_{ED,NEW,C,Y,S}$ = of the total amount of capacity upgraded or newly added, the fraction that is newly added in country *C* in year *Y* in scenario *S*

$RCC_{ED,UP/NEW}$ = the cost per kW of upgrading relative to the cost of adding new capacity (same for all countries, years, and scenarios)

Hence, we have

$$C_{CC,ED,C,Y,S} = CAPfr_{ED,NEW,C,Y,S} \cdot C_{CC,ED,NEW,C,Y,S} + \left(1 - CAPfr_{ED,NEW,C,Y,S}\right) \cdot RCC_{ED,UP/NEW} \cdot C_{CC,ED,NEW,C,Y,S}$$

$$= C_{CC,ED,NEW,C,Y,S} \cdot \left(CAPfr_{ED,NEW,C,Y,S} + \left(1 - CAPfr_{ED,NEW,C,Y,S}\right) \cdot RCC_{ED,UP/NEW}\right)$$

<u>Estimation of the BAU $/kW cost of the distribution system</u>

We use data on total expenditures on the BAU distribution system to estimate the BAU \$/kW-electricity cost. With the BAU \$/kW-electricity cost and other assumptions, we can estimate the associated levelized \$/kWh-electricity cost for the distribution system, and compare it with EIA's estimates of the \$/kWh-electricity cost. Table S27 details the calculation.

Table S27. Deriving estimates of the $/kW-electricity and $/kWh-electricity cost of the BAU distribution system from data on total expenditures on the distribution system.

Parameter	Low cost	High cost	Notes
Inputs			
Total annual average investment in the electricity distribution system in the U. S., 1980-2010 (billion $/year)	12.00	14.00	According to EPRI (2011), "investment in the distribution system has averaged $12 to $14 billion per year for last few decades, primarily to meet load growth, which includes both new connects and upgrades for existing customers" (p. 6-1). Willrich (2009) says that the "asset" value of the electricity distribution system was over $240 billion around 2009, which implies an annual investment of at least $6 if the system is completely replaced every 40 years. (Willrich also says that the asset value of the transmission system is 1/3 the value of the distribution system, which is consistent with EIA estimates that the cost of transmission is about 1/3 the cost of distribution.)
Average annual growth in electricity end use in the U. S. 1980-2010 (billion kWh/yr)	59.77	59.77	EIA (2016g).
Capacity factor for distribution system	60%	50%	DOE (2007) figures 1-3, 1-4, and 3-1 indicate that average continuous electricity consumption is about 55% of peak demand. Similarly, Willis (2004) provides several examples indicating that load factors for distribution systems – the ratio of average to peak demand – is in the range of 50 to 65 , with 55% being a typical value. If the maximum capacity of a distribution system is equal to the peak demand, then the capacity factor is the same as the load factor.
Distribution system efficiency	97%	96%	According to the International Electrotechnical Commission (2007), distribution losses (between the step-down substation and users) are in the range of 3% to 5% or more.
Average in-place capacity in U. S., 1980-2010 (billion kW, or TW)	0.79	0.79	EIA (2016g).
Average lifetime to replacement of in-place capacity (years)	50	65	Woo et al. (1995) write that "under normal operating conditions, a transformer can last up to 50 years" (p. 114). Brown (2009) shows curves that indicate that few substation transformers last past 60 years; few substation circuit breakers last past 50-60 years; and few wooden utility poles last past 60 years. Bumby et al. (2010) assume that for medium-voltage electricity distribution systems, overhead cables last 30 to 50 years, and underground cables last 20 to 40 years. Wang and J.-L. Bessède (2015) assume a life of 60 years for equipment for transmission and distribution networks. Willis (2004, p. 258) writes that, in the electricity distribution system, most electrical

			equipment has a service life of about 40 years (depending on ambient conditions, loading, faults, and so on); overhead conductors have a life of at least 60 years; poles have a life of 40-75 years; and steel structures last up to 100 years.
Assumed annual rate of return in utility calculations (%/year)	10.00	12.00	Powercor Australia (2012) uses a real 12% discount rate. In an example calculation, the DOE (2007, p. 3-12) assumes that Southern California Edison's fixed charge rate is 12% per year. We think this is an upper bound.
Assumed amortization period in utility calculations (years)	20	10	Woo et al. (1995) cite an example of amortizing over a 10-year period, but this seems like a low end.
O&M, annual fraction of capital cost ($/kW/year basis)	0.05	0.10	Willis (2004) believes that the range is 3% to 12%.
Calculated results			
Implied growth in distribution system capacity (billion kW/year)	0.0114	0.0136	
Estimated replacement of old distribution system capacity (billion kW/year)	0.0158	0.0122	
Cost per kW of distribution system capacity ($/kW)	441	542	Includes cost of expansion and cost of replacement and upgrades.
Amortized capital cost of distribution system ($/kWh-electricity)	0.010	0.023	
Total levelized cost of distribution system ($/kWh-electricity)	0.014	0.036	Amortized capital cost plus O&M costs.

Notes: EPRI= Electric Power Research Institute; DOE = Department of Energy; O&M = operations and maintenance.

The calculated cost in Table S27, about $500/kW, is consistent with several other estimates. Knapp et al. (2000) estimate that the marginal distribution capacity cost for several utilities in the U. S. ranges from about $200 to $2000/kW. Similarly, Willis (2004) gives a number of estimates that indicate that distribution systems in the U. S. cost in the range of $200/kW to more than $1000/kW. Willis' (2004) estimate breaks down as follows:

• Substations cost around $20-$30/kW. The $/kW costs are much higher in urban areas, but decrease with increasing capacity.

• The feeder distribution system, up to but not including the service system, costs from $10 to $30/kW-mile, or $100 to $900/kW for 10 to 30 miles of system. (In an example calculation, Willis [2004, p. 619] assumes a feeder system with 25.6 miles.)

• The service system, including transformers for the drop to utilization voltage, local neighborhood lines at utilization voltage, and the service drop, costs about $60/kW-transformer capacity.

Our estimated capital cost, along with our assumptions regarding lifetime and discount rate, result in a levelized electricity distribution cost of $ 0.14 to $0.036/kWh-electricity (Table S27), which is consistent with EIA's estimates that the average price of electricity distribution in the U. S. between 2005 and 2010 was $0.024/kWh-electricity (EIA, 2010).

We recognize that different components of a distribution system can have different capacity values, and that the capacity for a particular component is not necessarily fixed in all circumstances (DOE, 2007, p. 3-10), but for our purposes it is adequate to use a single capacity value for distribution systems.

Table S28 shows estimates from NREL's *Jobs and Economic Development Impact* (*JEDI*) transmission model. (*JEDI* is discussed in the major sections on jobs created in the 100% WWS scenario.)

Table S28. Costs and jobs per km of high-voltage transmission line.

SYSTEM CHARACTERISTICS										
Transmission line voltage (kV)	230	230	765	500	500	500	500	345	345	345
Transmission line type	AC	AC	AC	DC	DC	DC	DC	AC	AC	AC
Transmission line length (km)	32.2	1287	1287	1287	3218	3218	1931	644	644	644
Terrain classification	Flat w/access	Flat w/access	Flat w/access	Flat w/access	Flat w/access	Flat w/access	Flat w/access	Flat w/access	Rolling	Flat w/access
Population density classification	Rural	Rural	Rural	Rural	Rural	Rural	Rural	Rural	Rural	Near town
Construction period (months)	5.0	200	100	100	250	250	150	67	67	67
Voltage grid side of transformer (kV)	69	69	69	69	69	230	115	69	69	69
JOBS (jobs/km except as noted)										
During construction period										
Direct: project development, onsite-labor	2.1	1.8	5.9	4.0	3.9	3.9	3.9	3.3	3.7	3.8
Indirect: equipment, supply-chain	0.5	0.4	1.1	0.7	0.7	0.7	0.7	0.6	0.7	0.7
Induced Impacts	0.7	0.6	1.5	1.1	1.0	1.0	1.1	0.9	0.9	1.0
Total construction jobs	**3.3**	**2.8**	**8.5**	**5.8**	**5.7**	**5.7**	**5.8**	**4.8**	**5.3**	**5.5**
Multiplier for induced jobs	1.28	1.25	1.21	1.24	1.23	1.23	1.23	1.22	1.22	1.22
During operating years (annual)										
Direct: onsite labor impacts	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Indirect: local revenue, supply-chain	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Induced Impacts	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total operations jobs	**0.063**	**0.062**	**0.063**	**0.063**	**0.063**	**0.063**	**0.063**	**0.062**	**0.062**	**0.062**
Multiplier for induced jobs	1.21	1.22	1.24	1.24	1.24	1.24	1.24	1.22	1.22	1.22

Table S28, continued.

COST (million $/km)										
Line cost	$0.50	$0.50	$1.28	$0.82	$0.82	$0.82	$0.82	$0.69	$0.76	$0.81
Total system cost	$0.96	$0.57	$1.47	$1.50	$1.14	$1.14	$1.30	$0.81	$0.89	$0.94
Annual direct O&M (% of total cost)	0.78%	1.20%	0.46%	0.45%	0.59%	0.59%	0.52%	0.84%	0.77%	0.73%
Difference w.r.t prior column		Increase length of line	Increase line voltage	Switch to HVDC (and lower voltage)	Increase line length	Increase grid-side voltage	Base case for HVDC (reduce length, grid-side voltage)	Base case for AC, change to AC, reduce line length, reduce grid-side voltage	Change terrain to rolling	Change terrain back to flat, change population density to near town

Notes.

From NREL's *JEDI* transmission model (NREL, 2013).

Costs are millions of dollars in year 2012 dollars. Construction period related jobs are full time equivalent jobs for one year. "During operating years" represent impacts that occur from maintenance and repair operations/expenditures. All model cases are for a project located in Texas, starting construction in 2014.

The results indicate that the cost of the line itself (excluding the substation) is proport to line length and to (approximately) the 0.75 power of voltage. Most O&M costs pert the line itself and are fixed at $10,675/mile; a portion pertain to substations and are r to system voltage. As shown in Table S28, the annual O&M cost typically is between and 1.0% of the total system cost.

Table S29 shows the *JEDI* transmission model construction-cost multipliers for terrain and population density.

Table S29. NREL's *JEDI* transmission line model construction cost multipliers.

Terrain Class	**Multiplier**
Desert/remote	1.1
Farmland	1.0
Flat w/access	1.0
Mountainous	1.3
Rolling	1.1
Population Density Class	
In town	1.3
Near town	1.2
Rural	1.0
Line Length Cost Multiplier	
Equal to or greater than 20 miles	1.0
less than 20 miles	1.0

Notes. From NREL's *JEDI* transmission-line model (NREL, 2013). All of the multipliers pertain construction of the transmission line itself; i.e., not to the substations and the rest of the transmission s and not to O&M costs.

Powercor Australia et al. (2012) assume operating and maintenance expenditures for 1 the capital cost per year, for projects that augment the transmission connection and transmission capacity in the KTS supply area in Australia.

We effectively assume "ideal" distribution-system planning areas, which accordi PG&E have uniform load distributions and growth rates, a single primary distrib voltage, and strong ties among substations within the area but no ties to substations o of the area (Woo et al., 1995, p. 115).

Woo et al. (1995) assume that at the end of life equipment has no value because sa value is offset by removal cost.

S7.4. Transmission and Distribution Costs in the 100% WWS Scenario

<u>Overview</u>

Papaefthymiou and Dragoon (2016) outline the key components of a future power s based on 100% renewable energy, including demand management, expanded transmi networks, and distribution networks transformed into "smart" grids.

Note on recovering sunk cost

In the low-cost case, we assume that there will be relatively little prematurely retired equipment, and that some of the retired equipment can be re-purposed. For example, Papaefthymiou and Dragoon (2016) note that decommissioned power-plant generators can be redeployed as synchronous condensers used to help control reactive power in electricity grids.

Papaefthymiou and Dragoon (2016) note,

Wind and solar power plants typically inject power into the grid through power inverters. A largely untapped advantage of power inverters is their potential controllability. For example, inverters can be designed and instructed to provide the inertia properties of synchronous generators. The controllability of these devices adds to the complexity of the control and communication problem in operating the smart grid of the future. Despite the uncertainties, there are good indications that solar and wind re- sources can provide the needed services although further research and development is needed (p. 73).

In the 100% WWS scenario there will be many more electric vehicles, and hence much more EV charging, than in the BAU. Kessler et al. (2014) note that battery chargers can "supply power quality functions, such as reactive power compensation (inductive or capacitive), voltage regulation, harmonic filtering, and power factor correction, without the need of engaging the battery with the grid, thereby preserving their lifetime" (p. 6779). (It is likely, though, that this additional use of chargers will affect the lifetime of the chargers themselves.) As Kisacikoglu et al. (2015) note in a similar paper:

Today, in the utility grid, reactive power consumed at the residential load is compensated using capacitor banks, static VAR compensators, static synchronous compensators, etc. However, compensation of the reactive power very close to the residential load is more efficient and reduces the installation and maintenance costs associated with the aforementioned devices. Therefore, on-board chargers could be suited to sup- port advanced functions with limited modifications to the conventional topologies. Furthermore, reactive power support does not affect the battery state of charge (SoC) or battery lifetime. The ac–dc converter losses during reactive power compensation is supplied by the utility grid and, therefore, battery SoC is preserved (p. 767).

Kessler et al. (2014) describe, simulate, and bench-top test a control strategy for an *off*-board PEV charger with a three-phase ac-dc converter for battery charging and reactive power support; Kisacikoglu et al. (2015) design and implement a single-phase *on*-board bidirectional PEV charger that provides reactive power support in addition to charging the vehicle. See also Kisacikoglu et al. (2013).

As Papaefthymiou and Dragoon (2016) note, PV inverters can be controlled to provide grid-support services, such as reactive power control. Along these lines, Hassaine et al. (2009) describe a simple control strategy to regulate the reactive power from grid-connected PV inverters. Similarly, Turitsyn et al. (2010) suggest a local control scheme that dispatches reactive power from local PV inverters in order to simultaneously improve power quality and reduce power losses over the entire local distribution circuit.

More generally, both wind and solar generators can provide multiple grid-support services (Milligan et al., 2015; ReserviceS, 2014, 2013a, 2013b).

See Papaefthymiou and Dragoon (2016) for a list of policy actions to ensure a successful transition to an electricity system based on 100% variable renewable energy sources.

Distributed generation systems, such as rooftop photovoltaics, can supply end-use power without using (all parts of) the electricity distribution network, and thereby can defer the need to expand the capacity of the distribution network as total electricity demand grows (Woo et al., 1995; Hoff and Wenger, 1996; DOE, 2007; Hu and Li, 2012a,b; Cohen et al., 2015; Anaya and Pollitt, 2015).

There are a number of technical issues associated with managing reverse power flows, from distributed generators such as rooftop PVs, back through transformers to the low- and medium-voltage distribution network (e.g., Cipcigan and Taylor, 2007). We assume that addressing these issues (e.g., Liang et al., 2013) does not significantly increase the $/kW cost of the distribution system. For example, in regards to the changes in voltage regulation required by the introduction of distributed PVs, Cohen et al. (2015) estimate that any increase in the maintenance cost of voltage regulators is trivial, and note that their "earlier engineering simulations suggest feeder location and design can significantly impact the likelihood that PV will create voltage problems, suggesting that proactive distribution planning may serve to avoid these voltage problems altogether at relatively low cost" (p. 17).

Zhou et al. (2014) perform a cost-benefit assessment of the use of flexible EV charging to absorb peak renewable generation in excess of (non-EV) demand, to avoid having to curtail renewable generation. They assume that existing grid management hardware can (or, we add, in the future BAU scenario will be able to) handle monitoring and controlling EV charging, and that the cost of programing this equipment for EV-charging management is trivial.

Losses of electrical energy and "wear and tear" on the T&D system are especially sensitive to peak load, as opposed to average load, because of the greater stress and higher temperatures at peak loads. As DOE (2007) writes, "reductions in peak load can reduce 'wear and tear' on electric delivery equipment, thus reducing maintenance costs, extending equipment life, and reducing overall capital investment requirements" (p. 3-19).

The lifetime of major distribution-system equipment, such as transformers, is a nonlinear function of average and peak loading. A 100% WWS system will have a higher-capacity T&D system, and more distributed generation, than will a BAU T&D system. Whether these differences increase or reduce the aging of major equipment depends on the differences in load profiles in the 100% WWS scenario vs. the BAU – differences which depend mainly on how the system is designed and operated. For example, if on balance generation from rooftop PVs reduces power flows through transformers, then the life of transformer probably will increase, perhaps by 10% or more (Pezeshki et al., 2014). However, if installed PV capacity is large enough to produce large reverse power flows, from customers back to the low-voltage network, then the lifetime of transformers might decrease (Cohen et al., 2015).

Similarly, line losses on distribution are mainly a function of current levels, all else equal, and so rooftop PVs will decrease losses unless they generate large reverse power flows.

On the assumption that excess rooftop PV generation is not fed from the medium-voltage distribution network back to the high-voltage transmission system, then for the purpose of calculating the cost and efficiency of the baseline transmission system, distributed generation should be excluded from the assumed capacity requirements.

Pickard (2013) assumes a 65-year life for transmission line systems

Clack et al. (2015) use linear programming to develop an optimal electrical system including HVDC transmission and storage. In an example test case involving solar PV, onshore wind, and natural gas generation with an HVDC system for the contiguous US, they find that the cost-optimizing (minimizing) configuration of the transmission system results in a transmission capacity about 40% of generating capacity and an average transmission utilization (the ratio of total actual electricity throughput to potential throughput at continuous maximum capacity) of about 30%.

MacDonald et al. (2016) use the optimization techniques in Clack et al. (2015) to find the cost-optimal networks of wind, solar, and natural-gas generators connected by a US-wide HVDC transmission network. In a system with a single national HVDC network and low-cost wind and solar power and high-cost natural gas (along with constant amounts of hydro and nuclear power), the curtailment of wind and solar is only 7.6% of the generation from these sources, or 4.2% of total generation. (In this system, nuclear provides 16% of the total generation, hydro provides 8%, and natural gas provides 21%.)

Bahrman and Johnson (2007) present estimates of the capital costs of HVDC systems of different power ratings and transmission lengths (Table S31.A).

The *Power Distribution Planning Reference Book* (Willis, 2004) provides the most authoritative single source of information relevant to our simple analysis of the efficiency cost of the T&D system in the BAU and the 100% WWS scenarios. The main points are

-- Core losses in transformer are constant (independent of load) and typically are less than 1% of nameplate rating
-- Load losses in transformers are related to the square of the current—
-- Transmission line costs decrease with capacity and distance; can range from at least $0.50 to $1.00/kVA-mile
-- As a general rule of thumb, operating and maintenance costs are 3% to 12% of capital costs, per year.
-- Typical load factors – the ratio of average to peak demand – appear to be in the range of 50 to 65 , with 55% being a typical value.
-- Capacity ratings and lifetime are related as follows:

"More generally, capacity ratings, particularly for transformers, motors, regulators, and other wound devices, have their basis in deterioration rate, the concept being that loading causes deterioration which shortens remaining life and enough deterioration means the unit has exhausted its life" (p. 233).

Of course, while loading is a major factor in determining lifetime, other factors, such as damage events, or "through faults" (which cause transient mechanical stresses), affect lifetime. Willis (2004) believes that 50% transformer failures are due to long-term deterioration of the insulation (a direct function of loading), 40% are due to through faults, and 10% are due to "external damages".

Willis (2004) shows a relationship between expected service lifetime (specifically, insulation half-life) and annual peak load as a percent of nameplate capacity for transformers, when the peak load is reached 37 days of the year and the overall load factor is 63% (his Figure 7.7 p. 245). The lifetime is ~55 years when the peak load is 100% of the nameplate capacity, and ~78 years when the peak load is 95% of the nameplate capacity. This implies the relationship:

$$\left(\frac{PK\%_{TF}}{PK\%_{TF,REF}}\right)=\left(\frac{L_{TF,PK\%}}{L_{TF,PK\%,REF}}\right)^{\alpha}$$

where

$PK\%_{TF}$ = The peak loading of the transformer as a percent of its nameplate capacity
$PK\%_{TF,REF}$ = The reference peak loading of the transformer as a percent of its nameplate capacity
$L_{TF,PK\%}$ = The lifetime of the transformer at $PK\%_{TF}$ (years)
$L_{TF,PK\%,REF}$ = The lifetime of the transformer at $PK\%_{TF,REF}$ (years)
α = -6.81

Here we use Willis' (2004) definition: "Lifetime ends when a unit is no longer worth retaining, either because it cannot be repaired, because it is not worth repairing, or because it does not perform well enough to meet current needs" (p. 247).

Willis (2004) states that lifetime also is a function of equipment design and maintenance practices.

Global Data (2013) show a graph of average \$/kW price of HVDC converter stations as a function of capacity, from less than 100 MW to more than 8,000 MW; the slope indicates that the \$/kW price of a 1,000-MW station is about double the \$/kW price of a 5,000-MW station. This implies the relationship:

$$\left(\frac{CC_{HDVCC,P}}{CC_{HVDCC,P_{REF}}}\right)=\left(\frac{P_{HDVCC}}{P_{HVDCC,REF}}\right)^{\alpha}$$

where

$CC_{HVDCC,P}$ = The capital cost of an HVDC converter station of power *P* (\$/kW)

$CC_{HVDCC,P_{REF}}$ = The capital cost of an HVDC converter station of reference power P_{REF} ($/kW)
P_{HDVCC} = The power of the HVDC converter station (MW)
$P_{HVDCC,REF}$ = The reference power of the HVDC converter station (MW)
α = -0.43

The estimates of Bahrman and Johnson (2007), shown in Table S31.A, suggest that α = -0.44 to -0.59 in the relationship between relative HVDC station $/kV cost and station voltage.

These results are generally consistent with the earlier finding of Paris et al. (1984) that α = -0.40 in the relationship between power and total transmission cost.

Knapp et al. (2000) show the cost of distribution system transformers of ranging from 25 kVA to 2500 kVA capacity; a rough approximation of the relationship is

$$\left(\frac{C_{DTF,P}}{C_{DTF,P_{REF}}}\right)=\left(\frac{P_{DTFC}}{P_{DTF,REF}}\right)^{\alpha}$$

where

$C_{DTF,P}$ = The cost of a distribution-system transformer of power *P* ($/kVA)
$C_{DTF,P_{REF}}$ = The cost of distribution-system transformer of reference power P_{REF} ($/kVA)
P_{DTF} = The power of the distribution-system transformer (kVA)
$P_{DTF,REF}$ = The reference power of the distribution-system transformer
α = -0.50

However, Willis (2004) says that his experience is that transformer total cost varies as the 0.8 root of capacity, which means that in the following relationship, α^* = 0.80:

$$\left(\frac{C_{DTF,P}}{C_{DTF,P_{REF}}}\right)=\left(\frac{P_{DTFC}}{P_{DTF,REF}}\right)^{\alpha^*}$$

where the cost parameter here is the total cost, rather than the cost per kW. To convert to cost per kW:

$$\left(\frac{C^*_{DTF,P}}{C^*_{DTF,P_{REF}}}\right)\cdot\left(\frac{P_{DTFC}}{P_{DTF,REF}}\right)^{-1}=\left(\frac{P_{DTFC}}{P_{DTF,REF}}\right)^{\alpha^*}\cdot\left(\frac{P_{DTFC}}{P_{DTF,REF}}\right)^{-1}$$

$$\frac{C_{DTF,P}}{C_{DTF,P_{REF}}}\equiv\frac{\dfrac{C^*_{DTF,P}}{P_{DTFC}}}{\dfrac{C^*_{DTF,P_{REF}}}{P_{DTF,REF}}}$$

$$\alpha=\alpha^*-1$$

Therefore Willis' (2004) estimate translates into a value of α = -0.20.

IRENA (2015c) reports an estimate that the price of an HVDC converter stations can vary by a factor of three, from, for example, \$100/kW in China to \$275/kW in Germany. However, it is not clear how much of this is due to real differences in costs and how much is due to differences in non-cost components of price (e.g., taxes and subsidies) or exchange rate conventions.

We have re-examined the sources Delucchi and Jacobson (2011) use to estimate in detail the cost of long-distance, high-power HVDC transmission.

NREL's *JEDI* transmission model (NREL, 2013) estimates that O&M costs for transmission lines, including substations, is 0.6% of the total project cost, per year. (The *JEDI* model is discussed in the major section on jobs created in the 100% WWS scenario.)

<u>Additional long-distance HVDC transmission</u>
We assume that, in order to help balance supply and demand, some significant portion of the entire country's WWS generation will have to be transmitted through additional (newly constructed w.r.t to the BAU) onshore, long-distance, HVDC networks. We calculate the fully amortized cost of power actually sent through the additional HVDC system, and then multiply this cost per kWh-transmitted by the ratio of kWh through the additional system to total kWh required by end users, to come up with a system-wide additional transmission-cost "adder". We assign the additional on-shore transmission cost to all generators – the entire WWS system – because the need for additional transmission is based on supply and demand balancing considerations over the entire system.

We assume that additional HVDC transmission systems connect to AC distribution networks. Since the cost and efficiency of AC distribution is accounted for separately, so here we estimate the cost of additional HVDC per kWh transmitted out of the HVDC network and into the AC distribution system.

Note on system optimization

We emphasize that we have not attempted to find the least-cost configuration of transmission and distribution, generator location and mix, storage, demand management, and so on. Instead, we have estimated the cost of a system that we think plausibly, reliably will match supply and demand. We note also that because we are considering 100% WWS systems, rather than WWS systems integrated with conventional fossil and nuclear generators, that there are no system "integration" costs as estimated in other studies (e.g., Hirth et al., 2015; IRENA 2015d; Ueckerdt et al., 2013).

IRENA (2015e)'s analysis of the costs and benefits of "smart" grids and renewables indicates that the additional costs of advanced meters, distribution automation, smart inverters, demand-response, and so on, are relatively small.

Transmission and distribution efficiency

We estimate transmission and distribution efficiency in the BAU using IEA estimates of historical electricity transmission and distribution losses by country and EIA *IEO* projections of transmission and distribution efficiency by region.

<u>BAU scenario, to 2012</u>

The IEA reports data on electricity consumption, electricity "own use" in industry, and transmission and distribution losses, by country, through the year 2013 (IEA, 2015c).[8] We use the IEA data to calculate the efficiency of transmission and distribution through 2012 as the ratio of electricity end-use to net generation, as follows:

$$eff_{ETD,C,Y_{to2012}} = \frac{E_{El,TFC,C,Y_{to2012}} + E_{El,EIOU,C,Y_{to2012}}}{E_{El,TFC,C,Y_{to2012}} + E_{El,EIOU,C,Y_{to2012}} + E_{El,TD-loss,C,Y_{to2012}}}$$

where

$eff_{ETD,C,Y_{to2012}}$ = efficiency of electricity transmission and distribution in country C through 2012

$E_{El,TFC,C,Y_{to2012}}$ = total final consumption of electricity in country C through 2012 (GWh) (IEA data)

$E_{El,EIOU,C,Y_{to2012}}$ = energy-industry "own use" of electricity in country C through 2012 (GWh) (IEA data; we count energy-industry "own use" because it really is ordinary end-use consumption)

$E_{El,TD-loss,C,Y_{to2012}}$ = losses in electricity transmission and distribution in country C through 2012 (GWh) (IEA data)

<u>BAU scenario, 2013-2030</u>

The EIA's *IEO 2016* projects T&D efficiency by *IEO* region (EIA, 2016a). The EIA starts with *IEA* data on annual T&D losses by country for the period of 2001 to 2012 (the same data we use, above), and then estimates regional T&D efficiency for 2001 to 2012. EIA then uses its judgment to project regional T&D efficiency for the period 2013 to 2050 (EIA, 2016c). However, the EIA assumes no changes in T&D efficiency for any region after the year 2030.

We use the EIA's projections as the basis for our estimates of T&D efficiency for the period 2013 to 2030. We adjust the EIA regional projections so that the efficiency improvement in countries with a relatively low T&D efficiency is greater than the regional-average improvement, and the efficiency improvement in countries with a relatively high T&D efficiency is less than the regional average. We also make sure that T&D efficiency stays within upper and lower limits. Formally,

$$eff_{ETD,C,Y} = \min\left[eff_{ETD,\max}, \max\left[ff_{ETD,\min}, eff_{ETD,C,Y-1} \cdot \left(\frac{eff_{ETD,R:C\in R,Y}}{eff_{ETD,R:C\in R,Y-1}} \right)^{\left(\frac{eff_{ETD,C,Y-1}}{\beta_{eff-ETD}}\right)^{\alpha_{eff-ETD}}} \right] \right]$$

where

$eff_{ETD,C,Y}$ = T&D efficiency in country *C* in year *Y*

$eff_{ETD,\max}$ = the maximum allowable T&D efficiency (98.0%, based on the assumption that minimum possible losses from a distribution system are 2.0%)

$ff_{ETD,\min}$ = the minimum allowable T&D efficiency (65%)

$eff_{ETD,C,Y-1}$ = T&D efficiency in country *C* in year *Y-1* (note that the first year *Y-1* is the last year of historical data)

$eff_{ETD,R:C\in R,Y}$ = T&D efficiency in *IEO* region *R* (containing country *C*) in year *Y* (EIA, 2016c)

$eff_{ETD,R:C\in R,Y-1}$ = T&D efficiency in *IEO* region *R* (containing country *C*) in year *Y-1* (EIA, 2016c)

$\alpha_{eff-ETD}$ = exponent to amplify or dampen efficiency improvement relative to a reference value (see discussion below)

$\beta_{eff-ETD}$ = reference value for determining "flex" point in amplification (see discussion below)

The parameter $\beta_{eff-ETD}$ is the reference "flex" efficiency: for any $eff_{ETD,C,Y-1} < \beta_{eff-ETD}$, the effect of $\left(\frac{eff_{ETD,C,Y-1}}{\beta_{eff-ETD}}\right)^{\alpha_{eff-ETD}}$ is to amplify the efficiency improvement relative to the regional average, and vice versa. We choose a value of 90% for $\beta_{eff-ETD}$. To specify $\alpha_{eff-ETD}$, we first estimate the T&D efficiency after 10 years as a function of different values of $\alpha_{eff-ETD}$ and different T&D efficiencies at the start of the 10 years ($eff_{ETD,0}$), assuming $\beta_{eff-ETD}$ = 90% and $\frac{eff_{ETD,R:C\in R,Y}}{eff_{ETD,R:C\in R,Y-1}}$ = 1.001 or 1.004, which spans the range of values in the EIA *IEO* projections. Table S30 shows the results.

Table S30. T&D efficiency after 10 years as a function of $eff_{ETD,0}$ and $\alpha_{eff-ETD}$, for $\beta_{eff-ETD}$ = 90%.

S30.A. $\dfrac{eff_{ETD,R:C\in R,Y}}{eff_{ETD,R:C\in R,Y-1}}$ **= 1.001**

$eff_{ETD,0}$	$\alpha_{eff-ETD}$						
	-3.00	-4.00	-4.50	-5.00	-5.50	-6.00	0.00
65.0%	66.7%	67.4%	67.9%	68.4%	69.0%	69.7%	65.7%
70.0%	71.5%	71.9%	72.2%	72.5%	72.8%	73.2%	70.7%
80.0%	81.1%	81.3%	81.4%	81.5%	81.5%	81.6%	80.8%
85.0%	86.0%	86.1%	86.1%	86.1%	86.2%	86.2%	85.9%
88.0%	88.9%	89.0%	89.0%	89.0%	89.0%	89.0%	88.9%
90.0%	90.9%	90.9%	90.9%	90.9%	90.9%	90.9%	90.9%
92.0%	92.9%	92.8%	92.8%	92.8%	92.8%	92.8%	92.9%
95.0%	95.8%	95.8%	95.7%	95.7%	95.7%	95.7%	96.0%
98.0%	98.8%	98.7%	98.7%	98.6%	98.6%	98.6%	99.0%

S30.B. $\dfrac{eff_{ETD,R:C\in R,Y}}{eff_{ETD,R:C\in R,Y-1}}$ **= 1.004**

$eff_{ETD,0}$	$\alpha_{eff-ETD}$						
	-3.00	-4.00	-4.50	-5.00	-5.50	-6.00	0.00
65.0%	72.3%	75.3%	77.2%	79.6%	82.6%	86.1%	67.6%
70.0%	76.2%	78.1%	79.2%	80.5%	82.1%	83.8%	72.9%
80.0%	84.7%	85.3%	85.6%	86.0%	86.3%	86.7%	83.3%
85.0%	89.1%	89.4%	89.5%	89.6%	89.8%	89.9%	88.5%
88.0%	91.8%	91.9%	92.0%	92.0%	92.1%	92.1%	91.6%
90.0%	93.7%	93.7%	93.7%	93.7%	93.7%	93.7%	93.7%
92.0%	95.5%	95.4%	95.4%	95.3%	95.3%	95.3%	95.7%
95.0%	98.3%	98.1%	98.0%	97.9%	97.9%	97.8%	98.9%
98.0%	101.1%	100.8%	100.7%	100.6%	100.5%	100.4%	102.0%

Table S30 also shows the results when $\alpha_{eff-ETD}$ = 0, which eliminates the effect of amplification or dampening. On the basis of the results shown in Table S30, we believe $\alpha_{eff-ETD}$ = -5.00 gives reasonable results.

BAU scenario, beyond 2030

We estimate the T&D efficiency over the period 2030 to 2040 based on a 3-year moving linear extrapolation, subject to the same minimum and maximum values used above. Beyond 2040 we assume that the efficiency remains at the year 2040 value.

HVDC is more efficient and more economical than is HVAC to transmit very high power flows over long distances. In the simplest terms, an HVDC transmission system comprises the following:

- a converter station that rectifies the AC power incoming from a generating station;
- a monopolar or bipolar HVDC cable from the rectifying converter to a load center;
- a converter station that inverts the DC power to AC for distribution to the load center.

HVDC transmission systems can use either voltage-source converters (VSCs) with insulated-gate bipolar transistors (IGBTs) or line-commutated converters (LCCs) with thyristors. Generally, LCC-HVDC transmission is more efficient and cost-effective for transferring high levels of power over long distances (Barnes and Beddard, 2012). Today, most HVDC projects use LCCs (Wikipedia, 2016c). However, with shorter distances and lower power levels, as in the case of connecting offshore wind farms to shore, VSC-HVDC transmission can be attractive (Liang and Feng, 2015; Smith et al., 2013; Flourentzou 2009; Bresesti et al., 2007; Ackermann, 2002).

Upper and lower limits on the length of additional HVDC transmission lines in a super-grid developed for 100% WWS systems

The upper limit of HVDC transmission length is economic. At some point, the capital and energy-loss costs of extending the new HVDC transmission system likely exceed the costs of other methods of ensuring that supply meets demand (e.g., using storage) over the entire super-grid area. However, because we do not do a least-cost demand-matching optimization over all possible supply-demand matching options, we have no basis for imposing upper limits on HVDC transmission length for any particular new super-grid system. Therefore, in our analysis, the maximum length of HVDC transmission in a new super-grid system is a function of the total physical area of the countries in the super-grid.

Separating transmission and distribution efficiency

According to the International Electrotechnical Commission (2007), transmission losses (between the power plant and the step-down substation leading into the low-voltage network) range between 3% and 5%, and distribution losses (between the step-down substation and users are in “the same range or even greater” (p. 8). We assume that generally losses from the distribution system are 55% of total losses from the transmission and distribution system.

Here we analyze the efficiency and cost of a land-based LCC-HVDC system, operating at very high power (6400 MW; two 800-kV cables at 4000-A each), and an offshore VSC-HVDC system operating at 1200 MW (two 400-kV cables at 1500-A each).

ABB reports that a 2000-km, 800-kVDC line loses 5% of the electricity to heat (ABB, 2016b). A separate document states that "converter station losses are normally as low as 0.6% per station" (presumably for LCCs) and that DC cable losses are 3-4% per 1000 km (ABB, 2016a). A recent master's thesis states that LCCs have losses of 0.8% per converter (Kjørholt, 2014, p. 7).

Pickard (2013) assumes a 750 kV, 667-A cable with a resistance of 0.0263 Ω/km.

Clack et al. (2015) use linear programming to develop an optimal electrical system including HVDC transmission and storage. In an example test case involving solar PV, onshore wind, and natural gas generation with an HVDC system for the contiguous US, they find that the cost-optimizing (minimizing) configuration of the transmission system results in a transmission capacity of about 40% of generating capacity and an average transmission utilization (the ratio of total actual electricity throughput to potential throughput at continuous maximum capacity) of about 30%.

Table S31 presents estimates of losses in HVDC systems. In part A, Bahrman and Johnson (2007) present estimates of the costs of and losses in HVDC systems of different power ratings and transmission lengths. Bahrman and Johnson (2007) also note that full-load converter station losses are 9.75% per station, and that total substation losses (transformers, reactors) are assumed to be 0.5% of rated power.

In Table S31 part B, Kalcon et al. (2013) present methods for estimating losses from HVDC transmission based on VSCs using IGBTs. They consider several components and losses for a system with a nominal input power of 200 MW.

Negra et al. (2006) estimate transmission-system losses for an HVAC transmission system, an LCC-HVDC system, and a VSC-HVDC system connecting 500 and 1000 MW off-shore wind farms up to 200 km from shore. Table S31 part C shows their estimates for the LCC-HVDC system.

Table S31. Estimates of losses in HVDC systems.

S31.A. Bahrman and Johnson (2007).

	500 kV bipole	2-500 kV bipoles	600 kV bipole	800 kV bipole
Rated power (MW)	3,000	4,000	3,000	3,000
Maximum voltage (kV)	500	500	600	800
Number of cables	2	4	2	2
Max amps per cable	3,000	2,000	2,500	1,875
Trans. Distance (miles)	750	1500	750	750
Station cost incl. reactive compensation (million $)	$420	$680	$465	$510
Transmission line cost (million-$/mile)	$1,200	$2,400	$1,350	$1,463
Losses at full load (%)	6.44%	3.35%	4.93%	3.43%

Source: Bahrman and Johnson (2007, p. 39). We assume their cost estimates are in year-2006 US dollars. Maximum amps per cable is our calculation; all other figures directly from Bahrman and Johnson (2007).

S31.B. Kalcon et al. (2013).

Component	Loss function	Loss	Comments
Transformers and AC filters	general form $i^2 \cdot r$	0.6 MW (0.3% of input) each end	Transformer resistance 0.2178Ω
2-level VSCs with IGBTs	switching and conduction losses (general form $i \cdot v + i^2 \cdot r$)	2.4 MW (1.2% of input) each end	We note that Barnes and Beddard (2012) show losses of 1% to 1.4% per converter for recent VSC systems
DC cables	joule heating ($i^2 \cdot r$)	1.5 MW (5% of input per 1000 km)	DC cable (~ 400 kV) resistance 0.0125 Ω/km; 150 km cable

Source: Kalcon et al. (2013).

S31.C. Negra et al. (2006), analysis for LCC-HVDC system.

Component	Loss function	Loss	Comments
LCC converter stations (filters, transformers, thyristor converters, smoothing reactor, other)	not used	0.11% (no load) to 0.7% (100% load) of rated power, each end	It appears that losses from VSC stations are at least twice as high
DC cables	$i^2 \cdot r$ and temperature function	~3% of the cable rated power per 1000 km	450 kV, 1333 amp DC cable resistance 0.011 Ω/km

Source: Negra et al. (2006).

DOE (2007, p. 3-19) discusses a report indicating that the use of distributed generation can increase the efficiency of the distribution network by eliminating low and high-voltage buses, improving network voltage profiles, and reducing the amount of "power stress" in the system.

In 2015, the seven member countries of Bimstec (Bangladesh, Bhutan, India, Myanmar Nepal, Sri Lanka, and Thailand) finalized a draft deal to set up power grid connections between the countries (Karim, 2015).

S7.5. Cost of Ancillary Services in the Power Sector

Overview

In general, power-system operators must balance generation and load and keep voltage and frequency within prescribed limits. These monitoring and control actions often are called "ancillary services".[8] In some analyses of the costs and pricing of the power system, ancillary services are treated separately from the cost of electricity generation and the cost of electricity T&D. In this section we review ancillary services and explain how we

[8] The Federal Energy Regulatory Commission (FERC) glossary defines "ancillary services" as:

"those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system. Ancillary services supplied with generation include load following, reactive power-voltage regulation, system protective services, loss compensation service, system control, load dispatch services, and energy imbalance services" (FERC, 2016).

incorporate them into either generation costs or T&D costs, for both the BAU and the WWS scenarios.

The main purpose of ancillary services is load balancing, to "provide the resources the system operator requires to reliably maintain the instantaneous and continuous balance between generation and load" (Kirby, 2004, p. 3). Ancillary services used for grid balancing can be classified in different ways, according to whether they pertain to routine-operation imbalances between supply and demand or to unanticipated disruptions, how quickly they can respond to an imbalance, and how long they can be deployed. Our classification of ancillary services, based on Ela et al. (2011), the North American Electric Reliability Council (NERC, 2011), and Kirby (2004), distinguishes operating reserves for routine regulation, operating reserves for contingencies, voltage control, time control, and reactive-power control.

Operating reserves for routine regulation (also called "regulating reserve," "frequency regulation," or "frequency response") are capacity available for the automatic or manual control of generation sources on-line in order to "to track the minute-to- minute fluctuations in system load and to correct for unintended fluctuations in generator output" (Kirby, 2004, p. 3) during the routine (un-disrupted) operation of the grid. In North America, balancing authorities monitor and control the frequency of the grid within large "interconnection" regions, which are frequency-independent "islands" within which all generators and end-users are connected (NERC, 2011). If the frequency of the power system is increasing, then generation exceeds end-usage, and reversely. (This can be understood intuitively: if the rate of consumption is less than the rate of generation, then the differential will cause the generating machines to accelerate, and the resulting increase in angular velocity will be manifest as an increase in frequency.) The balancing authorities adjust generator output, demand from interruptible or curtailable loads, or energy to or from storage, in the most economical fashion (if there is sufficient time for economic dispatch), in order to return the frequency to the target value (60 Hz in North America) (NERC, 2011). For example, in modern power systems with turbine generators with output synchronized to the grid frequency, routine regulation can be accomplished by adjusting the mechanical output of the turbine, because changes in the angular velocity of turbine generators are proportional to changes in the frequency of synchronous generators. As mentioned above, energy storage devices such as batteries, and curtailable or interruptible loads also can be used for routine regulation (Ela et al., 2011).

Operating reserves for contingencies are unloaded power sources (constituting generating capacity in excess of load demand) reserved for responding to unanticipated, non-trivial transmission or generation outages. Often these reserves are further classified according to how quickly they can respond to outages; for example, in Kirby's (2004) classification, "spinning reserves" are already online, actually "spinning" and synchronized with the grid frequency, and can respond within seconds; "supplemental reserves" respond more slowly than do "spinning reserves, and need not be online; and "replacement reserves" have a 30-minute response time and are "used to restore spinning and supplemental reserves to their pre-contingency status" (Kirby, 2004, p. 3).

Voltage control is used to maintain system voltages within required ranges. Voltage can be controlled by a number of methods, including adjusting "reactive" power flows or changing the output of voltage transformers in the T&D system (see the discussion of reactive power next).

Time control. This is the maintenance of the grid frequency at the desired value, independent of the use of frequency regulation for balancing supply and demand. As NERC (2011) writes:

> The Time Monitor compares a clock driven off Interconnection frequency against "official time" provided by the National Institute of Standards and Technology (NIST). If average frequency drifts, it creates a Time Error between these two clocks. In the Western Interconnection, time-error-correction is done automatically through software maintained by the Time Monitor known as Automatic Time Error Correction (p. 13-14).

Reactive-power control. Reactive power is an inherent feature of an electricity system with any inductive or capacitive elements. As mentioned above, reactive power can be used to control voltage, but apart from that, as explained next it also needs to be managed to minimize current-related losses.

Reactive power in the electricity system is the cyclical flow of stored energy between the electric field of "sources" and the magnetic field of "sinks." It can be thought of as the electromagnetic-field energy "overhead" required to energize the fields that (for example) force an induction motor to rotate and provide mechanical power that does useful work. When a voltage is placed across the coils of an induction motor (typically the largest "sink" of reactive power in the grid), a magnetic field builds up and induces a current, but the current reaches its peak a bit after the peak of the voltage that originally induced it. Because in an *ac* system the voltage waveform is sinusoidal, the induced current waveform also is sinusoidal, but is offset from – occurs later in time than, or "lags" – the voltage waveform. Now, at any instant, power is the product of current and voltage. If the current and voltage wave forms are exactly in phase, the $V \cdot I$ product always will be positive, and the root-mean-square (RMS) area under the $V \cdot I$ product curve – the total energy – will be the maximum possible, because all voltage and current will pull together to produce useful work. However, if current slightly "lags" voltage, then a small portion of the $V \cdot I$ product curve will be negative, and as a result the total RMS energy available for work will be less than the maximum. This shortfall is the energy of the electromagnetic field, built up during the creation of the field and dissipated during its collapse, and the flow of this stored energy between a source and sink is "reactive power".

Although reactive power doesn't do work – as mentioned above, it is can be thought of as the field-energy "overhead" necessary to supply power for work – the current of reactive power has to be carried between sources and sinks, and this causes resistive heating and real losses. To reduce these losses, reactive power sources and sinks are located as close together as possible. For example, a "source" of reactive power, such as a capacitor, can be placed in close proximity to an induction motor "sink" of reactive power. The capacitor works in the opposite way from an inductor: the build-up of charge builds up – with a lag – an electric field, with an associated electric potential, or voltage. (The lag occurs because as the field and electric potential builds up, due to the accumulating separated, opposite charges, it is harder to add more separated, opposite charges, and hence the current slows. See the brief formal exposition following.) This offset between current and voltage waveforms also creates reactive power, just as a the offset in an induction motor does, but with voltage lagging current. The capacitor and the motor can be designed so that the voltage lag of the capacitor compensates for the current lag of the inductor, with the result that the minimum amount of reactive power flows, over the minimum distance, thus minimizing current-related losses.

Brief formal explanation of a capacitor. A capacitor consists of two minimally separated conductors that hold equal but opposite charges on their facing surfaces; between these oppositely charged faces, an electric field develops. The electric field generated by the separated charges stores electric potential energy. The work required (from an external source, such as a battery) to separate the charges and establish this electric field, and hence the electric energy stored, depends on the voltage – the energy per unit charge – as a function of the charge and the change in charge over the relevant range:

$$W = E = \int_0^Q V(q) \cdot dq$$

where

W = Work required to establish the electric field (joules)
E = Energy stored in the electric field (joules)
Q = The total charge on each conductor (coulomb)
V(q) = Voltage as a function of charge (joules/coulomb)
q = Electric charge (coulomb)

The capacitance C is defined as the ratio of the charge Q to on each conductor to voltage between them:

$$C \equiv \frac{Q}{V}$$

$$V = \frac{Q}{C}$$

$$V(q) = \frac{q}{C}$$

Thus,

$$W = E = \int_0^Q \frac{q}{C} \cdot dq = \frac{1}{2} \cdot \frac{Q^2}{C} = \frac{1}{2} \cdot C \cdot V^2$$

In an *ac* system the voltage fluctuates sinusoidally, so the stored energy fluctuates over time, and power must flow into or out of the capacitor over time. Since power P is the time derivative of the stored energy, we have

$$P = \frac{dE}{dt} = \frac{d}{dt}\left(\frac{1}{2} \cdot C \cdot V^2\right) = C \cdot V(t)\frac{dV(t)}{dt}$$

But power is also the product of voltage and current,

$$P = I(t) \cdot V(t)$$

With these equations we can write the relationship between *ac* (sinusoidally fluctuating) current and voltage in a capacitor,

$$P = C \cdot V(t)\frac{dV(t)}{dt} = I(t) \cdot V(t)$$

$$I(t) = C \cdot \frac{dV(t)}{dt}$$

We can consider the last equation to understand how current and voltage are 90 degrees out of phase in a capacitor. With a sinusoidally time-varying voltage, the first derivative is zero at the maximum and minimum voltage, and is maximum at zero voltage. Hence, the current is zero at maximum or minimum voltage, and maximum at zero voltage. Intuitively, this can be understood as follows: when the voltage is zero and there is no electric field to push against, the charge build up can, at that instant, proceed at the maximum rate. As the charge builds up, the voltage increases, from zero, but the charge build-up rate correspondingly decreases because it is working against the strengthening electric field. At the moment of maximum voltage and field strength it is not possible to store any more charge, and the current drops to zero. (This can be shown formally by expressing $\frac{dV(t)}{dt}$ as a sine function.)

An inductor is the so-called "dual" of the capacitor: it stores energy in a magnetic field instead of an electric field. The current voltage relationship is essentially the reverse, with inductance *L* instead of capacitance *C*,

$$V(t) = L \cdot \frac{dI(t)}{dt}$$

In summary, reactive power typically is the cyclical flow of stored energy between the magnetic field of an inductor and the electric field of a capacitor. This flow does not provide useful work but it does result in power losses due to the associated current. Put another way, from the standpoint of conservation of energy (or power), of the total energy initially generated in a power system, a (large) fraction goes to provide work, a small fraction is lost (i.e., not able to provide useful service) as low-grade heat, and a small fraction is stored or potential energy. "Reactive" power is energy stored in the system, but the any actual flow of reactive power still results in low-grade heat losses.

S7.6. Cost of Ancillary Services in the BAU and 100% WWS Scenarios

Table S32 summarizes our treatment of ancillary services in the BAU and the 100% WWS scenario. Generally, the cost of ancillary services in the BAU is included in our estimates of BAU T&D costs, and the cost of ancillary services in the 100% WWS scenario is estimated relative to the BAU costs.

Operating reserves and capacity factors in the BAU scenario

As stated in Table S32, the main cost of providing operating reserves is the reduction in the overall capacity factors for generators. The greater the amount of capacity reserved for routine regulation or contingencies, the more the total capacity exceeds the amount needed to supply load with no reserve, and the lower the capacity factor (the ratio of actual generation to the maximum potential generation from the installed capacity). Because our estimates of the BAU capacity factors are based on the EIA's *IEO* estimates of capacity and generation, and the "World Electricity Model" used in the *IEO* explicitly estimates reserve generating margins (EIA, 2011a, pp. 5 and 17), our capacity factors properly reflect the main cost of providing operating reserves in the BAU scenario.

Operating reserves and capacity factors in the 100% WWS scenario

We multiply the no-reserve capacity factor by a factor that accounts for the need to have capacity available as operating reserves. (Note that this multiplier, which represents capacity reserved for routine short-term supply-demand imbalances or for unplanned contingencies, is separate from what we call the "derating" multiplier, which represents *planned* "over capacity" for the purpose of ensuring that long-term average generation matches demand.)

Table S32. The cost of ancillary services in the BAU and the 100% WWS scenarios.

Ancillary service	BAU scenario	100% WWS scenario
Operating reserves	Assume that the costs of most monitoring and automatic control equipment are included in BAU T&D costs. Governors on generators presumably are included in generation costs. The main cost of providing reserves is the reduction in the capacity factors for generators. See discussion below.	We estimate the reduction in the capacity factor due to maintaining operating reserves. See the discussion below.
Voltage control	The costs of transformer and voltage regulators are included in BAU T&D costs.	We estimate these costs in the 100% WWS scenario relative to the assumed costs in the BAU. See discussion below.
Time control	Presumably included in BAU T&D costs, but in any case, undoubtedly trivial.	
Reactive-power control	Included in either T&D costs or generation costs, depending on whether the relevant equipment (e.g., a capacitor that cycles reactive power with an induction motor) is located at the site of generation or in the distribution network.	

Several studies provide information that helps us estimate this operating-reserve multiplier on the capacity factor. In the current power system, relatively little capacity is reserved for routine regulation ("regulating reserve"). Ela et al. (2011) report that the PJM Balancing Authority in North America requires the regulating reserve to be 1% of the peak load during peak hours, and 1% of the valley peak during off-peak hours. The ERCOT Balancing Authority in North America requires an additional 0-12 MW of additional "regulating reserve" capacity per 1000 MW of incremental wind generation capacity (0% to 1%), depending on the hour and month (Ela et al., 2011). The California Independent System Operator (CAISO) Balancing Authority requires a minimum of 350 MW of up and down regulating reserve (Ela et al., 2011), which is less than 1% of the total generating capacity in California (CAISO, 2015).

The total operating reserve, including the contingency reserve, of course should be larger. For example, CAISO (2015) projects that the operating reserve margin – generating capacity in excess of that needed to meet demand, as a percentage of demand – will range from 11% to about 40%, depending on scenarios regarding outages, temperature, net interchange with other systems, and other factors. However, the minimum acceptable operating reserve probably is between 5% and 10%. In NREL's resource planning model, "contingency reserve requirements in each hour are based on the maximum between 6% of the hourly demand and an absolute contingency requirement based on the single largest contingency within the system" (Mai et al., 2013, p. 50).

Costs of grid monitoring and control

Aravinthan and Jewell (2015) develop an algorithm for charging Evs that minimizes loss of life of transformers while ensuring that all vehicles are charged. They note that for "the proposed work to be implemented, power system-level communication needs to be improved" (p. 1008).

Weckx and Driesen (2015) show that three-phase PV inverters and EV chargers can be adapted to transfer power from highly loaded to less loaded phases, and thereby greatly mitigate any additional peak loading on transformers, line losses, and supply-demand imbalance due to the increased use of distributed generation and charging.

S7.7. Overall Energy, Health, and Climate Costs in the BAU Versus WWS Cases

Table S33 presents 2013 and 2050 139-country weighted average estimates of fully annualized levelized business costs of electric power generation for conventional fuels and WWS technologies. The table indicates that the 2013 business costs of hydropower, onshore wind, utility-scale solar PV, and solar thermal for heat are already similar to or less than the costs of natural gas combined cycle. Residential and commercial PV, offshore wind, tidal, and wave are more expensive. However, residential rooftop PV costs are given as if PV is purchased for an individual household; a common business model today involves multiple households entering a contract together with a solar provider to decrease the average cost.

By 2050, the costs of all WWS technologies are expected to drop, most significantly for offshore wind, tidal, wave, rooftop PV, CSP, and utility PV, whereas conventional fuel costs are expected to drop less significantly or rise. Because WWS technologies have zero fuel costs, the drop in their costs over time is due primarily to technology improvements. WWS costs are expected to decline also due to less expensive manufacturing and streamlined project deployment from increased economies of scale. Conventional fuels, on the other hand, face rising costs over time due to higher labor and transport costs for mining, transporting, and processing fuels continuously over the lifetime of fossil-fuel plants.

Table S33. Approximate fully annualized, unsubsidized 2013 and 2050 U.S.-averaged costs of delivered electricity, including generation, short- and long-distance transmission, distribution, and storage, but not including external costs, for conventional fuels and WWS power (2013 USD/MWh-delivered-electricity or USD/MWh-delivered-thermal).

Technology	**Technology year 2013**			**Technology year 2050**		
	LCHB	*HCLB*	*Average*	*LCHB*	*HCLB*	*Average*
Advanced pulverized coal	81.5	104.0	92.8	77.4	101.2	89.3
Advanced pulverized coal w/CC	112.3	157.5	134.9	97.9	137.5	117.7
IGCC coal	93.0	120.7	106.9	83.3	108.6	96.0
IGCC coal w/CC	138.3	214.9	176.6	95.5	134.2	114.9
Diesel generator (for steam turbine)	185.5	245.3	215.4	247.3	372.1	309.7
Gas combustion turbine	182.7	386.2	284.5	186.9	374.0	280.5
Combined cycle conventional	81.2	93.9	87.6	103.9	133.0	118.5
Combined cycle advanced	n.a.	n.a.	n.a.	95.2	117.2	106.2
Combined cycle advanced w/CC	n.a.	n.a.	n.a.	111.2	140.2	125.7
Fuel cell (using natural gas)	120.7	189.1	154.9	132.6	199.3	166.0
Microturbine (using natural gas)	122.6	145.0	133.8	151.7	190.7	171.2
Nuclear, APWR	80.9	125.0	103.0	73.2	108.5	90.9
Nuclear, SMR	92.9	123.1	108.0	79.6	103.1	91.4
Distributed gen. (using natural gas)	n.a.	n.a.	n.a.	246.9	383.4	315.2
Municipal solid waste	202.3	256.7	229.5	179.1	213.1	196.1

Biomass direct	130.9	167.5	149.2	104.8	126.4	115.6
Geothermal	86.3	127.4	106.9	79.2	108.6	93.9
Hydropower	61.1	83.6	72.4	54.2	72.3	63.3
On-shore wind	74.1	100.8	87.5	66.1	88.4	77.3
Off-shore wind	108.9	198.0	153.5	100.8	179.6	140.2
CSP no storage	124.3	191.6	158.0	90.1	141.2	115.7
CSP with storage	80.8	113.3	97.1	64.2	91.6	77.9
PV utility crystalline tracking	71.1	94.7	82.9	64.5	85.3	74.9
PV utility crystalline fixed	75.3	104.1	89.7	59.9	78.4	69.2
PV utility thin-film tracking	70.5	92.7	81.6	64.0	83.5	73.8
PV utility thin-film fixed	74.5	104.1	89.3	59.3	78.4	68.9
PV commercial rooftop	95.4	142.4	118.9	83.5	122.1	102.8
PV residential rooftop	130.4	193.4	161.9	113.1	164.1	138.6
Wave power	131.0	277.5	204.3	125.2	269.8	197.5
Tidal power	102.6	215.6	159.1	97.3	208.8	153.1
Solar thermal for heat ($/MWh-th)	56.7	67.0	61.9	52.3	62.6	57.5

LCHB = low cost, high benefits case; HCLB = high cost, low benefits case; n.a = not available. The methodology for calculating the costs is described in Jacobson et al. (2015a).

For the year 2050 100% WWS scenario, costs are shown for WWS technologies; for the year 2050 BAU case, costs of WWS are slightly different. The costs assume $11.5 (11-12)/MWh-electricity for standard (but not extra-long-distance) transmission for all technologies except rooftop solar PV (to which no transmission cost is assigned) and $25.7 (25-26.4)/MWh-electricity for distribution for all technologies. Transmission and distribution losses are accounted for in the energy available.

CC = carbon capture; IGCC = integrated gasification combined cycle; AWPR = advanced pressurized-water reactor; SMR = small modular reactor; PV = photovoltaics.

CSP w/storage assumes a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1.

Solar thermal for heat assumes $3,600-$4,000 per 3.716 m^2 collector and 0.7 kW-th/m^2 maximum power (Jacobson et al., 2015a).

Table S33 does not include externality costs. These are estimated as follows. The 2050 139-country air pollution cost (Table S36) plus global climate cost (Table S37) per unit energy (converted to kWh) produced in all sectors in all countries in the 2050 BAU case (Table S6) corresponds to a mean 2050 externality cost (in 2013 USD) due to conventional fuels of 27.5 (10.7-70) ¢/kWh-BAU-all-energy, with 12.6 (2.3-38) ¢/kWh-BAU-all-energy due to air pollution impacts and 14.9 (8.4-32) ¢/kWh-BAU-all-energy due to climate impacts. The mean air pollution cost, which applies across all BAU sectors, is well within the 1.4-17 ¢/kWh-BAU-electricity range of Buonocore et al. (2016) for the retail electricity sector only. Externality costs arise due to air pollution morbidity and mortality and global warming damage (e.g. coastline losses, fishery losses, agricultural losses, heat stress mortality and morbidity, famine, drought, wildfires, and severe weather) due to conventional fuels. When externality costs are added to the business costs of conventional fuels, all WWS technologies cost less than conventional technologies in 2050.

Table S34 provides the mean value of the 2013 and 2050 LCOEs weighted among all conventional generators (BAU cases) and WWS generators (WWS case) by country. The table also gives the 2050 energy, health, and global climate cost savings per person. The electric power cost of WWS in 2050 is not directly comparable with the BAU electric power cost, because the latter does not integrate transportation, heating/cooling, or industry energy costs. Conventional vehicle fuel costs, for example, are a factor of 4-5 higher than those of electric vehicles, yet the cost of BAU electricity cost in 2050 does not include the transportation cost, whereas the WWS electricity cost does.

The 2050 LCOEs, weighted among all electricity generators and countries in the BAU and WWS cases, are 9.73 ¢/kWh-BAU-electricity and 8.86 ¢/kWh-WWS-all-energy, respectively (Table S34). Taking the product of the first number and the kWh-BAU in the retail electricity sector, subtracting the product of the second number and the kWh-WWS-electricity replacing BAU electricity, and subtracting the amortized cost of energy efficiency improvements beyond BAU improvements in the WWS case, gives a 2050 business cost savings due to switching BAU electricity to WWS electricity of ~$113/yr per capita ($2013 USD). Adding 0.8 ¢/kWh-WWS-all-energy for additional storage described above gives a WWS business cost of ~9.66 ¢/kWh-WWS-all-energy, still providing ~$85/yr per capita savings for WWS relative to just BAU's retail electricity sector.

Whereas, the cost per kWh-WWS above applies across all energy sectors, the cost per kWh-BAU applies only to the retail electricity sector. We have not calculated the cost per kWh-BAU across the transportation, heating/cooling, industrial, or agriculture/forestry/fishing sectors. We suspect, though, that such a calculation will result in an additional cost benefit per capita for WWS beyond that in the retail electricity sector, particularly because far fewer kWh-WWS are needed than are kWh-BAU in the transportation sector (due to the greater energy:work ratio of electricity over combustion) and the industrial sector (due to eliminating the energy required to mine, transport, and refine fossil fuels).

In addition, WWS will save ~$2,600/yr in health costs plus ~$3,100/yr in global climate costs. The total up-front capital cost of the 2050 WWS system (for both average annual power and peaking storage in Table S7) for the 139 countries is ~$125 trillion for the 49.9 TW of new installed capacity needed (~$2.50 million/MW).

Table S34. Mean values of the levelized cost of energy (LCOE) for conventional fuels (BAU) in 2013 and 2050 in the electricity sector and for WWS in all energy sectors (which are now electrified) in 2050. The LCOE estimates do not include externality costs. The 2013 and 2050 values are used to calculate energy cost savings per person per year in each country due to switching from BAU to WWS in the electricity sector only (see footnotes). Health and climate cost savings per person per year among all sectors are derived from data in Section S8. All costs are in 2013 USD.

Country	(a) 2013 LCOE of BAU (¢/kWh-electricity)	(b) 2050 LCOE of BAU (¢/kWh-electricity)	(c) 2050 LCOE of WWS (¢/kWh-all-energy)	(d) 2050 Average BAU retail electricity cost savings to country due to switching to WWS electricity ($/person/yr)	(e) 2050 Average air quality health cost savings to country among all sectors due to switching to WWS in country ($/person/yr)	(f) 2050 Average climate cost savings to world among all sectors due to switching to WWS in country ($/person/yr)	(g) 2050 Average electricity + country health + world climate cost savings due to switching to WWS in country ($/person/yr)
Albania	7.24	6.33	7.96	16	1,552	1,079	2,648
Algeria	8.74	11.79	9.61	106	1,177	3,924	5,206
Angola	7.68	7.93	8.17	6	2,097	825	2,927
Argentina	8.66	10.34	11.01	72	1,271	2,876	4,219
Armenia	8.95	9.07	7.52	115	2,926	893	3,933
Australia	10.24	10.01	9.26	507	808	9,393	10,708
Austria	8.86	8.64	7.09	411	4,194	4,956	9,560
Azerbaijan	8.55	11.11	8.07	172	3,447	3,091	6,710

Bahrain	8.75	11.84	8.13	1,646	3,582	13,405	18,632
Bangladesh	8.77	11.70	6.99	25	1,678	305	2,008
Belarus	8.76	11.82	7.81	442	9,090	5,320	14,852
Belgium	10.53	10.24	6.81	638	4,459	5,958	11,055
Benin	8.80	11.85	8.48	7	1,648	298	1,953
Bolivia	8.51	10.12	8.95	23	437	897	1,358
Bosnia and Herzegovina	9.67	8.66	8.03	124	1,974	5,408	7,505
Botswana	10.68	9.60	9.52	66	1,156	2,173	3,395
Brazil	8.12	7.39	8.54	21	432	1,594	2,047
Brunei Darussalam	8.77	11.86	7.80	1,008	248	19,411	20,667
Bulgaria	10.53	9.43	8.04	482	5,338	5,884	11,704
Cambodia	8.91	11.58	9.88	16	617	258	891
Cameroon	7.71	7.81	6.74	10	1,804	263	2,077
Canada	8.62	7.96	9.71	41	2,677	7,900	10,618
Chile	9.42	9.57	10.67	83	1,479	3,739	5,302
China	10.24	9.22	8.59	164	4,730	6,005	10,898
Chinese Taipei	10.24	9.22	8.93	541	4,823	15,406	20,770
Colombia	7.88	7.48	7.29	31	228	1,228	1,487
Congo	7.83	8.47	8.11	6	1,009	296	1,311
Congo, Dem. Republic	7.25	6.36	6.49	2	196	25	223
Costa Rica	9.05	8.23	8.29	55	136	1,017	1,209
Cote d'Ivoire	8.38	10.25	8.17	17	299	200	516
Croatia	8.76	9.03	6.93	358	4,267	3,504	8,129
Cuba	5.27	6.90	10.84	-47	553	3,361	3,867
Cyprus	9.02	11.92	9.81	350	3,550	3,629	7,529
Czech Republic	10.94	9.65	7.03	474	4,926	7,026	12,425
Denmark	12.31	11.49	9.73	364	4,687	4,285	9,336
Dominican Republic	8.90	10.86	9.93	61	338	1,248	1,647
Ecuador	8.12	8.86	8.87	30	253	1,349	1,632
Egypt	8.73	11.42	10.23	114	1,764	1,885	3,763
El Salvador	10.56	10.57	9.04	50	157	796	1,004
Eritrea	8.80	11.85	10.11	4	627	67	697
Estonia	11.04	9.94	8.47	522	7,211	12,981	20,715
Ethiopia	7.28	6.39	8.90	0	449	29	478
Finland	9.89	9.10	9.12	472	6,200	6,223	12,895
France	10.54	9.19	9.82	164	3,153	2,932	6,249
Gabon	8.09	9.32	8.30	48	1,188	1,020	2,256
Georgia	7.58	7.57	8.60	40	3,147	1,067	4,254
Germany	11.12	10.36	8.28	467	5,033	6,307	11,806
Ghana	7.01	7.15	7.91	6	2,166	294	2,466
Gibraltar	10.69	10.71	6.11	390	8,055	9,692	18,137
Greece	10.18	10.42	8.64	352	3,491	4,386	8,229
Guatemala	10.44	9.87	8.47	20	180	383	583
Haiti	8.82	11.01	9.52	3	106	124	233
Honduras	8.49	9.70	8.74	23	71	488	582
Hong Kong, China	10.13	10.24	7.15	1,084	8,319	7,440	16,842
Hungary	10.47	10.31	6.44	366	5,325	2,895	8,585
Iceland	9.68	8.38	8.92	511	1,021	3,332	4,865
India	10.31	9.65	9.04	40	2,928	2,148	5,116
Indonesia	9.89	10.56	8.74	59	532	1,852	2,443
Iran, Islamic Republic	8.69	11.56	9.22	209	2,479	6,070	8,758
Iraq	7.12	9.36	9.81	24	1,827	2,164	4,015
Ireland	9.61	10.71	10.46	152	1,676	3,449	5,277
Israel	9.90	10.50	8.97	287	2,502	3,929	6,719
Italy	9.68	10.76	7.66	378	3,481	3,415	7,274
Jamaica	9.18	11.86	9.88	68	166	1,577	1,811
Japan	9.23	10.02	6.54	530	2,575	5,211	8,315
Jordan	8.75	11.82	10.26	127	907	1,988	3,023
Kazakhstan	10.18	9.52	8.72	131	3,598	9,126	12,856

Kenya	9.82	9.89	8.98	7	260	228	496
Korea, Dem. People's Rep.	8.53	7.66	8.55	1	589	3,331	3,920
Korea, Republic of	10.23	10.03	6.57	1,058	2,985	10,951	14,993
Kosovo	10.61	9.55	8.93	189	851	3,599	4,639
Kuwait	8.75	11.84	7.49	2,183	2,831	25,873	30,888
Kyrgyzstan	7.40	6.62	8.16	14	914	519	1,447
Latvia	8.27	9.29	8.13	301	10,626	3,156	14,083
Lebanon	8.68	11.57	9.23	354	1,670	5,230	7,254
Libya	8.75	11.84	10.12	231	649	6,665	7,545
Lithuania	9.16	10.80	8.98	285	10,674	3,057	14,016
Luxembourg	9.04	11.59	5.04	1,114	6,110	8,815	16,039
Macedonia, Republic of	9.92	8.97	8.00	229	2,131	3,653	6,013
Malaysia	9.52	10.62	7.93	338	463	6,270	7,071
Malta	8.78	11.84	6.74	656	3,855	4,291	8,802
Mexico	9.13	10.89	9.69	123	624	2,556	3,303
Moldova, Republic of	8.66	11.51	8.95	205	4,203	1,409	5,817
Mongolia	10.59	9.71	9.10	49	1,182	3,393	4,625
Montenegro	9.12	8.12	8.15	172	236	3,004	3,412
Morocco	9.76	10.43	10.46	42	1,016	1,506	2,564
Mozambique	7.24	6.33	9.67	-8	125	65	183
Myanmar	7.83	7.79	9.38	2	1,229	172	1,403
Namibia	7.29	6.39	9.69	-89	1,289	1,846	3,047
Nepal	7.24	6.33	7.33	1	1,231	109	1,341
Netherlands	9.93	11.29	9.30	389	4,374	5,476	10,239
Netherlands Antilles	7.59	9.19	6.28	98	227	9,685	10,010
New Zealand	9.43	9.00	9.52	267	342	4,977	5,586
Nicaragua	10.24	11.65	8.52	41	98	496	635
Nigeria	8.44	10.69	7.46	11	6,006	250	6,267
Norway	7.39	6.59	8.48	-19	4,522	6,935	11,439
Oman	8.75	11.84	9.76	473	13,306	10,879	24,659
Pakistan	8.41	10.03	9.02	21	2,615	664	3,300
Panama	8.12	8.84	8.17	82	125	1,512	1,719
Paraguay	7.24	6.33	6.60	25	455	441	921
Peru	8.09	8.81	8.44	34	433	1,372	1,839
Philippines	10.32	10.53	9.37	32	160	637	830
Poland	10.88	9.93	9.24	187	5,210	5,774	11,170
Portugal	10.52	10.60	9.90	216	3,332	3,109	6,657
Qatar	8.75	11.84	7.31	1,784	2,304	33,920	38,008
Romania	9.75	9.17	9.55	83	6,038	2,756	8,877
Russian Federation	9.12	10.14	10.28	214	9,687	8,398	18,299
Saudi Arabia	6.11	8.27	9.94	126	2,527	12,818	15,471
Senegal	8.63	11.22	9.66	12	2,371	331	2,714
Serbia	9.87	8.89	6.93	401	4,602	4,269	9,273
Singapore	8.81	11.74	6.35	1,033	1,105	2,387	4,525
Slovak Republic	10.24	9.36	8.22	227	4,882	4,085	9,193
Slovenia	10.02	8.85	7.94	323	4,003	5,764	10,091
South Africa	10.68	9.57	9.58	206	1,442	10,983	12,631
Spain	10.69	10.71	9.30	263	3,410	2,718	6,391
Sri Lanka	8.41	9.48	9.62	24	725	679	1,428
Sudan	7.61	7.69	9.68	1	2,429	189	2,620
Sweden	9.66	8.35	9.02	266	5,354	2,955	8,575
Switzerland	8.89	7.70	6.70	325	2,702	3,282	6,310
Syrian Arab Republic	8.63	11.40	10.10	67	907	1,896	2,870
Tajikistan	7.26	6.39	6.24	21	964	152	1,137
Tanzania, United Republic	8.03	9.10	8.31	6	201	132	338
Thailand	9.30	11.10	8.88	269	2,056	5,517	7,842
Togo	7.73	7.78	8.13	3	995	127	1,125
Trinidad and Tobago	8.75	11.84	7.75	782	762	37,353	38,898
Tunisia	8.80	11.84	10.15	140	1,072	2,684	3,896

Turkey	9.15	9.99	8.82	88	1,590	1,915	3,594
Turkmenistan	8.75	11.84	9.05	117	2,907	5,392	8,416
Ukraine	10.36	9.42	10.53	91	6,387	5,927	12,405
United Arab Emirates	8.75	11.84	7.97	1,712	3,194	22,927	27,834
United Kingdom	10.25	10.68	9.24	261	3,239	3,862	7,362
United States of America	10.19	10.00	9.62	304	1,425	6,587	8,316
Uruguay	8.50	8.58	9.67	62	999	1,500	2,562
Uzbekistan	8.54	10.67	8.99	64	1,481	1,935	3,480
Venezuela	7.72	8.06	8.28	64	216	4,290	4,571
Vietnam	8.71	9.71	9.28	57	939	1,788	2,783
Yemen	8.75	11.84	9.98	11	1,657	511	2,179
Zambia	7.24	6.34	8.24	-2	591	80	669
Zimbabwe	8.19	7.23	8.64	4	364	435	803
World total or average	**9.68**	**9.73**	**8.86**	**113**	**2,597**	**3,056**	**5,766**

a) The 2013 LCOE cost of retail electricity for conventional fuels in each country combines the distribution of conventional electricity generators in 2013 with 2013 mean LCOEs for each generator from Table S33. Costs include all-distance transmission, pipelines, and distribution, but they exclude externalities.

b) Same as (a), but for a 2050 BAU case and 2050 LCOEs for each generator from Table S33. The 2050 BAU case includes some existing WWS (mostly hydropower) plus future increases in WWS electricity in the BAU case and energy efficiency.

c) The 2050 LCOE of WWS in the country combines the 2050 distribution of WWS generators among all energy sectors from Table S8 with the 2050 mean LCOEs for each WWS generator from Table S33. The LCOE accounts for all-distance transmission and distribution (footnotes to Tables S7 and S33).

d) The 2050 average BAU retail electricity sectors cost savings per capita per year due to switching to WWS isis calculated as the cost of electricity use in the electricity sector in the BAU case (the product of BAU electricity use and the 2050 BAU LCOE) less the annualized cost of the assumed efficiency improvements in the WWS case beyond BAU improvements and less the total cost of BAU retail electricity converted to WWS (product of WWS electricity use replacing BAU electricity and the 2050 WWS LCOE), all divided by 2050 population. (See Delucchi et al., 2016 for details.)

e) Total cost of air pollution per year in the country from Table S36 divided by the 2050 population of the country.

f) Total climate cost per year to the world due to country's emissions (Table S37) divided by the 2050 population of the country.

g) The sum of columns (d), (e), and (f).

Section S8. Air Pollution and Global Warming Damage Costs Eliminated by WWS

Conversion to a 100% WWS energy infrastructure in the 139 countries eliminates energy-related air pollution mortality and morbidity and the associated health costs, along with energy-related climate change costs for individual countries and the world. This section discusses these topics.

S8.1. Air Pollution Cost Reductions due to WWS

The benefits of reducing air pollution mortality and its costs in each U.S. country can be quantified as follows.

First, the premature human mortality rate worldwide due to cardiovascular disease, respiratory disease, and complications from asthma arising from air pollution has been estimated previously by combining computer model estimates of human exposure to particulate matter ($PM_{2.5}$) and ozone (O_3) with the relative risk of mortality from these chemicals and population. Results suggest that an estimated 4-7 million people currently perish prematurely each year worldwide from outdoor plus indoor air pollution (e.g., Shindell et al., 2012; Anenberg et al., 2012; WHO, 2014a,b; OECD, 2014). These mortalities represent ~0.7-1.2% of the 570 million deaths/year worldwide in 2015. Here, modeled concentrations of $PM_{2.5}$ and O_3 in each of 139 countries are combined with the relative risk of mortality as a function of concentration and with population in a health-effects equation (e.g., Jacobson, 2010a) to estimate low, medium, and high mortalities due to $PM_{2.5}$ and O_3 by country. Results are then extrapolated forward to 2050 while accounting for efficiencies that occur under the BAU scenario.

General method

Here we follow the method of Jacobson et al. (2015a), with a new adjustment to the estimation of the value of statistical life (VOSL):

$$APcost_{C,Y} = N_{D,C,Y} \cdot V_{P/D,C,Y}$$

$$N_{D,C,Y} = N_{D,C,2010-12} \cdot \exp^{\Delta A_C \cdot (Y-2011)} \cdot \left(\frac{P_{C,Y}}{P_{C,2011}} \right)^{\kappa}$$

$$V_{P/D,C,Y} = V_{D,C,Y} \cdot F_1 \cdot F_2$$

where

$APcost_{C,Y}$ = The damage cost of fossil-fuel air pollution in country *C* year *Y*

$N_{D,C,Y}$ = The number of deaths D due to fossil-fuel air pollution in country *C* in year *Y*

$V_{P/D,,CY}$ = The total cost of pollution per death in country *C* in year *Y* (includes mortality, morbidity, and non-health costs)

$N_{D,C,2010-12}$ = The number of premature deaths in country *C* over the period 2010-2012 (see discussion in the main text)

ΔA_C = The annual rate of change in the damage-weighted ambient pollution levels, in country *C*; although it is possible to specify country-specific values, presently we assume the same values for all countries (Jacobson et al., 2015a):

LCHB	*Middle*	*HCLB*
-1.0%/yr	-1.5%/yr	-2.0%/yr

κ = The change in exposed population per change in population (Jacobson et al., 2015a):

LCHB	*Middle*	*HCLB*
1.14	1.11	1.08

$P_{C,Y}$ = The population in country *C* in year *Y* (see "Important general parameters")

$V_{D,C,Y}$ = The value per death *per se* (VOSL) in country *C* in year *Y* (see discussion below)

F_1 = Adjustment factor that accounts for morbidity effects of air pollution, relative to the mortality effect (see F_2)

F_2 = Adjustment factor that accounts for the non-health effects of air pollution, relative to the mortality effect; assumed to be the same for all countries and years, as follows (based on Jacobson et al., 2015a):

	LCHB	*Middle*	*HCLB*
F_1	1.25	1.15	1.05
F_2	1.10	1.10	1.05

The value of statistical life (VOSL)

As Lindhjem and Navrud (2015) note, many analyses assume that the VOSL for country *C* can be calculated as a function of the VOSL for a reference country (e.g., the U.S.) and the GDP/capita for country *C* relative to the GDP/capita for the reference country, where GDP/capita is expressed in terms of Purchasing Power Parity (PPP). Lindhjem and Navrud's (2015) own meta-analysis indicate that this simple relationship can be a good approximation. We follow this approach, with two adjustments.

First, we assume that in the high-benefits case, a small portion of the VOSL is constant across all countries in terms of *utility*. This constant term represents the fraction of the VOSL that is independent of relative wealth, productivity, or consumption; i.e., the fraction that represents the cross-country constant utility of enjoying life and avoiding pain and suffering.

Second, we follow the findings of Milligan et al. (2014) and Hammit and Robinson (2011) and assume that the GDP/capita elasticity γ of the VOSL is itself a function of the relative GDP/capita (based on PPP).

Formally,

$$V_{D,C,Y} = V_{D,US,Y} \cdot \left(D + (1-D) \cdot \left(GDPC'_{C,TY} \right)^{\gamma_{GDP,US,TY} \cdot \left(GDPC'_{C,TY} \right)^{\gamma_{GDP}}} \right)$$

$$GDPC'_{C,TY} = \frac{GDPC_{C,TY}}{GDPC_{US,TY}}$$

$$\gamma_{GDP,US,TY} = \gamma_{GDP,US,BY} \cdot \left(\frac{GDPC_{US,TY}}{GDPC_{US,BY}} \right)^{\gamma_{GDP}}$$

where

subscript BY is the base-year for the US data (2006)

D = The portion of the VOSL that is independent of GDP/capita (constant across all countries):

LCHB	*Middle*	*HCLB*
0.60	0.50	0.40

γ_{GDP}, $\gamma_{GDP,US,BY}$ = elasticity exponents (see discussion below)

Elasticity exponents. Jacobson et al. (2015a) review several estimates pertinent to $\gamma_{GDP,US,BY}$, and settle upon

	LCHB	*Middle*	*HCLB*
$\gamma_{GDP,US,BY}$	0.75	0.50	0.25

We adopt those values here. Analyses in Milligan et al. (2014) and Hammit and Robinson (2011) indicate that γ_{GDP} decreases with increasing GDP/capita, and can exceed 1.0 for relatively poor countries. Table S35 shows how our estimate of $\gamma_{GDP,US,TY}$ varies with different assumptions for γ_{GDP}, given the values above for $\gamma_{GDP,US,BY}$, at different values of GDPC'.

Table S35. Projected GDP/capita elasticity of VOSL as a function of relative GDP/capita (GDPC') and baseline elasticity parameters.

	LCHB	**mid**	**HCLB**	**LCHB**	**mid**	**HCLB**	**LCHB**	**mid**	**HCLB**
$\gamma_{GDP,US,BY}$	*0.75*	*0.50*	*0.25*	*0.75*	*0.50*	*0.25*	*0.75*	*0.50*	*0.25*
γ_{GDP}	*-0.20*	*-0.20*	*-0.20*	*-0.17*	*-0.17*	*-0.17*	*-0.15*	*-0.15*	*-0.15*
GDPC'									
0.05	1.37	0.91	0.46	1.25	0.83	0.42	1.18	0.78	0.39
0.10	1.19	0.79	0.40	1.11	0.74	0.37	1.06	0.71	0.35
0.33	0.93	0.62	0.31	0.90	0.60	0.30	0.88	0.59	0.29
0.50	0.86	0.57	0.29	0.84	0.56	0.28	0.83	0.55	0.28
0.80	0.78	0.52	0.26	0.78	0.52	0.26	0.78	0.52	0.26
1.00	0.75	0.50	0.25	0.75	0.50	0.25	0.75	0.50	0.25
1.50	0.69	0.46	0.23	0.70	0.47	0.23	0.71	0.47	0.24
2.00	0.65	0.44	0.22	0.67	0.44	0.22	0.68	0.45	0.23
2.50	0.62	0.42	0.21	0.64	0.43	0.21	0.65	0.44	0.22
3.00	0.60	0.40	0.20	0.62	0.41	0.21	0.64	0.42	0.21

Considering the results of Table S35, we think the following assumptions give results consistent with the findings of Milligan et al. (2014) and Hammit and Robinson (2011):

	LCHB	*Middle*	*HCLB*
γ_{GDP}	-0.15	-0.15	-0.15

Comparison of our results with a recent comprehensive estimate
We estimate 1.3 to 8.0 million deaths in 2011 due to indoor and outdoor pollution related to the combustion of fossil fuels and biofuels. Recently, Forouzanfar et al. (2015) performed a comprehensive analysis and estimated 5.1 to 5.9 million deaths worldwide in 2013 from ambient and indoor pollution (2.8 to 3.1 million from ambient $PM_{2.5}$ pollution, 0.2 to 0.3 million from ambient ozone pollution, and 2.5 to 3.3 million from household air pollution from solid fuels). This range is in the middle of our wider range.

A presentation based on the Forouzanfar et al. (2015) work estimated 1.6 million air-pollution deaths in China and 1.4 million in India in 2013 (University of British Columbia, 2016). By comparison, we estimate 0.3 to 2.1 million in China and 0.3 to 1.7 million in India in 2011. The UBC (2016) presentation also projects that air pollution deaths in China will decline 19% to 38% by 2030. By comparison, our methods result in a decline of 15% to 30% by 2030.

Premature mortalities by country
Figure S12 shows the results. Premature mortalities in 2015, summed over the 139 countries are estimated for $PM_{2.5}$ to be ~4.28 (1.19-7.56) million/yr, and those for O_3, ~279,000 (140,000-417,000)/yr. The sum is ~4.56 (1.33-7.98) million premature mortalities/yr for $PM_{2.5}$ plus O_3, which is in the range of the previous literature estimates.

Figure S12. Modeled worldwide (all countries, including the 139 discussed in this paper) (a) $PM_{2.5}$ and (b) O_3 premature mortalities in 2015 as estimated with GATOR-GCMOM (Jacobson, 2010b), a 3-dimensional global computer model.

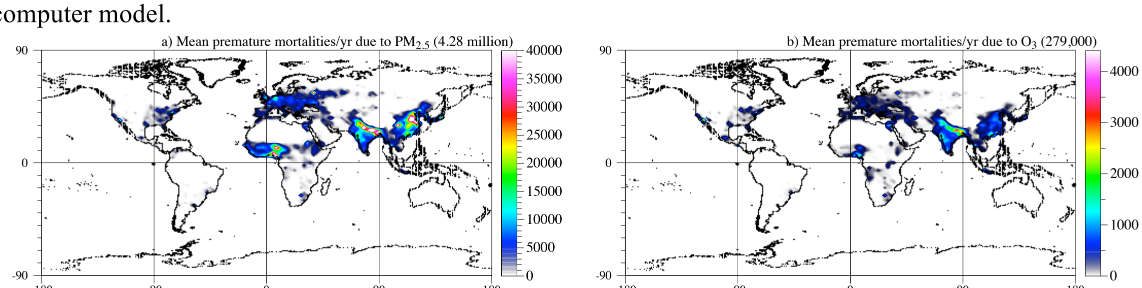


Table S36 shows estimated air pollution mortality and cost avoided by country in 2050 due to conversion to WWS, projected forward from 2015 with the methodology detailed in Delucchi et al. (2016). This method projects future pollution from current levels with an estimated annual rate of pollution change that considers increasing emission controls and more sources over time. The number of mortalities in 2050 then accounts for the growth of population by country and a nonlinear relationship between exposure and population. The resulting number of 2050 air pollution mortalities avoided in the 139 countries due to WWS is estimated at 3.5 (0.84-7.4) million/yr.

Table S36. Avoided air pollution $PM_{2.5}$ plus ozone premature mortalities by country in 2050 and mean avoided costs (in 2013 USD) from mortalities and morbidities.

Country	2050 High avoided premature mortalities /yr	2050 Mean avoided premature mortalities/ yr	2050 Low avoided premature mortalities /yr	2015 Mean avoided cost ($2013 mil./yr)	2050 Mean avoided cost as percent	2050 Mean avoided cost ($2013)

					of 2050 GDP	¢/kWh-BAU-all-energy
Albania	1,215	546	142	4,384	4.1	12.2
Algeria	16,794	7,546	1,899	51,964	4.0	4.1
Angola	47,748	20,588	4,928	96,206	12.5	36.8
Argentina	19,973	8,462	1,815	68,017	3.4	4.7
Armenia	2,751	1,230	298	8,610	9.7	20.1
Australia	4,966	2,073	447	23,449	1.2	1.3
Austria	6,163	2,718	639	31,540	5.7	7.1
Azerbaijan	8,646	3,867	922	38,636	6.3	22.7
Bahrain	1,133	549	135	6,615	4.5	4.9
Bangladesh	280,467	130,598	30,780	419,857	16.0	67.6
Belarus	15,555	7,055	1,605	70,348	16.5	19.6
Belgium	8,940	3,899	866	44,072	6.4	7.4
Benin	36,830	18,606	4,622	36,443	27.1	46.0
Bolivia	4,054	1,706	365	6,997	3.1	5.0
Bosnia and Herzegovina	2,203	973	237	7,683	5.4	13.3
Botswana	1,081	464	108	3,320	3.7	6.4
Brazil	37,924	15,954	3,480	112,642	1.4	2.3
Brunei Darussalam	26	11	2	158	0.2	0.3
Bulgaria	5,530	2,468	586	24,826	9.6	12.7
Cambodia	9,631	4,162	967	13,789	5.7	12.8
Cameroon	49,217	23,873	5,712	62,971	21.6	28.3
Canada	22,895	9,884	2,251	110,116	3.9	3.2
Chile	7,143	3,079	672	28,676	3.0	4.2
China	1,380,050	638,165	148,273	6,166,179	9.1	13.0
Chinese Taipei	13,939	6,236	1,481	97,232	3.4	6.6
Colombia	4,969	2,074	447	12,812	0.9	2.2
Congo	5,259	2,269	521	9,688	6.8	23.6
Congo, Dem. Republic	79,577	34,549	7,880	28,367	7.2	7.4
Costa Rica	295	126	30	827	0.5	1.2
Cote d'Ivoire	9,343	3,879	817	11,100	3.3	7.8
Croatia	3,430	1,515	362	16,488	6.6	13.1
Cuba	1,496	659	167	5,062	1.6	4.9
Cyprus	870	388	96	4,942	4.0	13.4
Czech Republic	9,619	4,263	973	42,064	9.1	11.1
Denmark	5,184	2,262	509	26,130	6.4	11.1
Dominican Republic	1,673	736	190	4,622	1.3	4.2
Ecuador	2,275	963	217	5,347	1.2	2.3
Egypt	89,901	41,491	10,136	243,256	7.7	13.0
El Salvador	466	207	54	973	0.9	2.0
Eritrea	9,948	4,587	1,059	7,133	13.0	72.7
Estonia	1,454	659	150	6,216	14.5	12.0
Ethiopia	182,850	78,819	17,493	124,909	9.1	20.0
Finland	6,093	2,712	603	29,883	9.3	7.9
France	46,399	20,258	4,660	219,990	4.9	9.4
Gabon	1,136	477	103	3,837	3.2	7.8
Georgia	3,536	1,582	384	11,913	9.3	21.1
Germany	70,669	30,984	7,011	360,057	6.8	10.8
Ghana	53,822	26,807	6,568	87,183	20.4	52.6
Gibraltar	41	18	4	226	9.9	0.4
Greece	8,707	3,869	951	35,037	7.6	11.3
Guatemala	2,151	940	242	4,139	1.2	3.2
Haiti	2,140	943	246	1,420	2.3	3.6
Honduras	647	275	65	925	0.6	1.3
Hong Kong, China	8,102	3,763	893	51,353	8.0	7.6
Hungary	11,253	5,005	1,151	45,206	11.6	19.0

Iceland	72	31	8	358	1.4	0.9
India	1,667,221	805,227	195,433	4,849,682	12.2	32.4
Indonesia	58,638	25,086	5,737	166,408	1.9	4.4
Iran, Islamic Republic	68,163	31,322	7,629	248,052	6.8	6.5
Iraq	31,140	14,277	3,566	102,864	5.8	19.4
Ireland	2,011	856	194	10,613	2.0	7.2
Israel	5,897	2,674	653	27,094	4.4	11.3
Italy	46,543	20,577	5,071	213,785	5.9	10.1
Jamaica	269	121	34	588	0.9	1.6
Japan	66,670	28,854	6,486	276,019	5.1	7.7
Jordan	3,693	1,671	415	10,199	3.7	7.9
Kazakhstan	15,580	6,844	1,593	80,019	4.8	8.0
Kenya	16,653	7,052	1,585	18,427	3.1	6.7
Korea, Dem. People's Rep.	20,159	8,931	1,998	15,877	10.7	5.6
Korea, Republic of	27,728	12,249	2,724	129,449	4.9	4.5
Kosovo	340	240	138	1,321	4.1	5.1
Kuwait	1,641	777	192	10,938	2.5	2.1
Kyrgyzstan	4,073	1,795	429	7,531	6.3	11.5
Latvia	3,137	1,445	333	16,407	15.1	21.2
Lebanon	2,196	997	249	6,941	5.6	7.0
Libya	2,345	1,044	267	7,052	2.3	2.2
Lithuania	5,350	2,466	567	29,760	13.4	28.9
Luxembourg	668	288	64	4,405	4.5	7.8
Macedonia, Republic of	1,085	480	120	4,244	4.8	12.0
Malaysia	4,500	1,956	490	19,873	0.8	1.4
Malta	271	122	31	1,526	4.5	4.9
Mexico	25,972	11,377	2,807	92,359	1.6	3.2
Moldova, Republic of	3,911	1,794	416	9,502	21.1	24.8
Mongolia	1,677	734	175	5,131	3.9	6.5
Montenegro	34	14	3	136	0.5	1.0
Morocco	19,572	8,821	2,160	42,718	5.8	10.8
Mozambique	14,734	6,128	1,375	7,399	3.3	4.0
Myanmar	50,932	22,334	5,079	86,829	9.3	29.5
Namibia	1,104	485	117	2,772	5.8	6.9
Nepal	46,833	21,851	5,150	56,608	15.0	31.4
Netherlands	15,212	6,605	1,460	78,332	5.7	7.8
Netherlands Antilles	24	10	2	87	0.5	0.1
New Zealand	364	153	35	1,778	0.5	0.7
Nicaragua	388	165	39	710	0.7	2.0
Nigeria	984,287	514,900	132,376	2,416,900	35.6	106.0
Norway	3,812	1,671	388	22,459	4.5	5.5
Oman	13,105	6,473	1,592	71,879	19.7	15.0
Pakistan	361,391	180,243	44,816	760,604	17.8	42.2
Panama	179	77	19	606	0.3	0.4
Paraguay	1,936	821	181	4,023	2.5	5.3
Peru	6,547	2,744	583	15,985	1.9	4.5
Philippines	12,164	5,193	1,238	27,531	0.8	4.1
Poland	40,992	18,382	4,180	167,156	11.2	16.0
Portugal	8,016	3,523	825	33,095	6.8	12.8
Qatar	671	334	83	5,896	1.2	1.0
Romania	22,747	10,121	2,337	109,044	9.5	24.5
Russian Federation	225,543	102,559	23,534	1,057,711	16.6	16.6
Saudi Arabia	16,860	8,026	1,957	101,706	2.9	3.4
Senegal	53,610	29,530	7,857	64,585	34.7	93.9
Serbia	6,873	3,039	726	27,011	10.3	16.3
Singapore	1,385	606	155	9,517	0.8	0.5
Slovak Republic	5,720	2,539	582	24,135	9.7	12.5
Slovenia	1,481	656	159	6,393	7.6	9.0
South Africa	25,497	10,955	2,467	71,219	5.4	3.3

Spain	39,487	17,402	4,163	179,009	5.9	12.1
Sri Lanka	6,179	2,661	622	18,237	2.5	7.7
Sudan	151,527	72,899	17,302	236,027	23.0	97.7
Sweden	9,420	4,140	932	48,640	7.1	9.2
Switzerland	3,535	1,555	383	19,712	3.0	6.2
Syrian Arab Republic	13,329	6,019	1,506	30,515	4.8	14.1
Tajikistan	7,088	3,189	768	11,695	7.8	38.2
Tanzania, United Republic	13,575	5,715	1,283	13,413	2.7	3.5
Thailand	40,325	17,709	4,100	143,145	5.4	5.8
Togo	22,400	11,403	2,840	16,503	22.0	38.0
Trinidad and Tobago	196	83	18	781	1.5	0.5
Tunisia	4,860	2,173	548	13,063	4.5	3.5
Turkey	45,007	20,054	4,995	160,548	4.3	13.0
Turkmenistan	4,427	1,984	475	19,204	5.6	5.4
Ukraine	69,690	31,576	7,261	214,452	22.3	16.5
United Arab Emirates	3,548	1,829	466	25,616	2.9	1.5
United Kingdom	48,833	20,910	4,542	230,441	4.9	10.5
United States of America	103,679	45,761	11,734	602,239	1.5	2.9
Uruguay	1,073	452	97	3,491	2.8	4.6
Uzbekistan	19,721	8,899	2,122	52,016	6.5	8.1
Venezuela	3,035	1,278	291	8,712	0.8	0.8
Vietnam	49,906	22,169	5,259	104,382	5.5	9.1
Yemen	47,561	22,541	5,404	75,875	15.0	83.2
Zambia	17,437	7,397	1,748	22,664	6.0	15.2
Zimbabwe	12,550	5,334	1,248	9,168	6.8	4.6
All-country sum/average	**7,376,181**	**3,487,163**	**838,205**	**22,836,625**	**7.6**	**12.7**

High, medium, and low estimates of premature mortalities in each country in 2050 are estimated by combining computer-modeled changes in $PM_{2.5}$ and ozone during 2015 due to anthropogenic sources in each country (Figure S12) with low, medium, and high relative risks and country population, as in Jacobson (2010a). 2015 values are then extrapolated forward to 2050 as described in the text. Human exposure is based on daily-averaged $PM_{2.5}$ exposure and 8-hr maximum ozone each day. Relative risks for long-term health impacts of $PM_{2.5}$ and ozone are as in Jacobson (2010a). However, the relative risks of $PM_{2.5}$ from Pope et al. (2002) are applied to all ages as in Lepeule et al. (2012) rather than to those over 30 years old as in Pope et al. (2002). The threshold for $PM_{2.5}$ is zero but concentrations below 8 $\mu g/m^3$ are down-weighted as in Jacobson (2010a). The low ambient concentration threshold for ozone premature mortality is assumed to be 35 ppbv.

Air pollution costs are estimated by multiplying the value of statistical life (VSL) in each country by the low, medium, and high number of excess mortalities due to $PM_{2.5}$ and ozone. Estimates of the VSL are calculated as in Delucchi et al. (2016). Values for the U.S. are projected to 2050 based on GDP per capita projections (on a PPP basis) for the U.S. then scaled for each country as a nonlinear function of GDP per capita relative to the U.S. Multipliers are then used to account for morbidity and non-health impacts of air pollution.

Cost of air pollution. The total damage cost of air pollution due to conventional fuels (fossil fuel and biofuel combustion and evaporative emissions) in a country is the sum of mortality costs, morbidity costs, and non-health costs such as lost visibility and agricultural output in the country. The mortality cost equals the number of mortalities in the country multiplied by the value of statistical life (VSL). The methodology for determining the VSL by country is provided in the footnote to Table S36. The morbidity plus non-health cost per country is estimated as the mortality cost multiplied by the ratio of the value of total air-pollution damages (mortality plus morbidity plus other damages) to mortality costs alone. The result of the calculation is that the 139-country avoided cost of air pollution in 2050 is ~\$23 (\$4.0-\$69) trillion/yr in 2013 USD, equivalent to ~7.6 (1.4-23) percent of the 2050 139-country gross domestic product on a purchasing power parity (PPP) basis, or ~12.7 (2.3-38) ¢/kWh-BAU-all-energy.

S8.2. Global-Warming Damage Costs Eliminated by 100% WWS in Each Country

This section provides estimates of two kinds of climate change avoided costs due to eliminating greenhouse gas (GHG) emissions from energy use (Table S37). GHG emissions are defined here to include emissions of carbon dioxide, other greenhouse gases, and air pollution particles that cause global warming, converted to equivalent carbon dioxide. A 100% WWS system in each country will eliminate such damages. The cost calculated is the cost of climate change impacts to the world *attributable to* emissions of GHGs from each country.

Costs of climate change include coastal flood and real estate damage costs, agricultural loss costs, energy-sector costs, water costs, health costs due to heat stress and heat stroke, influenza and malaria costs, famine costs, ocean acidification costs, increased drought and wildfire costs, severe weather costs, and increased air pollution health costs. These costs are partly offset by fewer extreme cold events and associated reductions in illnesses and mortalities and gains in agriculture in some regions. Net costs due to global-warming-relevant emissions are embodied in the social cost of carbon dioxide. The range of the 2050 social cost of carbon from recent papers is \$500 (282-1,063)/metric tonne-CO_2e in 2013 USD (Jacobson et al., 2015a). This range is used to derive the costs in Table S37.

Table S37. Percent of 2013 world CO_2 emissions by country (GCP, 2014) and low, medium, and high estimates of avoided 2050 global climate-change costs due to converting each country to 100% WWS for all purposes. All costs are in 2013 USD.

	2013	2050 avoided global climate cost (\$2013)			
Country	Percent of world CO_2 emissions	Low cost, high benefit (\$bil./yr)	Mean (\$bil./yr)	High cost, low benefit (\$bil./yr)	Mean ¢/kWh-BAU-all-energy
Albania	0.014	6.5	3.0	1.7	8.5
Algeria	0.419	368.8	173.3	97.7	13.7
Angola	0.092	80.6	37.9	21.3	14.5
Argentina	0.577	327.6	153.9	86.8	10.6
Armenia	0.012	5.6	2.6	1.5	6.1
Australia	1.000	580.1	272.5	153.6	14.7
Austria	0.184	79.3	37.3	21.0	8.4
Azerbaijan	0.154	73.8	34.6	19.5	20.3
Bahrain	0.073	52.7	24.8	14.0	18.4
Bangladesh	0.191	162.5	76.4	43.0	12.3
Belarus	0.183	87.6	41.2	23.2	11.5
Belgium	0.290	125.3	58.9	33.2	9.9
Benin	0.016	14.0	6.6	3.7	8.3
Bolivia	0.054	30.6	14.4	8.1	10.2
Bosnia and Herzegovina	0.094	44.8	21.0	11.9	36.5
Botswana	0.015	13.3	6.2	3.5	12.0
Brazil	1.413	884.5	415.5	234.3	8.6
Brunei Darussalam	0.031	26.4	12.4	7.0	22.7
Bulgaria	0.122	58.3	27.4	15.4	14.0
Cambodia	0.014	12.3	5.8	3.2	5.3
Cameroon	0.022	19.5	9.2	5.2	4.1
Canada	1.476	691.8	325.0	183.2	9.5
Chile	0.262	154.3	72.5	40.9	10.6
China	29.265	16663.4	7828.3	4413.2	16.5
Chinese Taipei	0.776	661.1	310.6	175.1	21.2
Colombia	0.259	147.0	69.0	38.9	11.7

Congo	0.007	6.0	2.8	1.6	6.9
Congo, Dem. Republic	0.009	7.8	3.7	2.1	1.0
Costa Rica	0.023	13.1	6.2	3.5	9.1
Cote d'Ivoire	0.018	15.8	7.4	4.2	5.3
Croatia	0.060	28.8	13.5	7.6	10.8
Cuba	0.116	65.5	30.8	17.4	30.1
Cyprus	0.022	10.8	5.1	2.8	13.7
Czech Republic	0.296	127.7	60.0	33.8	15.8
Denmark	0.118	50.9	23.9	13.5	10.1
Dominican Republic	0.064	36.4	17.1	9.6	15.5
Ecuador	0.107	60.6	28.5	16.0	12.0
Egypt	0.629	553.3	259.9	146.5	13.8
El Salvador	0.018	10.5	4.9	2.8	10.3
Eritrea	0.002	1.6	0.8	0.4	7.7
Estonia	0.055	23.8	11.2	6.3	21.7
Ethiopia	0.020	17.5	8.2	4.6	1.3
Finland	0.148	63.8	30.0	16.9	7.9
France	1.009	435.4	204.6	115.3	8.7
Gabon	0.008	7.0	3.3	1.9	6.7
Georgia	0.018	8.6	4.0	2.3	7.1
Germany	2.225	960.4	451.2	254.4	13.6
Ghana	0.029	25.2	11.8	6.7	7.1
Gibraltar	0.001	0.6	0.3	0.2	0.5
Greece	0.217	93.7	44.0	24.8	14.1
Guatemala	0.033	18.7	8.8	5.0	6.7
Haiti	0.006	3.5	1.7	0.9	4.2
Honduras	0.024	13.4	6.3	3.6	8.9
Hong Kong, China	0.115	97.8	45.9	25.9	6.8
Hungary	0.121	52.3	24.6	13.9	10.4
Iceland	0.006	2.5	1.2	0.7	3.0
India	7.059	7574.9	3558.6	2006.2	23.8
Indonesia	1.448	1234.2	579.8	326.9	15.5
Iran, Islamic Republic	1.793	1292.7	607.3	342.4	16.0
Iraq	0.360	259.5	121.9	68.7	23.0
Ireland	0.108	46.5	21.8	12.3	14.8
Israel	0.210	90.6	42.5	24.0	17.8
Italy	1.034	446.5	209.8	118.2	9.9
Jamaica	0.021	11.9	5.6	3.2	15.6
Japan	3.655	1189.1	558.6	314.9	15.5
Jordan	0.066	47.6	22.4	12.6	17.4
Kazakhstan	0.903	432.0	202.9	114.4	20.3
Kenya	0.039	34.3	16.1	9.1	5.9
Korea, Dem. People's Rep.	0.224	191.2	89.8	50.6	31.8
Korea, Republic of	1.805	1010.9	474.9	267.7	16.6
Kosovo	0.025	11.9	5.6	3.2	21.4
Kuwait	0.295	212.8	99.9	56.3	19.0
Kyrgyzstan	0.019	9.1	4.3	2.4	6.5
Latvia	0.022	10.4	4.9	2.7	6.3
Lebanon	0.064	46.3	21.7	12.2	22.0
Libya	0.175	154.3	72.5	40.9	23.0
Lithuania	0.038	18.1	8.5	4.8	8.3
Luxembourg	0.031	13.5	6.4	3.6	11.2
Macedonia, Republic of	0.032	15.5	7.3	4.1	20.6
Malaysia	0.672	572.9	269.1	151.7	19.4
Malta	0.008	3.6	1.7	1.0	5.5
Mexico	1.366	804.6	378.0	213.1	13.2
Moldova, Republic of	0.014	6.8	3.2	1.8	8.3
Mongolia	0.037	31.3	14.7	8.3	18.6
Montenegro	0.008	3.7	1.7	1.0	13.3

Morocco	0.153	134.7	63.3	35.7	16.0
Mozambique	0.009	8.1	3.8	2.2	2.1
Myanmar	0.030	25.9	12.2	6.9	4.1
Namibia	0.010	8.5	4.0	2.2	9.9
Nepal	0.013	10.7	5.0	2.8	2.8
Netherlands	0.484	208.7	98.1	55.3	9.8
Netherlands Antilles	0.014	7.9	3.7	2.1	6.2
New Zealand	0.095	55.1	25.9	14.6	9.5
Nicaragua	0.013	7.6	3.6	2.0	10.1
Nigeria	0.244	214.5	100.8	56.8	4.4
Norway	0.170	73.3	34.4	19.4	8.5
Oman	0.174	125.1	58.8	33.1	12.3
Pakistan	0.482	411.1	193.1	108.9	10.7
Panama	0.028	15.6	7.3	4.1	5.4
Paraguay	0.015	8.3	3.9	2.2	5.1
Peru	0.190	107.9	50.7	28.6	14.2
Philippines	0.274	233.3	109.6	61.8	16.3
Poland	0.914	394.3	185.2	104.4	17.7
Portugal	0.152	65.7	30.9	17.4	11.9
Qatar	0.256	184.8	86.8	48.9	14.4
Romania	0.221	106.0	49.8	28.1	11.2
Russian Federation	5.315	1951.8	917.0	516.9	14.4
Saudi Arabia	1.523	1098.2	515.9	290.9	17.4
Senegal	0.022	19.2	9.0	5.1	13.1
Serbia	0.111	53.3	25.1	14.1	15.1
Singapore	0.051	43.8	20.6	11.6	1.2
Slovak Republic	0.100	43.0	20.2	11.4	10.4
Slovenia	0.045	19.6	9.2	5.2	13.0
South Africa	1.314	1154.9	542.6	305.9	25.1
Spain	0.704	303.7	142.7	80.4	9.6
Sri Lanka	0.043	36.4	17.1	9.6	7.2
Sudan	0.045	39.2	18.4	10.4	7.6
Sweden	0.132	57.1	26.8	15.1	5.1
Switzerland	0.118	51.0	23.9	13.5	7.6
Syrian Arab Republic	0.188	135.9	63.8	36.0	29.5
Tajikistan	0.008	3.9	1.8	1.0	6.0
Tanzania, United Republic	0.021	18.8	8.8	5.0	2.3
Thailand	0.959	817.4	384.0	216.5	15.5
Togo	0.005	4.5	2.1	1.2	4.8
Trinidad and Tobago	0.143	81.4	38.2	21.6	22.5
Tunisia	0.079	69.6	32.7	18.4	8.8
Turkey	0.954	411.6	193.4	109.0	15.7
Turkmenistan	0.158	75.8	35.6	20.1	10.1
Ukraine	0.885	423.5	199.0	112.2	15.3
United Arab Emirates	0.543	391.4	183.9	103.6	10.7
United Kingdom	1.355	585.0	274.8	154.9	12.5
United States of America	15.350	5924.3	2783.2	1569.0	13.5
Uruguay	0.020	11.2	5.2	3.0	7.0
Uzbekistan	0.302	144.6	67.9	38.3	10.5
Venezuela	0.648	367.6	172.7	97.4	15.0
Vietnam	0.496	423.0	198.7	112.0	17.3
Yemen	0.069	49.7	23.4	13.2	25.6
Zambia	0.007	6.6	3.1	1.7	2.1
Zimbabwe	0.027	23.3	11.0	6.2	5.5
World total or average	**99.747**	**57,209**	**26,876**	**15,151**	**14.9**

Table S37 indicates that the sum of the 139-country greenhouse gas and particle emissions may cause, in 2050, $26.9 (15.1-57.2) trillion/year in climate damage to the world. Thus, the global climate cost savings per person, averaged among these countries, to reducing all climate-relevant emissions through a 100% WWS system, is ~$3,100/person/year (in 2013 USD), or 14.9 (8.4-32) ¢/kWh-BAU-all-energy (Table S34).

Section S9. Impacts of WWS on Jobs and Earnings in the Energy Power Sector

This section provides estimates of job and revenue creation and loss due to implementing WWS electricity. The analysis does not include the job changes in industries outside of electric power generation, such as in the manufacture of electric vehicles, fuel cells or electricity storage because of the additional complexity required and greater uncertainty as to where those jobs will be located.

S9.1. Jobs Created and Changes in Earnings in the 100% WWS Scenario

Overview

We estimate jobs created in the 100% WWS scenario with the same general methods used to estimate BAU jobs lost in the WWS scenario, with one major difference: estimates of jobs per unit of energy, in all cases but one, are based on the National Renewable Energy Laboratory's *Jobs and Economic Development Impacts (JEDI)* models (NREL, 2013), rather than on the BLS CES. In this section we briefly review changes to parameters other than jobs per energy unit, and in the following section we discuss the estimates of jobs per energy unit.

In the analysis of jobs created in the 100% WWS scenario, the job sectors are associated with the generation and transmission of WWS power: onshore wind, offshore wind, wave power, geothermal, hydropower, tidal, residential PV, commercial PV, utility PV, CSP, solar thermal storage, additional conventional transmission, extra conventional distribution, and HVDC supergrid.

Changes to major parameter values are as follows:

JM_I, the omitted jobs *multiplier*, is 1.0 for all WWS job sectors because as discussed below we assume that the JEDI results we use capture all relevant direct and indirect jobs.

IJM_I, The induced jobs multiplier, is 1.0 for all WWS job sectors because the *JEDI* results we use already included jobs induced in the broader economy.

$E_{I,C,Y}$, The energy associated with sector *I* in country *C* in year *Y,* is MW of capacity for all sectors except electricity transmission and distribution, for which the units are km.

$L_{G-wws-ave}$, The average lifetime of WWS technologies, is the average of our high and low estimates of generator lifetimes.

∂, the exponent relating changes in total energy to changes in jobs/energy unit, is -0.05 – smaller than in the case of BAU jobs lost because we assume that WWS jobs are slightly less sensitive to the scale of output, because of greater modularity in production.

Jobs per energy unit

Our estimates of jobs per energy unit for the 100% WWS scenario are based on NREL' *JEDI* models (NREL, 2013). The *JEDI* models estimate the economic impacts of constructing and operating power plants, fuel production facilities, electricity transmission lines, and other projects. As mentioned above, *JEDI* models estimate jobs in three categories:

- Project development and onsite labor (which we call "direct" jobs);
- Local revenue and supply chain (which we call "indirect" jobs); and
- Induced jobs, driven by the spending and re-investment of earnings from direct and indirect jobs.

Construction jobs are defined as full-time equivalents, or 2080-hour units of labor per year (NREL, 2013). As discussed above, for consistency we adjusted the estimates of job losses in the BAU scenario so that they also include induced jobs.

For the parameter , $J / E_{I,US,BY}$ jobs per energy unit in sector *I* in the U.S. in the base year *BY*, we assume the average values in Table S38.

Table S38. Jobs created per energy unit in the 100% WWS scenario.

	Onshore wind	Offshore wind	Wave	Geo-thermal	Hydro-electric	Tidal	Residential roof PV
Jobs per unit:	*MW-cap*	*MW-cap*	*MW-cap*	*MW-cap*	*MW-cap*	*MW-cap*	*MW-cap*
Operation low	0.35	0.60	0.56	0.44	0.30	0.60	0.31
Operation high	0.38	0.66	0.58	0.48	0.30	0.62	0.33
Operation average	0.37	0.63	0.57	0.46	0.30	0.61	0.32
Construction low	5.54	7.30	6.73	24.88	12.00	6.81	35.59
Construction high	8.58	11.31	7.18	38.68	12.00	7.25	40.87
Construction average	7.06	9.30	6.95	31.78	12.00	7.03	38.23

	Commercial roof PV	Utility PV	CSP plant	Solar thermal for heat	Extra trans-mission	Extra dis-tribution	HVDC grid
Jobs per unit:	*MW-cap*	*MW-cap*	*MW-cap*	*MW-cap*	*km*	*km*	*km*
Operation low	0.16	0.84	0.83	0.84	0.062	0.028	0.063
Operation high	0.16	0.87	0.89	0.87	0.062	0.028	0.100
Operation average	0.16	0.85	0.86	0.85	0.062	0.028	0.082
Construction low	28.10	20.60	10.68	20.60	4.94	2.00	5.97
Construction high	31.42	21.98	11.57	21.98	5.28	3.00	6.38
Construction average	29.76	21.29	11.13	21.29	5.11	2.50	6.17

Notes:
Extra transmission = extra conventional electricity transmission network; extra distribution = extra conventional electricity distribution system; MW-cap = MW of installed capacity; km = kilometers.

Onshore wind, offshore wind, wave, geothermal, hydro, tidal, PV, and *CSP*: based on our runs of NREL's *JEDI* models.

Solar thermal for heat: We assume jobs/MW for *solar thermal for heat* is the same as for *utility PV*.

E*xtra transmission*: based on the *JEDI* analysis presented in Tables S28 and S29. The estimates of construction jobs are equal to the base-case value for AC transmission from Table S28 multiplied by 1.03 (low case) or 1.10 (high case).

Extra distribution: Operations jobs/km are equal to the total jobs in the sector *Electric power distribution* (U.S. Bureau of Labor Statistics, 2016; same source used to estimate BAU jobs lost) divided by 9 million km of distribution lines (Weeks (2010) gives 8.9 million for the U. S., and Harris Williams & Co. (2014) gives 9.7 million for all of North America), and multiplied by 1.22 to account for induced jobs (Table S28). We assume that construction jobs/km are about two orders of magnitude higher than operations jobs, as is the case for transmission jobs.

HVDC Grid: based on the *JEDI* results from Table S28 and on Clean Line Energy Partners (2010), which estimates about 5 construction and 0.5 operations jobs/km.

Changes in earnings in the 100% WWS scenario

These are calculated using the same methods and parameter values in the analysis of changes in earnings in the BAU scenario.

JEDI Job Creation Analysis

Changes in jobs and total earnings are estimated here first with the Jobs and Economic Development Impact (JEDI) models (NREL, 2013). These are economic input-output models with several assumptions and uncertainties (e.g. Linowes, 2012). They incorporate three levels of impacts: 1) project development and onsite labor impacts; 2) local revenue and supply chain impacts; and 3) induced impacts. Jobs and revenue are reported for two phases of development: 1) the construction period and 2) operating years.

Scenarios for WWS powered electricity generation are run for each country assuming that the WWS electricity sector is fully developed by 2050. The calculations account for only new WWS jobs associated with new WWS generator capacity as identified in Table S7 and corresponding new transmission lines. As construction jobs are temporary, JEDI models report construction job creation as full-time equivalents (FTE), which equal 2,080 hours of work per year. Here construction jobs are further reported as 35-year jobs, where one person works on 35 separate 1-year construction jobs during the period 2015 to 2050.

The number of jobs associated with new transmission lines assumes 80% of new lines will be 500 kV high-voltage direct current (HVDC) lines and 20% 230 kV alternating current (AC) lines. Total line length is simplistically assumed to equal five times the circular radius of a country. The transmission line JEDI model is used to calculate construction FTE jobs and annual operations jobs for the 230 kV AC lines for each country. For HVDC lines, the actual average numbers of construction FTE jobs and annual operation jobs among five proposed projects in the U.S. (Clean Line Energy Partners, 2015) are multiplied by the ratio of JEDI-model predicted number of jobs in a given country to that of the U.S. assuming 500 kV HVDC lines.

Table S39. Estimated new 35-year construction jobs, new 35-year operation jobs, 35-year construction plus operation jobs minus jobs lost, annual earnings corresponding to new construction and operation jobs, and net earnings from new construction plus operation jobs minus jobs lost (current jobs plus future jobs lost due to not growing fossil-fuel infrastructure), by country, due to converting to 100% WWS, based on the number of new generators needed of each type for annual average power and peaking/storage (Table S7). Earnings include wages, services, and supply-chain impacts. Monetary values are in 2013 USD.

Country	35-year construction jobs	35-year operation jobs	Job losses in fossil-fuel and nuclear energy industries	35-year net construction plus operation jobs created minus jobs lost	Annual earnings from new 40-year construction jobs (bil $/yr)	Earnings from new 40-year operation jobs (bil $/yr)	Net earnings from new construct-ion plus operation jobs minus jobs lost (bil $/yr)
Albania	6,502	4,913	6,061	5,354	0.41	0.31	0.34
Algeria	170,354	126,039	436,847	(140,454)	9.15	6.77	-7.55
Angola	58,506	45,588	332,687	(228,593)	2.26	1.76	-8.84
Argentina	183,606	144,020	206,006	121,620	11.58	9.08	7.67
Armenia	8,787	7,845	3,351	13,281	0.48	0.43	0.73
Australia	233,135	253,024	307,664	178,495	22.80	24.74	17.45
Austria	57,545	69,527	47,163	79,909	5.85	7.07	8.12
Azerbaijan	38,654	34,161	89,491	(16,677)	3.17	2.80	-1.37
Bahrain	19,231	31,342	53,337	(2,765)	2.08	3.38	-0.30
Bangladesh	193,686	209,315	169,833	233,168	5.85	6.32	7.04
Belarus	43,693	59,047	33,518	69,222	3.58	4.83	5.67
Belgium	91,409	153,513	50,819	194,103	8.93	14.99	18.96
Benin	22,312	18,756	29,877	11,191	0.52	0.44	0.26
Bolivia	23,316	17,378	52,507	(11,813)	0.82	0.61	-0.42
Bosnia and Herzegovina	10,939	8,611	7,468	12,082	0.68	0.53	0.75
Botswana	11,027	7,942	8,445	10,524	0.62	0.44	0.59
Brazil	776,573	669,887	824,570	621,890	42.77	36.89	34.25
Brunei Darussalam	10,007	12,097	42,244	(20,141)	1.55	1.87	-3.12
Bulgaria	29,792	28,534	22,693	35,633	2.47	2.36	2.95
Cambodia	23,945	18,262	42,502	(295)	0.74	0.56	-0.01

Cameroon	90,458	91,288	70,521	111,225	2.45	2.47	3.01
Canada	316,341	368,837	604,242	80,937	30.24	35.25	7.74
Chile	77,994	65,284	93,481	49,797	5.85	4.89	3.73
China	5,835,853	6,698,844	3,374,787	9,159,910	458.34	526.11	719.40
Chinese Taipei	162,852	192,865	110,502	245,215	28.24	33.44	42.52
Colombia	113,713	89,100	188,798	14,016	5.52	4.33	0.68
Congo	14,443	10,957	66,732	(41,332)	0.52	0.40	-1.50
Congo, Dem. Republic	150,210	137,207	218,765	68,651	2.55	2.33	1.17
Costa Rica	8,075	7,385	9,752	5,708	0.41	0.38	0.29
Cote d'Ivoire	50,854	42,308	106,622	(13,460)	1.44	1.20	-0.38
Croatia	25,809	29,265	14,952	40,122	2.39	2.70	3.71
Cuba	23,221	17,717	20,525	20,413	1.39	1.06	1.23
Cyprus	5,239	4,746	2,494	7,491	0.62	0.56	0.88
Czech Republic	64,604	86,589	44,382	106,811	5.21	6.99	8.62
Denmark	30,336	45,222	41,049	34,509	3.06	4.56	3.48
Dominican Republic	18,456	15,067	12,551	20,973	0.91	0.74	1.03
Ecuador	38,915	32,815	76,251	(4,521)	1.72	1.45	-0.20
Egypt	278,497	207,249	363,323	122,423	12.91	9.61	5.67
El Salvador	7,237	5,757	8,881	4,112	0.28	0.22	0.16
Eritrea	4,491	3,198	8,342	(653)	0.10	0.07	-0.01
Estonia	7,112	9,182	8,464	7,829	0.54	0.70	0.60
Ethiopia	219,127	184,601	389,663	14,065	4.68	3.95	0.30
Finland	38,217	54,712	45,857	47,071	3.59	5.15	4.43
France	257,986	281,176	205,141	334,020	23.76	25.89	30.76
Gabon	13,584	10,937	49,024	(24,503)	0.86	0.69	-1.55
Georgia	10,448	7,517	6,619	11,346	0.61	0.44	0.67
Germany	436,941	608,494	281,873	763,562	44.50	61.97	77.77
Ghana	45,017	36,344	69,806	11,555	1.37	1.10	0.35
Gibraltar	2,903	4,925	2,205	5,623	0.32	0.54	0.62
Greece	41,746	39,146	32,198	48,694	3.02	2.83	3.53
Guatemala	27,802	22,040	38,453	11,389	1.03	0.82	0.42
Haiti	15,375	14,946	19,323	10,998	0.32	0.31	0.23
Honduras	20,153	16,236	16,136	20,253	0.63	0.50	0.63
Hong Kong, China	42,341	75,328	27,468	90,201	5.65	10.04	12.03
Hungary	59,333	73,442	28,739	104,035	4.28	5.30	7.51
Iceland	11,722	19,643	4,058	27,307	1.17	1.96	2.72
India	2,628,905	2,060,760	2,376,515	2,313,150	124.76	97.80	109.78
Indonesia	674,077	554,253	882,362	345,967	34.94	28.73	17.93
Iran, Islamic Republic	558,993	576,339	799,029	336,302	34.69	35.76	20.87
Iraq	98,942	70,985	358,690	(188,763)	5.56	3.99	-10.61
Ireland	17,164	18,048	13,262	21,949	1.94	2.04	2.48
Israel	38,707	46,567	22,268	63,006	3.24	3.89	5.27
Italy	299,961	350,872	164,419	486,414	25.95	30.36	42.09
Jamaica	8,979	7,951	5,404	11,526	0.36	0.32	0.46
Japan	567,533	884,217	255,975	1,195,776	44.00	68.56	92.71
Jordan	23,778	18,061	13,160	28,680	1.14	0.87	1.38
Kazakhstan	166,343	148,527	207,360	107,510	17.10	15.27	11.05
Kenya	76,835	59,289	147,073	(10,948)	2.07	1.60	-0.29
Korea, Dem. People's Rep.	67,046	79,520	38,903	107,663	1.50	1.78	2.41
Korea, Republic of	433,032	680,880	204,351	909,561	38.37	60.33	80.59
Kosovo	5,386	4,282	3,789	5,880	0.24	0.19	0.26
Kuwait	72,990	122,326	309,612	(114,296)	10.32	17.29	-16.16
Kyrgyzstan	14,567	11,933	8,453	18,047	0.52	0.43	0.65
Latvia	9,474	11,084	12,355	8,203	0.93	1.09	0.81
Lebanon	16,114	19,295	12,076	23,333	0.88	1.05	1.27
Libya	51,731	38,422	258,485	(168,331)	2.73	2.03	-8.88
Lithuania	15,206	15,426	12,482	18,151	1.64	1.67	1.96
Luxembourg	8,699	14,143	4,095	18,747	1.45	2.36	3.12
Macedonia, Republic of	9,564	8,348	3,582	14,330	0.67	0.59	1.01

Malaysia	242,400	251,101	286,715	206,786	20.35	21.08	17.36
Malta	3,126	4,841	2,163	5,804	0.36	0.56	0.67
Mexico	447,020	370,146	547,968	269,199	28.50	23.60	17.17
Moldova, Republic of	9,169	8,290	4,765	12,694	0.39	0.35	0.54
Mongolia	21,789	16,310	22,731	15,368	1.19	0.89	0.84
Montenegro	2,528	2,038	2,075	2,492	0.20	0.16	0.19
Morocco	76,837	56,255	44,568	88,524	3.05	2.23	3.51
Mozambique	55,548	49,115	121,563	(16,901)	1.07	0.95	-0.33
Myanmar	86,175	64,725	125,005	25,895	2.93	2.20	0.88
Namibia	8,620	6,510	27,348	(12,218)	0.39	0.30	-0.55
Nepal	77,167	79,744	68,718	88,193	2.07	2.14	2.36
Netherlands	106,757	186,066	134,413	158,410	11.22	19.56	16.65
Netherlands Antilles	8,368	13,554	6,788	15,134	0.57	0.93	1.03
New Zealand	34,770	31,748	44,005	22,513	3.53	3.22	2.29
Nicaragua	8,613	7,152	9,463	6,303	0.31	0.26	0.23
Nigeria	632,429	605,065	1,193,984	43,510	24.53	23.47	1.69
Norway	26,529	37,599	214,913	(150,784)	3.44	4.87	-19.55
Oman	62,459	63,476	158,289	(32,353)	5.94	6.04	-3.08
Pakistan	395,857	346,599	387,699	354,757	14.22	12.45	12.75
Panama	16,244	14,516	11,537	19,223	1.00	0.90	1.19
Paraguay	6,134	6,564	29,283	(16,585)	0.25	0.26	-0.66
Peru	54,350	45,326	75,934	23,743	2.51	2.09	1.09
Philippines	126,267	102,341	119,799	108,809	5.38	4.36	4.64
Poland	144,077	137,326	100,440	180,962	10.49	9.99	13.17
Portugal	40,517	34,503	30,084	44,936	3.07	2.61	3.41
Qatar	74,805	129,561	323,634	(119,269)	17.36	30.06	-27.67
Romania	62,583	59,474	63,208	58,849	5.70	5.41	5.36
Russian Federation	624,288	748,103	1,119,520	252,871	53.47	64.07	21.66
Saudi Arabia	339,010	293,273	1,074,084	(441,802)	39.69	34.34	-51.73
Senegal	19,614	14,673	28,950	5,337	0.48	0.36	0.13
Serbia	42,602	46,439	22,778	66,263	3.02	3.29	4.69
Singapore	86,125	152,646	88,553	150,219	15.15	26.85	26.42
Slovak Republic	24,636	25,464	16,398	33,702	1.89	1.96	2.59
Slovenia	10,695	9,901	9,148	11,449	0.85	0.79	0.91
South Africa	304,801	299,511	305,294	299,017	15.50	15.23	15.21
Spain	184,844	179,828	129,310	235,361	15.78	15.35	20.09
Sri Lanka	43,301	33,381	50,962	25,720	2.32	1.79	1.38
Sudan	61,072	43,399	116,258	(11,788)	1.85	1.32	-0.36
Sweden	46,668	64,204	72,569	38,304	4.84	6.65	3.97
Switzerland	44,385	48,755	28,610	64,529	5.20	5.71	7.56
Syrian Arab Republic	46,175	33,464	65,150	14,489	1.90	1.38	0.60
Tajikistan	2,804	3,287	5,418	674	0.09	0.11	0.02
Tanzania, United Republic	118,456	101,288	185,696	34,048	3.02	2.58	0.87
Thailand	408,404	409,076	369,771	447,709	25.92	25.96	28.41
Togo	14,499	13,127	31,034	(3,408)	0.30	0.27	-0.07
Trinidad and Tobago	30,927	43,481	81,095	(6,687)	2.36	3.32	-0.51
Tunisia	45,250	36,471	48,035	33,686	2.14	1.73	1.60
Turkey	225,507	169,251	100,732	294,026	14.16	10.63	18.46
Turkmenistan	56,596	54,740	104,524	6,812	4.45	4.31	0.54
Ukraine	154,914	184,875	124,638	215,151	8.21	9.80	11.41
United Arab Emirates	187,245	302,180	379,484	109,941	26.20	42.28	15.38
United Kingdom	257,511	400,683	247,025	411,169	24.22	37.69	38.68
United States of America	1,989,555	2,158,631	2,246,764	1,901,422	248.56	269.69	237.55
Uruguay	12,009	9,858	12,078	9,789	0.73	0.60	0.59
Uzbekistan	138,875	124,643	125,053	138,466	6.42	5.76	6.40
Venezuela	212,613	194,817	381,852	25,579	11.31	10.36	1.36
Vietnam	239,256	234,390	264,209	209,437	9.30	9.11	8.14
Yemen	25,572	21,586	51,463	(4,305)	0.79	0.67	-0.13
Zambia	44,054	33,026	75,377	1,703	1.29	0.97	0.05

Zimbabwe	60,673	53,360	82,887	31,146	1.34	1.18	0.69
World total or average	**25,378,526**	**26,603,450**	**27,744,572**	**24,237,405**	**1,864**	**2,062**	**1,863**

Table S39 indicates that 100% conversion to WWS across 139 countries may create ~25.4 million new 35-year construction jobs and ~26.6 million new 35-year operation and maintenance jobs, or a total of 52.0 million 35-year jobs for WWS generators and transmission. These employment numbers do not include all external jobs created in areas such as research and development, storage development, and local economy improvement.

S9.2. BAU Jobs Foregone (Lost) in the 100% WWS Scenario

General method

Total BAU jobs foregone. The total number of BAU jobs foregone in country *C* in year *TY* is the sum of jobs foregone in the country over all affected energy-industry categories *I*:

$$J_{T,C,TY} = \sum_{I} J_{I,C,TY}$$

where

$J_{T,C,TY}$ = Total number of BAU jobs foregone in country *C* in year *TY*

$J_{I,C,TY}$ = Jobs foregone in the BAU scenario in industry-employment sector *I* in country *C* in target year *TY*

Jobs foregone by energy industry

We estimate full-time operations jobs for most energy industries and full-time construction jobs for the power-plant sector and the petroleum-refinery sector in the BAU in the target year. Jobs are calculated for each industry (*I*) employment category as the product of jobs per unit of energy and total energy. Total energy is the product of energy in 2012, by country, and the ratio of energy in the target year to energy in 2012. In the case of operations jobs, the relevant "energy" metric refers to the amount of energy produced, processed, throughput, distributed, consumed in end use, or embodied in products, as appropriate for the sector. In the case of power-plant construction jobs, the relevant energy metric is the amount of generating capacity installed in the target year, which we assume is the amount required to replace retiring plants. In the case of petroleum-refinery construction jobs, the relevant energy metric is the amount of output from plants that we assume are replaced or majorly upgraded in the target year. (Note that these methods are consistent with those used to estimate jobs created in the WWS scenario.)

Jobs per energy unit is calculated as the product of jobs/energy in the US in 2012, the fraction of BAU jobs foregone in the WWS scenario, a multiplier for jobs omitted from our base data, a multiplier for "induced" jobs in the broader economy, and country-specific adjustment factors accounting for the relationship between jobs/energy and GDP/capita, and between jobs/energy and total energy.

Formally,

$$J_{I,C,TY} = J/E_{I,US,BY} \cdot JLfr_{I,TY} \cdot JM_I \cdot IJM_I \cdot E_{I,C,TY} \cdot GDPC^{\wedge}{}_{C,TY} \cdot E^{\wedge}{}_{I,C,TY}$$

$$J/E_{I,US,BY} = \frac{J^*{}_{I,US,BY}}{E_{I,US,BY}}$$

$$E_{I,C,TY} = E_{I,C,BY} \cdot E_{C,I,TY/BY}$$

where (all parameter values not discussed here are discussed in next subsection)

$J/E_{I,US,BY}$ = Jobs per energy unit in sector *I* in the U.S. in the base year *BY*
$JLfr_{I,TY}$ = Of the total jobs in the BAU sector *I* in target year *TY*, the fraction that actually are foregone in the 100% WWS scenario
JM_I = Omitted jobs multiplier: the ratio of total jobs actually in or related to sector *I*, to the jobs counted in our data $J^*{}_{I,US,BY}$
IJM_I = Induced jobs multiplier: the ratio of total jobs, including those induced in the broader economy, to the direct and indirect jobs in sector *I*
$J^*{}_{I,US,BY}$ = Jobs in sector *I* in the U.S. in the base year *BY*
$E_{I,C,Y}$ = Energy associated with sector *I* in country *C* in year *Y (BY* or *TY)* (KTOE)
$GDPC^{\wedge}{}_{C,TY}$ = Adjustment factor accounting for the effect on jobs/energy unit of differences in GDP per capita between country *C* in year *TY* and the U.S. in the base year *BY* of the U.S. jobs/energy-unit estimates.
$E^{\wedge}{}_{I,C,TY}$ = Adjustment factor accounting for the effect on jobs/energy unit of changes in total associated energy
$E_{I,C,TY/BY}$ = Target-year/base-year ratio for the energy measure in sector *I* in country *C*
subscript *I* = Industry employment categories (see spreadsheet Delucchi et al., 2016)
subscript *C* = Countries in the analysis
TY = Target year (2050)
BY = Base year (varies)
KTOE = Thousand tons of oil-equivalent

<u>An important simplifying assumption</u>
Our method assumes that the each country manufactures and maintains the amount of energy equipment that satisfies its own energy production or consumption; that is, we do not attempt to estimate manufacture of energy equipment for export. In reality there is a great deal of international trade in energy equipment: for example, China accounts for about 70% of total global production of solar PV modules (IRENA, 2015b). Without doing a more detailed analysis of international trade, we cannot say whether our simplifying assumption biases our estimates of net changes in jobs.

<u>Energy use for the power-plant-construction sector</u>
As mentioned above, the relevant energy-use in the power-plant-construction (*ppc*) sector, $E_{I-ppc,C,TY}$, is the amount of generating capacity newly installed in the target year. Assuming for simplicity that the system is in steady-state in the target year (capacity additions =

capacity retirements), then the generating capacity newly installed in the target year is the amount that replaces capacity at the end of its life in the target year, which in steady state is equal to the total target-year generating capacity divided by the capacity-weighted average lifetime of power plants. The capacity-weighted average lifetime is estimated on the basis of EIA/EIO-projected year-*TY* capacity by plant type and our estimates of lifetime by plant type.

The total generating capacity in the target year is equal to the total in the base year multiplied by the factor increase in total capacity between the target year and the base year. The factor increase for each country is assumed to equal the projected factor increase for the region of which it is a part.

The total base-year generating capacity is estimated by dividing total electricity output in country *C* by the electricity-system wide capacity factor for country *C* in the base year. The capacity factor for each country is assumed to equal the capacity factor for the region of which it is a part. The capacity factor for each region is calculated on the basis of EIA's *IEO* estimates of generation and capacity by region (EIA, 2016a).

Formally,

$$E_{I-ppc,C,TY} = \frac{El_{cap-total,C,BY} \cdot El_{cap-total,C,TY/BY}}{L_{cap-ave,C,TY}}$$

$$El_{cap-total,C,BY} = \frac{El_{gen-total,C,BY} \cdot 1000 \cdot K_{GWh/KTOE}}{8760 \cdot CF_{total,C,BY}}$$

$$El_{cap-total,C,TY/BY} = El_{cap-total,R:C\in R,TY/BY}$$

$$CF_{total,C,BY} = CF_{total,R:C\in R,BY}$$

$$CF_{total,R,BY} = \frac{El_{gen-total,R,BY}}{El_{cap-total,BY} \cdot 8760}$$

$$L_{cap-ave,C,TY} = \sum_{G} CAPFr_{G,R:C\in R,TY} \cdot L_{G-ave}$$

where

$E_{I-ppc,C,TY}$ = Energy associated with new power-plant construction in country *C* in year *TY* (MW of newly built generating capacity)

$El_{cap-total,C,BY}$ = Total electricity-generating capacity in country *C* in year *BY* (MW)

$El_{cap-total,C,TY/BY}$ = The ratio of total generating capacity in year *TY* to capacity in *BY*, in country *C*

$L_{cap-ave,C}$ = The capacity-weighted average lifetime of power plants in country *C* in year *TY*

$CAPFr_{G,R:C\in R,TY}$ = Generating-technology G share of total installed capacity in region R (containing country C) in year TY (calculated from EIA's *IEO* projections [EIA, 2016a] of capacity by general generating technology class)

L_{G-ave} = The average lifetime of EIA *IEO* technology G (based on our estimated lifetimes for the similar technology classes in our detailed cost analysis)

$El_{cap-total,R:C\in R,TY/BY}$ = The ratio of total generating capacity in year TY to capacity in BY, in region R containing country C (EIA, 2016a)

$El_{total,C,BY}$ = Total electricity generation output in country C in base year BY (KTOE) (IEA, 2015c)

1000 = MWh/GWh

$K_{GWh/KTOE}$ = GWh per KTOE (11.63) (IEA, 2015c)

8760 = Hours/year

$CF_{El_{TOT},C,BY}$ = Capacity factor for total electricity generation in country C in base year BY

$CF_{El_{TOT},R:C\in R,BY}$ = Capacity factor for total electricity generation in region R containing country C in base year BY

$El_{gen-total,R,BY}$ = Total electricity generation in EIA-*IEO* region R in year BY (GWh) (EIA, 2016a)

G = Generating technologies in the EIA's *IEO* (coal, natural gas, liquids, nuclear, hydropower, geothermal, wind, solar, and other renewables)

Energy use in the petroleum-refinery-construction sector. We assume simply that the amount of refinery output that is replaced or majorly upgraded ever year is

$$\frac{1}{L_{I-refinery}} \cdot E_{I-refinery}$$

where $L_{I-refinery}$ is the average lifetime of a refinery before replacement or major upgrade (we assume 50 years) and $E_{I-refinery}$ is the total annual energy output of refineries.

GDP per capita adjustment

The GDP per capita adjustment, $GDPC_{C,TY}\wedge$, is estimated as a function of GDP per capita for country C relative to that for the U. S. The adjustment exponent, or elasticity, is itself a function of the relative GDP per capita:

$$GDPC_{C,TY}\wedge = GDPC'_{C,TY}{}^{\gamma_{JOBS1}\cdot GDPC'_{C,TY}{}^{\gamma_{JOBS2}}}$$

$$GDPC'_{C,TY} = \frac{GDPC_{C,TY}}{GDPC_{US,BY_{J/E}}}$$

where

$GDPC'_{C,TY}$ = GDP per capita of country C in TY relative to that of the U.S. in a base year

$GDPC_{C,TY}$ = GDP per capita of country C in TY (see discussion of GDP per capita elsewhere)

$GDPC_{US,BY_{J/E}}$ = GDP per capita of the U. S. in the base year BY of the estimates of jobs/energy unit (see “Important general parameters”)

$\gamma_{JOBS1}, \gamma_{JOBS2}$ = Exponents relating changes in GDP per capital to changes in jobs per energy unit

<u>Energy/jobs adjustment</u>

Finally, the adjustment factor accounting for the effect on jobs/energy unit of changes in total associated energy, $E^{\wedge}_{I,C,TY}$, is estimated simply as

$$E^{\wedge}_{I,C,TY} = \left(\frac{E_{C,I,TY}}{E_{I,US,BY}} \right)^{\partial}$$

where

∂ = Exponent relating changes in total energy to changes in jobs/energy unit

Parameter values

For detailed data categories and data inputs, see the accompanying spreadsheet (Delucchi et al., 2016).

Jobs in the U.S. in the base year. Data on jobs by industry sector, except for the sectors *uranium mining, fossil generation, non-utilities, nuclear and biomass generation, power-sector construction*, and *petroleum-refinery construction* are from the Bureau of Labor Statistics (BLS), Current Employment Statistics (CES) (U.S. Bureau of Labor Statistics, 2016). BLS CES data are for the year 2012, which is the same year as the data on associated energy, from IEA (see below).

Jobs in *uranium mining* are from the EIA's *Domestic Uranium Production Report* (EIA, 2016i). EIA uranium employment estimates are the average for 2007 to 2014; we chose the average rather than the year 2012 because of large year-to-year variability.

For the sectors *fossil generation, non-utilities, nuclear and biomass generation*, and *power-sector construction*, we calculate jobs/energy unit differently, as discussed below.

<u>Associated energy, base year.</u> Energy data are from the IEA *World Energy Balances* (IEA, 2015c), except as noted here. *Fossil generation, utilities* are IEA-reported generation data (IEA reports in KTOE; we convert to GWh) for coal, oil, and NG generation by "main activity producers" (presumably utilities). *Fossil generation, non-utilities* data are the difference between total coal, oil, and NG generation and utility fossil generation. *Uranium mining* data are tonnes reported by the World Nuclear Association (WNA), the average for

2007 to 2014 (WNA, 2016). These WNA estimates agree to within a few percent with the estimates by the EIA (the source of our employment data).

For the power-plant construction sector, energy use is MW of capacity newly built in the target year. As shown above, capacity is calculated on the basis of total generation (IEA, 2015c), the capacity factor for total generation (based on EIA's *IEO*; EIA, 2016a) and the capacity-weighted average lifetime.

For the petroleum-refinery construction sector, energy use is refinery output in the target year, in KTOE. Now, as discussed below, to estimate petroleum-refining construction jobs, we use NREL's *JEDI* petroleum-refinery model, which estimates jobs per [barrels per calendar day capacity (BPCD)]. We convert BPCD to KTEO using EIA data (EIA, 2016h) on BPCD capacity in the U.S. in 2012, along with our estimate of KTOE output from refineries in the U. S. in 2012.

<u>Ratio of energy use in TY to BY</u>. As discussed in the section "Energy use in a 100%-WWS world vs. BAU," we estimate this ratio on the basis of EIA's *IEO* projections by region extrapolated past 2040, applied to individual countries.

<u>Jobs per energy unit</u>
This is equal to employment divided by energy production, except as noted here. Jobs/energy unit for *Fossil generation, non-utilities* is assumed to be the same as estimated for *Fossil generation, utilities.* Jobs/energy unit for *Nuclear and biomass generation, total* is assumed to be the same as for *Nuclear and other electric power generation, utilities.* Jobs/energy unit for *Bioenergy except for electricity* is our assumption based in part on the NREL's *JEDI* (Jobs and Economic Development Impact) model, which indicates a value of 1.8 jobs/KTOE for the operation of ethanol fuel plants (NREL, 2013; see the discussion of *JEDI* in the major section on job creation in the 100% WWS scenario). This value for *Bioenergy* is meant to include production of the feedstock as well as any processing and transportation. Jobs/energy unit for *Power-sector construction* is based on NREL's *JEDI* model estimates for various renewable-energy technologies and includes jobs induced in the broader economy (units here are full-time person-years per MW of capacity). Jobs/energy unit for *Petroleum-refinery construction* is from NREL's *JEDI* petroleum-refining model and includes jobs induced in the broader economy. (See the discussion of *JEDI* in the major section on jobs created in the 100% WWS scenario.)

Note that *JEDI* estimates of operations jobs/GWh for WWS technologies are generally slightly higher than job/GWh estimates based on BLS-CES data for all utility generation and for nuclear and renewable generation.

<u>GDP per capita</u>
See the section "Projection of GDP per capita."

<u>Fraction of jobs lost in WWS scenario</u>
For *Fossil fuel production and associated services, except petroleum refining,* this is the fraction of total fossil-fuel use that will be replaced in a 100% WWS scenario in the target

year, which we estimate as all fossil-fuels used for *energy* purposes plus a small portion of non-energy use of fossil fuels (see the discussion of the projection of jobs in the industrial sector in the BAU, under the section “Projections of end-use energy consumption by country, sector, and fuel, BAU“). For *Petroleum refineries* (for both operation and construction jobs), we assume that, in effect, only half of the non-energy fossil-fuel use is processed at petroleum refineries. We assumed that all jobs in the sector *Asphalt, paving, etc.* are retained (not foregone, or “lost”) in WWS scenario. We assume that most jobs in the sector *Gasoline stations with convenience stores* either are related to the convenience store, or else have a public-charging-station equivalent in the WWS scenario, and hence are not “lost.” We assume that half of the jobs in the sector *Other gasoline stations* have a public-charging equivalent in the WWS scenario, and hence are not “lost.” We assume that all existing jobs in the sector *Electric power transmission and distribution* will be retained in the WWS scenario. For the sector *Auto oil shops and other auto repair,* we use estimates of relative maintenance and repair (m & r) costs for EVs (Delucchi et al., 2000) to estimate the fraction of m & r activities and jobs *not* needed for electric vehicles (e.g., for oil changes, pollution control, and engine coolant m & r). For the sector *Rail transportation, Water transportation, Truck transportation,* the fraction of jobs foregone is equal to ton-miles moving coal or petroleum products divided by total ton-miles moved (U. S. Bureau of Transportation Statistics and U. S. Census Bureau, 2015), multiplied by 0.95 to account for non-energy uses of fossil fuels.

<u>Multipliers for omitted pertinent jobs in base data</u>
This multiplier accounts for jobs in the relevant sector that are not included in our base data. For the sector *Uranium mining*, this is the ratio of total world demand for uranium to total reported uranium production (WNA, 2016). For the sector *Power sector construction*, we assume that the IEA’s estimates of total generation, from which we calculate the base-year total generating capacity, capture all relevant installed capacity, which means that the multiplier is 1.0.

In all other cases, we assume that our employment estimates capture all of the important jobs in the sector.

<u>Multiplier for induced jobs</u>
We use this multiplier to make sure that our estimates of jobs lost in the BAU scenario are consistent with our estimates of jobs in the WWS scenario.

To estimate construction and operations jobs in the WWS scenario, we use NREL’s *JEDI* models (NREL, 2013) (see the next section). As discussed below, *JEDI* reports jobs in three categories: direct, indirect, and induced; for the WWS scenario, we include all three. Therefore, to ensure consistency, the estimates of jobs lost in the BAU scenario should include direct +indirect + jobs induced in the broader economy.

The first question is whether our base BLS CES data on BAU jobs in each sector include direct, direct+indirect, or direct+indirect+induced as defined by *JEDI*. It is clear that our base data include at least direct jobs, and do not include induced jobs. A comparison of our estimate of operations jobs for the petroleum-refinery sector (0.088 jobs/KTOE) with *JEDI* estimates (0.085 direct+indirect jobs/KTOE) suggests that our estimates also include what *JEDI* calls "indirect" jobs. Therefore, we assume that our estimates of BAU jobs in each sector *I* include direct *and* indirect jobs but not induced jobs as defined for *JEDI*. Therefore, for our estimates of BAU jobs to be consistent with our *JEDI*-based estimates of WWS jobs, we need to account for induced jobs in the BAU.

To estimate a general multiplier for induced jobs, we ran the *JEDI* models and calculated the ratio of total jobs (including induced jobs) to direct+indirect jobs. The results are shown in Table S40. For operations jobs lost in the sectors *petroleum refining, electric power generation,* and *electric power transmission*, we use the induced-job multiplier for the corresponding sector in Table S40. We assume that the multiplier for *electric power distribution* is the same as that for *electric power transmission*. For all of the other BAU operations-job-loss sectors (i.e., those not covered explicitly in Table S40), we assume that the induced-job multiplier is 1.25, which is an approximate average of the values in Table S40. Note that we do not apply the induced-job multiplier to BAU construction jobs for power plants or petroleum refineries because for these, as discussed elsewhere, we use *JEDI* estimates of total jobs including induced jobs.

Table S40. The induced-job multiplier from NREL's *JEDI* models.

Project	**Multiplier for induced jobs**	
	Construction	*Operation*
Residential PV	1.27	1.12
Commercial PV	1.29	1.21
Utility PV	1.29	1.20
CSP trough plant	1.41	1.20
Offshore wind farm	1.55	1.35
Onshore wind farm	1.29	1.29
Conventional hydro plants	1.26	1.22
Geothermal plants	1.19	1.25
Marine and hydrokinetic wave plants	1.58	1.28
Coal power plant	1.40	1.31
Natural gas combined-cycle plant	1.27	1.13
Petroleum refinery	1.36	1.33
Transmission line, 345 kV AC, 644 km	1.22	1.22

Note: the multiplier for induced jobs is equal to total jobs estimated by JEDI (including jobs induced in the broader economy) divided by direct (on-site) and indirect (supply-chain) jobs.

Elasticity of jobs/energy w.r.t. changes in energy

As energy production increases, jobs/energy-unit presumably will decrease slightly because of economies of scale and efficiencies in the use of labor. We assume a value of -0.08.

Elasticity of jobs/energy w.r.t. changes in GDP/capita

Assuming that labor is used more intensively in poorer countries, then as GDP/capita increases, Jobs/energy-unit will decrease slightly because of substitution of capital for labor. Now, as shown above, the adjustment factor is equal to the GDP/capita ratio raised to an overall exponent, where the overall exponent is a lower exponent multiplied by the GDP/capita ratio raised to an upper exponent.

Note that here we estimate the effect of changes in GDP per capita with respect to the base year of the estimates of jobs/energy unit in the U. S. Table S41 shows how the overall adjustment factor $GDPC_{C,TY}\wedge$ varies with different values of $\gamma_{JOBS1}, \gamma_{JOBS2}$, and $GDPC'_{C,TY}$:

Table S41. Variation in $GDPC_{C,TY}\wedge$ with different values of $\gamma_{JOBS1}, \gamma_{JOBS2}$, and $GDPC'_{C,TY}$

		$GDPC'_{C,TY}$													
γ_{JOBS2}	γ_{JOBS1}	3.50	2.75	2.00	1.50	1.20	0.80	0.50	0.40	0.25	0.20	0.15	0.10	0.05	0.02
-0.28	-0.30	0.77	0.80	0.84	0.90	0.95	1.07	1.29	1.43	1.85	2.13	2.63	3.73	8.00	33.4
-0.26	-0.30	0.76	0.79	0.84	0.90	0.95	1.07	1.28	1.42	1.82	2.08	2.54	3.51	7.09	25.7
-0.24	-0.30	0.76	0.79	0.84	0.90	0.95	1.07	1.28	1.41	1.79	2.03	2.45	3.32	6.32	20.1
-0.23	-0.30	0.75	0.79	0.84	0.90	0.95	1.07	1.28	1.40	1.77	2.01	2.41	3.23	5.99	17.9
-0.22	-0.30	0.75	0.78	0.84	0.89	0.95	1.07	1.27	1.40	1.76	1.99	2.37	3.15	5.68	16.0
-0.21	-0.30	0.75	0.78	0.84	0.89	0.95	1.07	1.27	1.40	1.74	1.97	2.33	3.07	5.40	14.4
-0.20	-0.30	0.75	0.78	0.83	0.89	0.95	1.07	1.27	1.39	1.73	1.95	2.30	2.99	5.14	13.0
-0.33	-0.25	0.81	0.83	0.87	0.92	0.96	1.06	1.24	1.36	1.73	1.98	2.43	3.42	7.48	35.0
-0.30	-0.25	0.81	0.83	0.87	0.91	0.96	1.06	1.24	1.35	1.69	1.92	2.31	3.15	6.29	23.6
-0.28	-0.25	0.80	0.83	0.87	0.91	0.96	1.06	1.23	1.34	1.67	1.88	2.24	2.99	5.66	18.6
-0.26	-0.25	0.80	0.82	0.87	0.91	0.96	1.06	1.23	1.34	1.64	1.84	2.17	2.85	5.11	14.9
-0.25	-0.25	0.80	0.82	0.86	0.91	0.96	1.06	1.23	1.33	1.63	1.83	2.14	2.78	4.87	13.5
-0.23	-0.25	0.79	0.82	0.86	0.91	0.96	1.06	1.23	1.33	1.61	1.79	2.08	2.66	4.44	11.1
-0.22	-0.25	0.79	0.82	0.86	0.91	0.96	1.06	1.22	1.32	1.60	1.77	2.05	2.60	4.25	10.1
-0.38	-0.20	0.86	0.87	0.90	0.93	0.97	1.05	1.20	1.30	1.60	1.81	2.18	3.02	6.49	31.8
-0.36	-0.20	0.85	0.87	0.90	0.93	0.97	1.05	1.19	1.29	1.58	1.78	2.12	2.87	5.82	24.5
-0.34	-0.20	0.85	0.87	0.90	0.93	0.97	1.05	1.19	1.28	1.56	1.74	2.06	2.74	5.25	19.3
-0.32	-0.20	0.85	0.86	0.89	0.93	0.97	1.05	1.19	1.28	1.54	1.71	2.01	2.62	4.77	15.4
-0.30	-0.20	0.84	0.86	0.89	0.93	0.97	1.05	1.19	1.27	1.52	1.68	1.95	2.51	4.36	12.6
-0.29	-0.20	0.84	0.86	0.89	0.93	0.97	1.05	1.18	1.27	1.51	1.67	1.93	2.45	4.17	11.4
-0.28	-0.20	0.84	0.86	0.89	0.93	0.97	1.05	1.18	1.27	1.50	1.66	1.91	2.40	4.00	10.4
-0.42	-0.17	0.88	0.89	0.92	0.94	0.97	1.04	1.17	1.26	1.52	1.71	2.05	2.80	6.00	31.2
-0.40	-0.17	0.88	0.89	0.91	0.94	0.97	1.04	1.17	1.25	1.51	1.68	1.99	2.67	5.41	24.0
-0.38	-0.17	0.88	0.89	0.91	0.94	0.97	1.04	1.17	1.25	1.49	1.66	1.94	2.56	4.90	18.9
-0.37	-0.17	0.87	0.89	0.91	0.94	0.97	1.04	1.16	1.24	1.48	1.64	1.92	2.50	4.68	16.9
-0.36	-0.17	0.87	0.89	0.91	0.94	0.97	1.04	1.16	1.24	1.47	1.63	1.89	2.45	4.47	15.2
-0.35	-0.17	0.87	0.89	0.91	0.94	0.97	1.04	1.16	1.24	1.47	1.62	1.87	2.40	4.28	13.7
-0.34	-0.17	0.87	0.89	0.91	0.94	0.97	1.04	1.16	1.24	1.46	1.60	1.85	2.35	4.10	12.4
-0.47	-0.14	0.91	0.92	0.93	0.95	0.98	1.04	1.14	1.22	1.45	1.62	1.91	2.59	5.55	31.3

-0.44	-0.14	0.90	0.91	0.93	0.95	0.98	1.04	1.14	1.21	1.43	1.58	1.84	2.43	4.79	21.4
-0.42	-0.14	0.90	0.91	0.93	0.95	0.98	1.03	1.14	1.21	1.42	1.56	1.80	2.33	4.38	17.0
-0.40	-0.14	0.90	0.91	0.93	0.95	0.98	1.03	1.14	1.20	1.40	1.54	1.76	2.25	4.02	13.7
-0.38	-0.14	0.90	0.91	0.93	0.95	0.98	1.03	1.13	1.20	1.39	1.51	1.73	2.17	3.70	11.3
-0.37	-0.14	0.90	0.91	0.93	0.95	0.98	1.03	1.13	1.20	1.38	1.50	1.71	2.13	3.56	10.3
-0.36	-0.14	0.89	0.91	0.93	0.95	0.98	1.03	1.13	1.20	1.38	1.50	1.69	2.09	3.43	9.4
-0.57	-0.10	0.94	0.94	0.95	0.97	0.98	1.03	1.11	1.17	1.36	1.50	1.75	2.35	5.22	38.0
-0.55	-0.10	0.94	0.94	0.95	0.97	0.98	1.03	1.11	1.16	1.35	1.48	1.71	2.26	4.74	28.9
-0.52	-0.10	0.94	0.94	0.95	0.97	0.98	1.03	1.10	1.16	1.33	1.45	1.66	2.14	4.15	19.9
-0.50	-0.10	0.94	0.94	0.95	0.97	0.98	1.03	1.10	1.16	1.32	1.43	1.63	2.07	3.82	15.9
-0.48	-0.10	0.93	0.94	0.95	0.97	0.98	1.03	1.10	1.15	1.31	1.42	1.60	2.00	3.53	12.9
-0.46	-0.10	0.93	0.94	0.95	0.97	0.98	1.03	1.10	1.15	1.30	1.40	1.57	1.94	3.28	10.6
-0.45	-0.10	0.93	0.94	0.95	0.97	0.98	1.02	1.10	1.15	1.30	1.39	1.56	1.91	3.17	9.7
-0.75	-0.05	0.98	0.98	0.98	0.99	0.99	1.01	1.06	1.10	1.22	1.31	1.48	1.91	4.12	39.6
-0.73	-0.05	0.98	0.98	0.98	0.99	0.99	1.01	1.06	1.09	1.21	1.30	1.46	1.86	3.80	30.0
-0.71	-0.05	0.97	0.98	0.98	0.98	0.99	1.01	1.06	1.09	1.20	1.29	1.44	1.80	3.51	23.2
-0.70	-0.05	0.97	0.98	0.98	0.98	0.99	1.01	1.06	1.09	1.20	1.28	1.43	1.78	3.39	20.6
-0.69	-0.05	0.97	0.98	0.98	0.98	0.99	1.01	1.06	1.09	1.20	1.28	1.42	1.76	3.27	18.3
-0.67	-0.05	0.97	0.97	0.98	0.98	0.99	1.01	1.06	1.09	1.19	1.27	1.40	1.71	3.05	14.7
-0.65	-0.05	0.97	0.97	0.98	0.98	0.99	1.01	1.06	1.09	1.19	1.26	1.38	1.67	2.86	12.0

The combination of γ_{JOBS1} = -0.25 and γ_{JOBS2} = -0.25, shaded reddish in Table S41, gives what we think are the most reasonable values of $GDPC_{C,TY}$^ .

It is possible that our method underestimates job losses in the BAU in some countries with a very large pool of relatively low paid laborers, such as China. For example, IRENA (2016b) reports an estimate that the fossil-fuel sector in China supports around 8 million jobs, more than double our estimate. However, to the extent that the reasons for this underestimation pertain also to our estimate of jobs *created* in the WWS scenario, we will have underestimated jobs created as well. In support of this, we note that according to IRENA (2015b), in 2014 China employed about 1.3 million people to manufacture 34 GW of solar PV systems – about 38 jobs per MW. This is roughly double the JEDI estimate that we use (excluding, for this comparison, induced jobs).

If there is constant underestimation factor in both scenarios, then we have underestimated *net* jobs created, and hence have underestimated the benefits of the WWS scenario.

Comparison with other estimates
As mentioned above, our estimate of operations jobs in the petroleum-refinery sector is very close to the *JEDI* model estimate of direct+indirect operations jobs for a petroleum refinery.

In addition, the BLS-CES estimate of 24,700 operations jobs in the sector *Electric bulk power transmission and control* in 2012 is within the range of 16,400 to 32,800 direct+indirect operations jobs based on JEDI model estimates of 0.082 direct+indirect operations jobs per mile of high-voltage AC line and 200,000 miles (Weeks, 2010) to 400,000 miles (Harris Williams & Co., 2014; they give a figure of 450,000 for all of North America) of high-voltage transmission line in the U. S.

IRENA (2016b) uses the econometric model E3ME to estimate the differences in total employment between a reference global energy scenario and two global scenarios with higher penetration of renewable energy, REmap and REmapE. The reference scenario is based on existing legislation in official country plans. In both high-renewable scenarios the global share of renewables in 2030 is double the 2010 share (reaching 36% of total final energy consumption); in the REmapE scenario, greater emphasis is placed on electrification of heating and transport (IRENA, 2016b, p. 18). IRENA (2016b) finds that the REmapE scenario has about 1 million fewer fossil-fuel and nuclear-industry jobs but about 9 million more renewable-energy jobs than does the reference scenario, for a net gain of over 8 million jobs. This is very broadly consistent with our estimate of about 24.2 million net new jobs, mainly in construction, in a 100% WWS scenario.

Changes in earnings due to changes in jobs

Changes in earnings are the product of changes in the number of jobs and the relevant wage rate. Here we distinguish between operations jobs and construction jobs as follows:

$$ER_{BAU,C,TY} = J_{T_{operations},C,TY} \cdot W_{operations,C,TY} + J_{T_{construction},C,TY} \cdot W_{construction,C,ave-TY}$$

where

$J_{T_{operations},C,TY}$ = Total number of BAU operations jobs foregone in country C in year TY (discussed above)

$J_{T_{construction},C,TY}$ = Total number of BAU construction jobs foregone in country C in year TY (discussed above)

$W_{operations,C,TY}$ = Wages for operations jobs in country C in year TY (discussed below)

$W_{construction,C,TY}$ = Wages for construction jobs in country C in year TY (discussed below)

Wage rate. We estimate wages in country C relative to wages in the U. S., assuming that relative wages are a function of the GDP/capita in country C relative to the GDP/capita in the U. S. Dropping the subscripts for "construction" and "operation" for succinctness of exposition:

$$\frac{W_{C,TY}}{W_{US,TY}} = \left(\frac{GDPC_{C,TY}}{GDPC_{US,BY}} \right)^{\gamma_{WAGE-INT}}$$

$$GDPC'_{C,TY} \equiv \frac{GDPC_{C,TY}}{GDPC_{US,BY}}$$

$$W_{C,TY} = W_{US,TY} \cdot GDPC'_{C,TY}{}^{\gamma_{WAGE-INT}}$$

where

$W_{C,TY}$ = The real wage rate in country *C* in the year *TY*
$W_{US,TY}$ = The real wage rate in the U.S. in the year *TY* (discussed below)
$GDPC_{C,TY}$ = GDP/capita in country *C* in year *TY* (see discussion of GDP/capita elsewhere)
$GDPC_{US,TY}$ = GDP/capita in the U.S. in year *TY* (see discussion of GDP/capita elsewhere)
$\gamma_{WAGE-INT}$ = Exponent determining how the GDP/capita in country *C* relative to that in the U. S. affects the wage rate in country *C* relative to the rate in the U. S. (discussed below)
$GDPC'_{C,TY}$ = The real GDP/capita ratio for country *C* w.r.t to the U.S.

The real wage rate in the U. S. in *TY* is a function of the wage rate in a base year *BY* and changes in the real U. S. GDP/capita from *BY* to *TY*:

$$W_{US,TY} = W_{US,BY} \cdot GDPC'_{US,TY/BY}{}^{\gamma_{WAGE-US}}$$

where

$W_{US,BY}$ = The annual wage rate in the U. S. in the base year *BY* (we assume $70,000/year in base year 2012, for construction jobs and operations jobs)
$GDPC'_{US,TY/BY}$ = The ratio of real U. S. GDP/capita in year *TY* to that in year *BY* (see discussion of GDP/capita elsewhere)
$\gamma_{WAGE-US}$ = Exponent determining how changes in U. S. GDP /capita affect the wage rate in the U. S.; we assume that changes in the real wage rate are nearly proportional to changes in GDP/capita ($\gamma_{WAGE-US}$ = 0.95)

The exponent ($\gamma_{WAGE-INT}$) that determines how the GDP/capita in country *C* relative to that in the U. S. affects the wage rate in country *C* relative to the rate in the U. S. is itself a nonlinear function of the relative GDP/capita. We assume that the lower the GDP/capita, the more sensitive the wage rate is to the relative GDP/capita; hence, the lower the GDP/capita, the higher the value of the $\gamma_{WAGE-INT}$. Formally,

$$\gamma_{WAGE-INT} = \gamma_{WAGE1} \cdot GDPC'_{C,TY}{}^{\gamma_{WAGE2}}$$

where

γ_{WAGE1}, γ_{WAGE2} = Parameters that determine the value of $\gamma_{WAGE-INT}$; we assume γ_{WAGE1} = 0.80 and γ_{WAGE2} = 0.10.

Table S42 provides a summary among 139 countries of job losses in the oil, gas, coal, nuclear, and bioenergy industries. Job loss is calculated as the product of jobs per unit energy in each employment category and total energy use. Total energy use is the product of energy use in 2012 from IEA World Energy Balances, by country, and the ratio of energy use in the target year to energy use in 2012 (from IEO projections by region, extrapolated past 2040, and mapped to individual countries). Jobs per unit energy are calculated as the product of jobs per unit energy unit in the U.S. in 2012, the fraction of conventional-fuel jobs lost due to converting to WWS (Table S42), a multiplier for jobs associated with the jobs lost but not counted elsewhere, and country-specific adjustment factors accounting for the relationship between jobs per unit energy and GDP per capita and total energy use. Calculations are detailed in Delucchi et al. (2016).

The fraction of fossil-fuel jobs lost in each job sector (Table S42), accounts for the retention of some jobs for non-energy uses of fossil fuels (e.g., some petroleum products will still be used as lubricants, asphalt, petrochemical feedstock, and petroleum coke) and transportation of goods other than fossil fuels.

Job losses include construction jobs lost from not building future fossil, nuclear, and bio-power plants because WWS plants are built instead. Job losses from not replacing existing conventional plants are not treated to be consistent with the fact that jobs created by replacing WWS plants with other WWS plants are not treated.

The shift to WWS is estimated to result in the loss of ~27.7 million jobs in the current fossil fuel, biofuel, and nuclear industries in the 139 countries. The job loss represents ~1% of the total workforce in the 139 countries.

Table S42. Estimated 139-country job losses due to eliminating energy generation and use from the fossil fuel and nuclear sectors. Also shown is the percent of total jobs in the sector that are lost. Not all fossil-fuel jobs are lost due to non-energy uses of petroleum, such as lubricants, asphalt, petrochemical feedstock, and petroleum coke. For transportation sectors, the jobs lost are those due to transporting fossil fuels; the jobs not lost are those for transporting other goods.

Energy sector	**Jobs lost in sector**	**Percent of jobs in sector that are lost**
Oil and gas extraction	2,783,000	89
Coal mining	969,000	96
Uranium mining	99,400	100

Support for oil and gas	4,179,000	89
Oil and gas pipeline construction	1,890,000	89
Mining & oil/gas machinery	1,348,000	89
Petroleum refining	689,000	94
Asphalt paving and roofing materials	0	0
Gas stations with stores	1,719,000	30
Other gas stations	407,000	50
Fossil electric power generation utilities	1,021,000	100
Fossil electric power generation non-utilities	184,000	100
Nuclear and other power generation	1,299,000	100
Natural gas distribution	1,306,000	100
Auto oil change shops/other repair	57,300	10
Rail transportation of fossil fuels	634,000	52
Water transportation of fossil fuels	264,600	23
Truck transportation of fossil fuels	836,000	8
Bioenergy except electricity	6,524,000	100
Total current jobs lost	**26,209,000**	
[h]**Jobs lost from not growing fossil fuels**	**1,535,000**	
All jobs lost	**27,744,000**	
[i]Total labor force	2.87 billion	
Jobs lost as percent of labor force	**0.97%**	

[a]See Delucchi et al. (2016) for detailed calculations and referencing.
[b]Jobs lost from not growing fossil fuels are additional refinery and electric power construction and operation jobs that would have accrued by 2050 if BAU instead of WWS continued.
[c]The total labor force in each country is obtained from World Bank (2015a).

Subtracting the number of jobs lost across the 139 countries from the number of jobs created gives a net of ~24.2 million 35-year jobs created due to WWS. Although all countries together are expected to gain jobs, some countries, particularly those that currently extract significant fossil fuels (e.g., Algeria, Angola, Iraq, Kuwait, Libya, Qatar, and Saudi Arabia) may experience net job loss in the energy production sector. However, such job loss in many of those countries can potentially be made up in the manufacture and service of storage technologies, hydrogen technologies, electric vehicles, electric heating and cooling appliances, and industrial heating equipment, although such job creation numbers were not determined here.

The direct and indirect earnings from producing WWS electricity amount to ~$1.86 trillion/yr during construction and ~$2.06 trillion/yr during operation. The annual earnings lost from the fossil-fuel industries total ~$2.06 trillion/yr giving a net gain in annual earnings of ~$1.86 trillion/yr.

Section S10. Timeline for Transitioning and Impacts on Global Temperatures

Figure 2 of the main text shows the mean proposed timeline for the complete transformation of the energy infrastructures of the 139 countries considered here. The timeline assumes 100% WWS by 2050, with 80% WWS by 2030. To meet this timeline, rapid transitions are needed in each technology sector. Whereas, much new infrastructure can be installed upon retirement of existing infrastructure or devices, other transitions will require aggressive policies (Section S11) to meet the timeline. Below is a list of proposed transformation timelines for individual sectors.

Development of super grids and smart grids: As soon as possible, countries should develop long-term power-transmission-and-distribution systems to provide "smart" management of energy demand and supply at all scales, from local to international (e.g., Smith et al., 2013; Blarke and Jenkins, 2013; Elliott, 2013).

Power plants**:** by 2020, no more construction of new coal, nuclear, natural gas, or biomass fired power plants; all new power plants built are WWS.

Heating, drying, and cooking in the residential and commercial sectors**:** by 2020, all new devices and machines are powered by electricity.

Large-scale waterborne freight transport**:** by 2020-2025, all new ships are electrified and/or use electrolytic hydrogen, all new port operations are electrified, and port retro-electrification is well underway. This should be feasible for relatively large ships and ports because large ports are centralized and few ships are built each year. Policies may be needed to incentivize the early retirement of ships that do not naturally retire before 2050.

Rail and bus transport**:** by 2025, all new trains and buses are electrified. This requires changing the supporting energy-delivery infrastructure and the manufacture method of transportation equipment. However, relatively few producers of buses and trains exist, and the supporting energy infrastructure is concentrated in cities.

Off-road transport, small-scale marine**:** by 2025 to 2030, all new production is electrified.

Heavy-duty truck transport**:** by 2025 to 2030, all new heavy-duty trucks and buses are BEVs or BEV-HFC hybrids.

Light-duty on-road transport: by 2025-2030, all new light-duty onroad vehicles are BEVs.

Short-haul aircraft**:** by 2035, all new small, short-range aircraft are BEVs or BEV-HFC hybrids.

Long-haul aircraft**:** by 2040, all remaining new aircraft are BEV-HFC hybrids.

During the transition, conventional fuels and existing WWS technologies are needed to produce the remaining WWS infrastructure. However, much of the conventional energy would be used in any case to produce conventional power plants and automobiles if the plans proposed here were not implemented. Further, as the fraction of WWS energy increases, conventional energy generation will decrease, ultimately to zero, at which point all new WWS devices will be produced with existing WWS. In sum, the creation of WWS infrastructure may result in a temporary increase in emissions before they are ultimately reduced to zero.

Impacts on global temperatures:
The WWS roadmaps proposed here will eliminate energy-related emissions of carbon dioxide (CO_2), black carbon (BC), and methane (CH_4), the first through third leading causes of global warming, respectively. They will also reduce tropospheric ozone (O_3) precursors, carbon monoxide (CO), and nitrous oxide (N_2O). O_3, CO, and N_2O are all greenhouse gases.

The global surface temperature change due to greenhouse gases is thought to be linearly proportional to cumulative carbon emissions, regardless of the timing of those emissions (e.g., Allen et al., 2009; Matthews et al., 2009; Meinhausen et al., 2009).

Currently, global greenhouse gas emissions are increasing with a low-mitigation business-as-usual trajectory. If this trajectory continues, global temperatures are expected to rise 2 ^{o}C above those in 1870 by 2035-2060 and 4.5 +/-1.2 ^{o}C by 2100 (IPCC, 2014b).

Friedlingstein et al. (2014) estimate that, for the globally-averaged temperature change since 1870 to increase by less than 2 ^{o}C with a 67% probability, cumulative emissions since 1870 must be kept below 3200 (2900-3600) Gt-CO_2. This accounts for non-CO_2 forcing agents in the temperature response and being reduced proportionately with CO_2. The cumulative emission limit to keep warming below 2^{o}C with a 50% probability is 3500 (3100-3900) Gt-CO_2. Matthews (2016) estimated (by scaling the 2 ^{o}C numbers by 1.5^{o}C/2^{o}C) that the corresponding limits to keeping temperatures under 1.5^{o}C are 2400 Gt-CO_2 (67% probability) and 2625 Gt-CO_2 (50% probability).

As of the end of 2015, ~2050 Gt-CO_2 from fossil-fuel combustion, cement munfacturing, and land use change had already been emitted cumulatively since 1870 (Le Quere et al., 2015; Matthews, 2016), suggesting no more than 350-575 Gt-CO_2 can be emitted for a 67-50% probability of keeping warming since 1870 under 1.5^{o}C, and 1150-1450 Gt-CO_2 can be emitted for a 67-50% probability of keeping warming under 2^{o}C.

In 2014, global CO_2 emissions from fossil-fuel burning and cement production were ~35.9 Gt-CO_2 and those from land use change were. ~4.0 Gt-CO_2, for a total of 39.9 Gt-CO_2 (Le Quere et al., 2015). Assuming the same emissions in 2015 but a linear 80% decrease in emissions between 2016 and 2030 and the remaining 20% decrease by 2050 results in an additional cumulative 419 Gt-C emitted to the atmosphere, in the range of the maximum allowable to keep warming under 1.5^{o}C.

The calculation here suggests that aggressive policies that strive to reduce CO_2 and other global warming agents (greenhouse gases and dark particles) emissions by 80% by 2030 and 100% by 2050 can limit warming to 1.5 ^{o}C with a probability of between 50% and 67%. This requires reductions not only in the energy sector but also in the land-use change sector, biological emissions from farming and agriculture sector, and halocarbon sector.

Section S11. Recommended First Steps and Possible Policies

The policy pathways necessary to transform the 139 countries treated here to 100% WWS will differ by country, depending largely on the willingness of the government and people in each country to affect rapid change. This study does not advocate specific policy measures for any country. Instead, it provides a set of policy options that each country can consider.

The list is by no means complete. Within each section, the policy options are listed roughly in order of proposed priority.

S11.1. Energy Efficiency Measures

- Expand clean, renewable energy standards and energy efficiency standards.

- Incentivize conversion from natural gas water and air heaters to electric heat pumps (air and ground-source) and rooftop solar thermal hot water pre-heaters.

- Promote, though municipal financing, incentives, and rebates for implementing energy efficiency measures in buildings and other infrastructure. Efficiency measures include, but are not limited to, using LED lighting; evaporative cooling; ductless heating and air conditioning; adding energy-storing materials to walls and floors to modulate temperature changes; water-cooled heat exchanging; night ventilation cooling; combined space and water heating; improved data center design; improved air flow management; advanced lighting controls; variable refrigerant flow; improved wall, floor, ceiling, and pipe insulation; double- and triple-paned windows; and passive solar heating. Additional measures include sealing windows, doors, and fireplaces; and monitoring/auditing building energy use to identify wasted energy.

- Revise building codes to incorporate "green building standards" based on best practices for building design, construction, and energy use.

- Incentivize landlord investment in energy efficiency. Allow owners of multi-family buildings to take a property tax exemption for energy efficiency improvements in their buildings that provide benefits to their tenants.

- Create energy performance rating systems with minimum performance requirements to assess energy efficiency levels and pinpoint areas of improvement.

- Create a green building tax credit program for the corporate sector.

S11.2. Energy Supply Measures

Increase Renewable Portfolio Standards (RPSs).

- Extend or create state WWS production tax credits.

- Streamline the permit approval process for large-scale WWS power generators and high-capacity transmission lines. Work with local and regional governments to manage zoning and permitting issues within existing planning efforts or pre-approve sites to reduce the cost and uncertainty of projects and expedite their physical build-out.

- Streamline the small-scale solar and wind installation permitting process. Create common codes, fee structures, and filing procedures across a country.

- Lock in fossil fuel and nuclear power plants to retire under enforceable commitments. Implement taxes on emissions by current utilities to encourage their phase-out.

- Incentivize clean-energy backup emergency power systems rather than diesel/gasoline generators at both the household and community levels.

- Incentivize home or community energy storage (through garage electric battery systems, for example) that accompanies rooftop solar to mitigate problems associated with grid power losses.

S11.3. Utility Planning and Incentive Structures

- Incentivize community seasonal heat storage underground using the Drake Landing solar community as an example.

- Incentive the development of utility-scale grid electric power storage, such as in CSP, pumped hydropower, and more efficient hydropower.

- Require utilities to use demand response grid management to reduce the need for short-term energy backup on the grid.

- Incentivize the use of excess WWS electricity to produce hydrogen to help manage the grid.

- Develop programs to use EV batteries, after the end of their useful life in vehicles, for local, short-term storage and balancing.

- Implement virtual net metering (VNM) for small-scale energy systems.

S11.4. Transportation

- Promote more public transit by increasing its availability and providing compensation to commuters for not purchasing parking passes.

- Increase safe biking and walking infrastructure, such as dedicated bike lanes, sidewalks, crosswalks, timed walk signals, etc.

- Adopt legislation mandating BEVs for short- and medium distance government transportation and use incentives and rebates to encourage the transition of commercial and personal vehicles to BEVS.

- Use incentives or mandates to stimulate the growth of fleets of electric and/or hydrogen fuel cell/electric hybrid buses starting with a few and gradually growing the fleets. Additionally, incentivize electric and hydrogen fuel cell ferries, riverboats, and other local shipping.

- Adopt zero-emission standards for all new on-road and off-road vehicles, with 100% of new production required to be zero-emission by 2030.

- Ease the permitting process for installing electric charging stations in public parking lots, hotels, suburban metro stations, on streets, and in residential and commercial garages.

- Set up time-of-use electricity rates to encourage charging at night.

- Incentivize the electrification of freight rail and shift freight from trucks to rail.

S11.5. Industrial Processes

- Provide financial incentives for industry to convert to electricity and electrolytic hydrogen for high temperature and manufacturing processes.

- Provide financial incentives to encourage industries to use WWS electric power generation for on-site electric power (private) generation.

Section 12. Summary

Roadmaps are presented for converting the energy systems for all purposes (electricity, transportation, heating/cooling, industry, and agriculture/forestry/fishing) of 139 countries into clean and sustainable ones powered by wind, water, and sunlight (WWS).

For each country, the study estimates 2050 BAU power demand from current data, converts the supply for each load sector to WWS supply, and proposes a mix of WWS generators within each the country that can match the projected 2050 all-sector power demand. The conversion from BAU combustion to WWS electricity for all purposes is calculated to reduce 139-country-averaged end-use load by ~42.5%, with 23.0% due to the higher work:energy ratio of WWS electricity over combustion 12.6% because WWS requires no mining, transporting, or processing of fuels, and 6.9% because WWS end-use efficiency exceed's BAU's**.**

Remaining all-purpose annually averaged end-use 2050 load over the 139 countries is proposed to be met with ~1.6 million new onshore 5-MW wind turbines (providing 23.5% of 139-country power for all purposes), 935,000 off-shore 5-MW wind turbines (13.6%), 251,000 50-MW utility-scale solar-PV power plants (21.4%), 21,500 100-MW utility-scale CSP power plants with storage (9.7%), 1.84 billion 5-kW residential rooftop PV systems (14.9%), 75.0 million 100-kW commercial/government rooftop systems (11.6%), 840 100-MW geothermal plants (0.67%), 410,000 0.75-MW wave devices (0.58%), 30,000 1-MW tidal turbines (0.06%), and 0 new hydropower plants. The capacity factor of existing hydropower plants will increase slightly so that hydropower supplies 4.0% of all-purpose power. Another estimated 12,900 100-MW CSP plants with storage and 84,500 50-MW solar thermal collectors for heat generation and storage will be needed to help stabilize the grid. This is just one possible mix of generators.

The additional footprint on land for WWS devices is equivalent to about 0.22% of the 139-country land area, mostly for utility scale PV. This does not account for land gained from eliminating the current energy infrastructure. An additional on-land spacing area of about 0.92% for the 139 countries is required for onshore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land.

The 2013 LCOE for hydropower, onshore wind, utility-scale solar, and solar thermal for heat is already similar to or less than the LCOE for natural gas combined-cycle power plants. Rooftop PV, offshore wind, tidal, and wave presently have higher LCOEs. However, by 2050 the LCOE for all WWS technologies is expected to drop, most significantly for offshore wind, tidal, wave, rooftop PV, CSP, and utility PV, whereas conventional fuel costs are expected to rise.

The 139-country roadmaps are anticipated to create 22.2 million 35-year construction jobs and 22.3 million 35-year operation jobs for the energy facilities alone, the combination of which would outweigh by ~16.8 million the 27.7 million jobs lost in the conventional energy sector.

The 139-country roadmaps will eliminate ~4.6 (1.3-8.0) million premature air pollution mortalities per year today and 3.5 (0.84-7.4) million/yr in 2050, avoiding ~$23 ($4.1-$69) trillion/yr in 2050 air-pollution damage costs (2013 USD).

Converting will further eliminate $26.9 (15.1-57.2) trillion/year in 2050 global warming costs (2013 USD) due to 139-country greenhouse-gas and particle emissions.

These plans will result in the average person in 2050 saving ~$85/yr in fuel costs compared with conventional fuels, ~2,600/yr (12.6 ¢/kWh-BAU-all-energy) in air-pollution damage costs, and $3,100/yr (14.9 ¢/kWh-BAU-all-energy) in climate costs (2013 USD).

Many uncertainties in the analysis here are captured in broad ranges of energy, health, and climate costs given. However, these ranges may miss costs due to limits on supplies caused by wars or political/social opposition to the roadmaps. As such, the estimates should be reviewed periodically.

The timeline for conversion is proposed as follows: 80% of all energy to be WWS by 2030 and 100% by 2050. As of the end of 2015, only 4.26% of the installed capacity needed had been installed among the 139 countries examined.

The major benefits of a conversion are the near-elimination of air pollution morbidity and mortality and global warming, net job creation, energy-price stability, reduced international conflict over energy because each country will largely be energy independent, increased access to distributed energy and reduced energy poverty to the 4 billion people worldwide who currently collect their own energy and burn it (2.7 billion people) or who have no access to energy (1.3 billion people), and reduced risks of large-scale system disruptions through power outage or terrorism because much of the world power supply will be decentralized. Finally, the aggressive worldwide conversion to WWS proposed here will avoid exploding levels of CO_2, thus potentially avoid 1.5 ^{o}C of net global warming since 1870.

The study finds that the conversion to WWS is technically and economically feasible. The main barriers are still social and political.

Appendices

Appendix S1. Projection of GDP per capita

Background. The Gross Domestic Product (GDP) per capita is an important factor in many estimates in our analysis, including projections of energy use, the estimation of the potential for rooftop photovoltaics, the value of statistical life, jobs in the BAU scenario, and more.

We estimate GDP per capita in real U.S. dollars, converted from each country's currency on the basis of Purchasing Power Parity (PPP). The PPP-based conversion to U.S. dollars expresses how much of a country's currency is needed to buy the amount of a given basket of goods that one dollar buys in the U.S. There are a number of theoretical and practical difficulties in constructing PPP indices, mainly because international variations in consumption patterns and in the quality of nominally similar goods and services make it difficult to construct a reference basket of goods (Deaton and Heston, 2010). Nonetheless, PPP-based conversions are better than market exchange rates because they are meant to hold consumption (and hence, partly at least, utility) constant. GDP-per-capita estimates based on PPP have much less inter-country variation than do estimates based on market exchange rates.

Historical estimates of GDP per capita. For most countries, we use the World Bank's World Development Indicators of GDP per capita, in PPP-based constant year-2011 international dollars, for the period 1990 to 2015 (World Bank, 2016c.) For countries for which the World Bank does not have estimates, we estimate the year-2011 GDP per capita as follows:

Argentina and Myanmar: year-2011 current-dollar PPP-based estimate from the International Monetary Fund (IMF, 2015). We use year 2011 because the IMF uses current international dollars, and the World Bank uses constant 2011 international dollars. Note that the IMF estimates generally are similar to the World Bank estimates.

Syria: year-2010 current-dollar estimate from the IMF, converted to year-2011 by multiplying by the ratio of the year-2010 to year-2009 GDP price deflator for Syria, from the same IMF source.

Chinese Taipei (Taiwan): year-2011 current-dollar estimate from the IMF.

Gilbraltar (year 2008) and North Korea (year 2013): PPP-based estimates from the CIA *World Factbook* (CIA, 2016b), scaled to year-2011 dollars assuming a GDP price-deflator change of 3%/year.

Netherland Antilles: year-2007 PPP-based estimate from Wikipedia (2016a), scaled to year-2011 dollars assuming a GDP price deflator change of 3%/year.

For all of those countries except *Chinese Taipei (Taiwan)*, we estimate GDP per capita for other years in the period 2005 to 2014 by scaling the country-specific values by the ratio of regional values estimated in the EIA's *IEO*, as discussed next. For *Chinese Taipei (Taiwan)*, we use current-dollar estimates from the IMF, for the period 2005 to 2014, and convert to year-2011 dollars with the GDP price deflator index in the IMF. For Taiwan we use IMF estimates through 2014 rather than use IMF data for 2011 and then scale to other years using EIA IEO regional projections because we feel the EIA IEO regional projections are too high for Taiwan specifically.

To fill in gaps in the World Bank data for the period 1990 to 2004 (i.e., prior to 2005, which is the earliest year of the EIA *IEO* regional projections), we use a ten-year moving linear back-extrapolation, except when that extrapolation results in unreasonably low values: for Boznia and Herzegovina 1990 to 1993 (we use the 1994 value); Myanmar 1990 to 1996 (we use the 1997 value); Syria 1990 to 2004 (we use the 2005 value), Kosovo 1990 to 1992 (we use the 1993 value); and Taiwan 1990 to 1999 (we use the 2000 value).

Projections. The EIA's *IEO* projects PPP-based GDP per capita for 16 regions of the world through the year 2040 (EIA, 2016a). We extend these projections to the year 2075 using a 10-year moving linear extrapolation. We project future GDP per capita for each country on the basis of the projected change in GDP per capita for the region of which the country is a part. We apply an exponent that accounts for the likelihood that countries with a GDP per capita below the regional GDP per capita will have a growth rate slightly above the regional growth rate, and vice versa. Formally,

Assume:

$$\frac{GDPC_{C,Y}}{GDPC_{R:C\in R,Y}} = \left(\frac{GDPC_{C,Y-1}}{GDPC_{R:C\in R,Y-1}}\right)^{\varphi}$$

Then:

$$GDPC_{C,Y} = GDPC_{C,Y-1}{}^{\varphi} \cdot \frac{GDPC_{R:C\in R,Y}}{GDPC_{R:C\in R,Y-1}{}^{\varphi}}$$

where

$GDPC_{C,Y}$ = GDP per capita in country C in year Y (PPP-based constant U.S. dollars) (first Y-1 are year-2014 estimates from the World Bank, as discussed above)

$GDPC_{R:C\in R,Y}$ = GDP per capita in region R including country C in year Y (PPP-based constant U.S. dollars; estimates from the EIA's *IEO* as described above)

φ = Exponent that slightly increases the rate of change in GDP per capita for countries below the regional GDP per capita, and vice versa (less than 1.000; we assume 0.994)

Note that although the exponent is close to 1.000, it is applied each year, and hence its effect is compounded over time, so that, for example, after 40 years the adjustment is 0.786.

Appendix S2. Annual social discount rate

In Jacobson et al. (2015a), we review literature on the social discount rate (SDR). Key findings from that review are

- The U.S. Office of Management and Budget (OMB) (2003) states that "if your rule will have important intergenerational benefits or costs you might consider a further sensitivity analysis using a lower but positive discount rate," and suggests a range of 1-3%.

- Moore et al. (2004) review the accepted methods for estimating the SDR and conclude that "no matter which method one chooses, the estimates for the SDR vary between 1.5 and 4.5 percent for intragenerational projects, and between 0 and 3.5 percent for projects with intergenerational impacts" (p. 809).

- The National Center for Environmental Economics (2014) indicates (without explicitly recommending) that a reasonable range is 2% to 5%.

On the basis of this review, Jacobson et al. (2015a) chose a LCHB SDR value of 1% and a HCLB value of 4.5%, even though a couple of the studies reviewed supported choosing a lower upper end. Recently, however, Drupp et al. (2015) surveyed 197 experts and find that 92% are comfortable with an SDR between 1% and 3%. This upper value of 3% is consistent with the values from OMB (2003) and Moore et al. (2004). *Therefore, for this analysis we assume SDR values of 1% (LCHB) and 3% (HCLB).*

Appendix S3. Urban population share

The World Bank Development Indicators provide the urban fraction of the population from 1960 to 2014 (World Bank, 2015b). We fill in data gaps using our judgment). To estimate the urban fraction from 2015 to 2075, we use a dampened 6-year moving linear extrapolation:

$$URB\%_{C,Y>2014} = \min\left[100\%, URB\%_{C,Y-1} \cdot \left(\frac{URB\%_{C,Y} : trend(6yr)}{URB\%_{C,Y-1}}\right)^{\beta^{\alpha(Y-Y_{base})}}\right]$$

where

$URB\%_{C,Y}$ = The urban population share in country *C* in year *Y*
trend(6yr) = The 6-year moving linear extrapolation
α = Fraction of year difference counted (we assume 0.35)
Y_{base} = A base year (2010)
β = The dampening base exponent (0.984)

This formulation, in which the dampening exponent decreases over time, serves to increasingly flatten the trend line over time, so that by 2075 there is relatively little year-to-year change. For example, with these assumptions, the urban population share increases by 10.5% from 2020 to 2050, but increases by only 1% from 2050 to 2075 (average of individual country changes).

Population
Wikipedia shows historical and projected population at five-year intervals from 1985 through 1950 (Wikipedia, 2016b). We linearly interpolate between the intervals, through 2050. We extend from 2050 to 2075 using a dampened 10-year moving linear extrapolation:

$$P_{C,Y>2050} = P_{C,Y-1} \cdot \left(\frac{P_{C,Y} : trend(10yr)}{P_{C,Y-1}}\right)^{\eta}$$

where

$P_{C,Y}$ = Population in country *C* in year *Y*
Trend(10yr) = The 10-year moving linear extrapolation
η = The dampening exponent (discussed below)

The dampening exponent is introduced because most projections show a declining rate of growth over time. For example, projections in Wikipedia (2016e) indicate that the decadal average growth rate declines 20-30% every decade. A value of 0.965 for the dampening exponent reproduces the long-term projections in Wikipedia.

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