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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