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Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk

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Key Points:

- Roadmaps to transition 139 countries to 100% clean, renewable energy have been developed
- Countries will reap massive benefits from a transition
- Transitioning will require concerted efforts by individuals, communities, businesses, and policy makers

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Abstract Solving the problems of global warming, air pollution, and energy security requires a massive effort by individuals, communities, businesses, nonprofits, and policy makers around the world. The first step in that process is to have a plan. To that end, roadmaps to transition 139 countries of the world to 100% clean, renewable wind, water, and solar power for all energy purposes (electricity, transportation, heating, cooling, industry, agriculture, forestry, and fishing) by 2050, with 80% by 2030, have been developed. The evolution, characteristics, and impacts to date of these plans are briefly described.

Plain Language Summary Global warming, air pollution death, and disease, and energy security are massive problems facing the world today. The solution to these problems requires individuals, communities, businesses, nonprofits, and policy makers around the world to transition themselves and their constituents from fossil fuels to clean and renewable energy sources. The first step in the transition is to develop a plan. Here, plans to transition 139 countries of the world to 100% clean, renewable wind, water, and solar power for all energy sectors (electricity, transportation, heating, cooling, industry, agriculture, forestry, and fishing) by 2050, with 80% by 2030, are summarized. The evolution, characteristics, and impacts to date of these plans are also described.

1. Background

The acceleration of global warming and air pollution health problems due to anthropogenic emissions is cause for alarm among nations worldwide. The increasing thirst for energy and competition for limited fossil fuel supplies among a growing population is another. Such worries have resulted in the international community seeking alternatives to fossil fuels.

In one set of proposals to address these problems, Jacobson and Delucchi (2009, 2011), Delucchi and Jacobson (2011), and Jacobson et al. (2015a, 2015b) posited that the world as a whole and individual U.S. states could run entirely on wind, water, and solar (WWS) power after all energy sectors were electrified or powered by heat directly and after energy efficiency measures were put in place. Only WWS electricity and heat generation were considered following the scientific assessment of Jacobson (2009). That study concluded that WWS technologies "will result in the most benefit among the options considered," in terms of carbon-equivalent emissions, air pollution health impacts, water use, land footprint, land spacing, wildlife impacts, resource availability, thermal pollution, water chemical pollution, radioactive waste, weapons proliferation, catastrophic risk, energy supply disruption, and normal operating reliability. The study further concluded that nuclear power, fossil fuels with carbon capture and sequestration (CCS), and biofuels for transportation offered less benefit than WWS options in terms of the same factors, thus were opportunity costs.

Since then, the Intergovernmental Panel on Climate Change (IPCC, 2014, p. 517) has similarly concluded with respect to nuclear that there is "robust evidence" and "high agreement" that "Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and adverse public opinion."

Several other large-scale energy transition plans have been proposed. Many have focused only on carbon-equivalent emissions, thus are commonly referred to as decarbonization plans. These plans have

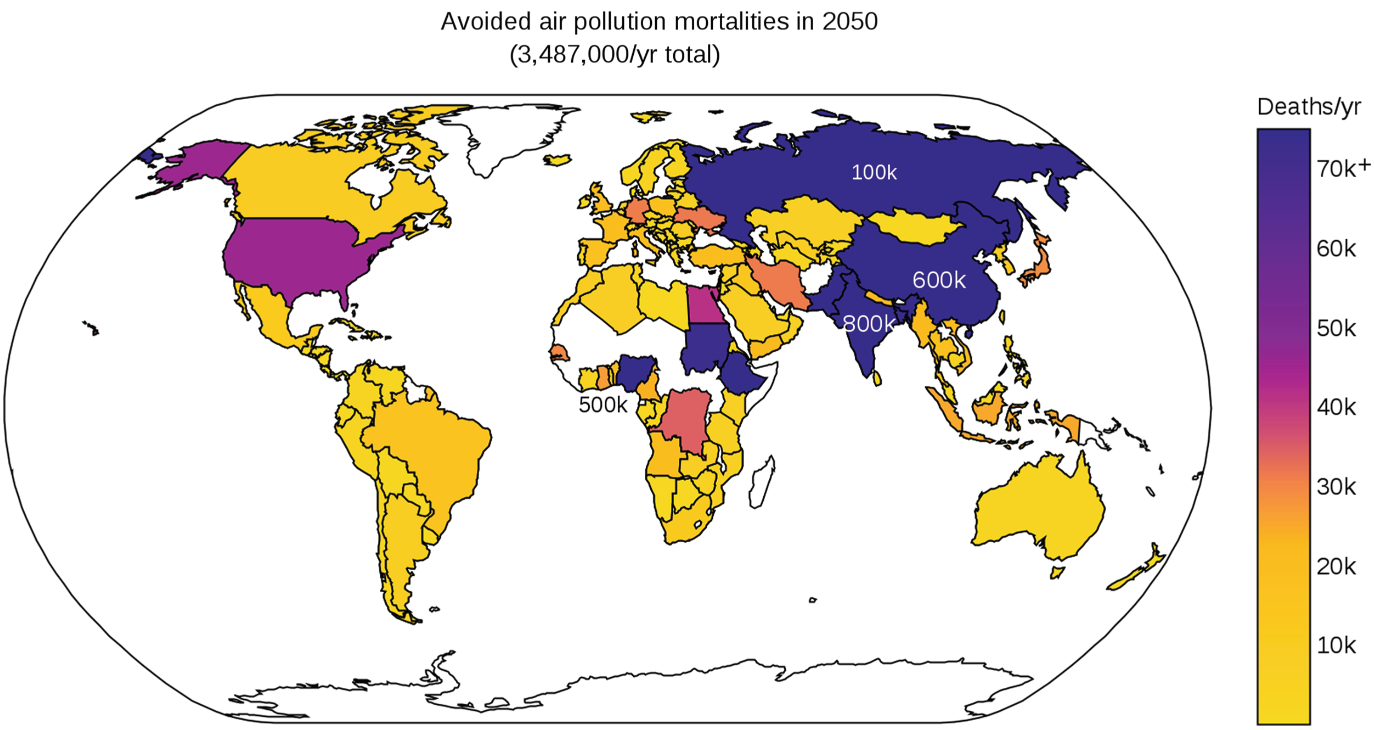

Figure 1. Avoided 2050 air pollution mortalities by country upon conversion to 100% WWS based on data from Jacobson et al. (2017b).

not considered impacts on air pollution, catastrophic risk, or land use, thereby allowing for the inclusion of nuclear power and fossil fuels with CCS. Cooper (2016) compared costs of 100% WWS scenarios with scenarios that included nuclear and fossil fuels with CCS and concluded, "Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio." Freed et al. (2017) similarly concluded, "Indeed, there is virtually no history of nuclear construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States." Such studies support the contention that a 100% WWS system may be the best path for solving the climate, pollution, and energy security problems together.

Nevertheless, advocates of nuclear power and fossil fuels with carbon capture still contend that those technologies are needed to keep the grid stable, because 100% WWS combined with storage and transmission on their own are unreliable due to the intermittent nature of WWS generators (e.g., Clack et al., 2017; Heard et al., 2017). Not only do those studies mischaracterize results of 100% WWS studies (e.g., see Jacobson et al., 2017a), at least 26 peer-reviewed papers contradict that contention. Such papers have examined grid stability in the presences of 100% or near-100% renewable energy providing electricity to one or more energy sectors and have concluded that the electric power grid can stay stable with no nuclear power or fossil fuels with CCS (Aghahosseini et al., 2016; Barbosa et al., 2017; Becker et al., 2014; Blakers et al., 2017; Bogdanov & Breyer, 2016; Budischak et al., 2013; Child & Breyer, 2016; Connolly et al., 2011, 2016; Connolly & Mathiesen, 2014; Elliston et al., 2012, 2013, 2014; Gulagi et al., 2017a, 2017b, 2017c; Hart & Jacobson, 2011, 2012; Jacobson et al., 2015a, 2015b; Lu et al., 2017; Lund & Mathiesen, 2009; Mason et al., 2010; Mathiesen et al., 2011, 2015; Rasmussen et al., 2012; Steinke et al., 2013).

1.1. Roadmaps for 139 Countries

With this background in mind, Jacobson et al. (2017b) proposed 100% WWS roadmaps for each of 139 countries, collectively representing more than 99% of world emissions. The study contemplates an 80% conversion to WWS in each country by 2030 and 100% by 2050. This aggressive timeline is necessary to eliminate the 4–7 million annual air pollution deaths currently occurring as fast as possible and avoid 1.5°C or greater net global warming since the mid-1800s. Avoiding 1.5–2°C

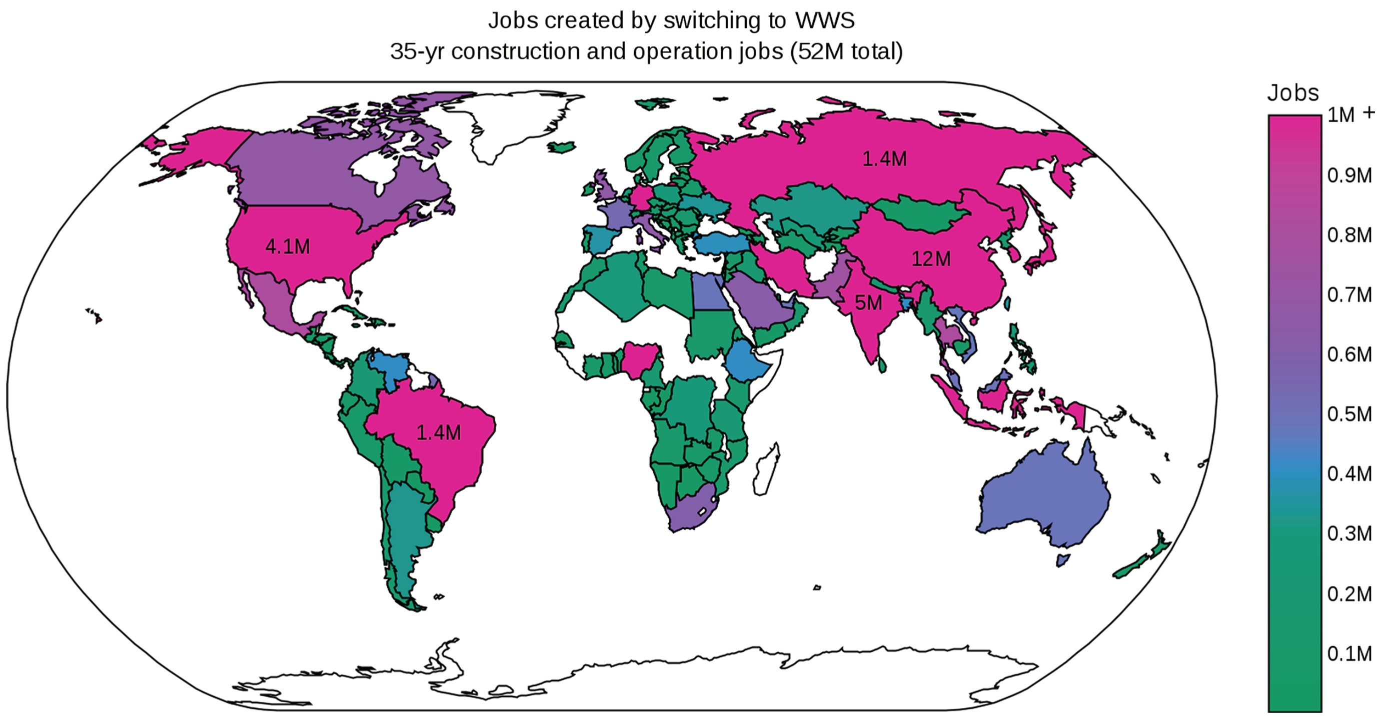

Figure 2. Long-term (35-year), full-time construction plus operation jobs created, before job losses are accounted for, by country due to converting to 100% WWS. The total number of jobs created is ~52 million and lost is ~28 million. Based on data from Jacobson et al. (2017b).

warming is the 2015 Paris Climate Agreement's most ambitious goal for avoiding catastrophic climate change.

Like previous 100% WWS roadmaps, the idea behind each new country roadmap is to electrify all energy sectors and provide the electricity with 100% WWS while incorporating energy efficiency measures. All energy sectors include electricity, transportation, heating, cooling, industry, agriculture, forestry, and fishing. If no transition occurs (the business-as-usual case), end-use all-sector power demand is projected to increase from 12.1 to 20.6 TW in 2050. However, a significant benefit of electrification and providing the electricity with 100% WWS is to reduce 2050 power demand by an average of 42.5% over the 139 countries. Of this, 23% is obtained because the work output to energy input ratio of WWS electricity significantly exceeds that of combustion. Another 12.6% is obtained because energy to mine, transport, or process fossil fuels and uranium is no longer needed. Increasing end-use energy efficiency and reducing energy use beyond that expected in the business-as-usual case accounts for the remaining 6.9% reduction.

The 100% WWS transition requires a shift to WWS electric power generators, which include onshore and offshore wind turbines, solar photovoltaics on rooftops and in power plants, concentrated solar power, geothethermal power, tidal and wave power, and existing hydroelectric dams. It also requires electricity, heat, cold, and hydrogen storage. Electricity storage is primarily in the form of concentrated solar power with storage, pumped hydroelectric power, batteries, and existing hydroelectric dams. Heat is stored in water, rocks, and cement. Cold is stored in water and ice. Hydrogen is used only for transportation under these roadmaps. The transition also requires the use of electric appliances, such as heat pumps for building air and water heat, air conditioning, and refrigeration. Other electric appliances for households and businesses include induction cooktop stoves, electric cars, LED light bulbs, and electric dryers. Electric machines for high-temperature industrial processes include induction furnaces, dielectric heaters, and arc furnaces. Aircraft and ships would be electric and hybrid electric-hydrogen fuel cell (HFC). All technologies listed, aside from electric and HFC aircraft and ships, are commercially available. Small prototypes of electric and HFC aircraft are available.

If implemented, the 139-country roadmaps are expected to.

1. Eliminate most of today's 4–7 million deaths (and hundreds of millions more illnesses) each year due to air pollution and 3.5 million deaths per year projected to occur in 2050 (Figure 1);
2. Eliminate nearly all emissions and damage associated with global warming;
3. Provide a net of ~24 million more long-term (35-year) full-time construction and operation jobs than lost, with ~52 million jobs created (Figure 2) and ~28 million lost;
4. Stabilize energy prices while reducing the social cost (direct plus health plus climate cost) of energy by ~75%;
5. Reduce terrorism and catastrophic risk associated with large, centralized energy plants by distributing energy more; and.
6. Improve access to power to ~4 billion people in energy poverty, including ~1.2 billion with no access to energy and the rest who must collect their own energy.

Implementing the roadmaps in the time proposed is possible only with massive public and private action around the world. Both individuals and policy makers must contribute to the solution. Individuals can transition their own households and lives. Policy makers can help transition by passing supporting laws and regulations.

While a slow transition is currently underway, the energy transition needs to speed up by a factor of 10–100. Already, though, over 45 cities in North America and over 100 international businesses have committed to 100% clean, renewable energy. Similarly, the U.S. House of Representatives has proposed a resolution (HRes 540) and a bill (HR 3314), and the U.S. Senate has also proposed a resolution (SRes 632) and a bill (S 987) for the United States to go to 100% clean, renewable energy for most purposes. Several U.S. states, including California, Hawaii, New York, and Massachusetts, have existing or proposed laws to get close to 100% in one or more sectors. Many countries have similarly increased their development of WWS and have set goals for high penetrations. Lastly, dozens of nonprofit organizations are now committed to 100% clean, renewable energy.

2. Conclusions

The energy roadmaps described here provide details of one 100% clean, renewable energy scenario across all energy sectors throughout most of the world that individuals, businesses, communities, nonprofits, and policy makers can aim for. The resulting mix of energy generators provided by country is not the only mix possible, as many 100% WWS solutions exist. The next step is to accelerate the transition in order to mitigate the growing climate, pollution, and energy security problems afflicting the world.

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