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By Mark Z. Jacobson, Stanford University (Witness)

Roadmaps for 139 Countries and the 50 United States to Transition to 100% Clean, Renewable Wind, Water, and Solar (WWS) Power for all Purposes by 2050 and 80% by 2030

Synopsis

- Researchers at Stanford University and the University of California have developed roadmaps to transition the energy infrastructures of 139 countries and the 50 United States to 100% clean, renewable infrastructures running on existing-technology wind, water, and solar (WWS) power for all purposes by 2050, with 80% conversion by 2030.

- All-purpose energy includes electricity, transportation, heating/cooling, industry, and agriculture/forestry/fishing.

- Converting the 50 states, 139 countries, and remaining countries of the world will have the following impacts: (1) eliminate 4-7 million annual worldwide premature air pollution mortalities and their costs, (2) eliminate global warming and its costs, (3) create over 20 million more 35-year global jobs than lost, (4) stabilize energy prices because fuel costs are near zero, (5) reduce international conflict by creating energy-independent regions, (6) reduce terrorism risk by decentralizing power, and (7) reduce the social cost (business + health + climate costs) of energy by 60%.

- The main barriers to a conversion are neither technical nor economic; rather, they are social and political.

- These roadmaps should give confidence to leaders at COP 21 in Paris that their countries can obtain 100% clean, renewable WWS energy by 2050 with substantial conversion by 2030, and that a commitment to a 100% by 2050 goal is scientifically based.

Methodology

- The idea is to electrify everything, thereby eliminating combustion (the burning of fuel) as a source of energy, pollution, and inefficiency. Electrifying everything reduces power demand relative to conventional fuels by ~32% averaged across all energy sectors due to the efficiency of electricity over combustion. Another ~7% reduction in demand can be obtained from end-use energy efficiency improvements beyond those that would occur by 2050 with conventional fuels.

- For electric power, the WWS technologies to be deployed include onshore and offshore wind turbines, rooftop and power-plant solar photovoltaics (PV), concentrated solar power (CSP) plants, solar heat collectors, geothermal power plants for electricity and heat, existing hydropower plants, and small numbers of tidal and wave devices.

- For ground transportation, the technologies to be used include battery electric vehicles (BEVs) and hydrogen fuel cell (HFC) vehicles, where the hydrogen is produced from electricity passing through water. BEVs with fast charging or battery swapping will dominate long-distance, light-duty ground transportation. Battery electric-HFC hybrids will dominate heavy-duty ground transportation and long-distance water-borne shipping. Batteries will power short-distance shipping. Electrolytic cryogenic hydrogen plus batteries will power aircraft.

- For air heating and cooling, the technologies to be used include electric heat pumps (ground-, air-, or water-source) and some electric-resistance heating. Heat pumps with electric resistance elements and/or solar hot water preheaters will be used to heat domestic water. Cook stoves will have either an electric induction or a resistance-heating element.

- Energy for high-temperature industrial processes will come from electric arc furnaces, induction furnaces, dielectric heaters, resistance heaters, and some combusted hydrogen.

- Storage for electricity includes hydroelectric plants, pumped-hydroelectric facilities, and CSP plants coupled with storage. Storage media for heat include water and rocks and soil under ground; for cold, they include water and ice. Excess electricity will also be used to produce hydrogen and to heat water and rocks.

Results

- Every country we looked at, including France, the Netherlands, Congo, South Africa, Bangladesh, Sri Lanka, Israel, Peru, Guatemala, and all major countries participating in the upcoming international climate negotiations, can ramp up to 100% clean, renewable energy by 2050. Across all continents, some combination of wind, water, and solar allows virtually every country to be energy independent and self sufficient in terms of annual-average power, although small countries and states will likely find advantage in exchanging electrical energy with neighbors.

- For example, a new study in the *Proceedings of the National Academy of Sciences* (embargoed until Monday, November 23) shows that a 100% conversion of the 48 contiguous United States to WWS will result in a 100% reliable grid 100% of the time even after accounting for the intermittency of wind, water, and solar resources and power demand, if the states are reasonable interconnected. Maintaining grid stability requires combining intermittent WWS generation with existing-technology low-cost electricity, heat, and cold storage and demand response.

- A 100% conversion to WWS worldwide will nearly eliminate 4-7 million premature air-pollution-caused mortalities per year worldwide and 60,000-65,000 premature mortalities per year in the United States. To put these findings in perspective, consider that the Centers for Disease Control and Prevention estimates that 6 million people die each year globally from tobacco-related diseases.

- In the United States, we calculate that 100% conversation to WWS will prevent 60,000-65,000 premature mortalities. Again, to put that in perspective, this is twice as many people as lost each year to motor vehicle accidents according to the National Highway Traffic and Safety Administration.

- Avoiding the mortalities, ten times more morbidities, and other environmental impacts of non-greenhouse-gas chemical air pollutants will save the United States and the world over 3% of their respective GDPs annually. Such savings accrue in the form of lower insurance rates, lower workman's compensation rates, lower taxes, higher worker productivity, fewer lost work days, fewer lost school days, fewer hospitalizations, fewer emergency room visits, less agricultural crop damage, less building, statuary, and tire erosion, and better quality of life.

- A 100% conversion worldwide will eliminate $16-20 trillion/year in global climate costs by 2050. 100% conversion in the U.S. alone will eliminated $3.3 trillion/year in global climate costs.

- A 100% conversion will stabilize energy prices because fuel costs of WWS electric power are zero, whereas fuel costs of fossil fuels are above zero and rise over time.

- A 100% conversion will save each U.S. consumer $260 (190-320)/year (in 2013 dollars) in energy costs in 2050 and will save the U.S. $1,500 (210-6,000)/year and $8,300 (4,700-17,600)/year per person in health and climate costs, respectively.

- A 100% conversion will create over 20 million more 35-year construction plus operation jobs worldwide than it costs. In the U.S., it will create over 2 million more jobs than it costs.

- A 100% conversion worldwide will require less than 0.4% of the world's land for the footprint of new devices and less than 1% of the land for spacing between onshore wind turbines. Spacing area can be used for multiple purposes.

- 100% conversions worldwide and in the U.S. will reduce terrorism risk by creating more distributed electric power sources, such as wind and rooftop solar, reducing the need for centralized power plants (such as coal, natural gas, and nuclear plants) and oil refineries that are subject to terrorist attack. As retired general and admirals at the Military Advisory Board recently concluded, a reliable grid is a safer grid (https://www.cna.org/CNA_files/PDF/National-Security-Assured-Electrical-Power.pdf).

- A 100% conversion worldwide and in the U.S. will reduce international conflict by reducing each country's dependence on energy from other countries.

- The 2050 business cost of a WWS energy, storage, plus long-distance transmission 100% reliable system is similar to the business cost of a 2050 business-as-usual system, but the 2050 social cost (business + health + climate costs) of a WWS system is ~40% that of a business-as-usual system.

- In sum, there is a significant benefit across the board and little downside to a 100% conversion to WWS for all purposes. The main barriers to a conversion are social and political, not technical or economic.

Resources

- Clickable maps summarizing each country and U.S. state roadmap are available at *The Solutions Project* website, http://thesolutionsproject.org and at the *National Geographic* website, http://www.nationalgeographic.com/climate-change/carbon-free-power-grid/#cover

- All papers and spreadsheets describing the roadmaps can be found at http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

- The specific published papers on the roadmaps to date include the following:

- **Roadmap to transition the world as a whole (but not individual countries):**

  Jacobson, M.Z., and M.A. Delucchi, A path to sustainable energy by 2030, *Scientific American*, November 2009 (cover), www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition the world as a whole in more detail and the U.S. as a whole (but not individual states or countries).**

  Jacobson, M.Z., and M.A. Delucchi, Providing all Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials, *Energy Policy*, 39, 1154-1169, doi:10.1016/j.enpol.2010.11.040, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html

  Delucchi, M.Z., and M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy*, 39, 1170-1190, doi:10.1016/j.enpol.2010.11.045, 2011, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition New York State:**

  Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, *Energy Policy*, 57, 585-601, 2013, www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition California:**

  Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all purposes with wind, water, and sunlight, *Energy, 73,* 875-889, doi:10.1016/j.energy.2014.06.099, 2014, http://www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html.

- **Roadmap to transition Washington State:**

Jacobson, M.Z., M.A. Delucchi, G. Bazouin, M.J. Dvorak, R. Arghandeh, Z. A.F. Bauer, A. Cotte, G.M.T.H. de Moor, E.G. Goldner, C. Heier, R.T. Holmes, S.A. Hughes, L. Jin, M. Kapadia, C. Menon, S.A. Mullendore, E.M. Paris, G.A. Provost, A.R. Romano, C. Srivastava, T.A. Vencill, N.S. Whitney, and T.W. Yeskoo, A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State, *Renewable Energy*, *86*, 75-88 2016, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

- **Roadmap to transition each of the 50 United States:**

Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, *Energy and Environmental Sciences*, *8*, 2093-2117, doi:10.1039/C5EE01283J, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html, http://pubs.rsc.org/en/content/articlelanding/2014/ee/c5ee01283j#!divAbstract

- **Grid reliability study of the 48 contiguous United States (Available Nov. 23)**

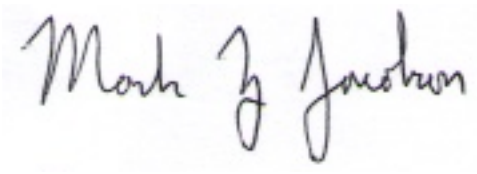
Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, *Proc. Nat. Acad. Sci.*, *112*, doi: 10.1073/pnas.1510028112, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html.

- **Roadmap to transition 139 countries of the world:**

Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, S.H. Harrison, T.M. Kwasnik, J. Liu, J. Lo, C.J. Yi, S.B. Morris, K.R. Moy, P.L. O'Neill, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, and A.S. Yachanin, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, 2015, http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html.

Thank you for considering this testimony.

Sincerely,



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