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Transitioning All Energy in 74 Metropolitan Areas, Including 30 Megacities, to 100% Clean and Renewable Wind, Water, and Sunlight (WWS)

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Abstract: To date, roadmaps and policies for transitioning from fossil fuels to clean, renewable energy have been developed for nations, provinces, states, cities, and towns in order to address air pollution, global warming, and energy insecurity. However, neither roadmaps nor policies have been developed for large metropolitan areas (aggregations of towns and cities), including megacities (metropolitan areas with populations above 10 million). This study bridges that gap by developing roadmaps to transition 74 metropolitan areas worldwide, including 30 megacities, to 100% wind, water, and sunlight (WWS) energy and storage for all energy sectors by no later than 2050, with at least 80% by 2030. Among all metropolitan areas examined, the full transition may reduce 2050 annual energy costs by 61.1% (from $2.2 to $0.86 trillion/yr in 2013 USD) and social costs (energy plus air pollution plus climate costs) by 89.6% (from $8.3 to $0.86 trillion/yr). The large energy cost reduction is due to the 57.1% lower end-used energy requirements and the 9% lower cost per unit energy with WWS. The air pollution cost reduction of ~$2.6 (1.5–4.6) trillion/yr is due mostly to the saving of 408,000 (322,000–506,000) lives/yr with WWS. Global climate cost savings due to WWS are ~$3.5 (2.0–7.5) trillion/yr (2013 USD). The transition may also create ~1.4 million more long-term, full-time jobs than lost. Thus, moving to 100% clean, renewable energy and storage for all purposes in metropolitan areas can result in significant economic, health, climate, and job benefits.

Keywords: megacities; urban air pollution; climate change; renewable energy; wind; solar

1. Introduction

Megacities and metacities are defined as metropolitan areas with populations above 10 and 20 million, respectively [1]. A metropolitan area (or metropolis) is a "major city together with its suburbs and nearby cities, towns, and environs over which the major city exercises a commanding economic and social influence" [2]. An area must have a population of at least 100,000, with at least 50,000 in the urban portion, to be considered a metropolitan area [2].

In 1950, the only megacities in the world were the New York–Newark and Tokyo metropolitan areas [1]. By 2020, this count had risen to 34, including nine metacities [3]. The largest of these were Tokyo (37.4 million), Delhi (30.3 million), Shanghai (27.1 million), and São Paulo (22.0 million) [3]. Based on current trends from [3], the number of megacities is expected to grow substantially by 2050. Furthermore, the physical expansion of megacities has been rapid. For example, between 2000 and 2009, the urban extent of Beijing quadrupled [4] and those of Delhi and Los Angeles increased by ~80% and ~23%, respectively [5]. Such increases in urban extent, even before considering concomitant changes in emissions, had notable impacts on air pollution and meteorology [4,5].

The addition of people to a megacity increases overall energy consumption, thereby increasing overall megacity emissions. However, this increase in energy consumption is not necessarily linear. For example, Facchini et al. [6] found that per capita energy consumption decreased with increasing population density according to a power law characterized by a −3/4 scaling. Emissions from energy consumption also depend on emission control technologies and the efficiencies of appliances and machines used.

Addressing climate and pollution problems requires policies implemented at national, regional, and local levels. To that point, by late 2020, 165 U.S. cities and towns [7] and at least 250 international cities [8] had passed resolutions or ordinances committing to being powered by 100% renewable electricity. Fifty of these international cities had committed to 100% renewables in more than one sector (e.g., transport, building heating/cooling, etc., in addition to electricity) [8].

Several previous studies have analyzed or reviewed some of the components necessary to transition individual cities or islands to clean, renewable energy (e.g., [9–16]). Many studies have also examined the ability of 100% or near 100% renewable energy to keep the electric power grid stable in one or multiple countries (e.g., [17–48]).

However, to date, no roadmap has been developed for a metropolitan area, let alone a megacity, to transition all energy sectors (electricity, transport, building heating/cooling, industry, agriculture/forestry/fishing, and the military) to 100% clean, renewable energy and storage. Moreover, the benefits to air pollution health and climate resulting from a transition to 100% clean, renewable energy remain wholly unexplored for metropolitan areas.

The goal of this paper is to provide such roadmaps for 74 metropolitan areas worldwide (including 30 megacities) to transition to 100% clean, renewable energy for all purposes by no later than 2050 (and ideally sooner), with at least 80% transition by 2030. These cities, collectively, represent about 9% of the projected 2050 world population. This paper builds upon a previous study that developed roadmaps for 53 individual towns and cities (rather than metropolitan areas) solely in North America [15].

The roadmaps here assume that all energy sectors will use electricity or direct heat. All electricity and direct heat will be generated with 100% wind, water, and sunlight (WWS). Some electricity will be used to produce hydrogen, primarily for transportation. The direct heat will come from either solar or geothermal sources. Electric heat pumps will provide remaining low-temperature heat. Less total energy will be needed because electrification of all energy sectors will lower energy demand. Because several WWS generators are intermittent, some electricity, heat, cold, and hydrogen will need to be stored. Finally, transmission lines will be needed to transmit electricity short and long distances.

Each roadmap provides a clean, renewable energy scenario for a metropolitan area to meet annual average all-purpose energy loads in 2050. This study assumes that each metropolitan area is connected to the heat and electricity grids of the country or region wherein the metropolitan area resides. The study does not attempt to quantify the energy mix needed, the storage needed, or the additional transmission/distribution needed to meet minute-by-minute energy demand. However, the study does provide an estimate of the additional levelized cost of energy (LCOE) needed to match such demand continuously; thus, it accounts for the cost of WWS supply, storage, and transmission/distribution needed to keep the grid stable. This estimate is based on results from a previous study focused on meeting demand with supply and storage in 24 world regions encompassing 143 countries [33]. All metropolitan areas examined here reside in one of those countries.

2. Methodology

This section describes the methodology for developing year 2050 roadmaps to transition each metropolitan area to 100% WWS among all energy sectors. First, country-specific data were obtained from

[33], who developed all-sector energy roadmaps for 143 countries. Such data included 2016 business-as-usual (BAU) end-use energy consumption data for all energy sectors (residential, commercial, transport, industrial, agriculture/forestry/fishing, and military), for each energy type (oil, natural gas, coal, electricity, waste heat, solar and geothermal heat, and biofuels and waste), for each of 143 countries [49]. These data were projected for each country, sector, and fuel type from 2016 to 2040 using "BAU reference scenario" projections for the same sectors and fuel types for 16 world regions from [50]. The projections for a given country were assigned from those of the region in which the country resided. The reference scenario is one of moderate economic growth and accounts for policies in different countries, population growth, economic and energy growth, the growth of some renewable energy, modest energy efficiency measures, and reduced energy use. Consumption of each fuel type in each sector in each country was then extrapolated in [33] from 2040 to 2050 using a 10-year moving linear extrapolation.

In [33], the 2050 BAU energy for each fuel type in each sector and country was then transitioned to 2050 WWS electricity and heat. WWS electricity generators included onshore and offshore wind turbines, rooftop and utility-scale solar photovoltaics (PV), concentrated solar power (CSP) plants, tidal and wave devices, geothermal electric power plants, and existing hydroelectric power plants (no new reservoirs were assumed). WWS heat generators included solar and geothermal heat.

Thus, for example, the source of building heat was converted from fossil fuels or bioenergy to air- and ground-source heat pumps running on WWS electricity and direct solar thermal or geothermal heat. Building cooling was also provided by heat pumps.

Fossil fuel and biofuel vehicles were transitioned primarily into battery electric (BE) vehicles and some hydrogen fuel cell (HFC) vehicles, where the hydrogen in that case was produced using WWS electricity (i.e., green hydrogen). BE vehicles were assumed to dominate short- and long-distance light-duty ground transportation, construction machines, agricultural equipment, short- and moderate-distance trains (except where powered by electric rails or overhead wires), ferries, speedboats, short-distance ships, and short-haul aircraft traveling under 1500 km. HFC vehicles were assumed to make up all long-distance, heavy payload transport by road, rail, water, and air.

High-temperature industrial processes were electrified with electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, and electron beam heaters.

Next, in each country, a mix of WWS resources was estimated to meet the all-sector annual-average end-use energy demand. The mix was determined after a WWS resource analysis was performed for each country. Air pollution and climate damage in 2050 were estimated for each country, and the social cost benefits of reducing such damage with WWS were then calculated. Energy costs between BAU and WWS were also calculated, as were the required land areas and changes in the number of jobs.

In [33], country populations were projected to 2050 with data from [51]. Here, metropolitan area populations are extrapolated linearly to 2050 from 2000–2020 population data [3]. Here, the ratio of metropolitan area-to-country population in 2050 is then used to scale down all country energy data from [33] to the metropolitan area level. While this is a simplistic method that does not account for the fact that urban energy consumption decreases with increasing population density [6], the country-level analysis that it relies on is detailed. In addition, urban energy consumption includes energy used to transport people, goods, heat, and electricity to and from urban areas, which is not accounted for if energy consumption is scaled by urban population. As such, the overestimate of urban energy consumption based on linear population scaling may be at least partly offset by the underestimate of energy consumption due to transport to and from a metropolitan area.

3. Results and Discussion

3.1. Resulting End-Use Demand and Nameplate Capacities of New Generators

Table 1 provides the resulting BAU and WWS end-use power demand (load) in 2050 for each metropolitan area. In 2016, the 74 metropolitan area all-purpose, end-use load was ~1730 GW (15,100 TWh/yr). Under BAU, the all-purpose end-use load is estimated to increase to ~2540 GW in 2050 (Table 1).

A move to 100% WWS by 2050 reduces the 74-metropolitan-area end-use load by ~57.1%, down to ~1090 GW (~9550 TWh/yr) (Table 1), with the largest percentage reduction (37.5%) due to the efficiency of WWS heat pumps, battery electric vehicles, hydrogen fuel cell vehicles, and industrial heat, when compared with their business-as-usual equivalents. An additional 12.9% reduction is due to eliminating the energy needed to extract, transport, and refine fossil fuels and uranium. The remaining 6.7% reduction is due to end-use energy efficiency improvements and reduced energy use beyond those under BAU. Megacities with the greatest all-purpose end-use WWS load needed in 2050 include Shanghai (80.7 GW), Tokyo (70.1 GW), Beijing (63.0 GW), New York City (45.5 GW), Seoul (36.3 GW), Shenzhen (35.6 GW), and Moscow (35.2 GW).

Table 2 summarizes the 2050 percent of annual-average end-use load summed among all metropolitan areas (from Table 1) to be met by each energy generator type. It also provides the new plus existing nameplate capacities of each generator type needed to meet such load, the nameplate capacities of existing generators of each type, and the capital cost of the new nameplate capacities, all summed among the metropolitan areas.

The average mix of generators in Table 2 is the end-use-load-weighted average mix of generators in each metropolitan area, obtained from Table 3. The total new plus existing nameplate capacity is the sum of values among each metropolitan area (Table 4). Nameplate capacities for each area are determined from the end-use WWS load for the metropolitan area (Table 1), the mix of generators for the area (Table 3), and the product of the capacity factor and the transmission and distribution efficiency of each generator type in each area (Table 5).

WWS generators are not constrained to exist within a metropolitan area due to land and renewable resource limitations in such areas. Nonetheless, all rooftop PV is proposed to exist within each metropolitan area. Table 6 provides estimated 2050 metropolitan area residential and commercial/government rooftop areas suitable for PV. It also shows the potential PV nameplate capacity in each area and the proposed installed nameplate capacity for each area (which is consistent with values in Table 4). Rooftop PV areas include existing plus new building roof areas plus elevated canopy areas above parking lots, highways, and structures. Table 6 indicates that only 22.3% of potential residential rooftop PV and 58.9% of potential commercial/government rooftop PV nameplate capacities are proposed for installation among all metropolitan areas. As such, rooftop area is not a limiting factor in transitioning to 100% WWS in these roadmaps.

Unlike PV, concentrated solar power is viable only in countries with significant direct sunlight. Thus, CSP penetration is limited to metropolitan areas in countries exposed to significant sunlight. As such, no CSP is proposed for use in Russia, Canada, Norway, Germany, Switzerland, Ukraine, or Mongolia.

Onshore wind is available in every country. Offshore wind, wave, and tidal power are assumed to be available only in metropolitan areas located in countries with ocean or substantial lake coastlines. Thus, for example, no offshore wind is available in Ethiopia, Nigeria, Uzbekistan, Mongolia, Austria, or Switzerland.

Table 2 indicates that ~8% of the 2050 nameplate capacity required for a 100% all-purpose WWS system among all metropolitan areas was already installed as of 2018 end. Table 2 also provides the nameplate capacities of new plus existing generators needed to meet annual average all-purpose energy demand in each metropolitan area. In most areas, additional generators, storage, transmission lines, and distribution lines are needed to keep the electricity and heat grids stable continuously due to the intermittency of WWS generators. The estimated costs of such equipment are accounted for in the following section.

Table 1. Business-as-usual (BAU) and wind, water, and sunlight (WWS) end-use energy load by sector and city. First row for each city: Estimated 2050 total annually averaged 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. Second row for each city: 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 four columns show 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 and demand reduction beyond those in the BAU case.

Metropolitan Area	Scenario	2050 Total End-use Load (GW)	Percent of End-use Load due to Residential Buildings	Percent of End-use Load due to Commercial and Government Build-Ings	Percent of End-use Load due to Indus-try	Percent of End-use Load due to Trans-port	(a) Percent Change in End-use Load with WWS due to Higher Work: Energy Ratio	(b) Percent Change in End-use Load with WWS due to Eliminating Energy in Mining, Transporting, Refining	(c) Percent Change in End-use Load with WWS due to Effic-iency Beyond BAU	Overall Percent Change in End-use Load with WWS
Abidjan, Côte d'Ivoire	BAU	3.943	44.4	13.4	13.7	26.7	-	-	-	-
	WWS	1.292	31.7	16.3	31.5	10.4	−57.4	−1.7	−8.2	−67.2
Addis Ababa, Ethiopia	BAU	2.374	83.1	2.4	4.6	8.9	-	-	-	-
	WWS	0.535	68.4	4.8	16.5	9.4	−66.8	−0.2	−10.4	−77.5
Ankara, Turkey	BAU	12.968	21.0	13.1	32.9	29.7	-	-	-	-
	WWS	5.685	19.4	16.6	45.8	15.3	−39.1	−9.9	−7.1	−56.2
Auckland, New Zealand	BAU	14.671	10.5	11.5	39.8	33.7	-	-	-	-
	WWS	7.964	12.6	15.2	53.7	14.9	−33.5	−5.2	−7.0	−45.7
Baghdad, Iraq	BAU	9.445	18.4	1.2	33.9	41.5	-	-	-	-
	WWS	3.617	25.9	2.4	35.7	25.9	−40.5	−14.7	−6.5	−61.7
Bangkok, Thailand	BAU	64.148	7.9	7.3	39.6	41.9	-	-	-	-
	WWS	29.646	9.3	11.5	58.9	18.2	−36.3	−11.6	−5.9	−53.8
Beijing, China	BAU	139.65	16.6	4.0	47.5	28.0	-	-	-	-
	WWS	63.049	15.8	5.0	64.5	10.4	−32.6	−16.0	−6.2	−54.9
Berlin, Germany	BAU	19.812	24.3	16.0	30.5	29.2	-	-	-	-
	WWS	8.392	19.2	19.2	43.2	18.4	−41.7	−8.4	−7.6	−57.6

Bogotá, Colombia	BAU	25.787	14.7	4.6	34.6	38.4	-	-	-	-
	WWS	9.446	17.5	8.4	46.0	10.4	−42.1	−15.3	−6.0	−63.4
Bologna, Italy	BAU	3.311	24.4	13.2	24.3	36.1	-	-	-	-
	WWS	1.267	19.2	20.3	35.6	23.5	−42.2	−11.6	−8.0	−61.7
Bucharest, Romania	BAU	4.226	31.9	9.1	31.7	25.0	-	-	-	-
	WWS	1.611	26.3	12.4	43.6	16.2	−44.7	−9.9	−7.3	−61.9
Buenos Aires, Argentina	BAU	58.408	20.5	6.4	31.6	37.2	-	-	-	-
	WWS	20.471	20.5	11.4	49.2	16.6	−39.1	−18.5	−7.3	−65.0
Cairo, Egypt	BAU	43.043	20.7	7.2	26.8	41.4	-	-	-	-
	WWS	19.277	27.7	12.5	38.7	18.3	−35.6	−11.4	−8.3	−55.2
Calgary, Canada	BAU	24.306	13.4	11.5	46.3	25.5	-	-	-	-
	WWS	9.107	17.3	18.2	44.0	17.7	−33.3	−23.2	−6.0	−62.5
Cape Town, South Africa	BAU	35.138	13.8	6.2	44.3	32.1	-	-	-	-
	WWS	15.899	13.5	8.0	58.0	17.7	−37.2	−11.9	−5.7	−54.8
Caracas, Venezuela	BAU	7.015	8.7	5.2	49.4	36.6	-	-	-	-
	WWS	2.749	12.1	8.7	56.6	22.5	−37.2	−19.0	−4.7	−60.8
Casablanca, Morocco	BAU	4.800	18.1	8.7	18.7	47.1	-	-	-	-
	WWS	2.030	19.9	9.6	37.0	27.1	−49.4	−0.9	−7.3	−57.7
Chicago, USA	BAU	53.288	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	21.736	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Delhi, India	BAU	57.329	21.6	4.1	39.7	27.5	-	-	-	-
	WWS	28.999	16.7	4.2	59.5	12.1	−36.6	−5.8	−7.0	−49.4
Dhaka, Bangladesh	BAU	11.045	38.4	2.1	30.4	25.2	-	-	-	-
	WWS	4.537	26.2	3.2	59.8	8.2	−40.4	−9.9	−8.7	−58.9
Dubai, United Arab Emirates	BAU	60.558	6.8	5.4	41.9	43.7	-	-	-	-
	WWS	32.533	9.5	7.9	60.1	19.4	−38.0	−2.6	−5.7	−46.3
Edmonton, Canada	BAU	22.313	13.4	11.5	46.3	25.5	-	-	-	-
	WWS	8.360	17.3	18.2	44.0	17.7	−33.3	−23.2	−6.0	−62.5
Guayaquil, Ecuador	BAU	5.309	11.2	6.7	20.0	54.8	-	-	-	-
	WWS	2.015	15.1	10.1	34.7	34.5	−50.7	−5.0	−6.3	−62.0
Hanoi, Vietnam	BAU	13.591	24.3	4.5	43.1	27.1	-	-	-	-
	WWS	7.501	18.5	4.8	64.3	11.7	−36.6	−1.0	−7.2	−44.8
Havana, Cuba	BAU	3.209	18.3	5.0	44.0	20.0	-	-	-	-
	WWS	1.794	20.7	6.8	58.4	10.4	−33.1	−4.1	−6.9	−44.1
Ho Chi Minh City, Vietnam	BAU	22.333	24.3	4.5	43.1	27.1	-	-	-	-
	WWS	12.326	18.5	4.8	64.3	11.7	−36.6	−1.0	−7.2	−44.8

Houston, USA	BAU	55.560	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	22.663	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Ibiza, Spain	BAU	0.240	15.6	12.4	29.4	40.1	-	-	-	-
	WWS	0.095	18.3	19.4	34.8	25.5	−39.8	−13.6	−6.9	−60.3
Istanbul, Turkey	BAU	41.175	21.0	13.1	32.9	29.7	-	-	-	-
	WWS	18.052	19.4	16.6	45.8	15.3	−39.1	−9.9	−7.1	−56.2
Jakarta, Indonesia	BAU	19.583	27.6	4.7	30.0	36.3	-	-	-	-
	WWS	7.988	21.0	8.2	49.0	21.0	−46.7	−5.7	−6.8	−59.2
Karachi, Pakistan	BAU	17.755	38.1	3.5	27.1	30.0	-	-	-	-
	WWS	7.198	25.9	4.7	52.6	14.7	−45.8	−5.5	−8.1	−59.5
Kiev, Ukraine	BAU	11.706	35.7	10.5	32.5	18.2	-	-	-	-
	WWS	4.607	30.8	13.6	42.5	10.9	−41.6	−11.0	−8.0	−60.6
Kinshasa, Congo	BAU	13.228	48.0	0.9	4.1	46.9	-	-	-	-
	WWS	3.259	41.9	0.7	11.8	10.4	−65.8	−1.6	−8.0	−75.4
Kyoto, Japan	BAU	5.031	16.0	20.0	35.1	27.4	-	-	-	-
	WWS	2.404	17.3	23.2	42.6	16.1	−34.5	−10.1	−7.6	−52.2
Lagos, Nigeria	BAU	16.931	63.4	3.4	12.1	20.9	-	-	-	-
	WWS	4.168	49.7	4.7	25.2	20.2	−62.7	−4.3	−8.4	−75.4
Lima, Peru	BAU	20.073	12.8	5.1	29.7	50.7	-	-	-	-
	WWS	7.525	13.4	9.1	49.3	26.7	−42.3	−13.9	−6.3	−62.5
London, United Kingdom	BAU	40.834	26.9	13.0	25.1	33.6	-	-	-	-
	WWS	15.517	24.6	19.6	31.7	23.1	−44.3	−9.5	−8.2	−62.0
Los Angeles, USA	BAU	73.803	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	30.104	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Madrid, Spain	BAU	28.678	15.6	12.4	29.4	40.1	-	-	-	-
	WWS	11.397	18.3	19.4	34.8	25.5	−39.8	−13.6	−6.9	−60.3
Mexico City, Mexico	BAU	58.154	12.6	4.9	38.6	39.2	-	-	-	-
	WWS	24.179	14.9	6.9	50.3	22.0	−38.9	−13.5	−6.0	−58.4
Montevideo, Uruguay	BAU	5.788	16.1	7.5	38.3	34.1	-	-	-	-
	WWS	2.990	17.1	10.3	55.1	15.6	−37.5	−4.4	−6.5	−48.3
Montreal, Canada	BAU	53.411	13.4	11.5	46.3	25.5	-	-	-	-
	WWS	20.011	17.3	18.2	44.0	17.7	−33.3	−23.2	−6.0	−62.5
Moscow, Russia	BAU	110.78	23.8	8.1	39.3	27.5	-	-	-	-
	WWS	35.178	25.2	12.8	45.1	15.6	−41.3	−21.1	−5.9	−68.2
Mumbai, India	BAU	29.570	21.6	4.1	39.7	27.5	-	-	-	-
	WWS	14.957	16.7	4.2	59.5	12.1	−36.6	−5.8	−7.0	−49.4

Nairobi, Kenya	BAU	4.521	56.2	1.1	10.6	31.5	-	-	-	-
	WWS	1.291	39.9	3.0	30.3	26.4	−62.0	−0.8	−8.7	−71.5
New York City, USA	BAU	111.58	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	45.515	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Oslo, Norway	BAU	13.738	17.5	13.2	45.8	22.2	-	-	-	-
	WWS	5.913	27.2	21.6	38.6	11.3	−24.0	−25.2	−7.8	−57.0
Palma, Spain	BAU	2.135	15.6	12.4	29.4	40.1	-	-	-	-
	WWS	0.849	18.3	19.4	34.8	25.5	−39.8	−13.6	−6.9	−60.3
Paris, France	BAU	46.643	26.9	17.5	22.1	30.6	-	-	-	-
	WWS	20.831	25.3	23.3	29.7	19.8	−40.6	−5.9	−8.9	−55.3
Perth, Australia	BAU	22.596	10.5	11.8	43.2	32.5	-	-	-	-
	WWS	9.857	12.8	19.5	48.3	18.4	−34.0	−16.1	−6.3	−56.4
Philadelphia, USA	BAU	36.055	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	14.707	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Phoenix, USA	BAU	37.756	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	15.401	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
Pyongyang, North Korea	BAU	2.594	1.3	0.0	58.5	7.8	-	-	-	-
	WWS	1.529	0.4	0.0	78.5	3.2	−34.8	−1.8	−4.6	−41.1
Quezon City, Philippines	BAU	2.522	17.0	11.8	24.6	45.4	-	-	-	-
	WWS	1.124	17.8	15.4	41.1	24.3	−44.9	−3.2	−7.4	−55.4
Rio de Janeiro, Brazil	BAU	64.811	8.6	5.1	42.7	39.2	-	-	-	-
	WWS	30.496	10.6	8.1	59.4	18.2	−37.0	−10.5	−5.5	−52.9
Rome, Italy	BAU	18.115	24.4	13.2	24.3	36.1	-	-	-	-
	WWS	6.932	19.2	20.3	35.6	23.5	−42.2	−11.6	−8.0	−61.7
San Jose, USA	BAU	11.901	14.3	15.0	30.8	37.3	-	-	-	-
	WWS	4.854	18.1	20.0	38.0	20.6	−40.1	−12.2	−6.9	−59.2
San José, Costa Rica	BAU	2.785	12.4	10.7	19.8	54.8	-	-	-	-
	WWS	1.273	17.6	16.8	35.0	10.4	−45.5	−1.5	−7.3	−54.3
Santiago, Chile	BAU	30.254	14.5	10.3	37.9	36.5	-	-	-	-
	WWS	15.219	13.2	12.3	58.9	15.0	−33.9	−8.6	−7.2	−49.7
Sao Paulo, Brazil	BAU	67.703	8.6	5.1	42.7	39.2	-	-	-	-
	WWS	31.857	10.6	8.1	59.4	18.2	−37.0	−10.5	−5.5	−52.9
Seoul, South Korea	BAU	74.142	10.9	15.6	42.6	28.8	-	-	-	-
	WWS	36.326	8.6	21.5	55.0	13.0	−33.0	−10.7	−7.3	−51.0
Shanghai, China	BAU	178.82	16.6	4.0	47.5	28.0	-	-	-	-
	WWS	80.732	15.8	5.0	64.5	10.4	−32.6	−16.0	−6.2	−54.9

Shenzhen, China	BAU	78.877	16.6	4.0	47.5	28.0	-	-	-	-
	WWS	35.611	15.8	5.0	64.5	10.4	−32.6	−16.0	−6.2	−54.9
Sydney, Australia	BAU	49.742	10.5	11.8	43.2	32.5	-	-	-	-
	WWS	21.699	12.8	19.5	48.3	18.4	−34.0	−16.1	−6.3	−56.4
Tashkent, Uzbekistan	BAU	4.724	40.3	8.6	25.6	10.1	-	-	-	-
	WWS	1.664	26.4	7.9	44.5	4.9	−46.3	−9.2	−9.3	−64.8
Tehran, Iran	BAU	52.486	22.5	4.9	37.6	30.6	-	-	-	-
	WWS	21.440	17.3	5.9	57.3	14.6	−39.5	−12.5	−7.2	−59.2
Tokyo, Japan	BAU	146.60	16.0	20.0	35.1	27.4	-	-	-	-
	WWS	70.053	17.3	23.2	42.6	16.1	−34.5	−10.1	−7.6	−52.2
Toronto, Canada	BAU	84.975	13.4	11.5	46.3	25.5	-	-	-	-
	WWS	31.837	17.3	18.2	44.0	17.7	−33.3	−23.2	−6.0	−62.5
Ulaanbaatar, Mongolia	BAU	5.621	22.7	7.0	32.6	22.6	-	-	-	-
	WWS	2.200	19.5	4.5	51.4	13.7	−53.6	−3.5	−3.7	−60.9
Vancouver, Canada	BAU	34.912	13.4	11.5	46.3	25.5	-	-	-	-
	WWS	13.080	17.3	18.2	44.0	17.7	−33.3	−23.2	−6.0	−62.5
Vienna, Austria	BAU	16.442	21.4	9.8	30.5	36.9	-	-	-	-
	WWS	7.029	18.8	13.1	44.7	22.3	−38.4	−12.1	−6.8	−57.3
Yangon, Myanmar	BAU	4.099	49.9	2.8	15.8	16.9	-	-	-	-
	WWS	1.282	33.2	4.0	33.7	10.4	−54.6	−5.4	−8.7	−68.7
Yixing, China	BAU	2.599	16.6	4.0	47.5	28.0	-	-	-	-
	WWS	1.173	15.8	5.0	64.5	10.4	−32.6	−16.0	−6.2	−54.9
Zurich, Switzerland	BAU	8.296	27.1	18.0	18.0	35.6	-	-	-	-
	WWS	3.948	25.4	20.8	27.4	25.5	−40.6	−3.3	−8.6	−52.4
All metropolitan areas	**BAU**	**2542.4**	**17.2**	**9.5**	**37.7**	**32.4**	**-**	**-**	**-**	**-**
	WWS	**1089.9**	**17.1**	**13.1**	**50.0**	**16.5**	**−37.5**	**−12.9**	**−6.7**	**−57.1**

Annually averaged end-use loads (GW) can be converted to energy per year units (TWh/yr) by multiplying the loads by 8760 h/year and dividing the result by 1000 GW/TW. BAU annually averaged end-use load in each sector for each metropolitan area is calculated as the country value from [33] multiplied by the city-to-country population ratio. The load reductions due to electrification are calculated as the country values from [33].

Table 2. (**a**) Percent of 2050 all-purpose end-use load met by each energy generator, averaged among all metropolitan areas. (**b**) Estimated nameplate capacities of WWS generators needed to meet annual average all-purpose energy demand. (**c**) Nameplate capacities of WWS generators existing in 2018. (**d**) Percent of 2050 needed nameplate capacity existing in 2018, which equals Column (**c**) divided by Column (**b**). (**e**) Capital cost of new generators needed to meet annual average power by 2050.

Energy Technology	(a) Percent of 2050 All-Purpose Annual Average Demand Met by Plant or Device	(b) Nameplate Capacity, Existing Plus New Plants or Devices Needed to Meet 2050 Annual Average Demand (GW)	(c) Nameplate Capacity of Generators Existing as of 2018 (GW)	(d) Percent of 2050 Needed Nameplate Capacity Already Installed 2018	(e) Total Average Capital Cost of New Generators Needed by 2050 (2013 USD Billion)
Onshore wind	29.14	1056	70.4	6.66	1234
Offshore wind	14.71	444	2.3	0.53	811
Wave device	0.50	28.3	0.022	0.08	114
Geothermal electricity	0.75	10.1	2.1	20.7	31
Hydropower plant [f]	7.91	192.7	192.7	100	0
Tidal turbine	0.12	5.9	0.12	2.01	21
Res. roof PV	10.81	606	13.9	2.29	1730
Com./gov. roof PV [g]	13.56	817	13.9	1.70	1627
Utility PV plant [g]	18.92	1011	41.5	4.11	1382
Utility CSP plant [g]	3.58	70	0.90	1.28	300
Total	**100**	**4241**	**338**	**7.97**	**7250**

All values are summed or averaged over all metropolitan areas. "Annual average power" is annual average all-purpose energy demand divided by the number of hours per year. The percent of annual-average power demand met by each device type, shown in Column (a), is a demand-weighted average among the mixes given for all metropolitan areas. [f] No increase in the number of dams or in the peak discharge rate of hydropower is assumed. [g] The solar PV panels used for this calculation are SunPower E20 panels. CSP is assumed to have storage with a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1. See the footnotes to Table S7 of [31] for more details.

Table 3. Percent of the annually averaged 2050 metropolitan area all-purpose end-use WWS load (not nameplate capacity) in Table 1 to be met with the given type of electric power generator. Each row sum to 100%.

Metropolitan Area	Onshore Wind	Offshore Wind	Wave	Geo-thermal	Hydro-electric	Tidal	Res. PV	Com./gov. PV	Utility PV	CSP
Abidjan, Côte d'Ivoire	35.38	10.99	0.93	0.00	6.67	0.05	9.42	20.94	10.99	4.62
Addis Ababa, Ethiopia	35.94	0.00	0.00	7.11	8.83	0.00	7.91	17.57	18.45	4.20
Ankara, Turkey	35.48	2.08	0.00	1.33	15.65	0.02	7.81	17.35	16.13	4.15
Auckland, New Zealand	32.42	10.38	0.77	9.32	13.83	0.25	8.90	9.97	10.38	3.79
Baghdad, Iraq	40.83	0.91	0.00	0.00	4.49	0.00	8.98	19.96	20.04	4.78
Bangkok, Thailand	3.75	18.81	0.00	0.08	1.31	0.01	22.28	15.65	33.18	4.93
Beijing, China	34.84	14.29	0.05	0.07	6.30	0.02	12.25	13.22	14.29	4.68
Berlin, Germany	41.05	20.42	0.10	0.02	1.35	0.01	8.18	8.46	20.42	0.00
Bogotá, Colombia	34.42	8.83	0.81	0.00	18.30	0.38	7.57	16.83	8.83	4.03
Bologna, Italy	37.31	13.97	0.35	0.98	7.79	0.02	11.97	9.10	13.97	4.54
Bucharest, Romania	37.45	12.03	0.00	0.44	16.32	0.01	10.31	11.42	12.03	0.00
Buenos Aires, Argentina	38.77	9.95	0.00	1.40	7.90	0.02	8.53	18.95	9.95	4.53
Cairo, Egypt	42.10	10.80	0.00	0.00	1.52	0.01	9.26	20.58	10.80	4.92
Calgary, Canada	32.74	8.87	0.73	2.63	23.60	0.29	7.60	14.67	8.87	0.00
Cape Town, South Africa	42.19	13.70	1.00	0.00	0.30	0.01	11.74	12.43	13.70	4.93
Caracas, Venezuela	35.91	9.22	0.18	0.00	15.80	0.02	7.90	17.56	9.22	4.20
Casablanca, Morocco	41.01	10.53	0.97	0.00	3.06	0.03	9.02	20.05	10.53	4.80
Chicago, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Delhi, India	36.92	6.23	0.06	0.02	2.12	0.02	12.03	15.86	21.85	4.89
Dhaka, Bangladesh	7.08	7.12	0.62	0.00	0.32	0.10	23.18	9.68	46.96	4.95
Dubai, United Arab Emirates	5.90	12.26	0.00	0.00	0.00	0.01	7.05	3.95	65.83	5.00
Edmonton, Canada	32.74	8.87	0.73	2.63	23.60	0.29	7.60	14.67	8.87	0.00
Guayaquil, Ecuador	33.38	3.09	0.79	0.33	20.23	0.56	7.34	16.32	14.05	3.90
Hanoi, Vietnam	0.72	25.19	0.57	0.00	8.07	0.01	21.59	14.08	25.19	4.57
Havana, Cuba	42.12	10.81	1.00	0.00	0.35	0.13	9.27	20.59	10.81	4.93
Ho Chi Minh City, Vietnam	0.72	25.19	0.57	0.00	8.07	0.01	21.59	14.08	25.19	4.57
Houston, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Ibiza, Spain	37.36	11.92	0.88	0.06	11.34	0.33	10.21	11.61	11.92	4.37
Istanbul, Turkey	35.48	2.08	0.00	1.33	15.65	0.02	7.81	17.35	16.13	4.15
Jakarta, Indonesia	15.79	15.28	0.94	4.45	1.34	0.03	13.10	29.11	15.28	4.66
Karachi, Pakistan	23.99	10.55	0.24	0.00	3.65	0.00	15.23	16.55	24.98	4.81
Kiev, Ukraine	42.41	15.21	0.00	0.00	5.73	0.02	13.04	8.39	15.21	0.00
Kinshasa, Congo	41.43	10.63	0.93	0.00	6.91	0.09	9.11	20.25	10.63	0.00

Kyoto, Japan	10.24	31.55	0.93	0.69	5.84	0.28	11.78	7.14	31.55	0.00
Lagos, Nigeria	13.63	0.00	0.30	0.00	1.29	0.01	14.37	31.94	33.54	4.92
Lima, Peru	33.56	0.02	0.79	6.62	14.04	0.05	7.38	16.41	17.21	3.93
London, United Kingdom	20.29	32.66	0.96	0.00	0.93	2.81	5.41	4.27	32.66	0.00
Los Angeles, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Madrid, Spain	37.36	11.92	0.88	0.06	11.34	0.33	10.21	11.61	11.92	4.37
Mexico City, Mexico	39.44	10.12	0.93	2.96	3.84	0.02	8.68	19.28	10.12	4.61
Montevideo, Uruguay	36.55	9.38	0.86	0.00	13.57	0.07	8.04	17.87	9.38	4.27
Montreal, Canada	32.74	8.87	0.73	2.63	23.60	0.29	7.60	14.67	8.87	0.00
Moscow, Russia	40.25	13.06	0.50	0.17	8.96	0.03	11.19	11.88	13.06	0.90
Mumbai, India	36.92	6.23	0.06	0.02	2.12	0.02	12.03	15.86	21.85	4.89
Nairobi, Kenya	35.46	9.10	0.84	12.92	3.27	0.03	7.80	17.34	9.10	4.15
New York City, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Oslo, Norway	13.71	5.56	0.31	0.00	68.83	0.39	4.77	0.87	5.56	0.00
Palma, Spain	37.36	11.92	0.88	0.06	11.34	0.33	10.21	11.61	11.92	4.37
Paris, France	40.28	13.15	0.92	0.03	7.51	0.20	11.27	11.65	13.15	1.83
Perth, Australia	26.95	15.09	0.96	0.36	3.99	0.12	9.43	15.72	22.64	4.73
Philadelphia, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Phoenix, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
Pyongyang, North Korea	36.13	13.74	0.00	0.00	17.55	1.73	11.78	4.91	13.74	0.43
Quezon City, Philippines	7.68	15.13	0.60	11.24	3.95	0.27	12.97	28.82	15.13	4.20
Rio de Janeiro, Brazil	35.53	9.12	0.84	0.00	16.04	0.02	7.82	17.37	9.12	4.16
Rome, Italy	37.31	13.97	0.35	0.98	7.79	0.02	11.97	9.10	13.97	4.54
San Jose, USA	31.44	16.42	0.96	0.57	3.90	0.01	10.95	14.60	16.42	4.73
San José, Costa Rica	21.46	5.51	0.51	24.74	24.43	0.13	4.72	10.49	5.51	2.51
Santiago, Chile	36.71	10.06	0.87	3.80	9.41	0.06	8.62	16.13	10.06	4.29
São Paulo, Brazil	35.53	9.12	0.84	0.00	16.04	0.02	7.82	17.37	9.12	4.16
Seoul, South Korea	4.44	37.18	0.00	0.00	1.98	0.15	8.90	5.27	37.18	4.89
Shanghai, China	34.84	14.29	0.05	0.07	6.30	0.02	12.25	13.22	14.29	4.68
Shenzhen, China	34.84	14.29	0.05	0.07	6.30	0.02	12.25	13.22	14.29	4.68
Sydney, Australia	26.95	15.09	0.96	0.36	3.99	0.12	9.43	15.72	22.64	4.73
Tashkent, Uzbekistan	40.94	0.00	0.00	0.00	4.23	0.00	9.01	20.02	21.02	4.79
Tehran, Iran	28.92	12.56	0.00	0.00	2.68	0.00	14.67	14.63	21.67	4.87
Tokyo, Japan	10.24	31.55	0.93	0.69	5.84	0.28	11.78	7.14	31.55	0.00
Toronto, Canada	32.74	8.87	0.73	2.63	23.60	0.29	7.60	14.67	8.87	0.00
Ulaanbaatar, Mongolia	44.87	0.00	0.00	0.00	0.28	0.00	9.87	21.94	23.03	0.00
Vancouver, Canada	32.74	8.87	0.73	2.63	23.60	0.29	7.60	14.67	8.87	0.00
Vienna, Austria	36.18	0.00	0.00	0.00	19.59	0.00	10.55	9.05	24.62	0.00

Yangon, Myanmar	37.67	9.67	0.89	0.00	10.65	0.33	8.29	18.42	9.67	4.41
Yixing, China	34.84	14.29	0.05	0.07	6.30	0.02	12.25	13.22	14.29	4.68
Zurich, Switzerland	26.91	0.00	0.00	0.00	39.31	0.00	6.56	11.90	15.32	0.00
All metropolitan areas	**29.14**	**14.71**	**0.50**	**0.75**	**7.91**	**0.12**	**10.81**	**13.56**	**18.92**	**3.58**

Table 4. Existing plus new nameplate capacities (MW) needed for each WWS electricity generation source in each metropolitan area to meet 2050 metropolitan area all-purpose end-use WWS load in the annual average. These capacities are determined by taking the product of end-use WWS load (Table 1) and the fraction of load met by each generator (Table 3), all divided by the product of the capacity factor and transmission/distribution efficiency (Table 5).

Metropolitan Area	Onshore Wind	Offshore Wind	Wave	Geother-mal	Hydro-electric	Tidal	Res. PV	Com./gov. PV	Utility PV	CSP
Abidjan, Côte d'Ivoire	3154	552	100	0	200	3	688	1501	785	129
Addis Ababa, Ethiopia	560	0	0	51	114	0	259	564	584	49
Ankara, Turkey	6043	356	0	102	2169	6	2443	5993	4890	497
Auckland, New Zealand	6637	1985	187	907	2424	91	4018	5005	4647	656
Baghdad, Iraq	4946	233	0	0	447	1	1859	4403	4113	378
Bangkok, Thailand	5330	17,497	0	29	846	10	33,196	22,976	48,431	2772
Beijing, China	55,741	24,851	231	51	8630	55	39,950	46,294	45,198	5840
Berlin, Germany	8598	4094	61	2	241	2	3980	4963	9320	0
Bogotá, Colombia	22,296	3239	576	0	3782	161	4350	9555	5004	807
Bologna, Italy	1384	505	35	15	218	1	818	696	857	119
Bucharest, Romania	1656	518	0	9	584	1	938	1209	1036	0
Buenos Aires, Argentina	21,191	5057	0	362	3678	20	7841	18,946	9204	1596
Cairo, Egypt	21,201	5899	0	0	655	8	8160	18,692	9419	1661
Calgary, Canada	7870	1992	243	300	4856	120	3523	8430	4121	0
Cape Town, South Africa	17,053	5173	511	0	104	6	9424	10,360	10,894	1516
Caracas, Venezuela	8319	1064	47	0	1168	3	1331	2912	1524	271
Casablanca, Morocco	2262	542	77	0	145	3	943	2176	1091	192
Chicago, USA	24,296	10,131	764	151	1852	8	10,620	15,771	15,859	1229
Delhi, India	28,426	5060	131	9	1396	22	20,606	27,426	32,113	2749
Dhaka, Bangladesh	872	1919	232	0	34	22	6645	2822	13,282	543
Dubai, United Arab Emirates	4895	9232	0	0	0	7	10,123	5790	93,326	2749
Edmonton, Canada	7225	1829	223	276	4458	110	3234	7739	3783	0
Guayaquil, Ecuador	4715	356	55	8	912	52	680	1505	1295	138
Hanoi, Vietnam	178	5886	344	0	1371	4	7992	5166	9152	638
Havana, Cuba	2308	607	51	0	14	10	780	1748	897	159
Ho Chi Minh City, Vietnam	293	9672	566	0	2252	6	13,132	8488	15,038	1049
Houston, USA	25,332	10,563	796	157	1931	8	11,073	16,443	16,535	1281

Ibiza, Spain	105	28	3	0	25	1	54	66	61	9
Istanbul, Turkey	19,190	1131	0	324	6888	18	7758	19,030	15,527	1579
Jakarta, Indonesia	8967	4645	310	447	243	12	5550	12,253	6423	756
Karachi, Pakistan	5030	2067	156	0	655	2	6905	7873	9905	763
Kiev, Ukraine	5066	1697	0	0	585	4	3411	2590	3634	0
Kinshasa, Congo	11,970	2507	307	0	638	17	1939	4295	2253	0
Kyoto, Japan	735	1907	172	20	301	30	1474	956	3607	0
Lagos, Nigeria	2405	0	104	0	126	1	3663	7983	8352	466
Lima, Peru	17,372	9	232	607	2318	15	2625	5723	5980	534
London, United Kingdom	8274	12,445	517	0	326	1992	5027	4929	29,209	0
Los Angeles, USA	33,649	14,031	1058	209	2565	11	14,709	21,843	21,965	1702
Madrid, Spain	12,510	3386	377	9	2952	174	6442	7899	7276	1016
Mexico City, Mexico	39,253	8745	1937	954	2233	18	10,535	23,810	12,128	2144
Montevideo, Uruguay	3627	663	200	0	879	9	1099	2589	1268	224
Montreal, Canada	17,294	4378	534	660	10,671	264	7741	18,525	9055	0
Moscow, Russia	37,306	11,307	743	75	7105	53	22,615	29,740	24,293	699
Mumbai, India	14,662	2610	67	5	720	11	10,628	14,146	16,564	1418
Nairobi, Kenya	1762	410	93	222	101	2	561	1244	653	109
New York City, USA	50,875	21,214	1599	316	3879	17	22,239	33,024	33,209	2573
Oslo, Norway	2073	786	72	0	8904	102	1804	436	1954	0
Palma, Spain	931	252	28	1	220	13	480	588	542	76
Paris, France	21,520	6565	759	6	3436	185	13,475	16,103	14,424	836
Perth, Australia	8456	3537	307	42	848	53	4902	8396	10,946	857
Philadelphia, USA	16,439	6855	517	102	1253	5	7186	10,671	10,731	831
Phoenix, USA	17,214	7178	541	107	1312	6	7525	11,174	11,237	870
Pyongyang, North Korea	1720	671	0	0	658	132	1072	498	1209	15
Quezon City, Philippines	350	598	54	159	101	14	733	1604	837	91
Rio de Janeiro, Brazil	75,546	8425	2015	0	10,953	22	12,152	26,687	13,907	2473
Rome, Italy	7576	2763	191	83	1194	6	4474	3806	4688	650
San Jose, USA	5426	2263	171	34	414	2	2372	3522	3542	274
San José, Costa Rica	1555	393	51	383	681	8	288	628	329	57
Santiago, Chile	14,396	3685	403	708	3159	43	6301	12,691	6551	1074
São Paulo, Brazil	78,916	8801	2105	0	11,442	23	12,694	27,878	14,528	2583
Seoul, South Korea	5046	42,634	0	0	1519	234	16,670	10,671	68,852	3508
Shanghai, China	71,374	31,820	296	66	11,050	71	51,154	59,277	57,875	7478
Shenzhen, China	31,483	14,036	131	29	4874	31	22,564	26,147	25,528	3299
Sydney, Australia	18,614	7785	676	93	1866	116	10,790	18,482	24,095	1886
Tashkent, Uzbekistan	1731	0	0	0	153	0	747	1863	1653	152

Tehran, Iran	16,314	6619	0	1	1296	4	16,493	17,421	21,211	1939
Tokyo, Japan	21,421	55,561	4999	575	8765	866	42,957	27,860	105,114	0
Toronto, Canada	27,514	6965	850	1050	16,977	420	12,316	29,473	14,406	0
Ulaanbaatar, Mongolia	2792	0	0	0	15	0	1243	3212	2584	0
Vancouver, Canada	11,304	2861	349	432	6975	173	5060	12,109	5919	0
Vienna, Austria	7380	0	0	0	2985	0	4074	4111	9225	0
Yangon, Myanmar	2269	407	106	0	355	23	628	1395	720	128
Yixing, China	1037	462	4	1	161	1	743	862	841	109
Zurich, Switzerland	3212	0	0	0	3421	0	1460	3091	3312	0
All metropolitan areas	**1056,442**	**443,915**	**28,260**	**10,149**	**192,677**	**5945**	**605,936**	**816,748**	**1010,516**	**70,192**

Table 5. 2050 product of capacity factor and transmission/distribution efficiency for each energy generating technology and metropolitan area. Values are derived for each country in [33]. Capacity factors for onshore and offshore wind account for the competition among wind turbines for limited kinetic energy (array losses). A "--" indicates no installed generators.

Metropolitan Area	Onshore Wind	Offshore Wind	Wave	Geo-thermal	Hydro-electric	Tidal	Res. PV	Com./gov. PV	Utility PV	CSP
Abidjan, Côte d'Ivoire	0.145	0.257	0.121	--	0.432	0.212	0.177	0.180	0.181	0.462
Addis Ababa, Ethiopia	0.343	--	--	0.743	0.413	--	0.163	0.167	0.169	0.455
Ankara, Turkey	0.334	0.332	--	0.739	0.410	0.202	0.182	0.165	0.188	0.475
Auckland, New Zealand	0.389	0.416	0.326	0.818	0.454	0.224	0.176	0.159	0.178	0.461
Baghdad, Iraq	0.299	0.142	--	--	0.363	0.179	0.175	0.164	0.176	0.457
Bangkok, Thailand	0.208	0.319	--	0.826	0.459	0.226	0.199	0.202	0.203	0.527
Beijing, China	0.394	0.363	0.129	0.829	0.460	0.227	0.193	0.180	0.199	0.505
Berlin, Germany	0.401	0.419	0.131	0.845	0.469	0.231	0.172	0.143	0.184	--
Bogotá, Colombia	0.146	0.258	0.133	--	0.457	0.225	0.164	0.166	0.167	0.471
Bologna, Italy	0.341	0.350	0.126	0.814	0.452	0.223	0.186	0.166	0.207	0.485
Bucharest, Romania	0.364	0.374	--	0.811	0.450	0.222	0.177	0.152	0.187	0.463
Buenos Aires, Argentina	0.374	0.403	--	0.792	0.440	0.216	0.223	0.205	0.221	0.582
Cairo, Egypt	0.383	0.353	--	--	0.447	0.220	0.219	0.212	0.221	0.572
Calgary, Canada	0.379	0.405	0.275	0.797	0.443	0.218	0.197	0.158	0.196	--
Cape Town, South Africa	0.393	0.421	0.310	--	0.460	0.226	0.198	0.191	0.200	0.518
Caracas, Venezuela	0.119	0.238	0.104	--	0.372	0.183	0.163	0.166	0.166	0.426
Casablanca, Morocco	0.368	0.394	0.256	--	0.430	0.212	0.194	0.187	0.196	0.507
Chicago, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Delhi, India	0.377	0.357	0.123	0.793	0.440	0.217	0.169	0.168	0.197	0.516

Dhaka, Bangladesh	0.368	0.168	0.120	--	0.430	0.212	0.158	0.156	0.160	0.413
Dubai, United Arab Emirates	0.392	0.432	--	--	--	0.232	0.227	0.222	0.229	0.592
Edmonton, Canada	0.379	0.405	0.275	0.797	0.443	0.218	0.197	0.158	0.196	--
Guayaquil, Ecuador	0.143	0.175	0.289	0.805	0.447	0.220	0.217	0.218	0.219	0.568
Hanoi, Vietnam	0.305	0.321	0.123	--	0.442	0.217	0.203	0.204	0.206	0.537
Havana, Cuba	0.327	0.320	0.351	--	0.437	0.215	0.213	0.211	0.216	0.557
Ho Chi Minh City, Vietnam	0.305	0.321	0.123	--	0.442	0.217	0.203	0.204	0.206	0.537
Houston, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Ibiza, Spain	0.340	0.401	0.267	0.788	0.438	0.216	0.181	0.168	0.187	0.490
Istanbul, Turkey	0.334	0.332	--	0.739	0.410	0.202	0.182	0.165	0.188	0.475
Jakarta, Indonesia	0.141	0.263	0.243	0.794	0.441	0.217	0.189	0.190	0.190	0.493
Karachi, Pakistan	0.343	0.367	0.112	--	0.401	0.197	0.159	0.151	0.182	0.453
Kiev, Ukraine	0.386	0.413	--	--	0.451	0.222	0.176	0.149	0.193	--
Kinshasa, Congo	0.113	0.138	0.099	--	0.354	0.174	0.153	0.154	0.154	--
Kyoto, Japan	0.335	0.398	0.131	0.841	0.467	0.230	0.192	0.180	0.210	--
Lagos, Nigeria	0.236	--	0.118	--	0.424	0.209	0.164	0.167	0.167	0.440
Lima, Peru	0.145	0.178	0.258	0.820	0.456	0.224	0.212	0.216	0.217	0.553
London, United Kingdom	0.380	0.407	0.289	--	0.445	0.219	0.167	0.134	0.174	--
Los Angeles, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Madrid, Spain	0.340	0.401	0.267	0.788	0.438	0.216	0.181	0.168	0.187	0.490
Mexico City, Mexico	0.243	0.280	0.116	0.749	0.416	0.205	0.199	0.196	0.202	0.520
Montevideo, Uruguay	0.301	0.423	0.129	--	0.462	0.227	0.219	0.206	0.221	0.572
Montreal, Canada	0.379	0.405	0.275	0.797	0.443	0.218	0.197	0.158	0.196	--
Moscow, Russia	0.380	0.406	0.237	0.798	0.443	0.218	0.174	0.141	0.189	0.455
Mumbai, India	0.377	0.357	0.123	0.793	0.440	0.217	0.169	0.168	0.197	0.516
Nairobi, Kenya	0.260	0.287	0.117	0.752	0.417	0.205	0.179	0.180	0.180	0.489
New York City, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Oslo, Norway	0.391	0.419	0.254	--	0.457	0.225	0.156	0.117	0.168	--
Palma, Spain	0.340	0.401	0.267	0.788	0.438	0.216	0.181	0.168	0.187	0.490
Paris, France	0.390	0.417	0.253	0.820	0.456	0.224	0.174	0.151	0.190	0.455
Perth, Australia	0.314	0.421	0.307	0.836	0.464	0.229	0.190	0.185	0.204	0.544
Philadelphia, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Phoenix, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
Pyongyang, North Korea	0.321	0.313	--	--	0.408	0.201	0.168	0.151	0.174	0.439

Quezon City, Philippines	0.247	0.284	0.123	0.794	0.441	0.217	0.199	0.202	0.203	0.520
Rio de Janeiro, Brazil	0.143	0.330	0.127	--	0.447	0.220	0.196	0.198	0.200	0.512
Rome, Italy	0.341	0.350	0.126	0.814	0.452	0.223	0.186	0.166	0.207	0.485
San Jose, USA	0.281	0.352	0.272	0.825	0.458	0.225	0.224	0.201	0.225	0.837
San José, Costa Rica	0.176	0.178	0.128	0.822	0.456	0.225	0.209	0.212	0.213	0.559
Santiago, Chile	0.388	0.415	0.327	0.816	0.453	0.223	0.208	0.193	0.234	0.608
São Paulo, Brazil	0.143	0.330	0.127	--	0.447	0.220	0.196	0.198	0.200	0.512
Seoul, South Korea	0.320	0.317	--	--	0.472	0.233	0.194	0.179	0.196	0.507
Shanghai, China	0.394	0.363	0.129	0.829	0.460	0.227	0.193	0.180	0.199	0.505
Shenzhen, China	0.394	0.363	0.129	0.829	0.460	0.227	0.193	0.180	0.199	0.505
Sydney, Australia	0.314	0.421	0.307	0.836	0.464	0.229	0.190	0.185	0.204	0.544
Tashkent, Uzbekistan	0.394	--	--	--	0.460	--	0.201	0.179	0.212	0.524
Tehran, Iran	0.380	0.407	--	0.800	0.444	0.219	0.191	0.180	0.219	0.538
Tokyo, Japan	0.335	0.398	0.131	0.841	0.467	0.230	0.192	0.180	0.210	--
Toronto, Canada	0.379	0.405	0.275	0.797	0.443	0.218	0.197	0.158	0.196	--
Ulaanbaatar, Mongolia	0.354	--	--	--	0.413	--	0.175	0.150	0.196	--
Vancouver, Canada	0.379	0.405	0.275	0.797	0.443	0.218	0.197	0.158	0.196	--
Vienna, Austria	0.345	--	--	0.831	0.461	--	0.182	0.155	0.188	--
Yangon, Myanmar	0.213	0.304	0.108	--	0.385	0.189	0.169	0.169	0.172	0.442
Yixing, China	0.394	0.363	0.129	0.829	0.460	0.227	0.193	0.180	0.199	0.505
Zurich, Switzerland	0.331	--	--	--	0.454	--	0.178	0.152	0.183	--
All metropolitan areas	**0.301**	**0.361**	**0.195**	**0.801**	**0.447**	**0.221**	**0.194**	**0.181**	**0.204**	**0.556**

Table 6. Year 2050 (**a,e**) rooftop areas suitable for photovoltaics (PV) panels, (**b,f**) potential nameplate capacities of suitable rooftop areas, (**c,g**) proposed nameplate capacities for 2050, and (**d,h**) percent of potential capacity to be installed (proposed capacity divided by potential capacity) for both residential and commercial/government buildings.

Metropolitan Area	**Residential Rooftop PV**				**Commercial/Government Rooftop PV**			
	(a) Rooftop Area Suitable for PV in 2050 (km^2)	**(b) Potential Nameplate Capacity of Suitable Area in 2050 (MW$_{dc\text{-}peak}$)**	**(c) Proposed Nameplate Capacity in 2050 (MW$_{dc\text{-}peak}$)**	**(d) Percent of Potential Capacity to be Installed**	**(e) Rooftop Area Suitable for PV in 2050 (km^2)**	**(f) Potential Nameplate Capacity of Suitable Area in 2050 (MW$_{dc\text{-}peak}$)**	**(g) Proposed Nameplate Capacity in 2050 (MW$_{dc\text{-}peak}$)**	**(h) Percent of Potential Capacity to be Installed**

Abidjan, Côte d'Ivoire	122.2	29,237	688	2.4	25.5	6089	1501	24.6
Addis Ababa, Ethiopia	114.9	27,472	259	0.9	8.1	1944	564	29.0
Ankara, Turkey	71	17,034	2443	14.3	49	11,727	5993	51.1
Auckland, New Zealand	37	8810	4018	45.6	28	6677	5005	75.0
Baghdad, Iraq	115	27,587	1859	6.7	64	15,401	4403	28.6
Bangkok, Thailand	322	77,112	33,196	43.0	117	27,961	22,976	82.2
Beijing, China	418	99,918	39,950	40.0	254	60,792	46,294	76.2
Berlin, Germany	25	5948	3980	66.9	27	6493	4963	76.4
Bogotá, Colombia	310	74,135	4350	5.9	116	27,789	9555	34.4
Bologna, Italy	11	2581	818	31.7	4	933	696	74.5
Bucharest, Romania	16	3797	938	24.7	8	1866	1209	64.8
Buenos Aires, Argentina	216	51,651	7841	15.2	150	35,877	18,946	52.8
Cairo, Egypt	452	108,138	8160	7.5	159	38,122	18,692	49.0
Calgary, Canada	23	5551	3523	63.5	44	10,611	8430	79.5
Cape Town, South Africa	102	24,333	9424	38.7	52	12,493	10,360	82.9
Caracas, Venezuela	50	12,060	1331	11.0	20	4684	2912	62.2
Casablanca, Morocco	49	11,769	943	8.0	21	5112	2176	42.6
Chicago, USA	191	45,703	10,620	23.2	131	31,427	15,771	50.2
Delhi, India	600	143,481	20,606	14.4	159	37,999	27,426	72.2
Dhaka, Bangladesh	199	47,703	6645	13.9	29	6849	2822	41.2
Dubai, United Arab Emirates	64	15,270	10,123	66.3	32	7577	5790	76.4
Edmonton, Canada	21	5096	3234	63.5	41	9741	7739	79.5
Guayaquil, Ecuador	90	21,542	680	3.2	29	6921	1505	21.8
Hanoi, Vietnam	111	26,434	7992	30.2	27	6423	5166	80.4
Havana, Cuba	31	7519	780	10.4	15	3563	1748	49.1
Ho Chi Minh City, Vietnam	182	43,437	13,132	30.2	44	10,554	8488	80.4
Houston, USA	199	47,652	11,073	23.2	137	32,767	16,443	50.2
Ibiza, Spain	1	194	54	27.8	0	88	66	75.1
Istanbul, Turkey	226	54,086	7758	14.3	156	37,237	19,030	51.1
Jakarta, Indonesia	272	65,096	5550	8.5	86	20,591	12,253	59.5
Karachi, Pakistan	233	55,741	6905	12.4	62	14,743	7873	53.4
Kiev, Ukraine	24	5693	3411	59.9	20	4902	2590	52.8
Kinshasa, Congo	553	132,157	1939	1.5	179	42,849	4295	10.0
Kyoto, Japan	10	2313	1474	63.7	5	1298	956	73.7

Lagos, Nigeria	307	73,410	3663	5.0	81	19,446	7983	41.1
Lima, Peru	296	70,773	2625	3.7	117	27,934	5723	20.5
London, United Kingdom	34	8098	5027	62.1	58	13,796	4929	35.7
Los Angeles, USA	265	63,298	14,709	23.2	182	43,526	21,843	50.2
Madrid, Spain	97	23,175	6442	27.8	44	10,523	7899	75.1
Mexico City, Mexico	357	85,472	10,535	12.3	179	42,804	23,810	55.6
Montevideo, Uruguay	22	5235	1099	21.0	13	3184	2589	81.3
Montreal, Canada	51	12,198	7741	63.5	97	23,317	18,525	79.5
Moscow, Russia	133	31,916	22,615	70.9	246	58,848	29,740	50.5
Mumbai, India	309	74,006	10,628	14.4	82	19,599	14,146	72.2
Nairobi, Kenya	151	36,178	561	1.6	24	5684	1244	21.9
New York City, USA	400	95,702	22,239	23.2	275	65,809	33,024	50.2
Oslo, Norway	12	2962	1804	60.9	23	5446	436	8.0
Palma, Spain	7	1725	480	27.8	3	783	588	75.1
Paris, France	100	24,032	13,475	56.1	88	21,080	16,103	76.4
Perth, Australia	96	22,843	4902	21.5	57	13,713	8396	61.2
Philadelphia, USA	129	30,923	7186	23.2	89	21,264	10,671	50.2
Phoenix, USA	135	32,382	7525	23.2	93	22,267	11,174	50.2
Pyongyang, North Korea	19	4586	1072	23.4	6	1352	498	36.8
Quezon City, Philippines	59	14,152	733	5.2	15	3536	1604	45.3
Rio de Janeiro, Brazil	403	96,388	12,152	12.6	178	42,464	26,687	62.8
Rome, Italy	59	14,121	4474	31.7	21	5105	3806	74.5
San Jose, USA	43	10,207	2372	23.2	29	7019	3522	50.2
San José, Costa Rica	21	5126	288	5.6	9	2126	628	29.6
Santiago, Chile	104	24,978	6301	25.2	69	16,400	12,691	77.4
São Paulo, Brazil	421	100,688	12,694	12.6	185	44,358	27,878	62.8
Seoul, South Korea	107	25,614	16,670	65.1	59	14,142	10,671	75.5
Shanghai, China	535	127,942	51,154	40.0	325	77,841	59,277	76.2
Shenzhen, China	236	56,435	22,564	40.0	144	34,336	26,147	76.2
Sydney, Australia	210	50,285	10,790	21.5	126	30,187	18,482	61.2
Tashkent, Uzbekistan	29	6881	747	10.9	15	3473	1863	53.7
Tehran, Iran	146	34,944	16,493	47.2	88	20,975	17,421	83.1
Tokyo, Japan	282	67,389	42,957	63.7	158	37,817	27,860	73.7
Toronto, Canada	81	19,406	12,316	63.5	155	37,096	29,473	79.5

Ulaanbaatar, Mongolia	33	7894	1243	15.7	31	7355	3212	43.7
Vancouver, Canada	33	7973	5060	63.5	64	15,241	12,109	79.5
Vienna, Austria	27	6559	4074	62.1	22	5314	4111	77.4
Yangon, Myanmar	114	27,224	628	2.3	25	6096	1395	22.9
Yixing, China	8	1860	743	40.0	5	1131	862	76.2
Zurich, Switzerland	20	4696	1460	31.1	17	3987	3091	77.5
All metropolitan areas	**11,355**	**2715,925**	**605,936**	**22.3**	**5797**	**1386,473**	**816,748**	**-**

3.2. Energy Costs

Table 7 shows the BAU levelized costs of energy in 2015 and projected for 2050, in each metropolitan area. The LCOEs include those of keeping the BAU electricity and heat grids stable. The LCOEs were derived for the electric power sector only, but are assumed, for simplicity, to equal the LCOEs for all BAU energy. Because of the large (57.1%) reduction in end-use energy that occurs upon converting from BAU to WWS (Table 1), the uncertainty in the LCOE of non-electricity versus electricity BAU energy is small, so makes no difference in the conclusions drawn here.

Table 7 also shows the capital cost of the WWS infrastructure needed to meet annual average end-use power demand (load), the 2050 WWS LCOE needed to meet annual average load, and the 2050 WWS LCOE needed to meet continuous load (thus to keep the electric and heat grids stable). Footnote (e) of Table 7 describes the methodology for deriving the LCOE of WWS needed to meet continuous load. Finally, Table 7 provides the private and social cost savings of using WWS instead of BAU energy.

The total capital cost of all WWS infrastructure needed to meet annual average power for all metropolitan areas is $7.25 trillion (Table 7, 2013 USD) for 3903 GW of new WWS generators (Table 2). This results in a capital cost of ~$1.86 million per MW. Shanghai requires the greatest capital input ($513 billion), followed by Tokyo ($443 billion), then Beijing ($401 billion).

The LCOE accounts for capital, land, operating, maintenance, fuel, short- and long-distance transmission, distribution, and decommissioning costs. Table 7 indicates that the mean BAU LCOE in 2013 USD increased only ~1.9% between 2015 and 2050 (from 9.72 to 9.9 ¢/kWh), increasing in many locations but decreasing in others. However, the 2050 WWS LCOE (9.0 ¢/kWh) for meeting continuous end-use load, averaged over all metropolitan areas, was about 9.1% less than the 2050 BAU LCOE (9.9 ¢/kWh) due to the projected drop in WWS generator cost due to both economies of scale and improvements in WWS technologies.

The 2050 LCOE needed to meet continuous load with WWS (9.0 ¢/kWh) was about 18% higher than that required for meeting annual average load with WWS (7.6 ¢/kWh) (Footnote (e) of Table 7). The difference (1.4 ¢/kWh) is similar to the 1.35 ¢/kWh difference found among 139 countries in [32] and the 1.39 ¢/kWh difference found among 143 countries in [33]. The higher cost of meeting continuous load than annual average load with WWS was due to (1) the need to overbuild WWS to meet continuous load, (2) the need for more electricity, heat, cold, and hydrogen storage to meet continuous load, and (3) the need for more transmission and distribution lines to meet continuous load.

Combining the 57.1% lower energy requirement (Table 1) with the 9% lower LCOE (Table 7) in the WWS case gives a 61.1% lower annual energy cost ($0.86 instead of $2.2 trillion/yr, in 2013 USD) with WWS (Table 8). This energy cost savings translates to a benefit of ~$1500 per person per year in 2050 (Table 7). The annual health and climate cost savings per person due to converting to WWS are even larger, an average of $2500 and $4300 per person per year, respectively (Table 7). The average energy plus air pollution health plus climate cost (i.e., the total social cost) savings of WWS over BAU is thus $8200 per person per year (Table 7), or $7.4 trillion/yr among all people in all metropolitan areas (Table 8).

The social cost savings is greatest in locations with high CO_2 emissions per capita. Social costs here do not include the insurance cost against nuclear accidents, the costs of conflicts over fossil fuel resources, groundwater pollution costs, lower land values due to mining and drilling operations, or costs of road repair due to road transport of fossil fuel extraction equipment and the fuels themselves.

Table 7. (**a**) Mean year 2050 capital cost estimate for new generators to meet annual average WWS electric power demand after electrification of all energy sectors (this does not include the additional generators beyond those needed for annual average power in Table 2). (**b**) Mean values of the private levelized cost of energy (LCOE) for conventional fuels (BAU) in the electricity sector in 2015, which is assumed to be the LCOE for all BAU energy. LCOE estimates do not include externality costs and are assumed to account for meeting continuous load (thus accounting for grid stability). (**c**) Same as (**b**), but for 2050. (**d**) Same as (**b**), but for WWS averaged over all energy sectors in 2050 and for generators to meet annual average load. (**e**) Same as (**b**) but for WWS averaged over all energy sectors in 2050 and for generators, storage, transmission/distribution, and demand response to meet continuous load (thus accounting for grid stability). (**f**) Mean private energy cost savings per person per year due to switching from BAU to WWS in all energy sectors in 2050. (**g**) Mean estimates by metropolitan area of 2050 air pollution health and non-health cost savings per person per year due to switching to WWS. (**h**) Mean estimates of climate cost savings to the world per person per year due to switching to WWS. (**i**) Mean estimates of private energy plus health plus climate cost savings per person per year in the metropolitan area due to switching to 100% WWS. All costs are in 2013 USD.

Metropolitan Area	(a) 2050 Capital Cost of New WWS Electricity Generators Needed to Meet Annual Average Load ($bil)	(b) 2015 LCOE of BAU for Meeting Continuous Load (¢/kWh-All-Energy)	(c) 2050 LCOE of BAU Energy for Meeting Continuous Load (¢/kWh-All-Energy)	(d) 2050 LCOE of WWS for Meeting Annual avg. Load (¢/kWh-All-Energy)	(e) 2050 LCOE of WWS for Meeting Continuous Load (¢/kWh-All-Energy)	(f) 2050 Mean Private Energy Cost Savings due to Switch-ing All Energy to WWS ($/person/yr)	(g) 2050 Mean Air Pollution Damage Cost Savings to Metro Area due to Switching all Energy to WWS ($/per-son/yr)	(h) 2050 Mean Climate Cost Savings to World due to Switch-ing All Energy to WWS ($/per-son/yr)	(i) 2050 Mean Energy + Health + Climate Cost Savings due to Switching to WWS ($/per-son/yr)
Abidjan, Côte d'Ivoire	12.1	8.61	11.05	5.84	6.62	364	2339	400	3102
Addis Ababa, Ethiopia	3.8	7.89	6.91	7.39	8.17	127	780	64	971
Ankara, Turkey	35.2	9.40	9.94	7.40	8.77	862	2033	2814	5708
Auckland, New Zealand	45.7	9.83	9.20	7.93	7.77	2716	892	5906	9513
Baghdad, Iraq	28.5	8.65	11.51	7.85	9.22	658	1440	3881	5980
Bangkok, Thailand	262.1	9.53	11.41	7.44	10.80	2150	3720	4886	10,756
Beijing, China	400.7	10.24	9.27	7.96	8.36	1868	7273	5562	14,704
Berlin, Germany	44.7	11.85	10.85	7.95	8.70	3213	2789	7363	13,365
Bogotá, Colombia	79.4	8.24	8.10	5.30	7.67	659	1157	1238	3054
Bologna, Italy	7.6	10.51	11.06	7.53	8.28	2445	2749	3889	9083
Bucharest, Romania	9.4	10.35	9.69	7.52	8.27	1520	7023	3473	12,015

Buenos Aires, Argentina	118.2	8.62	10.31	8.66	11.04	1720	1643	3644	7007
Cairo, Egypt	119.1	8.71	11.49	8.66	9.44	863	2424	2225	5512
Calgary, Canada	48.0	8.87	8.24	7.79	7.04	4824	918	11,880	17,622
Cape Town, South Africa	102.2	10.78	9.69	8.49	9.27	2254	2148	11,228	15,630
Caracas, Venezuela	25.7	7.79	8.37	5.89	8.26	1033	1104	3365	5503
Casablanca, Morocco	13.2	10.41	10.40	8.53	9.30	584	1073	1738	3395
Chicago, USA	138.3	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Delhi, India	216.0	10.51	9.68	7.61	10.07	444	4727	1906	7076
Dhaka, Bangladesh	52.0	8.79	11.80	5.91	9.28	211	1865	412	2487
Dubai, United Arab Emirates	209.1	8.77	11.89	7.03	8.40	8470	1274	14,956	24,699
Edmonton, Canada	44.1	8.87	8.24	7.79	7.04	4824	918	11,880	17,622
Guayaquil, Ecuador	14.5	8.14	9.13	6.03	8.40	633	680	1739	3052
Hanoi, Vietnam	62.0	8.78	9.20	8.04	11.41	379	1682	2396	4457
Havana, Cuba	12.0	9.18	11.98	8.26	12.01	726	3660	3171	7558
Ho Chi Minh City, Vietnam	101.9	8.78	9.20	8.04	11.41	379	1682	2396	4457
Houston, USA	144.2	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Ibiza, Spain	0.5	11.24	10.84	7.76	8.52	2056	1514	3550	7121
Istanbul, Turkey	111.7	9.40	9.94	7.40	8.77	862	2033	2814	5708
Jakarta, Indonesia	75.9	10.10	10.40	6.99	10.35	741	2966	1989	5697
Karachi, Pakistan	63.9	8.45	10.07	7.68	8.96	393	2452	826	3671
Kiev, Ukraine	29.4	10.55	9.55	8.15	8.90	1727	4885	4737	11,349
Kinshasa, Congo	38.5	7.95	8.95	5.43	6.20	327	1814	681	2823
Kyoto, Japan	15.2	9.90	10.78	7.81	9.76	1862	2183	6437	10,482
Lagos, Nigeria	44.2	8.48	10.88	6.34	7.12	549	4385	280	5213
Lima, Peru	54.7	8.29	9.23	6.11	8.49	668	1863	1406	3938
London, United Kingdom	99.0	11.33	11.16	7.98	8.73	2256	1927	3524	7707
Los Angeles, USA	191.6	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Madrid, Spain	65.3	11.24	10.84	7.76	8.52	2056	1514	3550	7121
Mexico City, Mexico	179.6	9.30	11.10	7.31	9.52	1336	1482	3391	6209
Montevideo, Uruguay	16.5	9.95	9.11	7.55	9.93	1012	1342	1842	4195
Montreal, Canada	105.5	8.87	8.24	7.79	7.04	4824	918	11,880	17,622
Moscow, Russia	234.7	9.16	10.21	7.95	7.73	4568	4682	10,321	19,571
Mumbai, India	111.4	10.51	9.68	7.61	10.07	444	4727	1906	7076
Nairobi, Kenya	9.4	11.75	10.65	7.38	8.15	380	591	312	1283
New York City, USA	289.6	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Oslo, Norway	13.0	7.44	6.61	6.58	7.33	2867	1386	6251	10,504
Palma, Spain	4.9	11.24	10.84	7.76	8.52	2056	1514	3550	7121
Paris, France	132.0	10.71	9.39	7.97	8.72	1737	1475	3206	6418

Perth, Australia	66.7	10.50	10.34	7.47	9.04	4144	1066	11,569	16,779
Philadelphia, USA	93.6	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Phoenix, USA	98.0	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
Pyongyang, North Korea	9.8	8.06	7.39	7.47	7.87	176	2710	1706	4592
Quezon City, Philippines	9.1	10.56	10.59	7.95	9.35	297	3515	971	4784
Rio de Janeiro, Brazil	235.9	8.86	8.53	6.01	8.38	915	1209	1841	3965
Rome, Italy	41.5	10.51	11.06	7.53	8.28	2445	2749	3889	9083
San Jose, USA	30.9	10.28	10.43	7.81	9.33	3164	1757	7255	12,176
San José, Costa Rica	6.8	9.44	8.24	6.81	9.01	516	979	1246	2741
Santiago, Chile	84.8	9.87	9.53	8.50	10.87	1279	1781	4607	7668
São Paulo, Brazil	246.4	8.86	8.53	6.01	8.38	915	1209	1841	3965
Seoul, South Korea	265.2	10.31	10.14	6.82	11.87	2766	2154	11,314	16,234
Shanghai, China	513.1	10.24	9.27	7.96	8.36	1868	7273	5562	14,704
Shenzhen, China	226.3	10.24	9.27	7.96	8.36	1868	7273	5562	14,704
Sydney, Australia	146.7	10.50	10.34	7.47	9.04	4144	1066	11,569	16,779
Tashkent, Uzbekistan	11.1	8.52	10.65	7.58	8.85	1005	1739	2099	4844
Tehran, Iran	154.6	8.72	11.57	8.23	9.60	2921	1530	7360	11,811
Tokyo, Japan	443.3	9.90	10.78	7.81	9.76	1862	2183	6437	10,482
Toronto, Canada	167.8	8.87	8.24	7.79	7.04	4824	918	11,880	17,622
Ulaanbaatar, Mongolia	17.1	10.77	9.86	7.58	7.98	1161	3768	7224	12,152
Vancouver, Canada	69.0	8.87	8.24	7.79	7.04	4824	918	11,880	17,622
Vienna, Austria	40.5	9.24	8.67	6.53	7.28	3178	2422	6353	11,953
Yangon, Myanmar	10.3	7.90	8.60	6.93	10.29	241	2496	490	3228
Yixing, China	7.5	10.24	9.27	7.96	8.36	1868	7273	5562	14,704
Zurich, Switzerland	18.2	8.91	7.79	6.33	7.08	1786	1703	3602	7090
All metropolitan areas	**7250**	**9.72**	**9.90**	**7.60**	**9.00**	**1508**	**2467**	**4270**	**8245**

All costs are in 2013 USD. (a) Capital costs are only for new electricity generators needed to meet annual average WWS load (Table 1). (b) The 2015 LCOE cost of retail electricity in the BAU case in each metropolitan area combines the percentage mix of conventional electricity generators by country in which the metropolitan area resides in 2015 with contemporary mean LCOEs for each BAU generator in the country, taken from [33]. Such BAU costs include all-distance transmission, distribution, and pipeline costs, but they exclude health and climate costs. This LCOE is assumed to apply to all BAU sectors. (c) Same as (b), but for the 2050 BAU case and using 2050 LCOEs for each generator as derived in [33]. The 2050 BAU case includes some existing WWS (mostly hydropower) plus future increases in WWS electricity in the BAU case, as well as energy efficiency measures. The cost of keeping the grid stable in the BAU case is conservatively assumed to be made possible by BAU generators, and this is accounted for in the BAU costs. This LCOE is assumed to apply to all BAU sectors. (d) The 2050 LCOE of WWS for meeting load in the annual average is found by combining the 2050 mix of WWS generators among all energy sectors by metropolitan area from Table 3 with the 2050 mean LCOEs for each WWS generator by country from [33]. (e) The 2050 LCOE of WWS for meeting continuous load is the sum of the LCOE from meeting annual average load plus the difference in cost between meeting continuous and annual average load in each metropolitan region. This difference is determined from data in [33]. That study calculated the LCOEs to meet annual average load (LCOEA) with 100% WWS in 143 countries and the LCOEs to meet continuous load (LCOEC) with

100% WWS in 24 world regions encompassing the 143 countries. The LCOEAs for each country were first averaged (weighted by end-use WWS load) to find average LCOEAs for each region. The difference between the LCOEC and LCOEA for each region was then assigned to each country in the region. The difference for each metropolitan area was then assigned as the difference in the country that the metropolitan area resided in. This difference was then added to the LCOEA from Table 7, Column (d) to obtain the value in Column (e). Note that, for some regions (Canada, Iceland, New Zealand, and Russia), the cost of keeping the grid stable was less than the estimated cost of meeting annual average load. The reason is that the number of generators estimated to meet annual average load was a rough estimate. However, the WWS resource strength (usually wind) in these countries was stronger when calculated with a weather prediction model used to predict continuous WWS supply than when estimated for determining the number of generators to meet annual average power in [33]. (f) The 2050 mean private energy cost savings per capita per year due to switching from BAU to WWS retail electricity is calculated as the cost of all energy use in the BAU case (the product of BAU end-use power from Table 1, 8760 h per year, and the 2050 BAU LCOE from Column (c) of Table 7) less the WWS private energy cost (which is the product of WWS end-use power from Table 1, 8760 h per year, and the 2050 WWS LCOE from Column (e) of Table 7), all divided by 2050 population from Table 9. (g) This column equals the total air pollution cost per year for the metropolitan area from Table 8 divided by the 2050 metropolitan area population. (h) This column equals the total climate cost per year to the world due to the metropolitan area's emissions (from Table 8) divided by the 2050 metropolitan area population. (i) This column equals the sum of Columns (f), (g), and (h).

Table 8. (**a**) BAU annual energy cost, (**b**) BAU annual air pollution cost (from mortalities, morbidities, and non-air pollution effects) due to energy, (**c**) BAU annual climate cost due to energy, (**d**) BAU annual total social (energy+air pollution+climate) cost, (**e**) WWS annual social cost (= energy cost), and percent reduction in (**f**) energy cost and (**g**) social cost due to transitioning from WWS to BAU. All costs are in 2013 USD.

Metropolitan Area	(a) 2050 BAU Energy Cost ($bil/yr)	(b) 2050 BAU Air Pollution Cost ($bil/yr)	(c) 2050 BAU Climate cost ($bil/yr)	(d) 2050 BAU Total Social Cost (a + b + c) ($bil/yr)	(e) 2050 WWS Energy and Total Social Cost ($bil/yr)	(f) Percent Change in Energy Cost due to WWS (e − a)/a	(g) Percent Change in Total Social Cost due to WWS (e − d)/d
Abidjan, Côte d'Ivoire	3.8	19.7	3.4	26.9	0.7	−80.4	−97.2
Addis Ababa, Ethiopia	1.4	6.5	0.5	8.5	0.4	−73.4	−95.5
Ankara, Turkey	11.3	16.3	22.6	50.2	4.4	−61.3	−91.3
Auckland, New Zealand	11.8	2.1	13.9	27.8	5.4	−54.1	−80.5
Baghdad, Iraq	9.5	14.4	38.9	62.9	2.9	−69.3	−95.4
Bangkok, Thailand	64.1	62.4	82.0	208.6	28.1	−56.3	−86.6
Beijing, China	113.4	261.7	200.1	575.2	46.2	−59.3	−92.0
Berlin, Germany	18.8	10.8	28.5	58.1	6.4	−66.0	−89.0
Bogotá, Colombia	18.3	21.0	22.5	61.7	6.3	−65.3	−89.7
Bologna, Italy	3.2	2.6	3.6	9.4	0.9	−71.3	−90.2
Bucharest, Romania	3.6	11.2	5.5	20.3	1.2	−67.5	−94.3
Buenos Aires, Argentina	52.8	31.5	69.9	154.1	19.8	−62.5	−87.2
Cairo, Egypt	43.3	77.0	70.7	191.0	15.9	−63.2	−91.7
Calgary, Canada	17.5	2.3	29.4	49.2	5.6	−68.0	−88.6
Cape Town, South Africa	29.8	16.1	84.3	130.3	12.9	−56.7	−90.1
Caracas, Venezuela	5.1	3.4	10.3	18.8	2.0	−61.3	−89.4
Casablanca, Morocco	4.4	5.0	8.1	17.4	1.7	−62.2	−90.5
Chicago, USA	48.7	17.2	70.9	136.8	17.8	−63.5	−87.0
Delhi, India	48.6	245.1	98.8	392.6	25.6	−47.4	−93.5
Dhaka, Bangladesh	11.4	68.5	15.1	95.0	3.7	−67.7	−96.1
Dubai, United Arab Emirates	63.1	5.9	69.1	138.1	23.9	−62.0	−82.7
Edmonton, Canada	16.1	2.1	27.0	45.1	5.2	−68.0	−88.6
Guayaquil, Ecuador	4.2	3.0	7.6	14.8	1.5	−65.1	−90.0
Hanoi, Vietnam	11.0	15.4	21.9	48.2	7.5	−31.6	−84.5
Havana, Cuba	3.4	7.5	6.5	17.3	1.9	−44.0	−89.1

Ho Chi Minh City, Vietnam	18.0	25.3	36.0	79.2	12.3	−31.6	−84.5
Houston, USA	50.8	17.9	74.0	142.6	18.5	−63.5	−87.0
Ibiza, Spain	0.2	0.1	0.3	0.6	0.1	−68.8	−88.4
Istanbul, Turkey	35.8	51.8	71.7	159.4	13.9	−61.3	−91.3
Jakarta, Indonesia	17.8	42.4	28.4	88.7	7.2	−59.4	−91.8
Karachi, Pakistan	15.7	62.5	21.1	99.2	5.6	−63.9	−94.3
Kiev, Ukraine	9.8	17.5	17.0	44.4	3.6	−63.3	−91.9
Kinshasa, Congo	10.4	47.7	17.9	75.9	1.8	−82.9	−97.7
Kyoto, Japan	4.8	3.2	9.3	17.2	2.1	−56.8	−88.1
Lagos, Nigeria	16.1	108.2	6.9	131.3	2.6	−83.9	−98.0
Lima, Peru	16.2	29.6	22.4	68.2	5.6	−65.5	−91.8
London, United Kingdom	39.9	24.0	43.8	107.7	11.9	−70.3	−89.0
Los Angeles, USA	67.4	23.8	98.2	189.5	24.6	−63.5	−87.0
Madrid, Spain	27.2	13.8	32.3	73.4	8.5	−68.8	−88.4
Mexico City, Mexico	56.6	40.4	92.4	189.3	20.2	−64.4	−89.3
Montevideo, Uruguay	4.6	2.7	3.7	11.0	2.6	−43.7	−76.3
Montreal, Canada	38.5	5.0	64.5	108.1	12.3	−68.0	−88.6
Moscow, Russia	99.1	77.2	170.1	346.4	23.8	−76.0	−93.1
Mumbai, India	25.1	126.4	51.0	202.5	13.2	−47.4	−93.5
Nairobi, Kenya	4.2	5.1	2.7	12.0	0.9	−78.1	−92.3
New York City, USA	102.0	36.0	148.5	286.5	37.2	−63.5	−87.0
Oslo, Norway	8.0	2.0	9.1	19.1	3.8	−52.3	−80.1
Palma, Spain	2.0	1.0	2.4	5.5	0.6	−68.8	−88.4
Paris, France	38.4	19.1	41.5	98.9	15.9	−58.5	−83.9
Perth, Australia	20.5	3.3	35.4	59.1	7.8	−61.9	−86.8
Philadelphia, USA	32.9	11.6	48.0	92.6	12.0	−63.5	−87.0
Phoenix, USA	34.5	12.2	50.3	96.9	12.6	−63.5	−87.0
Pyongyang, North Korea	1.7	9.6	6.1	17.3	1.1	−37.3	−93.9
Quezon City, Philippines	2.3	16.8	4.6	23.8	0.9	−60.7	−96.1
Rio de Janeiro, Brazil	48.4	34.4	52.5	135.3	22.4	−53.8	−83.5
Rome, Italy	17.5	14.1	19.9	51.5	5.0	−71.3	−90.2
San Jose, USA	10.9	3.8	15.8	30.6	4.0	−63.5	−87.0
San José, Costa Rica	2.0	1.9	2.4	6.3	1.0	−50.0	−84.2
Santiago, Chile	25.3	15.0	38.8	79.1	14.5	−42.6	−81.7

São Paulo, Brazil	50.6	36.0	54.8	141.4	23.4	−53.8	−83.5
Seoul, South Korea	65.9	21.9	114.9	202.6	37.8	−42.6	−81.4
Shanghai, China	145.2	335.1	256.2	736.5	59.1	−59.3	−92.0
Shenzhen, China	64.1	147.8	113.0	324.9	26.1	−59.3	−92.0
Sydney, Australia	45.1	7.2	77.8	130.1	17.2	−61.9	−86.8
Tashkent, Uzbekistan	4.4	5.4	6.5	16.3	1.3	−70.7	−92.1
Tehran, Iran	53.2	18.4	88.6	160.2	18.0	−66.1	−88.7
Tokyo, Japan	138.5	92.1	271.6	502.2	59.9	−56.8	−88.1
Toronto, Canada	61.3	7.9	102.7	171.9	19.6	−68.0	−88.6
Ulaanbaatar, Mongolia	4.9	10.8	20.6	36.3	1.5	−68.3	−95.8
Vancouver, Canada	25.2	3.3	42.2	70.6	8.1	−68.0	−88.6
Vienna, Austria	12.5	6.1	16.0	34.6	4.5	−64.1	−87.0
Yangon, Myanmar	3.1	20.0	3.9	27.0	1.2	−62.5	−95.7
Yixing, China	2.1	4.9	3.7	10.7	0.9	−59.3	−92.0
Zurich, Switzerland	5.7	3.1	6.5	15.2	2.4	−56.8	−83.9
All metropolitan areas	**2205**	**2554**	**3529**	**8288**	**859**	**−61.1**	**−89.6**

The 2050 BAU annual energy cost is the 2050 BAU LCOE from Table 7 multiplied by the 2050 BAU end-used load from Table 1 and 8760 h per year. The 2050 BAU air pollution cost per year is the 2050 air pollution cost from energy in the country each metropolitan area resides in, from [33], multiplied by the metropolitan area-to-country population ratio. The 2050 BAU climate cost per year is derived by multiplying the 2050 climate cost to the world from energy emissions in the country that each metropolitan area in, from [33], multiplied by the metropolitan area-to-country population ratio. The climate cost due to the country's emissions assume a 2050 mid-value of the social cost of carbon (SCC) from Table S18 of [33] of \$500/tonne-CO_2e.

3.3. Air Pollution Cost Reductions due to WWS

Air pollution contributes to death from heart disease, stroke, chronic obstructive pulmonary disease (COPD), lower respiratory tract infection, lung cancer, and asthma. Common types of COPD are chronic bronchitis and emphysema. Common types of lower respiratory tract infections are the flu, bronchitis, and pneumonia [52]. In 2016, 56.9 million people died worldwide from all causes [53]. Air pollution may cause between 24% and 45% of the deaths for each of five out of the six leading causes of death [53]. About 4.5 million people died prematurely from outdoor air pollution and 7.1 million died from indoor plus outdoor air pollution in 2016 [53]. Thus, about 12.5% of all deaths worldwide in 2016 were due to indoor plus outdoor air pollution, making it the second leading cause of death after heart disease. The authors of [33] estimated that, in the 143 countries examined, 6.8 million people died prematurely due to air pollution in 2016, and 5.3 million may die prematurely per year in 2050. The reduction is due to some BAU improvements in emission control technologies.

Scaling the 2050 individual country numbers from [33] by population to each metropolitan area gives approximately 408,000 (322,000–506,000) premature deaths per year in these areas in the BAU case (or avoided deaths in the WWS case) (Table 9). The greatest numbers of premature deaths occur in Delhi (45,200/yr), Shanghai (38,500/yr), Beijing (30,100/yr), Lagos (25,600/yr), Dhaka (23,700/yr), and Mumbai (23,300/yr).

The damage cost due to air pollution from fossil fuel and biofuel burning and evaporative emissions in a metropolitan area is the sum of mortality, morbidity, and non-health costs. Non-health costs include costs from lower visibility and agricultural losses. Mortality, morbidity, and non-health costs are estimated as in [33]. The avoided air pollution cost among all metropolitan areas due to transitioning to 100% WWS is ~$2.6 ($1.5–$4.6) trillion/yr (Table 8), or ~11.5 (6.5–20.5) ¢/kWh-BAU-all-energy (Table 9), which translates to a mean of $2500/yr per person (2013 USD) (Table 7).

Table 9. (**a**) Year 2050 estimated population by metropolitan area (bold indicates a megacity, whose population exceeds 10 million). Year 2050 (**b**) high, (**c**) mean, and (**d**) low avoided air pollution premature mortalities by metropolitan area due to transitioning to 100% WWS. (**e**) Mean avoided air pollution cost (from avoided mortalities, morbidities, and non-air pollution effects) per unit BAU-energy from all sectors due to converting each metropolitan area to 100% WWS for all energy purposes. (**f**) 2017 estimated percent of global energy-related carbon-dioxide-equivalent (CO_2e) emissions due to the metropolitan area. 2050. (**g**) 2050 mean avoided climate-change costs to the world per unit BAU-energy from all sectors due to converting each metropolitan area to 100% WWS for all energy purposes. All costs are in 2013 USD.

Metropolitan Area	(a) 2050 Population	(b) 2050 High Avoided Premature Mortalities/yr	(c) 2050 Mean Avoided Premature Mortalities/yr	(d) 2050 Low Avoided Premature Mortalities/yr	(e) 2050 Mean Avoided Air Pollution Cost ¢/kWh-BAU-All-Energy	(f) 2017 Percent of Global CO_2 Emissions	(g) 2050 Mean Avoided Climate Change Cost ¢/kWh-BAU-All-Energy
Abidjan, Côte d'Ivoire	8431,503	8922	7658	6441	57.1	0.008	9.8
Addis Ababa, Ethiopia	8325,962	5266	4556	3914	31.3	0.001	2.5
Ankara, Turkey	8030,105	2716	2265	1893	14.4	0.095	19.9
Auckland, New Zealand	2356,994	299	201	125	1.6	0.047	10.8
Baghdad, Iraq	**10,024,201**	2740	2227	1878	17.5	0.099	47.0
Bangkok, Thailand	**16,781,431**	11,183	8582	6243	11.1	0.188	14.6
Beijing, China	**35,979,014**	37,973	30,092	22,261	21.4	0.837	16.4
Berlin, Germany	3867,994	1394	1031	756	6.2	0.120	16.4
Bogotá, Colombia	**18,135,932**	4965	3775	2882	9.3	0.067	9.9
Bologna, Italy	935,435	371	275	201	8.9	0.015	12.5
Bucharest, Romania	1592,918	1969	1154	738	30.2	0.020	14.9
Buenos Aires, Argentina	**19,168,044**	6001	4353	3165	6.2	0.210	13.7
Cairo, Egypt	**31,755,779**	19,057	14,588	12,205	20.4	0.166	18.7
Calgary, Canada	2472,004	329	226	145	1.1	0.103	13.8
Cape Town, South Africa	7508,657	3416	2757	2227	5.2	0.198	27.4

Caracas, Venezuela	3053,642	713	550	436	5.5	0.031	16.7
Casablanca, Morocco	4651,724	1491	1145	907	11.9	0.019	19.2
Chicago, USA	9776,493	2016	1450	985	3.7	0.330	15.2
Delhi, India	**51,860,328**	52,855	45,226	37,213	48.8	0.214	19.7
Dhaka, Bangladesh	**36,712,296**	26,925	23,665	20,641	70.8	0.035	15.6
Dubai, United Arab Emirates	4620,000	581	467	389	1.1	0.176	13.0
Edmonton, Canada	2269,284	302	208	133	1.1	0.095	13.8
Guayaquil, Ecuador	4363,855	873	594	414	6.4	0.023	16.3
Hanoi, Vietnam	9136,630	4409	3628	2953	12.9	0.050	18.4
Havana, Cuba	2038,221	2147	1079	583	26.5	0.019	23.0
Ho Chi Minh City, Vietnam	**15,013,384**	7244	5961	4853	12.9	0.082	18.4
Houston, USA	**10,193,400**	2102	1512	1027	3.7	0.344	15.2
Ibiza, Spain	76,253	18	12	8	5.5	0.001	12.9
Istanbul, Turkey	**25,497,667**	8624	7193	6011	14.4	0.303	19.9
Jakarta, Indonesia	**14,300,698**	8854	7105	5479	24.7	0.065	16.6
Karachi, Pakistan	**25,485,193**	21,161	18,001	15,078	40.2	0.048	13.5
Kiev, Ukraine	3592,437	3721	2871	2144	17.1	0.061	16.6
Kinshasa, Congo	**26,264,119**	14,345	12,399	10,458	41.1	0.042	15.4
Kyoto, Japan	1448,307	519	367	257	7.2	0.050	21.2
Lagos, Nigeria	**24,681,419**	29,672	25,618	21,464	73.0	0.016	4.7
Lima, Peru	**15,903,093**	6995	5652	4496	16.9	0.067	12.7
London, United Kingdom	**12,432,159**	3368	2415	1746	6.7	0.185	12.2
Los Angeles, USA	**13,540,336**	2792	2008	1364	3.7	0.457	15.2
Madrid, Spain	9107,722	2117	1490	1011	5.5	0.136	12.9
Mexico City, Mexico	**27,241,895**	6798	5525	4502	7.9	0.261	18.1
Montevideo, Uruguay	1997,046	562	386	267	5.3	0.011	7.3
Montreal, Canada	5432,087	724	498	319	1.1	0.227	13.8

Moscow, Russia	**16,482,525**	10,832	8314	6395	8.0	0.743	17.5
Mumbai, India	**26,749,083**	27,262	23,327	19,194	48.8	0.111	19.7
Nairobi, Kenya	8671,968	2512	2180	1821	12.9	0.006	6.8
New York City, USA	**20,472,016**	4222	3037	2063	3.7	0.690	15.2
Oslo, Norway	1452,425	245	166	101	1.7	0.038	7.5
Palma, Spain	678,064	158	111	75	5.5	0.010	12.9
Paris, France	**12,933,803**	2669	1952	1432	4.7	0.175	10.1
Perth, Australia	3055,748	471	320	217	1.6	0.118	17.9
Philadelphia, USA	6614,938	1364	981	667	3.7	0.223	15.2
Phoenix, USA	6926,976	1428	1027	698	3.7	0.234	15.2
Pyongyang, North Korea	3547,976	5722	4960	4080	42.3	0.014	26.6
Quezon City, Philippines	4776,173	4224	3519	2726	76.0	0.011	21.0
Rio de Janeiro, Brazil	**28,484,171**	7457	5418	4030	6.1	0.150	9.2
Rome, Italy	5118,666	2033	1505	1098	8.9	0.084	12.5
San Jose, USA	2183,404	450	324	220	3.7	0.074	15.2
San José, Costa Rica	1946,835	424	323	241	7.8	0.007	9.9
Santiago, Chile	8421,901	2493	1789	1281	5.7	0.109	14.6
São Paulo, Brazil	**29,755,050**	7789	5659	4210	6.1	0.157	9.2
Seoul, South Korea	**10,151,877**	3099	2104	1575	3.4	0.440	17.7
Shanghai, China	**46,069,710**	48,623	38,532	28,505	21.4	1.072	16.4
Shenzhen, China	**20,321,319**	21,448	16,996	12,573	21.4	0.473	16.4
Sydney, Australia	6726,779	1036	705	477	1.6	0.260	17.9
Tashkent, Uzbekistan	3101,384	1362	1025	785	13.0	0.023	15.7
Tehran, Iran	**12,037,089**	3149	2583	2128	4.0	0.225	19.3
Tokyo, Japan	**42,200,304**	15,112	10,699	7493	7.2	1.450	21.2
Toronto, Canada	8642,211	1152	792	508	1.1	0.362	13.8
Ulaanbaatar, Mongolia	2858,569	2025	1713	1422	21.9	0.047	41.9
Vancouver, Canada	3550,633	473	325	209	1.1	0.149	13.8
Vienna, Austria	2517,227	788	584	406	4.2	0.067	11.1

Yangon, Myanmar	7995,350	6554	5704	4911	55.6	0.009	10.9
Yixing, China	669,586	707	560	414	21.4	0.016	16.4
Zurich, Switzerland	1800,243	377	269	187	4.2	0.027	8.9
All metropolitan areas	**892,969,664**	**506,188**	**408,270**	**322,358**	**11.5**	**13.10**	**15.8**

Metropolitan area populations between 2000 and 2020 were obtained from [3]. The full trend was then extrapolated to 2050. Avoided air pollution mortalities are calculated from country values determined in [33], then scaled by the metropolitan area-to-country population ratio. Mean ¢/kWh-BAU-all-energy equals the mean avoided annual air pollution cost from Table 8 divided by the total (all-sector) BAU end-use energy in 2050 (which equals the annual-average end-use BAU power demand from Table 1 multiplied by 8760 h/year). CO_2e emissions are estimated from country energy-related CO_2 emissions [54] scaled by population to give metropolitan area emissions, then adjusted for non-CO_2 climate-relevant emissions, as described in [55]. Emissions are then projected to 2050 as in [33]. The avoided climate cost per unit energy is the annual mean BAU climate cost from Table 8 divided by the kWh of all energy consumed per year in the metropolitan area in the BAU case from Table 1.

3.4. Global-Warming Damage Costs Eliminated

Damage arising from global warming includes damage from higher sea levels (coastal infrastructure losses), reduced crop yields for certain crops, more intense hurricanes, more droughts and floods, more wildfires and air pollution, more migration due to crop losses and famine, more heat stress and heat stroke, more malaria and dengue fever, fishery and coral reef losses, and greater air cooling requirements, among other impacts. These costs are partly offset by fewer extreme cold events and concomitant decreases in illness and mortality, and the increase in agricultural output in some regions.

The damage caused by carbon dioxide equivalent (CO_2e) emissions to the global economy through their impacts on climate is quantified with the social cost of carbon (SCC). The SCC is usually expressed in cost per metric tonne-CO_2e emissions. The SCC from several recent studies is estimated for 2050 as ~$500 (282–1060)/metric tonne-CO_2e in 2013 USD [33]. Multiplying the SCC by estimated 2050 CO_2e emissions in each metropolitan area suggests that BAU emissions from the metropolitan areas here may cause $3.5 (2.0–7.5) trillion/yr in climate losses to the world by 2050 (Table 8), or 15.8 (8.9–33.7) ¢/kWh-BAU-all-energy (Table 9), which translates to ~$4300/yr per person (in 2013 USD) (Table 7). Transitioning to 100% WWS will avoid these costs.

3.5. Impacts of WWS on Job Creation and Loss

Governments are concerned about changes in employment upon transitioning their energy economies to entirely clean, renewable energy ones. Here, the numbers of long-term, full-time jobs created and lost are estimated for each metropolitan area. Job changes may not necessarily occur in the metropolitan area itself, but at least in the state, province, or country wherein the metropolitan area resides.

The calculation is done starting with the 2050 country job production and loss numbers from [33], determined for 143 individual countries for meeting annual average load and, separately, for 24 world regions encompassing the 143 countries, for meeting continuous load. That study relied substantially on results from NREL *Jobs and Economic Development Impact* (JEDI) Models [56]. Job production and loss for individual countries (after removing jobs created for producing generators beyond those needed to meet annual average load) were scaled by population to job production and loss for individual megacities. Those numbers were then scaled further by the LCOE needed to meet continuous load (Column (e) of Table 7) to that needed to meet annual average load (Column (d) of Table 7). This ratio mostly exceeds unity but is less than unity for some countries or regions (e.g., in Canada, Iceland, New Zealand, and Russia) where the initial number of generators estimated to meet annual average load was too high compared with what was needed to meet continuous load [33]. When the ratio exceeds unity, the additional jobs are for installing and operating additional electricity and heat generators; additional electricity, heat, cold, and hydrogen storage equipment; and additional transmission and distribution lines needed to meet continuous load rather than annual average load.

Jobs created include onsite (direct) jobs, local revenue and supply chain (indirect) jobs, and induced jobs. Indirect jobs include jobs associated with construction material and component suppliers, analysis and attorneys who assess project feasibility and negotiate agreements, banks financing the project, all equipment manufacturers, and manufacturers of blades and replacement parts. Indirect manufacturing jobs are included in the number of construction jobs. Induced jobs result from the reinvestment and spending of earnings from direct and indirect jobs. They include jobs resulting from increased business at local restaurants, hotels, and retail stores, and for childcare providers.

Table 10 suggests that a 100% conversion to WWS across the metropolitan areas may create ~2.3 million new long-term, full-time construction jobs and ~2.3 million new plus existing long-term, full-time operation plus maintenance jobs, totaling ~4.6 million new plus existing long-term, full-time jobs for WWS generators and transmission.

Job losses due to a transition to WWS will include losses of jobs to extract, transport, and process fossil fuels, bioenergy, and uranium. Job losses will also occur in the BAU electricity generation industry and in the manufacturing of appliances that use combustion fuels. Finally, jobs will be lost upon ceasing the construction of BAU electricity generation plants, petroleum refineries, and oil and gas pipelines.

Overall, shifting to 100% WWS is estimated to result in ~3.2 million jobs lost in the fossil fuel, bioenergy, and nuclear industries by 2050 (Table 10). Subtracting jobs lost from jobs created gives a *net* of ~1.4 million long-term, full-time jobs created among the metropolitan areas due to replacing fossil fuel, bioenergy, and nuclear generation among all sectors with WWS generation and transmission (Table 10). Job earnings show a net gain of ~$110 billion/yr (2013 USD) (Table 10).

Metropolitan areas in countries with significant fossil extraction may experience net job losses in the energy production sector. Several such metropolitan areas include Abidjan, Addis Ababa, Baghdad, Calgary, Caracas, Edmonton, Kinshasa, Lagos, Moscow, Oslo, Tehran, Toronto, and Yangon. These losses may be offset by the manufacturing, servicing, and exporting of machines and appliances associated with WWS energy (e.g., electric vehicles, fuel cell vehicles, electric heat pump air and water heaters, electric heat pump dryers, induction cooktops, etc.). Neither those jobs produced nor the jobs lost producing the equivalent machines and appliances replacing them were included in the job calculations here.

Table 10. Estimated numbers of 2050 new long-term, full-time (**a**) construction and (**b**) operation jobs produced due to converting to 100% WWS. (**c**) Job losses due to the transition. (**d**) Long-term, full-time construction plus operation jobs produced minus jobs lost. Annual earnings corresponding to new (**e**) construction and (**f**) operation jobs produced. (**g**) Net earnings from new construction plus operation jobs produced minus jobs lost due to converting to 100% WWS. Costs are in 2013 USD.

Metropolitan Area	(a) New Long-Term, Full-Time Construction Jobs	(b) New Plus Existing Long-Term, Full-Time Operation Jobs	(c) Job Losses in Fossil-Fuel, Biofuel, and Nuclear Energy Industries	(d) Net Jobs: Long-Term, Full-Time Net Construction Plus Operation Jobs Created Minus Jobs Lost	(e) Annual Earnings from New Construction Jobs ($bil/yr)	(f) Annual Earnings from New and Existing Operation Jobs ($bil/yr)	(g) Net Annual Earnings from New Construction Plus New + Existing Operation Jobs Minus Jobs Lost ($bil/yr)
Abidjan, Côte d’Ivoire	5667	5406	23,194	−12,120	0.16	0.15	−0.34
Addis Ababa, Ethiopia	2032	1867	12,037	−8138	0.04	0.04	−0.17
Ankara, Turkey	12,890	11,907	9105	15,692	0.81	0.75	0.99
Auckland, New Zealand	12,745	11,994	18,143	6596	1.29	1.22	0.67
Baghdad, Iraq	10,770	10,024	64,321	−43,527	0.61	0.56	−2.45
Bangkok, Thailand	107,220	103,817	88,152	122,884	6.80	6.59	7.80
Beijing, China	93,761	88,751	76,805	105,707	7.36	6.97	8.30
Berlin, Germany	14,075	15,472	15,546	14,001	1.43	1.58	1.43
Bogotá, Colombia	34,861	34,583	60,636	8809	1.69	1.68	0.43
Bologna, Italy	2261	2259	2305	2215	0.20	0.20	0.19
Bucharest, Romania	3221	2942	5284	880	0.29	0.27	0.08
Buenos Aires, Argentina	43,273	37,863	66,617	14,519	2.73	2.39	0.92
Cairo, Egypt	38,847	33,944	61,859	10,933	1.80	1.57	0.51

Calgary, Canada	11,524	9996	35,471	−13,952	1.10	0.96	−1.33
Cape Town, South Africa	31,562	30,370	44,887	17,044	1.61	1.54	0.87
Caracas, Venezuela	10,434	10,575	21,180	−171	0.56	0.56	−0.01
Casablanca, Morocco	5198	4476	4626	5048	0.21	0.18	0.20
Chicago, USA	33,883	34,334	50,976	17,240	4.23	4.29	2.15
Delhi, India	77,221	71,597	77,477	71,341	3.66	3.40	3.39
Dhaka, Bangladesh	31,350	33,780	25,900	39,230	0.95	1.02	1.18
Dubai, United Arab Emirates	61,021	92,554	108,104	45,471	8.54	12.95	6.36
Edmonton, Canada	10,579	9176	32,563	−12,808	1.01	0.88	−1.22
Guayaquil, Ecuador	7006	7478	14,522	−38	0.31	0.33	0.00
Hanoi, Vietnam	28,313	27,118	21,471	33,959	1.10	1.05	1.32
Havana, Cuba	5604	5010	4312	6302	0.34	0.30	0.38
Ho Chi Minh City, Vietnam	46,524	44,560	35,281	55,802	1.81	1.73	2.17
Houston, USA	35,328	35,798	53,150	17,976	4.41	4.47	2.25
Ibiza, Spain	171	166	173	164	0.01	0.01	0.01
Istanbul, Turkey	40,930	37,809	28,912	49,826	2.57	2.37	3.13
Jakarta, Indonesia	31,022	26,190	39,045	18,167	1.61	1.36	0.94
Karachi, Pakistan	26,236	23,733	34,928	15,040	0.89	0.80	0.51
Kiev, Ukraine	10,189	9654	11,422	8420	0.54	0.51	0.45
Kinshasa, Congo	19,461	19,012	148,562	−110,089	0.71	0.69	−3.99
Kyoto, Japan	5139	6198	3428	7908	0.40	0.48	0.61
Lagos, Nigeria	17,452	14,954	62,911	−30,504	0.68	0.58	−1.18
Lima, Peru	24,967	26,056	33,187	17,836	1.15	1.20	0.82

London, United Kingdom	27,727	39,456	40,426	26,758	2.61	3.71	2.52
Los Angeles, USA	46,928	47,552	70,602	23,878	5.86	5.94	2.98
Madrid, Spain	20,423	19,826	20,720	19,529	1.74	1.69	1.67
Mexico City, Mexico	58,735	55,270	83,592	30,413	3.75	3.52	1.94
Montevideo, Uruguay	7975	7301	9523	5754	0.48	0.44	0.35
Montreal, Canada	25,323	21,965	77,947	−30,658	2.42	2.10	−2.93
Moscow, Russia	56,542	50,701	160,801	−53,559	4.84	4.34	−4.59
Mumbai, India	39,830	36,929	39,962	36,797	1.89	1.75	1.75
Nairobi, Kenya	4331	3879	19,307	−11,097	0.12	0.10	−0.30
New York City, USA	70,952	71,895	106,745	36,102	8.86	8.98	4.51
Oslo, Norway	5015	6447	53,418	−41,956	0.65	0.84	−5.44
Palma, Spain	1521	1476	1543	1454	0.13	0.13	0.12
Paris, France	37,431	34,347	36,061	35,717	3.45	3.16	3.29
Perth, Australia	20,720	21,250	36,028	5942	2.03	2.08	0.58
Philadelphia, USA	22,926	23,231	34,491	11,665	2.86	2.90	1.46
Phoenix, USA	24,007	24,327	36,118	12,215	3.00	3.04	1.53
Pyongyang, North Korea	4658	4929	5269	4318	0.11	0.12	0.11
Quezon City, Philippines	3566	2826	3585	2807	0.15	0.12	0.12
Rio de Janeiro, Brazil	81,891	83,962	96,059	69,794	4.51	4.62	3.84
Rome, Italy	12,374	12,364	12,615	12,123	1.07	1.07	1.05
San Jose, USA	7567	7668	11,385	3850	0.95	0.96	0.48
San José, Costa Rica	3216	3228	3434	3009	0.16	0.17	0.15
Santiago, Chile	31,203	27,387	37,569	21,021	2.34	2.05	1.58

São Paulo, Brazil	85,545	87,708	100,345	72,908	4.71	4.83	4.02
Seoul, South Korea	105,988	147,897	44,311	209,574	10.69	14.91	21.13
Shanghai, China	120,058	113,642	98,346	135,354	9.43	8.93	10.63
Shenzhen, China	52,957	50,127	43,380	59,704	4.16	3.94	4.69
Sydney, Australia	45,612	46,778	79,310	13,080	4.46	4.57	1.28
Tashkent, Uzbekistan	4586	4108	8600	94	0.21	0.19	0.00
Tehran, Iran	49,370	45,385	88,671	6084	3.06	2.82	0.38
Tokyo, Japan	149,729	180,583	99,883	230,429	11.61	14.00	17.87
Toronto, Canada	40,287	34,946	124,009	−48,776	3.85	3.34	−4.66
Ulaanbaatar, Mongolia	7334	6110	18,290	−4846	0.40	0.33	−0.26
Vancouver, Canada	16,552	14,357	50,949	−20,040	1.58	1.37	−1.92
Vienna, Austria	14,407	15,068	15,073	14,403	1.46	1.53	1.46
Yangon, Myanmar	5723	5348	14,750	−3680	0.19	0.18	−0.13
Yixing, China	1745	1652	1429	1967	0.14	0.13	0.15
Zurich, Switzerland	6857	6702	6359	7200	0.80	0.79	0.84
All metropolitan areas	**2274,348**	**2310,046**	**3187,398**	**1396,996**	**174**	**184**	**110**

A temporary construction job is a full-time equivalent (FTE) job (one that provides 2080 h per year of work) required for building infrastructure for one year. A long-term construction job is defined as the number of consecutive temporary one-year construction jobs for *L* years to replace *1/L* of the total nameplate capacity of an energy device every year, all divided by *L* years, where *L* is the average facility life. By way of example, suppose 40 GW of nameplate capacity of an energy technology must be installed over 40 years, which is also the lifetime of the technology. Also, suppose the installation of 1 MW creates 40 one-year construction jobs (direct, indirect, and induced jobs). In that case, 1 GW of wind is installed each year and 40,000 one-year construction jobs are required each year. Thus, over 40 years, 1.6 million one-year jobs are required. This is equivalent to 40,000 40-year jobs. After the technology life of 40 years, 40,000 more one-year jobs are needed continuously each year in the future. As such, the 40,000 construction jobs are long-term jobs. Long-term operation jobs are full-time jobs that last as long as the energy facility lasts and that are needed to manage, operate, and maintain an energy generation facility. In a 100% WWS system, long-term jobs are effectively indefinite because, once a plant is decommissioned, another one must be built to replace it. The new plant requires additional construction and operation jobs. Monetary values are in 2013 USD. Calculations are based on individual country job and monetary changes from [33] (after removing jobs created due to generators beyond those needed to meet annual average load). The calculated number, for each country that a metropolitan area resides in, is scaled by the 2050 metropolitan area-to-country population ratio and by the LCOE that results from keeping the grid stable (Table 7, Column (e)) to the LCOE that results from meeting annual average load (Table 7, Column (d)). The job change numbers are across all energy sectors. Construction jobs are for new WWS devices only. Operation jobs are for new and existing devices. The jobs created account for new jobs in the electricity, heat, cold, and hydrogen generation, storage, and transmission (including high-voltage direct current transmission) industries. By accounting for the LCOE ratio of keeping the grid stable to meeting annual average load, the job change numbers also attempt to account for jobs created for building additional electricity and heat generators beyond those needed to meet annual average load; electricity, heat, cold, and hydrogen storage; and additional transmission and distribution lines. They do not account for changes in the numbers of jobs due to the production of electric appliances and machines or due to increasing building energy efficiency. Job losses are due to eliminating jobs for mining, transporting, processing, and using fossil fuels, biofuels, and uranium. Fossil-fuel jobs due to non-energy uses of petroleum (e.g., lubricants, asphalt, petrochemical feedstock, and petroleum coke) are retained. For transportation sectors, the jobs lost are those due to transporting fossil fuels (e.g., through truck, train, barge, ship, or pipeline). The jobs not lost are solely those for transporting other goods. The table does not account for jobs lost in the manufacture of combustion appliances, including the manufacture of automobiles, ships, or industrial machines.

4. Conclusions

Transitioning 74 metropolitan areas, including 30 megacities, to 100% wind, water, and solar energy and storage for all energy purposes has the potential to prevent ~408,000 (322,000–506,000) premature air-pollution mortalities/yr in 2050. This, along with non-mortality impacts, avoids a 2050 air pollution cost of ~$2.6 (1.5–4.6) trillion/yr, or a mean of 11.5 ¢/kWh-BAU-all-energy (2013 USD). Transitioning also avoids ~$3.5 (2.0–7.5) trillion/yr (a mean of 15.8 ¢/kWh-BAU-all-energy) in 2050 global warming costs, ~$1.35 trillion/yr (a mean of 0.9 ¢/kWh-BAU-all-energy) in 2050 energy costs, and energy plus health and climate costs of ~$7.4 trillion/yr (a mean of 27.3 ¢/kWh-BAU-all-energy). These translate to ~$1500/person/yr in energy cost savings and ~$6700/person/yr in health plus climate cost savings. Finally, transitioning creates ~1.4 million more new long-term, full-time jobs than lost and stabilizes energy prices.

Due to the current severity of air pollution, global warming, and energy insecurity problems worldwide, a transition to 100% WWS should occur no later (and ideally earlier) than 2050, with at least 80% by 2030 [32,33]. Although a natural transition is currently occurring due to decreases in WWS generation and storage costs, such a timeline can be met only with aggressive policies.

Because metropolitan areas consist of a core city surrounded by other towns and cities, effective policies in a metropolitan area are best instituted if the cities and towns making up the area act in a unified manner rather than in piecemeal fashion. In many countries, each town and city in the area must pass its own resolutions and ordinances; nonetheless, such resolutions and ordinances can be proposed in sync or at least with consistent goals. Sometimes, the competition among towns and cities in a metropolitan area can increase the aggressiveness of policies adopted among these entities. Given that transitioning to 100% WWS for all energy purposes presents minimal downside, metropolitan areas and their constituent towns and cities have significant motivation to transition.

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Abbreviations

The following abbreviations are used in this manuscript:

BAU	Business-as-Usual
BE	Battery Electric
CO_2e	Carbon Dioxide Equivalent
COPD	Chronic Obstructive Pulmonary Disorder
CSP	Concentrated Solar Power
EIA	Energy Information Administration
GW	Gigawatt
HFC	Hydrogen Fuel Cell
JEDI	Jobs and Economic Development Impact
LCOE	Levelized Cost of Energy
LCOEA	LCOE to meet annual average load
LCOEC	LCOE to meet continuous load

MW	Megawatt
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SCC	Social Cost of Carbon
TW	Terawatt
TWh	Terawatt-hour
USD	United States Dollars
WWS	Wind, Water, and Sunlight (or Solar)

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