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100% clean and renewable Wind, Water, and Sunlight (WWS) all-sector energy roadmaps for 53 towns and cities in North America

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ABSTRACT

Towns and cities worldwide emit significant pollution and are also increasingly affected by pollution's health and climate impacts. Local decision makers can alleviate these impacts by transitioning the energy they control to 100% clean, renewable energy and energy efficiency. This study develops roadmaps to transition 53 towns and cities in the United States, Canada, and Mexico to 100% wind, water, and sunlight (WWS) in all energy sectors by no later than 2050, with at least 80% by 2030. The roadmaps call for electrifying transportation and industrial heat; using electricity, solar heat, or geothermal heat for water and air heating in buildings; storing electricity, cold, heat, and hydrogen; and providing all electricity and heat with WWS. This full transition in the 53 towns and cities examined may reduce 2050 air pollution premature mortality by up to 7000 (1700-16,000)/yr, reduce global climate costs in 2050 by \$393 (221–836) billion/yr (2015 USD), save each person ~\$133/yr in energy costs, and create ~93,000 more permanent, full-time jobs than lost.

1. Introduction

Air pollution morbidity and mortality, global warming, and energy insecurity are the three most important energy-related problems affecting the world today (e.g., Smith and Michael, 2009; Bose, 2010; Asif and Muneer, 2007). Although international, national, and state policies are needed to address fully these problems, individuals and localities can help as well. Individuals and businesses can electrify their homes, offices, and industrial buildings; switch to electric heat pumps, induction cooktops, LED light bulbs, and electric transportation; weatherize buildings; reduce energy and transportation needs; and install small-scale wind (in some locations), water, or solar systems coupled with battery storage. These solutions are largely cost effective today. Decision makers in towns and cities can further incentivize these individual transitions while investing in large-scale clean, renewable electricity and storage; electric-vehicle charging infrastructure; and improved bike paths, public transit, and ride sharing.

Several previous studies have analyzed or reviewed some of the components necessary to transition cities or islands to clean, renewable energy (e.g., Agar and Renner, 2016; Calvillo et al., 2016; Park and Kwon, 2016; Bibri and Krogstie, 2017; Noorollahi et al., 2017; Newman, 2017; Dahal et al., 2018). Recently, over 65 towns and cities in the United States and over 130 international companies made commitments to transition to 100% clean, renewable energy in one or more energy sectors by between 2030 and 2050 (Sierra Club, 2018; RE100, 2018). While several localities have started to develop plans to achieve this 100% goal, no end-point roadmaps, derived with a uniform methodology, have been developed for multiple towns and cities to transition them across all energy sectors (electricity, transportation, heating/cooling, industry) to 100% clean, renewable energy.

The main purpose of this paper is to provide quantitative roadmaps for 53 towns and cities in North America (Canada, the United States, and Mexico). The ones selected are either among those that have already committed to 100% clean, renewable energy or are large or geographically diverse.

The roadmaps provide one of many possible clean, renewable energy scenarios for 2050 for each town and city and a timeline to get there. They assume that all energy sectors will be electrified, or use hydrogen produced from electricity (only for some transportation), or use direct heat. All electricity and heat will be generated with 100%

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wind, water, and sunlight (WWS). Electrification will lower energy demand. Electricity, heat, and cold will be stored; and electricity will be transmitted both short and long distances. All WWS generating technology and most all devices, machines, and appliances needed currently exist. Reaching a goal of 100% WWS will eliminate the maximum possible energy-related air pollution and greenhouse gas emissions in each town and city.

This work builds upon prior 100% WWS all-sector roadmaps for the world as a whole (e.g. Jacobson and Delucchi, 2011; Delucchi and Jacobson, 2011), the 50 U.S. states (Jacobson et al., 2015a), and 139 individual countries (Jacobson et al., 2017) as well as studies that suggest the grid can stay stable with 100% WWS (Jacobson et al., 2015b, 2018a). These studies uniformly conclude that the main barriers to transitioning are social and political rather than technical or economic. Some of these studies also discuss why technologies such as nuclear power, fossil fuels with carbon capture, and biofuels and biomass are not included in the roadmaps, namely because they have higher catastrophic risk, carbon emissions, or air pollution emissions than WWS technologies (Jacobson et al., 2011, 2017). One exception could be the capture of methane from waste and its use in a fuel cell (but not for combustion, since that increases air pollution). Although this technology is neither treated here nor necessary for low-cost energy, it should help to reduce carbon emissions that would otherwise occur from leaks.

Independent studies have also concluded that the electric grid can remain stable with 100% or near 100% renewable energy (e.g., Lund and Mathiesen, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011, 2014,2016; Connolly and Mathiesen, 2014; Mathiesen et al., 2011, 2012,2015; Elliston et al., 2012, 2013, 2014; Rasmussen et al., 2012; Steinke et al., 2013; Budischak et al., 2013; Becker et al., 2014; Child and Breyer, 2016; Bogdanov and Breyer, 2016; Aghahosseini et al., 2016; Blakers et al., 2017; Barbosa et al., 2017; Lu et al., 2017; Gulagi et al., 2017a, 2017b, 2017c). The comprehensive reviews by Brown et al. (2018) and Diesendorf and Elliston (2018) address, point by point, criticisms and concerns of such systems.

The first stage in this analysis is to estimate 2050 annually averaged power demand in a Business-as-Usual (BAU) case from contemporary demand for the 53 towns and cities, before any energy sector has been electrified. All energy sectors are then electrified, and some additional energy efficiency improvements beyond BAU are assumed. An example set of clean, renewable generators that can satisfy the resulting annual average demand (WWS case) in each town or city is then provided. Finally, the resulting energy costs, air pollution damage costs, climate costs, and job creation/loss numbers for the WWS versus BAU systems are estimated.

This study specifies mixes of WWS technologies that can satisfy *annual* average energy demand. To match demand with supply on shorter timescales (seconds, minutes, hours, etc.), energy systems need additional features, including load shifting, large-scale grid interconnections, and energy storage. Previously, we found low-cost methods for balancing total energy supply and demand at all timescales among the 48 contiguous U.S. states (Jacobson et al., 2015b) and in 20 world regions, including North America and Central America (Jacobson et al., 2018a). Because the towns and cities in this study are all within one of the regions examined in the previous studies, we believe that it is possible for the grid to remain stable if towns and cities examined here transition to 100% WWS. Although this paper does not provide *new* grid-balancing calculations, it does include the costs of storage and transmission needed for grid balancing based on Jacobson et al. (2018a).

2. Projections of 2050 BAU and WWS Demand

The first step in this study is to quantify 2050 BAU and WWS end use loads and the resulting numbers of WWS generators in each town and city. This calculation starts with contemporary end-use energy consumption data in each energy sector of each U.S. state (EIA, 2015), Canada (Statistics Canada, 2014), and Mexico (IEA, 2015). End-use energy is defined as total all-purpose primary energy minus energy lost during generation, transmission, and distribution of electricity. End-use energy includes energy for mining, transporting, and refining fossil fuels and uranium, which is accounted for in the industry sector. Electricity-system losses, which are the difference between primary and end-use energy, include the waste heat during nuclear reaction and the burning of fossil fuels to produce electricity but not the waste heat due to the burning of fossil fuels for transportation, industrial heat, or home heat. In 2015, such electrical losses in the U.S. accounted for 25.8% of all U.S. primary energy (EIA, 2015). End-use energy accounted for the remaining ~74.2% of primary energy. End-use retail electricity was ~17.8% of all end-use energy, whereas end-use retail electricity plus electricity-system losses were ~39% of total primary energy (EIA, 2015). Here, we transition end-use energy. In a 100% WWS world, end-use energy is converted entirely to electricity, lowering end-use demand significantly compared with the BAU case.

Contemporary energy use is projected in each sector to 2050 from the 2015 data for the U.S. and Mexico, and from 2014 data for Canadian provinces in a BAU scenario (Table 1), with the projections calculated as in Jacobson et al. (2015a, 2017). For the U.S., such projections use data from EIA (2017a). Future BAU estimates account for higher demand; some transition from coal to natural gas, biofuels, bioenergy, and WWS; and modest end-use energy efficiency improvements.

After all energy-consuming processes in each sector are electrified for each town and city, the resulting end-use energy required for a fully electrified all-purpose energy infrastructure is estimated (Table 1). Some end-use electricity is used to produce hydrogen for long-distance ground, ship, and air transportation. Additional modest end-use energy efficiency improvements are then assumed. Finally, the resulting power demand is supplied with a combination of WWS technologies limited by available natural WWS resources and the rooftop, land, and water areas of the state or province in which each town or city is located. Although towns and cities are part of a larger interconnected grid, the numbers of WWS generators needed to power the annual average end-use energy are calculated here as if each town or city is isolated. The cost of additional generators and storage needed to keep the larger grid stable is then estimated.

For electricity generation, this study assumes that only onshore and offshore wind turbines, rooftop and utility-scale solar photovoltaics (PV), concentrated solar power (CSP) plants, tidal and wave devices, geothermal electricity and heat plants, and hydropower plants (collectively called WWS technologies) will be used in the future. With respect to hydropower, zero new reservoirs are assumed.

Under the plans, all future devices, machines, and appliances will run directly or indirectly on WWS electricity or heat. Battery electric vehicles (BEVs) and BEV/hydrogen-fuel-cell hybrids (where the hydrogen is produced by electrolysis) will constitute all forms of transportation. BEVs will make up 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. Battery-electric/hydrogen-fuel-cell hybrids will make up all long-distance, heavy payload transportation by road, rail, water, and air. These technologies are all commercially available except for electric and hybrid electric/hydrogen-fuel-cell aircraft and ships, which are still being developed. However, companies are currently working on all-electric vertical take off and landing replacements for helicopters (Zart, 2018), all-electric commercial aircraft for short-haul flights (e.g., Ampaire, 2018; Wright Electric, 2018), and hydrogen fuel cell-electric hybrid aircraft for all-distance travel (e.g., HY4, 2018). We expect that all commercial short-haul flights will be electric by no later than the early 2030 s (Knapp and Said, 2018; Wright Electric, 2018) and long-haul flights will be

Table 1
BAU and WWS end-use energy use by sector and town or city. First line of each town or 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 line of each town or 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.

Town or city	Scen-ario	2050 Total end-use load (GW)	Resid-ential percent of total end-use load	Com-mercial per-cent of total end-use load	Indus-trial per-cent of total end-use load	Trans-port per-cent of total end-use load	(a) Percent change in end-use load w/ WWS due to higher work: energy ratio	(b) Percent change in end-use load w/WWS due to eliminating energy in mining, transporting, refining	(c) Percent change in end-use load w/ WWS due to efficiency beyond BAU	Overall percent change in end-use load with WWS
Abita Springs, LA	BAU	0.090	4.2	3.0	77.4	15.4				
	WWS	0.027	11.1	8.8	66.9	13.2	−13.7	−42.2	−14.5	−70.4
Arlington, VA	BAU	1.610	17.9	19.6	23.9	38.7				
	WWS	0.847	25.3	32.3	20.7	21.6	−31.1	−11.2	−5.1	−47.4
Aspen, CO	BAU	0.055	19.1	13.0	32.2	35.7				
	WWS	0.030	28.2	22.7	31.5	17.6	−28.4	−13.2	−4.0	−45.6
Atlanta, GA	BAU	20.887	17.1	14.0	32.2	36.7				
	WWS	9.875	26.7	25.9	24.6	22.9	−30.4	−17.7	−4.6	−52.7
Boone, NC	BAU	0.111	18.6	18.5	26.0	37.0				
	WWS	0.058	28.3	30.4	20.4	20.9	−28.9	−12.8	−6.0	−47.7
Boston, MA	BAU	9.714	22.2	22.9	14.6	40.3				
	WWS	5.632	29.5	33.3	17.2	19.9	−32.3	−7.7	−2.0	−42.0
Buffalo, NY	BAU	1.232	22.1	28.8	12.5	36.6				
	WWS	0.651	29.1	44.2	9.3	17.4	−22.6	−9.4	−15.1	−47.2
Burlington, VT	BAU	0.262	20.2	22.0	18.1	39.6				
	WWS	0.145	30.8	32.4	16.9	19.9	−29.4	−10.9	−4.2	−44.6
Calgary, CAN	BAU	6.763	8.3	5.7	66.1	19.9				
	WWS	3.705	10.7	10.2	70.2	8.8	−26.0	−17.9	−1.4	−45.2
Chicago, IL	BAU	20.890	18.0	14.6	35.2	32.1				
	WWS	9.513	25.4	28.1	28.2	18.3	−24.4	−18.0	−12.1	−54.5
Cleveland, OH	BAU	3.021	17.5	14.4	37.5	30.7				
	WWS	1.450	24.5	26.0	32.8	16.7	−24.7	−16.3	−11.0	−52.0
Columbia, MD	BAU	0.619	22.7	24.1	10.9	42.2				
	WWS	0.330	29.5	39.2	8.4	22.9	−29.7	−6.9	−10.1	−46.7
Denton, TX	BAU	5.437	19.1	13.0	32.2	35.7				
	WWS	2.955	28.2	22.7	31.5	17.6	−28.4	−13.2	−4.0	−45.6
Denver, CO	BAU	3.953	22.7	24.1	10.9	42.2				
	WWS	2.107	29.5	39.2	8.4	22.9	−29.7	−6.9	−10.1	−46.7
Des Moines, IA	BAU	0.558	10.9	10.0	57.6	21.5				
	WWS	0.220	19.8	20.1	45.6	14.5	−28.2	−33.5	1.1	−60.6
Detroit, MI	BAU	4.643	21.1	16.9	29.9	32.1				
	WWS	2.276	27.5	30.3	25.1	17.1	−26.1	−14.0	−10.9	−51.0
East Hampton, NY	BAU	0.105	22.1	28.8	12.5	36.6				
	WWS	0.055	29.1	44.2	9.3	17.4	−22.6	−9.4	−15.1	−47.2
Georgetown, TX	BAU	1.010	7.7	6.4	59.9	26.1				
	WWS	0.334	17.7	16.7	45.5	20.1	−17.4	−34.0	−15.6	−67.0
Grand Rapids, MI	BAU	1.347	21.1	16.9	29.9	32.1				
	WWS	0.660	27.5	30.3	25.1	17.1	−26.1	−14.0	−10.9	−51.0
Greensburg, KS	BAU	0.008	14.8	12.1	42.6	30.5				
	WWS	0.003	25.4	23.3	32.3	19.0	−22.4	−23.3	−12.0	−57.6
Hanover, NH	BAU	0.062	19.3	19.6	17.8	43.2				
	WWS	0.034	29.6	28.8	19.4	22.2	−34.7	−9.5	−1.4	−45.6
Honolulu, HI	BAU	5.279	4.3	12.9	21.3	61.5				
	WWS	2.279	12.3	27.5	15.8	44.4	−43.2	−14.0	0.3	−56.8
Houston, TX	BAU	37.462	7.7	6.4	59.9	26.1				
	WWS	12.370	17.7	16.7	45.5	20.1	−17.4	−34.0	−15.6	−67.0
Lancaster, NH	BAU	0.900	10.7	15.4	28.8	45.1				
	WWS	0.458	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Los Angeles, CA	BAU	22.093	10.7	15.4	28.8	45.1				
	WWS	11.239	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Madison, WI	BAU	1.872	16.8	15.2	38.5	29.5				
	WWS	0.879	24.0	28.2	31.6	16.2	−25.5	−18.0	−9.4	−53.0
Mexico City, MEX	BAU	16.830	10.2	10.2	42.6	37.0				
	WWS	7.325	17.6	18.9	41.9	21.5	−25.6	−11.9	−19.0	−56.5
Miami, FL	BAU	2.236	17.6	18.5	16.2	47.6				
	WWS	1.152	30.9	31.4	10.4	27.3	−33.1	−10.0	−5.4	−48.5
Milwaukee, WI	BAU	4.512	16.8	15.2	38.5	29.5				
	WWS	2.120	24.0	28.2	31.6	16.2	−25.5	−18.0	−9.4	−53.0
Moab, UT	BAU	0.042	16.0	13.6	29.1	41.3				

(continued on next page)

Table 1 (*continued*)

Town or city	Scen-ario	2050 Total end-use load (GW)	Resid-ential percent of total end-use load	Com-mercial per-cent of total end-use load	Indus-trial per-cent of total end-use load	Trans-port per-cent of total end-use load	(a) Percent change in end-use load w/ WWS due to higher work: energy ratio	(b) Percent change in end-use load w/WWS due to eliminating energy in mining, transporting, refining	(c) Percent change in end-use load w/ WWS due to efficiency beyond BAU	Overall percent change in end-use load with WWS
	WWS	0.021	25.3	25.7	27.6	21.4	−28.0	−15.8	−5.4	−49.1
Montreal, CAN	BAU	9.104	14.4	12.2	43.9	29.5				
	WWS	5.353	24.4	16.7	46.1	12.8	−22.3	−12.1	−6.8	−41.2
Nassau, NY	BAU	0.023	22.1	28.8	12.5	36.6				
	WWS	0.012	29.1	44.2	9.3	17.4	−22.6	−9.4	−15.1	−47.2
New Orleans, LA	BAU	47.854	4.2	3.0	77.4	15.4				
	WWS	14.158	11.1	8.8	66.9	13.2	−13.7	−42.2	−14.5	−70.4
New York City, NY	BAU	40.877	22.1	28.8	12.5	36.6				
	WWS	21.594	29.1	44.2	9.3	17.4	−22.6	−9.4	−15.1	−47.2
Oakland, CA	BAU	2.336	10.7	15.4	28.8	45.1				
	WWS	1.189	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Palo Alto, CA	BAU	0.377	10.7	15.4	28.8	45.1				
	WWS	0.192	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Philadelphia, PA	BAU	12.449	14.1	14.1	42.8	29.0				
	WWS	5.995	22.3	23.7	39.6	14.4	−21.1	−19.0	−11.7	−51.8
Phoenix, AZ	BAU	8.330	15.8	17.5	17.0	49.7				
	WWS	4.502	32.7	29.8	12.7	24.7	−29.2	−12.3	−4.5	−46.0
Portland, OR	BAU	3.747	12.8	17.3	28.9	41.0				
	WWS	2.046	24.5	29.1	22.8	23.6	−35.5	−14.3	4.4	−45.4
Pueblo, CO	BAU	0.869	19.1	13.0	32.2	35.7				
	WWS	0.473	28.2	22.7	31.5	17.6	−28.4	−13.2	−4.0	−45.6
Rochester, MN	BAU	1.001	17.0	14.6	40.3	28.2				
	WWS	0.439	27.3	27.1	28.6	17.0	−23.8	−22.4	−9.9	−56.1
San Diego, CA	BAU	7.804	10.7	15.4	28.8	45.1				
	WWS	3.970	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
San Francisco, CA	BAU	4.820	10.7	15.4	28.8	45.1				
	WWS	2.452	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
San Jose, CA	BAU	5.755	10.7	15.4	28.8	45.1				
	WWS	2.928	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Santa Monica, CA	BAU	0.522	10.7	15.4	28.8	45.1				
	WWS	0.266	19.6	27.5	25.2	27.7	−36.8	−11.9	−0.4	−49.1
Seattle, WA	BAU	4.656	11.6	16.0	30.7	41.7				
	WWS	2.378	23.6	28.7	22.0	25.7	−35.4	−18.1	4.5	−48.9
St Petersburg, FL	BAU	1.314	17.6	18.5	16.2	47.6				
	WWS	0.677	30.9	31.4	10.4	27.3	−33.1	−10.0	−5.4	−48.5
Standing Rock, ND	BAU	0.190	7.5	9.1	58.0	25.5				
	WWS	0.085	12.6	16.5	55.9	15.1	−26.7	−29.2	0.6	−55.3
Sylva, NC	BAU	0.016	18.6	18.5	26.0	37.0				
	WWS	0.008	28.3	30.4	20.4	20.9	−28.9	−12.8	−6.0	−47.7
Toronto, CAN	BAU	10.341	17.9	18.8	32.9	30.5				
	WWS	5.402	24.5	29.1	32.1	14.3	−22.7	−11.4	−13.7	−47.8
Vancouver, CAN	BAU	1.197	13.2	12.9	34.2	39.8				
	WWS	0.675	22.1	19.9	35.7	22.3	−33.5	−11.6	1.5	−43.6
Washington DC	BAU	2.151	7.7	6.4	59.9	26.1				
	WWS	0.710	17.7	16.7	45.5	20.1	−17.4	−34.0	−15.6	−67.0
Woodstock, CAN	BAU	0.208	19.8	16.1	34.3	29.8				
	WWS	0.106	25.3	27.5	32.0	15.2	−24.0	−10.6	−14.4	−49.0
All towns and cities	**BAU**	**339.54**	**13.3**	**14.0**	**39.7**	**33.0**				
	WWS	**154.36**	**22.6**	**26.4**	**31.1**	**19.9**	**−25.0**	**−19.8**	**−9.7**	**−54.5**

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 U.S. town and city starts with 2015 BAU state load data from EIA (2015). That is projected to 2050 with data from EIA (2017a), as described in Jacobson et al. (2015a), then multiplied by an estimated 2050 town- or city-to-state population ratio. The 2050 estimated population of each town and city is provided in Jacobson et al. (2018b) in the "City population projections" tab. For Mexico City, the 2015 all-Mexico annually averaged end-use load from IEA (2015) is projected to 2050 with a projection for Mexico from Jacobson et al. (2017) and multiplied by the Mexico City-to-all Mexico population ratio. The load reductions due to electrification are calculated by fuel type in each sector as in Jacobson et al. (2015a, 2017). For Canadian towns and cities, the Canadian province BAU annually averaged end-use load for 2014 from Statistics Canada (2014) is projected to 2050 with a projection for Canada from Jacobson et al. (2017) and multiplied by the city-to-province CO_2 ratio.

hydrogen fuel cell-electric hybrids by 2035–2040. In addition, electric ferries have already been built that reduce operating costs by 80% due to their efficiency and many other types of electric ships are currently being built (e.g., Hockenos, 2018).

Hydrogen fuel cells are not proposed here for electricity generation due to their relative inefficiency and high cost for this application.

In a future WWS world, air and water heating will be powered primarily by air-source heat pumps in mild climates, ground-source

Table 2
Number, nameplate capacity, footprint area, and spacing area of WWS power plants or devices needed to meet total annually averaged end-use all-purpose load, summed over the 53 towns and cities considered.

Energy Technology	Nameplate capacity of one plant or device (MW)	[a]Percent of 2050 all-purpose load met by plant/ device	Nameplate capacity, existing plus new plants or devices (GW)	Percent of name-plate capacity already installed 2016	Number of new plants or devices needed for 53 towns and cities	[b]Percent of all-cities land or roof area for footprint of new plants or devices	Percent of all-cities area for spacing of new plants or devices
Annual average power							
Onshore wind	5	22.10	127,374	8.40	23,335		0.00
Offshore wind	5	22.68	88,944	0.00	17,789		0.00
Wave device	0.75	0.50	3,521	0.00	4,695		0.01
Geothermal plant	100	1.77	3,217	15.61	27		0.03
Hydropower plant[c]	1300	4.37	13,193	327.68	0		0.00
Tidal turbine	1	0.16	992	0.00	992		0.00
Res. roof PV	0.005	7.19	62,039	3.17	12,014,840		1.68
Com/gov roof PV [d]	0.1	6.39	49,650	1.98	486,674		1.36
Solar PV plant[d]	50	27.58	212,149	0.46	4,223		5.89
Utility CSP plant [d]	100	7.24	24,372	0.00	244		4.51
Total for average power		**100.00**	**585,451**	**9.97**			**13.49**
New land average power[e]							10.40

All values are summed over 53 towns and cities. Annual average power is total annual energy divided by the number of hours per year.
[a] Total end-use load in 2050 with 100% WWS is from Table 1.
[b] The all-cities land area is 26,802 km^2.
[c] The average capacity factors of hydropower plants are assumed to be 54.4%.
[d] The solar PV panels used for this calculation are Sun Power E20 panels. For footprint calculations alone, the CSP mirror sizes are set to those at Ivanpah. CSP is assumed to have storage with a maximum charge to discharge rate (storage size to generator size ratio) of 2.61:1 (Jacobson et al., 2015b). For utility solar PV plants, "spacing" between panels is included in the plant footprint area.
[e] The footprint area requiring new land equals the sum of the footprint areas for new onshore wind, geothermal, hydropower, and utility solar PV. Offshore wind, wave and tidal generators are in water and thus do not require new land. Similarly, rooftop solar PV does not use new land because the rooftops already exist. Only onshore wind requires new land for spacing area. Spacing area is for onshore and offshore wind is calculated as $44D^2$, where D = rotor diameter. The 5-MW Senvion (RePower) turbine is assumed here, where D = 126 m. The other energy sources are either in water or on rooftops, or do not use new land, so they do not require spacing area. Note that the spacing area for onshore wind can be used for multiple purposes, such as open space, agriculture, grazing, etc.

heat pumps in more extreme hot and/or cold climates, and direct or stored solar or geothermal heat. Similarly, air conditioning and refrigeration will be powered by heat pumps and cold energy storage. Cooktops will use electric induction. Electric induction furnaces, dielectric heaters, and arc furnaces will be used for high-temperature industrial heat.

Table 1 provides the resulting town and city BAU and WWS end-use power demand (load) in 2050. Town and city loads are obtained by scaling 2050 U.S. state and total Mexico end-use loads by city-to-state and city-to-country population ratios, respectively. Canadian town or city loads are obtained by scaling Canadian province loads by city-to-province CO_2 emissions. Canadian cities are scaled by CO_2 rather than population because of the relatively large population of Calgary relative to Alberta province, for example, would overestimate Calgary's load since it would not account for the substantial load used in the low-populated tar sands energy extraction region of Alberta.

In the WWS case, all end uses directly use WWS power, with one exception: some transportation uses hydrogen produced from WWS electricity for fuel cells. Here, ~8.9% of all 2050 WWS energy (47.8% of transportation energy) is used for the production, storage, and use of hydrogen.

In 2015, the 53 town and city all-purpose, end-use load was ~303 G W (2654 TW h/yr). 52.4 GW (17.3%) of this was the 53 town and city electricity load. Under BAU, the all-purpose end-use load is estimated to increase to 339.5 GW in 2050 (Table 1). This modest demand growth is less than the population growth because of assumed energy efficiency improvements in North America in the BAU case. A move to 100% WWS by 2050 reduces the 53-city end-use load by ~54.5%, down to 154.4 GW (1353 TW h) (Table 1), with the largest percentage reduction in transportation, followed by the industrial, residential, and commercial sectors, respectively.

With WWS, electricity use increases but conventional (non-WWS) fuel use decreases far more and down to zero because (a) electricity and electrolytic hydrogen have a higher energy-to-work conversion efficiency than do fossil fuels (accounting for ~25 percentage points of the overall net energy reduction due to WWS); (b) the use of WWS eliminates the energy needed to mine, transport, and refine coal, oil, gas, biofuels, bioenergy, and uranium (~19.8 percentage points); and (c) modest policy-driven energy efficiency measures are assumed to reduce demand another ~9.7 percentage points beyond those under BAU (Table 1). Most of the greater energy-to-work efficiency of electricity occurs in the transportation sector due to the fact that charging and driving an electric car versus driving a gasoline car reduces end-use energy by 65–75% due to the much greater heat (thus energy) loss in an internal combustion engine than in an electric motor. Because other appliances and sectors do not see such a large benefit, the average across all sectors is ~25%.

The reductions in Table 1 may be minimum numbers because they conservatively assume the use of electric resistance to replace fossil fuels and wood for air and water heating in buildings, and they assume standard electric air conditioners and refrigeration for cooling. However, energy demand can be reduced much further with heat pumps for air and domestic water heating, air conditioning, and refrigeration. Air source heat pumps have a coefficient of performance (CP) of 3.2–4.5, whereas ground source heat pumps have a CP of 4.2–5.2 (Fischer and Madani, 2017). This compares with electric resistance heaters, which have a CP ~ 1 and fossil-fuel-powered boilers, which have a typical CP < 1. Since, only 1 J (J) of electricity is therefore needed to move 3.2–5.2 J of hot or cold air with a heat pump, heat pumps reduce power demand compared with other electric resistance heaters or boilers and

Table 3
Percent of the annually averaged 2050 town- or city-specific all-purpose end-use WWS load (not nameplate capacity) in Table 1 to be met with the given electric power generator. All rows add up to 100%.

Town or city	On-shore wind	Offshore wind	Wave	Geo-thermal	Hydro-electric	Tidal	Res PV	Com/ gov PV	Utility PV	CSP
Abita Springs, LA	0.65	60.00	0.40	0.00	0.11	0.00	2.00	2.00	29.84	5.00
Arlington, VA	10.00	50.00	0.50	0.00	1.29	0.05	5.00	4.50	23.66	5.00
Aspen, CO	45.00	0.00	0.00	3.00	1.24	0.00	7.70	7.20	20.86	15.00
Atlanta, GA	5.00	25.00	0.30	0.00	2.27	0.08	3.70	3.00	45.65	15.00
Boone, NC	5.00	50.00	0.75	0.00	2.69	0.03	9.00	7.00	20.53	5.00
Boston, MA	13.00	55.00	1.00	0.00	1.42	0.06	1.30	1.20	27.02	0.00
Buffalo, NY	10.00	36.00	0.80	0.00	6.54	0.10	2.00	1.90	42.66	0.00
Burlington, VT	25.00	0.00	0.00	0.00	64.35	0.00	4.50	3.50	2.65	0.00
Calgary, CAN	35.00	0.00	0.00	9.00	19.15	0.00	4.00	4.00	18.85	10.00
Chicago, IL	60.00	5.00	0.00	0.00	0.03	0.00	2.85	2.90	26.22	3.00
Cleveland, OH	45.00	10.00	0.00	0.00	0.10	0.00	6.20	6.00	29.70	3.00
Columbia, MD	5.00	60.00	1.00	0.00	1.53	0.03	5.40	4.80	22.24	0.00
Denton, TX	50.00	13.90	0.10	0.50	0.16	0.00	8.00	7.00	6.34	14.00
Denver, CO	45.00	0.00	0.00	3.00	1.24	0.00	7.70	7.20	20.86	15.00
Des Moines, IA	68.00	0.00	0.00	0.00	0.25	0.00	5.00	5.00	18.75	3.00
Detroit, MI	40.00	31.00	1.00	0.00	0.69	0.00	3.50	3.20	18.61	2.00
East Hampton, NY	10.00	36.00	0.80	0.00	6.54	0.10	2.00	1.90	42.66	0.00
Georgetown, TX	50.00	13.90	0.10	0.50	0.16	0.00	8.00	7.00	6.34	14.00
Grand Rapids, MI	40.00	31.00	1.00	0.00	0.69	0.00	3.50	3.20	18.61	2.00
Greensburg, KS	60.00	0.00	0.00	0.00	0.01	0.00	4.30	4.00	21.69	10.00
Hanover, NH	40.00	20.00	1.00	0.00	6.48	0.50	4.50	3.30	24.22	0.00
Honolulu, HI	12.00	16.00	1.00	30.00	0.33	1.00	14.00	9.00	9.67	7.00
Houston, TX	50.00	13.90	0.10	0.50	0.16	0.00	8.00	7.00	6.34	14.00
Lancaster, NH	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Los Angeles, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Madison, WI	45.00	30.00	0.00	0.00	0.96	0.00	5.00	4.00	13.04	2.00
Mexico City, MEX	19.16	15.97	0.71	2.20	2.94	0.01	25.00	25.00	4.22	4.79
Miami, FL	5.00	8.00	1.00	0.00	0.05	0.04	23.00	18.00	34.91	10.00
Milwaukee, WI	45.00	30.00	0.00	0.00	0.96	0.00	5.00	4.00	13.04	2.00
Moab, UT	40.00	0.00	0.00	8.00	1.03	0.00	9.00	9.00	17.97	15.00
Montreal, CAN	10.00	36.00	0.80	0.00	6.54	0.10	6.50	6.00	34.06	0.00
Nassau, NY	10.00	36.00	0.80	0.00	6.54	0.10	2.00	1.90	42.66	0.00
New Orleans, LA	0.65	60.00	0.40	0.00	0.11	0.00	2.00	2.00	29.84	5.00
New York City, NY	10.00	36.00	0.80	0.00	6.54	0.10	2.00	1.90	42.66	0.00
Oakland, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Palo Alto, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Philadelphia, PA	20.00	3.00	1.00	0.00	0.74	0.85	2.70	2.00	69.71	0.00
Phoenix, AZ	18.91	0.00	0.00	2.00	6.49	0.00	12.50	18.00	12.10	30.00
Portland, OR	32.50	15.00	1.00	5.00	27.25	0.05	6.00	5.00	3.20	5.00
Pueblo, CO	45.00	0.00	0.00	3.00	1.24	0.00	7.70	7.20	20.86	15.00
Rochester, MN	60.00	19.00	0.00	0.00	3.61	0.00	2.50	3.00	9.89	2.00
San Diego, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
San Francisco, CA	17.00	8.00	0.50	5.00	4.48	0.50	7.30	5.60	36.62	15.00
San Jose, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Santa Monica, CA	17.00	8.00	0.50	5.00	4.48	0.50	14.00	10.00	25.52	15.00
Seattle, WA	35.00	13.00	0.50	0.65	35.42	0.30	4.00	3.00	8.13	0.00
St Petersburg, FL	5.00	8.00	1.00	0.00	0.05	0.04	23.00	18.00	34.91	10.00
Standing Rock, ND	55.00	0.00	0.00	0.00	2.95	0.00	1.00	1.00	35.05	5.00
Sylva, NC	5.00	50.00	0.75	0.00	2.69	0.03	9.00	7.00	20.53	5.00
Toronto, CAN	20.00	20.00	0.80	0.00	6.54	0.10	12.00	12.00	28.56	0.00
Vancouver, CAN	30.00	8.00	0.50	0.65	35.42	0.30	8.00	8.00	9.13	0.00
Washington DC	5.00	60.00	1.00	0.00	1.53	0.03	5.40	4.80	22.24	0.00
Woodstock, CAN	40.00	31.00	1.00	0.00	0.69	0.00	6.00	5.00	14.31	2.00
All towns and cities	**22.10**	**22.68**	**0.50**	**1.77**	**4.37**	**0.16**	**7.19**	**6.39**	**27.58**	**7.24**

cooling appliances by 69–81% (2.2–4.2 J). The use of heat pumps for all air and water heating, air conditioning, and refrigeration worldwide is estimated to reduce world all-purpose end-use power demand by an additional ~15% (Jacobson et al., 2018a). These additional savings are applicable here; however, to be conservative, they are not included in the numbers in Table 1.

3. Numbers of Electric Generators and Land Requirements

Given the end-use loads for each town and city (Table 1), the nameplate capacities of each WWS generator type (Table 2), the estimated mixes of WWS generators for each town and city (Table 3), capacity factors, and transmission/distribution losses, we estimate the numbers of each WWS generator type needed to power each town and city in 2050 for all energy purposes in the annual average. The capacity factors, provided in Jacobson et al. (2018b), are based on state data or country data that the town or city resides in, and account for competition among wind turbines for limited kinetic energy (array losses).

Table 2 provides the mix of generators summed across all towns and cities and additional statistics. The numbers conservatively assume that all generators produce power only for the town and cities considered, and that no power in the annual average is obtained from any other source. In reality, towns and cities will be part of a regional grid.

Utility-scale and rooftop PV can operate in any town or city, even if exposed to lots of cloud cover, because they can take advantage of both direct and diffuse sunlight and can optimize tilt angle (for rooftop PV) or tracking (for utility PV) (e.g., Jacobson and Jadhav, 2018). Whereas, utility PV is limited by available land or water area in a state or

Table 4
Rooftop areas suitable for PV panels, potential nameplate capacities of suitable rooftop areas, and proposed nameplate capacities for both residential and commercial/government buildings by town or city.

Town or city	Residential rooftop PV				Commercial/government rooftop PV			
	Rooftop area suitable for PV in 2012 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)	Proposed nameplate capacity in 2050 ($MW_{dc-peak}$)	Percent of potential capacity to be installed	Rooftop area suitable for PV in 2012 (km^2)	Potential nameplate capacity of suitable area in 2050 ($MW_{dc-peak}$)	Proposed nameplate capacity in 2050 ($MW_{dc-peak}$)	Percent of potential capacity to be installed
Abita Springs, LA	0.03	5	3	59	0.02	4	3	63
Arlington, VA	2.39	472	277	59	1.78	358	224	63
Aspen, CO	0.06	14	13	92	0.05	12	11	91
Atlanta, GA	10.13	2,397	2,218	93	7.16	1,717	1,612	94
Boone, NC	0.22	51	34	67	0.14	33	24	73
Boston, MA	4.04	590	515	87	3.20	478	426	89
Buffalo, NY	5.27	642	95	15	4.30	540	81	15
Burlington, VT	0.40	60	49	82	0.24	36	34	93
Calgary, CAN	18.88	3,055	1,125	37	13.29	2,194	1,009	46
Chicago, IL	14.62	2,165	1,875	87	13.91	2,108	1,711	81
Cleveland, OH	5.19	752	631	84	4.48	665	548	82
Columbia, MD	1.07	204	121	59	0.86	168	96	57
Denton, TX	1.28	373	316	85	1.04	303	248	82
Denver, CO	7.16	1,641	1,295	79	5.95	1,384	1,086	78
Des Moines, IA	2.84	403	73	18	2.67	387	65	17
Detroit, MI	6.74	961	565	59	5.71	833	463	56
East Hampton, NY	0.07	8	7	86	0.05	7	6	87
Georgetown, TX	0.60	175	150	85	0.49	142	117	82
Grand Rapids, MI	3.43	489	160	33	2.91	424	131	31
Greensburg, KS	0.01	1	1	56	0.01	1	1	52
Hanover, NH	0.12	21	11	52	0.08	14	7	50
Honolulu, HI	5.91	1,516	1,406	93	3.48	907	810	89
Houston, TX	50.82	14,781	5,831	39	41.00	12,014	4,575	38
Lancaster, NH	1.39	343	308	90	0.91	228	198	87
Los Angeles, CA	38.66	9,564	7,576	79	25.38	6,364	4,853	76
Madison, WI	3.98	622	304	49	3.23	515	218	42
Mexico City, MEX	68.63	19,960	8,736	44	55.36	16,223	7,834	48
Miami, FL	6.94	2,603	1,442	55	4.49	1,688	1,012	60
Milwaukee, WI	6.26	979	726	74	5.08	811	521	64
Moab, UT	0.11	31	10	33	0.10	28	9	33
Montreal, CAN	40.78	4,970	2,577	52	33.31	4,180	2,133	51
Nassau, NY	0.04	5	2	35	0.03	4	1	36
New Orleans, LA	15.41	2,817	1,681	60	12.67	2,373	1,507	64
New York City, NY	27.42	3,342	2,957	88	22.40	2,811	2,519	90
Oakland, CA	4.52	1,119	948	85	2.97	744	607	82
Palo Alto, CA	1.06	262	153	58	0.70	175	98	56
Philadelphia, PA	8.82	1,220	1,086	89	5.68	802	721	90
Phoenix, AZ	6.11	3,038	2,747	90	40.45	20,035	3,547	18
Portland, OR	11.43	2,258	901	40	5.67	1,138	673	59
Pueblo, CO	1.82	418	201	48	1.51	353	168	48
Rochester, MN	1.57	276	77	28	1.62	290	83	28
San Diego, CA	18.80	4,650	2,857	61	12.34	3,094	1,830	59
San Francisco, CA	4.55	1,126	1,019	91	2.99	749	701	94
San Jose, CA	13.52	3,345	2,102	63	8.88	2,226	1,347	60
Santa Monica, CA	1.12	276	179	65	0.73	184	115	62
Seattle, WA	7.54	1,438	739	51	3.80	735	497	68
St Petersburg, FL	5.60	2,102	772	37	3.63	1,363	542	40
Standing Rock, ND	0.08	11	6	53	0.08	10	5	48
Sylva, NC	0.03	7	5	65	0.02	5	3	71
Toronto, CAN	61.70	7,520	4,705	63	50.41	6,325	4,219	67
Vancouver, CAN	18.75	3,578	408	11	9.46	1,829	366	20
Washington DC	6.81	1,301	744	57	5.52	1,073	593	55
Woodstock, CAN	0.44	62	46	73	0.37	54	34	63
All towns and cities	**525**	**110,020**	**62,783**	**57.06**	**433**	**101,141**	**50,243**	**49.68**

province, rooftop PV is limited by rooftop area and elevated canopy area. Table 4 provides estimated 2050 town and city rooftop areas, potential PV nameplate capacity, and proposed nameplate capacity. Rooftop PV area includes elevated canopy areas above parking lots, highways, and structures, in addition to existing rooftop areas. Rooftop areas are derived largely from satellite data (Google, 2017) for most towns and cities and by scaling state rooftop areas from Jacobson et al. (2015a) to city areas by population for the rest. The rooftop PV potential summed over all 53 towns and cities in 2050 is 62.8 $GW_{dc-peak}$ of nameplate capacity for residential (including garages and carports), of

Table 5
Approximate fully annualized, unsubsidized 2050 baseline costs of delivered electricity, including generation costs, short- and long-distance transmission costs, distribution costs, operation and maintenance costs, decommissioning costs, and the costs of storage and additional generators required to keep the grid stable (2015 U.S. $/kWh-delivered). External costs of air pollution and climate change are not included here. These 2050 baseline costs are adjusted by state and region (Jacobson et al., 2018b) to obtain town and city costs.

Technology	Technology year 2050		
	LCHB	*HCLB*	*Average*
Geothermal	0.096	0.130	0.113
Hydropower	0.068	0.090	0.079
On-shore wind	0.077	0.101	0.089
Off-shore wind	0.107	0.178	0.142
CSP no storage	0.152	0.264	0.208
CSP with storage	0.075	0.105	0.090
PV utility crystalline tracking	0.073	0.091	0.082
PV utility crystalline fixed	0.082	0.110	0.096
PV utility thin-film tracking	0.072	0.090	0.081
PV utility thin-film fixed	0.082	0.110	0.096
PV commercial rooftop	0.082	0.115	0.098
PV residential rooftop	0.093	0.135	0.114
Wave power	0.151	0.386	0.268
Tidal power	0.094	0.195	0.145
Solar thermal for heat ($/kWh-th)	0.065	0.078	0.071

Jacobson et al. (2018b) provide a full derivation of these costs. LCHB = low cost, high benefits case; HCLB = high cost, low benefits case.
The baseline total costs in this table account for overnight capital costs; changes in capital costs over time; fixed and variable operation and maintenance (O&M) costs; changes in O&M costs over time; decommissioning costs; build times; facility lifetimes; fleet-averaged capacity factors; degradation of capacity factors over time; changes in resource availability over time; technology performance change over time; short-and long-distance transmission costs; distribution costs; and the cost of electricity, heat, cold, and hydrogen storage to keep the grid stable. Mean values of most of these variables are provided in the footnote to Table 6. Jacobson et al. (2018b, 'Cost of delivered electricity' tab) contains the full details of the calculations.
The costs assume a discount rate of 2.0 (1–3)%, which is a social discount rate for a social cost analysis of an intergenerational project, as discussed extensively in Jacobson et al. (2017) and references therein.
Baseline costs in this table are adjusted by state and region (Jacobson et al., 2015b) to obtain town and city costs in Table 6.
CSP w/storage assumes a maximum charge rate of solar collectors to discharge rate of 2.61:1. Thus, for example, for a 100 MW CSP plant, the peak charge rate is 261 MW of which 100 MW can be discharged immediately through the turbine and the remainder is stored as high-temperature heat in a phase-change material or molten nitrate salt.
Solar thermal for heat assumes $3,600-$4000 per 3.716 m^2 collector and 0.7 kW-th/m^2 maximum power.

which 57.1% is proposed for use, and 50.2 GW$_{\text{dc-peak}}$ for commercial/government (including canopies over parking lots and over parking structures), of which 49.7% is proposed for use.

CSP is viable only where significant direct sunlight exists. Thus, CSP penetration is limited to several towns and cities exposed to high solar radiation. Onshore wind is available in every U.S. state, Canadian province, and in Mexico, but is assumed here to make up a large portion of supply primarily in towns and cities near good wind resources and sufficient land. Offshore wind, wave, and tidal power are assumed to be prevalent only in the towns and cities located in states or provinces with ocean or lake coastline, as in Jacobson et al. (2015a; 2017).

The installed capacity of hydropower equals either the nameplate capacity of turbines or the practically determined capacity, which is the maximum possible annual average power output when limited by water availability in a reservoir (Business Dictionary, 2017; McGraw Hill Dictionary of Scientific and Technical Terms, 6E, 2003). We assume the 2050 installed capacities in each U.S. state, Canada, and Mexico equal the nameplate capacities in 2015. Thus, no additional hydropower turbines are added to any reservoir for the results in Table 2. The installed hydropower capacity apportioned to each town or city is determined from the hydropower annual energy used in each city (calculated as the product of end use demand from Table 1 and the fraction of demand satisfied by hydropower from Table 3), divided by the hydropower capacity factor for each state or country the town or city resides in, determined from Jacobson et al. (2015a, 2017). Geothermal, tidal, and wave power are similarly limited by each state's or country's technical potentials, as determined from Jacobson et al. (2015a, 2017).

The numbers of generators proposed in Table 2 were estimated for meeting annually averaged end use load. We discuss additional generators and storage devices needed to keep the grid stable during the year in Section 4. Table 2 indicates that almost 10% of the 2050 nameplate capacity required for a 100% all-purpose WWS system among the 53 towns and cities was already installed as of 2016 end.

The land or water area required for an energy system is a factor that affects whether the system has a reasonable chance of being implemented. Two metrics of area are footprint and spacing area. Footprint is the physical area on the top surface of soil or water needed for each energy device. New land footprint includes the land required for utility-scale solar PV and CSP plants and the tower areas touching the topsoil of wind turbines, but it excludes rooftop areas for PV or any offshore water areas. The new land footprint required for the 53 towns and cities is ~10.4% of the total town plus city land area (Table 2), mostly from utility PV. However, most of that footprint will be located outside of the towns and cities. The footprint area does not account for the decrease in footprint area from eliminating the current energy infrastructure, which includes space for the continuous mining, transporting, and refining of fossil fuels and uranium and for the growing, transporting, and refining of crops for biofuels. WWS has no direct footprint associated with mining fuels, but both WWS and BAU energy infrastructures require one-time mining for raw materials for new plus repaired equipment construction.

Spacing is the area between wind, tidal, and wave turbines. It is needed to minimize interference of the wake of one turbine with other turbines downstream. Spacing area can be used for multiple purposes. Onshore wind turbines proposed here will require spacing that equates to ~38.7% of the 53 town and city land area, but almost all wind turbines will be located outside of the towns or cities.

4. Energy Costs

Here, the social costs of a WWS versus a BAU system are estimated. The social cost of energy, as calculated here, includes direct energy, health, and climate costs. Some additional social costs not quantified here, 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, and costs of road repair due to road transport of fossil fuel mining equipment and the fuels themselves.

Direct energy costs account for capital, land, operating, maintenance, fuel, short- and long-distance transmission, distribution, and decommissioning costs. Table 5 provides estimated North American baseline costs of energy for each energy-producing technology proposed in 2050. The baseline values are adjusted by state and region to estimate LCOEs for each town and city (see Jacobson et al., 2018b, for details). The costs in Table 5 also include the estimated costs of electricity, heat, cold, and hydrogen storage; additional CSP generators; and solar thermal collectors required to keep the grid stable, as quantified shortly.

The 2050 WWS system has a total capital cost for generators of annual average power among the 53 towns and cities of ~$1.33 trillion for the 557 GW of new nameplate capacity needed (~$2.38 million/MW). However, the fuel cost of WWS is zero, whereas that of BAU fuels is not. The levelized cost of energy (LCOE) is used to account for these factors as well as for operation, maintenance, transmission,

Table 6
Mean values of the levelized cost of energy (LCOE) for the BAU retail electricity sector in 2015 and 2050 and for WWS in all energy sectors (which are all electrified) in 2050. The 2050 BAU and WWS LCOEs are used to calculate energy cost savings per person per year in each town or city due to switching from BAU to WWS in the BAU electricity sector only (see footnotes).

Town or city	(a) 2015 LCOE of BAU elec-tricity (¢/kWh-elec-tricity)	(b) 2050 LCOE of BAU elec-tricity (¢/kWh-elec-tricity)	(c) 2050 LCOE of WWS (¢/kWh-all-energy)	(d) 2050 Average cost savings in BAU retail electricity sector in town or city due to switching to WWS electricity ($/per-son/yr)	(e) 2050 Average air pollution damage cost savings to town or city due to switching all sectors in city to WWS ($/person/yr)	(f) 2050 Average climate cost savings to world due to switching all sectors in town or city to WWS ($/person/yr)	(g) 2050 Average electricity + town or city health + world climate cost savings due to switching to WWS ($/person/yr)
Abita Springs, LA	10.3	10.5	12.8	176	1,270	30,574	32,019
Arlington, VA	10.4	10.3	11.9	−36	1,276	5,917	7,156
Aspen, CO	9.2	12.9	9.0	433	1,050	8,005	9,488
Atlanta, GA	10.6	10.4	9.6	268	1,594	6,519	8,381
Boone, NC	10.4	10.3	12.1	−46	1,343	5,154	6,451
Boston, MA	11.4	11.8	12.5	54	1,167	5,264	6,485
Buffalo, NY	13.0	12.2	11.7	106	1,188	4,875	6,168
Burlington, VT	11.4	11.8	8.6	325	738	5,367	6,431
Calgary, CAN	8.5	9.8	10.2	99	1,833	6,454	8,386
Chicago, IL	9.5	9.7	12.6	−17	1,820	9,631	11,434
Cleveland, OH	10.0	10.4	9.5	433	1,864	11,270	13,567
Columbia, MD	11.0	10.8	12.6	−31	1,754	5,103	6,827
Denton, TX	9.9	11.2	11.4	266	1,288	9,969	11,522
Denver, CO	9.2	12.9	9.0	433	1,050	8,005	9,488
Des Moines, IA	8.9	11.6	10.2	753	1,291	15,729	17,773
Detroit, MI	10.0	11.4	11.7	239	1,302	9,974	11,514
East Hampton, NY	13.0	12.2	11.7	154	1,188	4,875	6,216
Georgetown, TX	9.9	11.2	11.4	266	1,288	9,969	11,522
Grand Rapids, MI	10.0	11.4	11.7	239	1,302	9,974	11,514
Greensburg, KS	9.1	11.5	12.5	197	978	12,240	13,415
Hanover, NH	11.4	11.8	10.1	174	983	5,383	6,540
Honolulu, HI	20.6	29.9	11.2	1,381	1,045	8,574	11,000
Houston, TX	9.9	11.2	11.4	266	1,288	9,969	11,522
Lancaster, NH	11.4	12.1	11.0	85	2,545	5,055	7,685
Los Angeles, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
Madison, WI	9.7	11.5	11.1	360	1,217	9,748	11,325
Mexico City, MEX	9.9	11.2	11.8	76	639	2,895	3,611
Miami, FL	11.8	11.2	10.2	149	1,118	3,925	5,192
Milwaukee, WI	9.7	11.5	11.1	360	1,217	9,748	11,325
Moab, UT	8.5	9.8	10.0	67	1,667	8,445	10,178
Montreal, CAN	13.0	12.2	11.9	143	557	1,704	2,404
Nassau, NY	13.0	12.2	11.7	154	1,188	4,875	6,216
New Orleans, LA	10.3	10.5	12.8	176	1,270	30,574	32,019
New York City, NY	13.0	12.2	11.7	154	1,188	4,875	6,216
Oakland, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
Palo Alto, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
Philadelphia, PA	11.0	10.8	10.2	226	1,775	10,457	12,459
Phoenix, AZ	10.2	11.3	11.0	25	1,883	4,294	6,202
Portland, OR	8.5	9.8	10.1	13	909	4,585	5,507
Pueblo, CO	9.2	12.9	9.0	433	1,050	8,005	9,488
Rochester, MN	8.9	11.6	10.5	398	979	7,885	9,262
San Diego, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
San Francisco, CA	11.4	12.1	10.7	101	2,545	5,055	7,700
San Jose, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
Santa Monica, CA	11.4	12.1	11.0	85	2,545	5,055	7,685
Seattle, WA	8.5	9.8	11.4	−80	965	4,687	5,572
St Petersburg, FL	11.8	11.2	10.2	149	1,118	3,925	5,192
Standing Rock, ND	8.9	11.6	8.7	1,594	608	51,411	53,613
Sylva, NC	10.4	10.3	12.1	−46	1,343	5,154	6,451
Toronto, CAN	13.0	12.2	11.4	57	522	1,597	2,176
Vancouver, CAN	8.5	9.8	11.5	4	162	635	800
Washington DC	11.0	10.8	12.6	−31	1,754	5,103	6,827
Woodstock, CAN	10.0	11.4	11.8	238	3,158	6,206	9,602

(*continued on next page*)

Table 6 (*continued*)

Town or city	(a) 2015 LCOE of BAU elec-tricity (¢/kWh-elec-tricity)	(b) 2050 LCOE of BAU elec-tricity (¢/kWh-elec-tricity)	(c) 2050 LCOE of WWS (¢/kWh-all-energy)	(d) 2050 Average cost savings in BAU retail electricity sector in town or city due to switching to WWS electricity ($/per-son/yr)	(e) 2050 Average air pollution damage cost savings to town or city due to switching all sectors in city to WWS ($/person/yr)	(f) 2050 Average climate cost savings to world due to switching all sectors in town or city to WWS ($/person/yr)	(g) 2050 Average electricity + town or city health + world climate cost savings due to switching to WWS ($/person/yr)
All towns and cities	**11.0**	**11.59**	**11.35**	**133**	**1,261**	**5,315**	**6,709**

All costs are in 2015 USD.
a) The 2015 LCOE cost of retail electricity in the BAU case in each town or city combines the percentage mix of conventional electricity generators in 2015 with 2015 mean LCOEs for each BAU generator from Jacobson et al. (2018b). Such BAU costs include all-distance transmission, distribution, and pipeline costs, but they exclude health and climate costs.
b) Same as (a), but for the 2050 BAU case and using 2050 LCOEs for each generator as derived in Jacobson et al. (2018b). The 2050 BAU case includes some existing WWS (mostly hydropower) plus future increases in WWS electricity in the BAU case, and energy efficiency measures. The cost of keeping the grid stable in the BAU case is conservatively assumed to be made possible by BAU generators, thus accounted for in the BAU costs.
c) The 2050 LCOE of WWS in the town or city combines the 2050 mix of WWS generators among all energy sectors from Table 3 with the 2050 mean LCOEs for each WWS generator from Table 5 and with a regional adjustment for initial costs and capacity factor for each technology. The 2050 baseline WWS capital cost before regional variations in initial cost and capacity factor are accounted for is $0.0285/kWh-delivered in 2015 USD. This includes CapEx for life extension and decommissioning. The fleet-averaged variable and fixed operation and maintenance (O&M) costs are $0.0051 and $0.0132/kWh-delivered, respectively. The fleet-averaged transmission and distribution costs assumed in 2050 are as follows: Short-distance transmission, $0.0117/kWh-delivered; long-distance transmission, $0.0044/kWh-delivered; and distribution, $0.026/kWh-delivered. No transmission costs are included for rooftop solar PV. Transmission and distribution losses are accounted for in the calculation of delivered energy. The 2050 fleet-averaged cost to keep the grid stable of electricity, heat, cold, and hydrogen storage; additional CSP generators; and solar thermal collectors, are estimated as a mean of $0.0139 kW h-delivered in 2015 USD, as quantified in the text. This cost is applied equally to each generator in the present table. The sum of above costs is $0.1029/kWh-delivered. The difference between that and the $0.1135/kWh-delivered is due to regional variations in initial cost and capacity factor in each town or city relative to the baseline cost.
d) The 2050 average cost savings per capita per year due to switching from BAU to WWS retail electricity is calculated as the cost of electricity use in the electricity sector in the BAU case (the product of BAU electricity use and the 2050 BAU LCOE) less the annualized cost of the assumed efficiency improvements in the WWS case beyond BAU improvements and less the total cost of BAU retail electricity converted to WWS (product of WWS electricity use replacing BAU electricity and the 2050 WWS LCOE), all divided by 2050 population. (See Jacobson et al., 2018b for details.).
e) This equals the total air pollution cost per year for the town or city from Table 7 divided by the 2050 town or city population.
f) This equals the total climate cost per year to the world due to the town or city's emissions from Table 8 divided by the 2050 town or city population.
g) The sum of columns (d), (e), and (f).

distribution, decommissioning, and storage/grid stability costs.

In the BAU case, the 2050 mean LCOE (weighted among all electricity generators and towns and cities) to satisfy annual average power while keeping the grid stable was ~11.59 ¢/kWh-BAU-electricity (2015 USD) (Table 6).

In the WWS case, the 2050 mean LCOE, excluding costs of keeping the grid stable, was ~9.96 ¢/kWh-WWS-all-energy (2015 USD). The additional 2050 cost of keeping the grid stable was estimated to be a mean of ~1.39 ¢/kWh-WWS-all-energy (2015 USD) for a total WWS business cost of 11.35 ¢/kWh-WWS-all-energy (Table 6), which is less than the 2050 BAU LCOE. The additional grid stability cost in the WWS case is estimated from the data in Table S9 of Jacobson et al. (2018a), averaged over all three storage scenarios (Cases A–C) for North America, as follows (in 2013 USD): 0.42 ¢/kWh-WWS-all-energy for additional CSP plants for satisfying peaks; 0.079 ¢/kWh-WWS-all-energy for additional solar thermal collectors, and 0.85¢/kWh-WWS-all-energy for all costs of storage, including pumped hydropower (in all 3 cases in Jacobson et al., 2018a), batteries (2 cases); added hydropower turbines (1 case); phase-change material storage for CSP (3 cases); chilled water storage (2 cases); ice storage (2 cases); hot water storage (2 cases); underground thermal energy storage in rocks (2 cases); and hydrogen production, compression, and storage (3 cases). These costs were adjusted to 2015 USD.

The resulting 2050 savings in business cost just due to switching BAU retail electricity sector electricity to WWS was ~$133/yr per capita (2015 USD) (Table 6). Absolute cost savings due to WWS are not proportional to the difference in cost per unit energy because WWS requires less than half the energy than does BAU (Table 1), lowering the absolute energy cost. The lower cost of 100% WWS than BAU for towns and cities is consistent with the grid integration results in Jacobson et al. (2018a) for North America.

5. Air Pollution Cost Reductions due to WWS

A 100% WWS system is expected to reduce health effects significantly by reducing air pollution mortality from cardiovascular disease, respiratory illness, and complications from asthma arising from human exposure to $PM_{2.5}$ and O_3. Reductions in 2050 air pollution premature mortality in each town or city due to 100% WWS are estimated by apportioning state, Canada, and Mexico avoided premature mortalities due to transitioning (Jacobson et al., 2015a, 2017) by each town or city's share of state or country population. This method results in an estimated 2050 reduction in outdoor plus indoor premature mortalities among the 53 towns and cities of ~7000 (1700–16,000)/yr in 2050 (Table 7) upon conversion to WWS. If the transition hypothetically had occurred during 2010–12, the reduction would be ~9750 (2900–18,200)/yr in those years, which is higher than in 2050 because of the greater total emissions in 2010-12.

The damage cost due to air pollution from fossil fuel and biofuel burning and evaporative emissions in a town or city is the sum of mortality, morbidity, and non-health costs, which include visibility and agricultural losses. Mortality, morbidity, and non-health costs are estimated as in Jacobson et al. (2017). The resulting 53 town and city 2050 BAU air pollution avoided cost due to 100% WWS is ~$93.2 ($12.9–$374) billion/yr, or ~3.1 (0.4–12.6) ¢/kWh-BAU-all-energy, or $1,260/yr per person. The mean avoided air pollution cost falls in the range of 1.4–17 ¢/kWh-BAU-electricity, which is the air pollution cost in the retail electricity sector from Buonocore et al. (2016).

6. Global-Warming Damage Costs Eliminated

Damage due to global warming includes coastal flooding and real estate loss; agricultural loss; health issues from greater heat stress and

Table 7
Year 2050 avoided high, mean, and low avoided air pollution $PM_{2.5}$ plus ozone premature mortalities by town and city due to transitioning to 100% WWS and the corresponding mean avoided total costs (from avoided mortalities, morbidities and non-air pollution effects) and avoided costs per unit energy (2015 USD).

Town or city	2050 High avoided premature mortalities/yr	2050 Mean avoided premature mortalities/yr	2050 Low avoided premature mortalities/yr	2050 Mean avoided total cost ($2015 mil./yr)	2050 Mean avoided cost ($2015) ¢/kWh-BAU-all-energy
Abita Springs, LA	1	0	0	3	0.4
Arlington, VA	64	28	7	379	2.7
Aspen, CO	2	1	0	10	2.0
Atlanta, GA	1,020	447	113	5,949	3.3
Boone, NC	6	3	1	36	3.7
Boston, MA	393	175	46	2,327	2.7
Buffalo, NY	75	32	8	429	4.0
Burlington, VT	6	2	1	33	1.4
Calgary, CAN	536	231	53	3,077	5.2
Chicago, IL	875	383	94	5,097	2.8
Cleveland, OH	117	52	13	691	2.6
Columbia, MD	38	17	4	226	4.2
Denton, TX	46	20	5	263	1.4
Denver, CO	151	71	22	943	2.0
Des Moines, IA	8	3	1	46	0.9
Detroit, MI	141	63	17	841	2.1
East Hampton, NY	4	2	0	25	2.7
Georgetown, TX	21	9	2	123	1.4
Grand Rapids, MI	41	18	5	244	2.1
Greensburg, KS	0	0	0	1	1.2
Hanover, NH	2	1	0	14	2.5
Honolulu, HI	201	85	18	1,125	2.4
Houston, TX	793	344	86	4,578	1.4
Lancaster, NH	92	40	10	536	6.8
Los Angeles, CA	2,247	990	246	13,157	6.8
Madison, WI	53	23	6	312	1.9
Mexico City, MEX	1,198	525	130	6,979	4.7
Miami, FL	156	67	17	895	4.6
Milwaukee, WI	127	57	15	752	1.9
Moab, UT	2	1	0	14	3.8
Montreal, CAN	458	198	45	2,628	3.3
Nassau, NY	1	0	0	6	2.7
New Orleans, LA	301	132	33	1,755	0.4
New York City, NY	1,703	738	174	9,810	2.7
Oakland, CA	238	105	26	1,391	6.8
Palo Alto, CA	38	17	4	224	6.8
Philadelphia, PA	458	202	50	2,685	2.5
Phoenix, AZ	978	438	120	5,819	8.0
Portland, OR	146	63	15	844	2.6
Pueblo, CO	24	11	3	151	2.0
Rochester, MN	22	10	2	129	1.5
San Diego, CA	794	350	87	4,648	6.8
San Francisco, CA	490	216	54	2,870	6.8
San Jose, CA	585	258	64	3,427	6.8
Santa Monica, CA	53	23	6	311	6.8
Seattle, WA	187	80	19	1,061	2.6
St Petersburg, FL	92	40	10	526	4.6
Standing Rock, ND	1	0	0	4	0.3
Sylva, NC	1	0	0	5	3.7
Toronto, CAN	649	280	64	3,726	4.1
Vancouver, CAN	82	36	8	472	4.5
Washington DC	244	109	29	1,446	4.2
Woodstock, CAN	22	9	2	124	6.8
All towns and cities	**15,985**	**7,008**	**1,735**	**93,166**	**3.1**

Avoided air pollution mortalities in U.S. towns and cities are calculated from state values in Jacobson et al. (2015a) scaled by the city-to-state population ratio. Avoided mortalities in Canada and Mexico are calculated from country values in Jacobson et al. (2017), scaled by the city-to-country population ratio. Mean cents/kWh-BAU-all-energy equals the mean avoided air pollution cost 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).

stroke, urban and wildfire air pollution, influenza, malaria, and dengue fever; magnified drought, wildfires, water shortages, famine, and flooding; ocean acidification; and more severe weather. These costs are partly offset by fewer extreme cold events, resulting reductions in illness and mortality, and improvements in agricultural output in some regions. The social cost of carbon (SCC) is often used to quantify the estimated damage cost of climate-relevant emissions. The SCC from several recent studies is estimated for 2050 as $500 ($282-$1063)/metric tonne–$CO_2$e in 2015 USD (Jacobson et al., 2017). Multiplying the SCC by estimated 2050 CO_2e emissions suggests that BAU emissions from the 53 town and city may cause $393 ($221-$836) billion/yr in climate losses to the world by 2050, or 13.2 (7.4–28.1) ¢/kWh-BAU-all-energy and ~$5,300/yr per person (in 2015 USD) (Table 8).

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

Another metric relevant to policy decision-making is net job

Table 8
2015 estimated city or town energy-related carbon-dioxide-equivalent (CO_2e) emissions and low, medium, and high estimates of avoided 2050 climate-change costs to the world due to converting each town or city to 100% WWS for all purposes.

Town or city	2015	2050 avoided global climate cost ($2015)			
	Energy-related CO_2 emissions (MT CO_2)	Low cost, high benefit ($bil./yr)	Mean ($bil./yr)	High cost, low benefit ($bil./yr)	Mean ¢/kWh-BAU-all-energy
Abita Springs, LA	0.12	0.2	0.1	0.0	10.1
Arlington, VA	2.79	3.7	1.8	1.0	12.5
Aspen, CO	0.11	0.2	0.1	0.0	15.1
Atlanta, GA	38.70	51.8	24.3	13.7	13.3
Boone, NC	0.22	0.3	0.1	0.1	14.1
Boston, MA	18.30	22.3	10.5	5.9	12.3
Buffalo, NY	3.18	3.8	1.8	1.0	16.3
Burlington, VT	0.42	0.5	0.2	0.1	10.4
Calgary, CAN	17.00	23.1	10.8	6.1	18.3
Chicago, IL	46.41	57.4	27.0	15.2	14.7
Cleveland, OH	7.19	8.9	4.2	2.4	15.8
Columbia, MD	1.05	1.4	0.7	0.4	12.1
Denton, TX	2.99	4.3	2.0	1.1	10.8
Denver, CO	11.28	15.3	7.2	4.1	15.1
Des Moines, IA	0.97	1.2	0.6	0.3	11.5
Detroit, MI	11.08	13.7	6.4	3.6	15.8
East Hampton, NY	0.19	0.2	0.1	0.1	11.2
Georgetown, TX	1.40	2.0	1.0	0.5	10.8
Grand Rapids, MI	3.21	4.0	1.9	1.1	15.8
Greensburg, KS	0.02	0.0	0.0	0.0	14.7
Hanover, NH	0.13	0.2	0.1	0.0	13.8
Honolulu, HI	12.99	19.6	9.2	5.2	20.0
Houston, TX	52.03	75.4	35.4	20.0	10.8
Lancaster, NH	1.50	2.3	1.1	0.6	13.5
Los Angeles, CA	36.79	55.6	26.1	14.7	13.5
Madison, WI	4.30	5.3	2.5	1.4	15.2
Mexico City, MEX	46.39	67.3	31.6	17.8	21.4
Miami, FL	5.00	6.7	3.1	1.8	16.0
Milwaukee, WI	10.36	12.8	6.0	3.4	15.2
Moab, UT	0.11	0.2	0.1	0.0	19.2
Montreal, CAN	14.52	17.1	8.0	4.5	10.1
Nassau, NY	0.04	0.0	0.0	0.0	11.2
New Orleans, LA	62.01	89.9	42.2	23.8	10.1
New York City, NY	72.69	85.7	40.3	22.7	11.2
Oakland, CA	3.89	5.9	2.8	1.6	13.5
Palo Alto, CA	0.63	0.9	0.4	0.3	13.5
Philadelphia, PA	28.55	33.7	15.8	8.9	14.5
Phoenix, AZ	20.82	28.3	13.3	7.5	18.2
Portland, OR	5.99	9.1	4.3	2.4	13.0
Pueblo, CO	1.80	2.4	1.1	0.6	15.1
Rochester, MN	1.80	2.2	1.0	0.6	11.9
San Diego, CA	13.00	19.7	9.2	5.2	13.5
San Francisco, CA	8.03	12.1	5.7	3.2	13.5
San Jose, CA	9.58	14.5	6.8	3.8	13.5
Santa Monica, CA	0.87	1.3	0.6	0.3	13.5
Seattle, WA	7.25	11.0	5.2	2.9	12.6
St Petersburg, FL	2.94	3.9	1.8	1.0	16.0
Standing Rock, ND	0.65	0.8	0.4	0.2	22.6
Sylva, NC	0.03	0.0	0.0	0.0	14.1
Toronto, CAN	20.59	24.3	11.4	6.4	12.6
Vancouver, CAN	2.61	3.9	1.9	1.0	17.7
Washington DC	6.69	9.0	4.2	2.4	12.1
Woodstock, CAN	0.42	0.5	0.2	0.1	13.4
All towns and cities	**5,246**	**836.0**	**392.8**	**221.4**	**13.2**

All costs are in 2015 USD. CO_2e emissions for U.S. towns and cities are estimated from state energy-related CO_2 emissions (EIA, 2017b) scaled by population to the town or city, then adjusted for non−CO_2 climate-relevant pollutants, as described in Jacobson et al. (2015a). Emissions are then projected to 2050 as in Jacobson et al. (2015a). Emissions for Canadian and Mexican towns and cities are calculated in the same way but using direct estimates of CO2 emissions, as provided in Jacobson et al. (2018b). Avoided costs are derived assuming elimination of all emissions with 100% WWS and multiplying the emission change by the social cost of carbon, described in the text. Mean cents/kWh-BAU-all-energy equals the mean avoided climate cost 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).

creation or loss. NREL's Jobs and Economic Development Impact (JEDI) models (NREL, 2017) are used here to estimate the net job and earning changes from developing the full WWS electricity generation and transmission system proposed by 2050. The models treat 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 (NREL, 2017). Indirect manufacturing jobs are included in the numbers 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, for example (NREL, 2017). A breakdown of direct, indirect, and induced jobs per unit nameplate capacity can be obtained from the JEDI models themselves (NREL, 2017) but are not estimated here.

Job number estimates exclude job changes in industries aside from electric power generation, such as the manufacture of electric vehicles, fuel cells, or electricity or heat storage. This is because of the uncertainty about where those jobs will arise and the extent to which they will be offset by job losses in BAU-equivalent industries.

Specific output from the JEDI models are jobs and earnings per MW of nameplate capacity of each energy device, summarized in Table 9 (footnote). Jacobson et al. (2018b) contain details of additional assumptions, inputs, and outputs from the job calculations. We multiply jobs per MW for each energy device by the new nameplate capacity of each device for each town or city to obtain job totals.

Both construction and operation jobs arise from building the WWS generation and transmission infrastructure. The job numbers calculated here are permanent, full-time (2,080 h/yr) jobs. One temporary construction job in the JEDI models is defined as one full-time job for one year. One permanent construction job is defined here as the number of consecutive 1-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. In other words, suppose 40 GW 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 1-year construction jobs (direct, indirect, and induced jobs). In that case, 1 GW of wind is installed each year and 40,000 1-year construction jobs are required each year. Thus, over 40 years, 1.6

Table 9
Estimated numbers of 2050 new permanent, full-time construction and operation jobs, permanent, full-time construction plus operation jobs minus jobs lost, annual earnings corresponding to new construction and operation jobs, and net earnings from new construction plus operation jobs minus jobs lost, by town and city, due to converting to 100% WWS.

Town or city	Permanent, full-time construction jobs	Permanent, full-time operation jobs	Job losses in fossil-fuel and nuclear energy industries	Net jobs: permanent, full-time net construction plus operation jobs created minus jobs lost	Annual earnings from new construction jobs (mil $/ yr)	Annual Earnings from new operation jobs (mil $/yr)	Net annual earnings from new construction plus operation jobs minus jobs lost (mil $/yr)
Abita Springs, LA	57	41	64	33	3	3	1.5
Arlington, VA	2,120	1,302	1,984	1,438	124	88	70.6
Aspen, CO	72	24	50	46	4	2	2.2
Atlanta, GA	31,064	13,334	25,050	19,349	1,783	871	874.1
Boone, NC	170	95	154	111	10	6	5.3
Boston, MA	11,546	8,970	16,369	4,147	673	618	128.0
Buffalo, NY	2,101	1,029	2,128	1,003	119	68	35.7
Burlington, VT	161	59	425	−204	9	4	−16.6
Calgary, CAN	8,308	2,821	11,911	−782	479	195	−172.8
Chicago, IL	22,119	8,940	25,123	5,936	1,259	633	106.9
Cleveland, OH	4,854	1,752	3,639	2,967	275	120	136.4
Columbia, MD	840	561	864	537	49	38	25.2
Denton, TX	1,263	609	1,895	−24	75	43	−16.3
Denver, CO	7,190	2,376	4,774	4,792	416	162	238.6
Des Moines, IA	481	169	375	274	27	12	12.5
Detroit, MI	4,873	3,093	6,300	1,666	284	220	55.9
East Hampton, NY	155	81	181	55	9	5	1.4
Georgetown, TX	598	287	823	61	36	20	−2.6
Grand Rapids, MI	1,388	890	1,802	477	81	63	16.2
Greensburg, KS	6	2	10	−1	0	0	−0.2
Hanover, NH	86	44	103	28	5	3	0.7
Honolulu, HI	4,695	2,340	10,156	−3,121	271	163	−288.0
Houston, TX	22,892	10,811	33,432	270	1,360	766	−250.7
Lancaster, NH	1,278	479	1,555	201	73	32	−5.4
Los Angeles, CA	30,856	11,586	38,046	4,396	1,771	771	−161.7
Madison, WI	1,727	1,023	2,232	518	101	73	14.9
Mexico City, MEX	27,761	9,499	59,385	−22,125	1,585	632	−2004.8
Miami, FL	5,674	1,768	3,471	3,971	320	113	186.7
Milwaukee, WI	4,123	2,456	5,411	1,168	241	175	31.0
Moab, UT	52	17	36	33	3	1	1.6
Montreal, CAN	19,121	8,624	34,960	−7,215	1,081	568	−835.8
Nassau, NY	37	19	40	16	2	1	0.5
New Orleans, LA	30,274	21,929	34,932	17,271	1,777	1,478	771.4
New York City, NY	64,507	32,724	70,330	26,901	3,649	2,181	830.3
Oakland, CA	3,919	1,406	4,004	1,321	225	93	32.9
Palo Alto, CA	632	227	649	210	36	15	5.0
Philadelphia, PA	26,900	9,437	9,386	26,950	1,491	612	1435.5
Phoenix, AZ	12,555	3,692	13,247	2,999	738	248	44.3
Portland, OR	3,259	1,768	5,331	−304	192	125	−62.3
Pueblo, CO	1,116	371	802	685	65	25	32.9
Rochester, MN	621	380	1,007	−6	37	28	−7.2
San Diego, CA	11,712	4,316	13,366	2,662	672	286	8.2
San Francisco, CA	7,179	2,734	8,256	1,658	411	181	5.5
San Jose, CA	8,704	3,205	9,850	2,060	499	213	11.9
Santa Monica, CA	741	278	900	119	43	18	−2.9
Seattle, WA	3,549	1,887	5,591	−155	204	134	−59.8
St Petersburg, FL	3,040	962	2,042	1,961	172	62	88.3
Standing Rock, ND	172	62	40	194	10	4	11.1
Sylva, NC	24	13	22	15	1	1	0.7
Toronto, CAN	23,153	8,352	44,385	−12,879	1,305	548	−1302.2
Vancouver, CAN	1,338	450	3,001	−1,213	75	29	−109.1
Washington DC	5,210	3,553	5,500	3,263	303	241	152.2
Woodstock, CAN	244	146	1,182	−792	14	10	−59.5
All towns and cities	**426,518**	**192,996**	**526,572**	**92,942**	**24,448**	**13,002**	**18**

Monetary values are in 2015 USD. Calculations are based on the number of new generators needed of each type for annual average power and peaking/storage (Table 2). Earnings include wages, services, and supply-chain impacts. BAU jobs lost in 2050 are estimate from jobs lost in 2015 multiplied by the ratio of all-town-and-city BAU end use load in 2050 (Table 1) divided by that in 2015 (see text). The numbers of permanent construction (operation) jobs per MW of new nameplate capacity are as follows: onshore wind: 0.09 (0.14); offshore wind: 0.17 (0.63); wave: 0.34 (2.37); geothermal: 0.35 (0.12); hydroelectric: 0.30 (0.30); tidal: 0.30 (2.27); residential rooftop PV: 1.34 (0.40); commercial/government rooftop PV: 1.74 (0.30); utility PV: 1.05 (0.30); CSP: 0.26 (0.19).

million 1-year jobs are required. This is equivalent to 40,000 40-year jobs. Since the technology life is 40 years, after that period, 40,000 more 1-year jobs are needed continuously in the future. As such, the 40,000 construction jobs are permanent jobs.

Table 9 suggests that a 100% conversion to WWS across 53 towns and cities can create ~427,000 new permanent, full-time construction jobs and ~193,000 new permanent, full-time, operation plus maintenance jobs, totaling 620,000 new ongoing, full-time jobs for WWS generators and transmission.

Table 9 also summarizes jobs lost from coal, oil, gas, and nuclear companies from switching to WWS. Job losses are calculated assuming that almost all jobs related to uranium and fossil fuel mining, transporting, refining, and dispensing, as well as electricity generation and transmission, will be lost. Jobs not lost include petroleum-refining jobs needed to produce non-energy related petroleum products. In addition, jobs associated with net exports of fossil fuels out of a state or country, are retained, since the roadmaps here are only for specific towns and cities.

To estimate job losses in towns and cities, nuclear and fossil fuel job data are first obtained for each U.S. state, Canada, and Mexico. The jobs, and thus job losses, are then apportioned by population to each town or city within the state or country it resides in. The jobs lost are not necessarily lost in the city of interest; instead, they are jobs lost anywhere due to the city's transition to 100% clean, renewable energy.

Many current jobs in the nuclear and fossil fuel industries in the United States, Canada, and Mexico are estimated using the North American Industry Classification System (NAICS). NAICS categorizes employment into 20 broad categories, with subcategories of increasing specificity. For this study, 5- or 6-digit NAICS codes were generally used, indicating significant specificity.

For oil, gas, and coal jobs, U.S. state job data were obtained from BLS (2015) using NAICS codes for oil and gas extraction, drilling and gas wells, support activities for oil and gas operations, oil and gas pipeline construction, petroleum refining, coal mining, support activities for coal mining, natural gas distribution, and fossil fuel electric power generation. EIA (2017c) supplemented limited BLS (2015) data on state uranium jobs. Nuclear job data were obtained from NEI (2014). BLS (2016) provided data on fossil fuel and uranium transportation jobs by truck, ship, train, and pipeline; and tank car, truck, and ship loaders. Indirect employment data, such as jobs pertaining to designing and manufacturing extraction equipment or building gas stations, were obtained from DOE (2017). Indirect employment jobs exclude jobs generated by direct employees' paycheck spending.

Canadian city data were estimated primarily from all-Canada employment numbers from Government of Canada (2016), Canadian Manufacturers and Exporters (2012), IAEA (2016), Natural Resources Canada (2017), Canadian Nuclear Association (2013), and Coal Association of Canada (2012) using the same NAICS codes as for the U.S., where available. Where Canadian subcategory NAICS values were not available, they were partitioned from Canadian higher-category values using U.S. ratios between the subcategory and higher category.

The Mexico City boundaries in this study were defined as those within the Federal District, not the Mexico City metropolitan area. Job data in the Federal District were obtained primarily from INEGI (2013), the National Institute for Statistics and Geography using NAICS codes, and the World Nuclear Association (2016).

Because WWS plants replace BAU fossil, nuclear, bioenergy, and BAU-WWS plants, jobs lost from not constructing BAU plants are included in our calculations. Jobs lost from stopping construction of petroleum refineries and oil and gas pipelines are counted as well. Jobs lost from the BAU case in 2050 are estimated by multiplying the jobs lost in 2015 by the ratio of all-town-and-city BAU end use load in 2050 (Table 1) to that in 2015 (~303 G W). Overall, shifting to WWS is estimated to result in ~527,000 jobs lost in the fossil fuel, biofuel, and nuclear industries in 2050 if full conversion took place that year (Table 9).

Subtracting jobs lost from jobs created gives a *net* of ~93,000 permanent, full-time jobs created across the 53 towns and cities due to replacing fossil fuel generation among all sectors with WWS generation and transmission (Table 9). Job earnings show a net gain of ~\$18 million/yr (USD 2015) (Table 9). Although the number of operation jobs declines slightly, the gain of permanent construction jobs far outweighs the loss. Individually, towns or cities near significant fossil extraction (e.g., Mexico City) may experience net job losses or fewer job gains than other towns or cities in the energy production sector. These losses may be offset by the manufacture, service, and export of technologies associated with WWS energy (e.g., liquid hydrogen production and storage, electric vehicles, electric heating and cooling, etc.). Those offsetting jobs are not included in the job estimates here.

8. Timeline

Jacobson et al. (2017) propose a WWS transformation timeline of 80% conversion to WWS by 2030 and 100% by 2050 in order to eliminate air pollution mortality as soon as possible and to avoid 1.5 C net global warming. To realize such a rapid conversion, new policies are needed to accelerate retirement of existing equipment and infrastructure and ramp up production of WWS technologies.

9. Conclusions

Transitioning 53 towns and cities in North America to 100% WWS for all energy purposes has the potential to (1) avoid ~9750 (2900–18,200) premature air-pollution mortalities/yr today and 7000 (1700–16,000)/yr in 2050, which along with non-mortality impacts, avoids ~\$93.2 (\$12.9-\$374) billion/yr in 2050 air-pollution damage costs (2015 USD); (2) avoid ~\$393 (221–836) billion/yr in 2050 global warming costs (2015 USD); (3) avoid a total health plus climate cost of ~16.3 (7.8–40.7) ¢/kWh-BAU-all-energy, or \$6,600/yr per person, over 53 towns and cities; (4) save ~\$133/person/yr in BAU-electricity-sector fuel costs; (5) create ~93,000 more new long-term, full-time jobs than lost; (6) stabilize energy prices; and (7) use minimal new land. While social and political barriers exist, converting to 100% WWS using existing technologies appears technically and economically feasible. Reducing the barriers will require dissemination of information, education, effective policies, and actions by individuals to transition their homes and lives.

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