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2016 Frew and Jacobson, *Energy*
https://web.stanford.edu/group/efmh/jacobson/Articles/Others/16-Frew-Energy-B.pdf
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2018 Jacobson et al., *Renewable Energy*
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2018 Jacobson et al., *Sustainable Cities and Society*
http://web.stanford.edu/group/efmh/jacobson/Articles/I/TownsCities.pdf
2019 Jacobson et al., *One Earth*
http://web.stanford.edu/group/efmh/jacobson/Articles/I/143WWSCountries.pdf

Link to Infographic Maps of 100% WWS Roadmaps for Cities, States, Countries

The Solutions Project - Infographics
http://www.thesolutionsproject.org/why-clean-energy/

Review of solutions to global warming, air pollution, and energy security†

Mark Z. Jacobson*

Received 12th June 2008, Accepted 31st October 2008
First published as an Advance Article on the web 1st December 2008
DOI: 10.1039/b809990c

This paper reviews and ranks major proposed energy-related solutions to global warming, air pollution mortality, and energy security while considering other impacts of the proposed solutions, such as on water supply, land use, wildlife, resource availability, thermal pollution, water chemical pollution, nuclear proliferation, and undernutrition. Nine electric power sources and two liquid fuel options are considered. The electricity sources include solar-photovoltaics (PV), concentrated solar power (CSP), wind, geothermal, hydroelectric, wave, tidal, nuclear, and coal with carbon capture and storage (CCS) technology. The liquid fuel options include corn-ethanol (E85) and cellulosic-E85. To place the electric and liquid fuel sources on an equal footing, we examine their comparative abilities to address the problems mentioned by powering new-technology vehicles, including battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), and flex-fuel vehicles run on E85. Twelve combinations of energy source-vehicle type are considered. Upon ranking and weighting each combination with respect to each of 11 impact categories, four clear divisions of ranking, or tiers, emerge. Tier 1 (highest-ranked) includes wind-BEVs and wind-HFCVs. Tier 2 includes CSP-BEVs, geothermal-BEVs, PV-BEVs, tidal-BEVs, and wave-BEVs. Tier 3 includes hydro-BEVs, nuclear-BEVs, and CCS-BEVs. Tier 4 includes corn- and cellulosic-E85. Wind-BEVs ranked first in seven out of 11 categories, including the two most important, mortality and climate damage reduction. Although HFCVs are much less efficient than BEVs, wind-HFCVs are still very clean and were ranked second among all combinations. Tier 2 options provide significant benefits and are recommended. Tier 3 options are less desirable. However, hydroelectricity, which was ranked ahead of coal-CCS and nuclear with respect to climate and health, is an excellent load balancer, thus recommended. The Tier 4 combinations (cellulosic- and corn-E85) were ranked lowest overall and with respect to climate, air pollution, land use, wildlife damage, and chemical waste. Cellulosic-E85 ranked lower than corn-E85 overall, primarily due to its potentially larger land footprint based on new data and its higher upstream air pollution emissions than corn-E85. Whereas cellulosic-E85 may cause the greatest average human mortality, nuclear-BEVs cause the greatest upper-limit mortality risk due to the expansion of plutonium separation and uranium enrichment in nuclear

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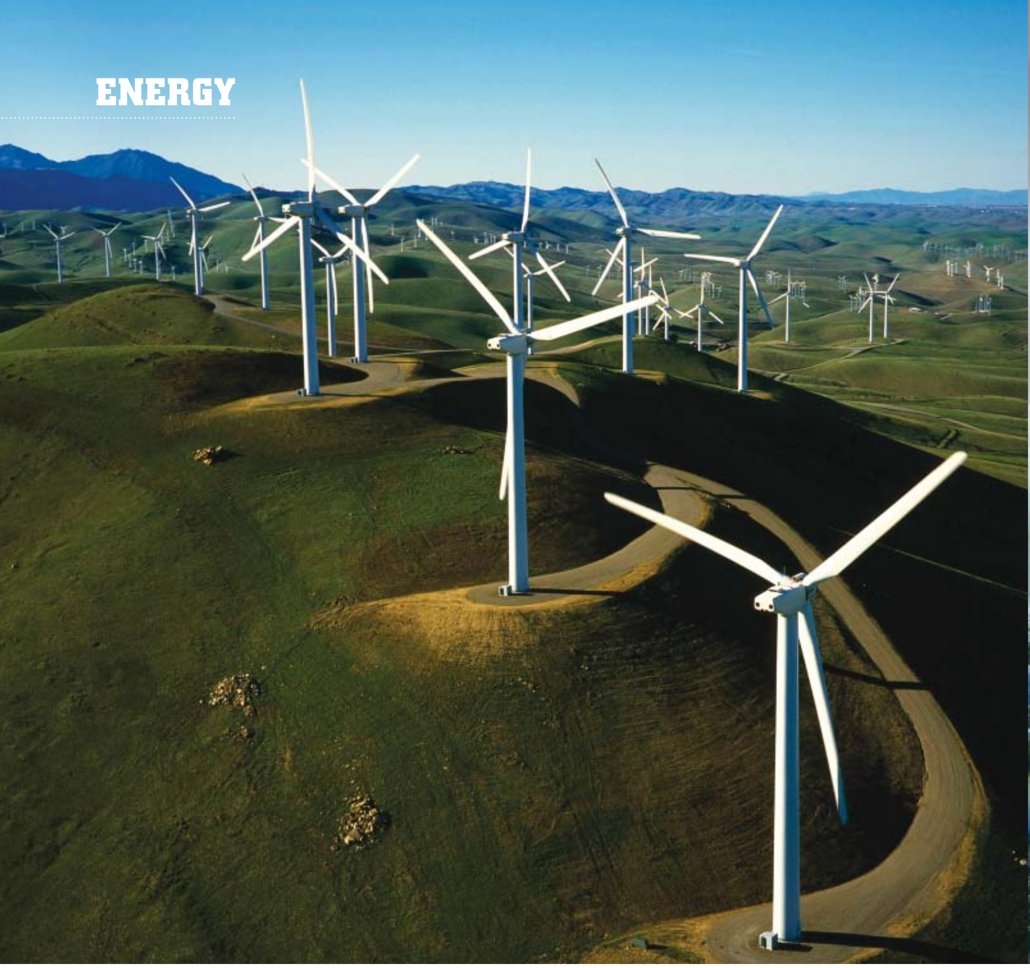
† Electronic supplementary information (ESI) available: Derivation of results used for this study. See DOI: 10.1039/b809990c

Broader context

This paper reviews and ranks major proposed energy-related solutions to global warming, air pollution mortality, and energy security while considering impacts of the solutions on water supply, land use, wildlife, resource availability, reliability, thermal pollution, water pollution, nuclear proliferation, and undernutrition. To place electricity and liquid fuel options on an equal footing, twelve combinations of energy sources and vehicle type were considered. The overall rankings of the combinations (from highest to lowest) were (1) wind-powered battery-electric vehicles (BEVs), (2) wind-powered hydrogen fuel cell vehicles, (3) concentrated-solar-powered-BEVs, (4) geothermal-powered-BEVs, (5) tidal-powered-BEVs, (6) solar-photovoltaic-powered-BEVs, (7) wave-powered-BEVs, (8) hydroelectric-powered-BEVs, (9-tie) nuclear-powered-BEVs, (9-tie) coal-with-carbon-capture-powered-BEVs, (11) corn-E85 vehicles, and (12) cellulosic-E85 vehicles. The relative ranking of each electricity option for powering vehicles also applies to the electricity source providing general electricity. Because sufficient clean natural resources (e.g., wind, sunlight, hot water, ocean energy, etc.) exist to power the world for the foreseeable future, the results suggest that the diversion to less-efficient (nuclear, coal with carbon capture) or non-efficient (corn- and cellulosic E85) options represents an opportunity cost that will delay solutions to global warming and air pollution mortality. The sound implementation of the recommended options requires identifying good locations of energy resources, updating the transmission system, and mass-producing the clean energy and vehicle technologies, thus cooperation at multiple levels of government and industry.



A PATH TO SUSTAINABLE ENERGY BY 2030

Wind, water and solar technologies can provide 100 percent of the world's energy, eliminating all fossil fuels. HERE'S HOW

By Mark Z. Jacobson and Mark A. Delucchi

In December leaders from around the world will meet in Copenhagen to try to agree on cutting back greenhouse gas emissions for decades to come. The most effective step to implement that goal would be a massive shift away from fossil fuels to clean, renewable energy sources. If leaders can have confidence that such a transformation is possible, they might commit to an historic agreement. We think they can.

A year ago former vice president Al Gore threw down a gauntlet: to repower America with 100 percent carbon-free electricity within 10 years. As the two of us started to evaluate the feasibility of such a change, we took on an even larger challenge: to determine how 100 percent of the world's energy, for *all* purposes, could be supplied by wind, water and solar resources, by as early as 2030. Our plan is presented here.

Scientists have been building to this moment for at least a decade, analyzing various pieces of the challenge. Most recently, a 2009 Stanford University study ranked energy systems according to their impacts on global warming, pollution, water supply, land use, wildlife and other concerns. The very best options were wind, solar, geothermal, tidal and hydroelectric power—all of which are driven by wind, water or sunlight (referred to as WWS). Nuclear power, coal with carbon capture, and ethanol were all poorer options, as were oil and natural gas. The study also found that battery-electric vehicles and hydrogen fuel-cell vehicles recharged by WWS options would largely eliminate pollution from the transportation sector.

Our plan calls for millions of wind turbines, water machines and solar installations. The numbers are large, but the scale is not an insurmountable hurdle; society has achieved massive

JOHN LEE *Aurora Photos (wind farm)*; BILL HEINSOHN *Aurora Photos (dam)*

Energy Policy 39 (2011) 1154–1169

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials

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ARTICLE INFO

Article history:
Received 3 September 2010
Accepted 22 November 2010
Available online 30 December 2010

Keywords:
Wind power
Solar power
Water power

ABSTRACT

Climate change, pollution, and energy insecurity are among the greatest problems of our time. Addressing them requires major changes in our energy infrastructure. Here, we analyze the feasibility of providing worldwide energy for all purposes (electric power, transportation, heating/cooling, etc.) from wind, water, and sunlight (WWS). In Part I, we discuss WWS energy system characteristics, current and future energy demand, availability of WWS resources, numbers of WWS devices, and area and material requirements. In Part II, we address variability, economics, and policy of WWS energy. We estimate that ~3,800,000 5 MW wind turbines, ~49,000 300 MW concentrated solar plants, ~40,000 300 MW solar PV power plants, ~1.7 billion 3 kW rooftop PV systems, ~5350 100 MW geothermal power plants, ~270 new 1300 MW hydroelectric power plants, ~720,000 0.75 MW wave devices, and ~490,000 1 MW tidal turbines can power a 2030 WWS world that uses electricity and electrolytic hydrogen for all purposes. Such a WWS infrastructure reduces world power demand by 30% and requires only ~0.41% and ~0.59% more of the world's land for footprint and spacing, respectively. We suggest producing all new energy with WWS by 2030 and replacing the pre-existing energy by 2050. Barriers to the plan are primarily social and political, not technological or economic. The energy cost in a WWS world should be similar to that today.

1. Introduction

A solution to the problems of climate change, air pollution, water pollution, and energy insecurity requires a large-scale conversion to clean, perpetual, and reliable energy at low cost together with an increase in energy efficiency. Over the past decade, a number of studies have proposed large-scale renewable energy plans. Jacobson and Masters (2001) suggested that the U.S. could satisfy its Kyoto Protocol requirement for reducing carbon dioxide emissions by replacing 60% of its coal generation with 214,000–236,000 wind turbines rated at 1.5 MW (million watts). Also in 2001, Czisch (2006) suggested that a totally renewable electricity supply system, with intercontinental transmission lines linking dispersed wind sites with hydropower backup, could supply Europe, North Africa, and East Asia at total costs per kWh comparable with the costs of the current system. Hoffert et al. (2002) suggested a portfolio of solutions for stabilizing atmospheric CO_2, including increasing the use of renewable energy and nuclear energy, decarbonizing fossil fuels and sequestering carbon, and improving energy efficiency. Pacala and Socolow (2004) suggested a similar portfolio, but expanded it to include reductions in deforestation and conservation tillage and greater use of hydrogen in vehicles.

More recently, Fthenakis et al. (2009) analyzed the technical, geographical, and economic feasibility for solar energy to supply the energy needs of the U.S. and concluded (p. 397) that "it is clearly feasible to replace the present fossil fuel energy infrastructure in the U.S. with solar power and other renewables, and reduce CO_2 emissions to a level commensurate with the most aggressive climate-change goals". Jacobson (2009) evaluated several long-term energy systems according to environmental and other criteria, and found WWS systems to be superior to nuclear, fossil-fuel, and biofuel systems (see further discussion in Section 2). He proposed to address the hourly and seasonal variability of WWS power by interconnecting geographically disperse renewable energy sources to smooth out loads, using hydroelectric power to fill in gaps in supply. He also proposed using battery-electric vehicles (BEVs) together with utility controls of electricity dispatch to them through smart meters, and storing electricity in hydrogen or solar-thermal storage media. Cleetus et al. (2009) subsequently presented a "blueprint" for a clean-energy economy to reduce CO_2-equivalent GHG emissions in the U.S. by 56% compared with the 2005 levels. That study featured an economy-wide CO_2

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doi:10.1016/j.enpol.2010.11.040

Energy Policy 39 (2011) 1170–1190

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies

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ARTICLE INFO

Article history:
Received 3 September 2010
Accepted 22 November 2010
Available online 31 December 2010

Keywords:
Wind power
Solar power
Water power

ABSTRACT

This is Part II of two papers evaluating the feasibility of providing all energy for all purposes (electric power, transportation, and heating/cooling), everywhere in the world, from wind, water, and the sun (WWS). In Part I, we described the prominent renewable energy plans that have been proposed and discussed the characteristics of WWS energy systems, the global demand for and availability of WWS energy, quantities and areas required for WWS infrastructure, and supplies of critical materials. Here, we discuss methods of addressing the variability of WWS energy to ensure that power supply reliably matches demand (including interconnecting geographically dispersed resources, using hydroelectricity, using demand-response management, storing electric power on site, over-sizing peak generation capacity and producing hydrogen with the excess, storing electric power in vehicle batteries, and forecasting weather to project energy supplies), the economics of WWS generation and transmission, the economics of WWS use in transportation, and policy measures needed to enhance the viability of a WWS system. We find that the cost of energy in a 100% WWS will be similar to the cost today. We conclude that barriers to a 100% conversion to WWS power worldwide are primarily social and political, not technological or even economic.

1. Variability and reliability in a 100% WWS energy system in all regions of the world

One of the major concerns with the use of energy supplies, such as wind, solar, and wave power, which produce variable output is whether such supplies can provide reliable sources of electric power second-by-second, daily, seasonally, and yearly. A new WWS energy infrastructure must be able to provide energy on demand at least as reliably as does the current infrastructure (e.g., De Carolis and Keith, 2005). In general, any electricity system must be able to respond to changes in demand over seconds, minutes, hours, seasons, and years, and must be able to accommodate unanticipated changes in the availability of generation. With the current system, electricity-system operators use “automatic generation control” (AGC) (or frequency regulation) to respond to variation on the order of seconds to a few minutes; spinning reserves to respond to variation on the order of minutes to an hour; and peak-power generation to respond to hourly variation (De Carolis and Keith, 2005; Kempton and Tomic, 2005a; Electric Power Research Institute, 1997). AGC and spinning reserves have very low cost, typically less than 10% of the total cost of electricity (Kempton and Tomic, 2005a), and are likely to remain this inexpensive even with large amounts of wind power (EnerNex, 2010; DeCesaro et al., 2009), but peak-power generation can be very expensive.

The main challenge for the current electricity system is that electric power demand varies during the day and during the year, while most supply (coal, nuclear, and geothermal) is constant during the day, which means that there is a difference to be made up by peak- and gap-filling resources such as natural gas and hydropower. Another challenge to the current system is that extreme events and unplanned maintenance can shut down plants unexpectedly. For example, unplanned maintenance can shut down coal plants, extreme heat waves can cause cooling water to warm sufficiently to shut down nuclear plants, supply disruptions can curtail the availability of natural gas, and droughts can reduce the availability of hydroelectricity.

A WWS electricity system offers new challenges but also new opportunities with respect to reliably meeting energy demands. On the positive side, WWS technologies generally suffer less downtime than do current electric power technologies. For example, the average coal plant in the US from 2000 to 2004 was down 6.5% of the year for unscheduled maintenance and 6.0% of the year for scheduled maintenance (North American Electric Reliability Corporation, 2009a), but modern wind turbines have a down time of only 0–2% over land and 0–5% over the ocean (Dong Energy et al.,

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doi:10.1016/j.enpol.2010.11.045

Renewable Energy 36 (2011) 2278–2286

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables

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ARTICLE INFO

Article history:
Received 28 September 2010
Accepted 13 January 2011

Keywords:
Renewable energy
Intermittent generation
Wind power
Solar power
Carbon emissions

ABSTRACT

A new generator portfolio planning model is described that is capable of quantifying the carbon emissions associated with systems that include very high penetrations of variable renewables. The model combines a deterministic renewable portfolio planning module with a Monte Carlo simulation of system operation that determines the expected least-cost dispatch from each technology, the necessary reserve capacity, and the expected carbon emissions at each hour. Each system is designed to meet a maximum loss of load expectation requirement of 1 day in 10 years. The present study includes wind, centralized solar thermal, and rooftop photovoltaics, as well as hydroelectric, geothermal, and natural gas plants. The portfolios produced by the model take advantage of the aggregation of variable generators at multiple geographically disperse sites and the incorporation of meteorological and load forecasts. Results are presented from a model run of the continuous two-year period, 2005–2006 in the California ISO operating area. A low-carbon portfolio is produced for this system that is capable of achieving an 80% reduction in electric power sector carbon emissions from 2005 levels and supplying over 99% of the annual delivered load with non-carbon sources. A portfolio is also built for a projected 2050 system, which is capable of providing 96% of the delivered electricity from non-carbon sources, despite a projected doubling of the 2005 system peak load. The results suggest that further reductions in carbon emissions may be achieved with emerging technologies that can reliably provide large capacities without necessarily providing positive net annual energy generation. These technologies may include demand response, vehicle-to-grid systems, and large-scale energy storage.

1. Introduction

In the United States, approximately 40% of the total annual carbon dioxide emissions are associated with the generation of electricity [1]. Significant reductions in carbon emissions within the United States will therefore require a dramatic shift in the composition of the electric power sector. Several technologies already exist to replace generation from coal and natural gas with cleaner alternatives, but the variability and uncertainty in many renewable resources is anticipated to pose political, financial, and technological challenges to large-scale grid integration. Without practical examples of large systems with very high penetrations of variable generation, models must be employed to predict the behavior of these systems. To date, most grid integration models have focused on wind power, though some have included solar technologies. An extensive review of wind power integration studies across Europe can be found in [2] and a review of current energy system modeling tools can be found in [3].

Early attempts at modeling grid integration of variable generation were based on load duration curve analyses, similar to those used for portfolios of conventional generators [4–6]. More recently, however, grid integration has been formulated primarily as an optimization problem with load balance constraints over multiple time steps. Deterministic load balance models have been used to develop scenarios with high penetrations of wind power within different types of preexisting generation portfolios [7], to study the affects of aggregating multiple geographically disperse wind farms [8], and to analyze the operational costs associated with intrahour fluctuations of wind power output [9]. Other grid integration studies have explored how the complementary nature of different renewable energy resources (including wind, solar, wave, geothermal, and/or hydroelectric power) can be used to best match a time-varying power demand [10–16].

The stochastic nature of wind and solar complicates the treatment of system reliability in grid integration studies. Probabilistic models are already used to account for forced outages of

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0960-1481/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2011.01.015

Energy &
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Cite this: *Energy Environ. Sci.*, 2012, **5**, 6592

www.rsc.org/ees

ANALYSIS

The carbon abatement potential of high penetration intermittent renewables†

Elaine K. Hart* **and Mark Z. Jacobson**

Received 18th December 2011, Accepted 23rd February 2012
DOI: 10.1039/c2ee03490e

The carbon abatement potentials of wind turbines, photovoltaics, and concentrating solar power plants were investigated using dispatch simulations over California with 2005–06 meteorological and load data. A parameterization of the simulation results is presented that provides approximations of both low-penetration carbon abatement rates and maximum carbon abatement potentials based on the temporal characteristics of the resource and the load. The results suggest that shallow carbon emissions reductions (up to 20% of the base case) can be achieved most efficiently with geothermal power and demand reductions *via* energy efficiency or conservation. Deep emissions reductions (up to 89% for this closed system), however, may require the build-out of very large fleets of intermittent renewables and improved power system flexibility, communications, and controls. At very high penetrations, combining wind and solar power improved renewable portfolio performance over individual build-out scenarios by reducing curtailment, suggesting that further reductions may be met by importing uncorrelated out-of-state renewable power. The results also suggest that 90–100% carbon emission reductions will rely on the development of demand response and energy storage facilities with power capacities of at least 65% of peak demand and energy capacities large enough to accommodate seasonal energy storage.

1 Introduction

In response to a growing concern over global warming, the last decade has seen a surge in proposals for reducing the carbon dioxide emissions associated with electric power generation, many of which include large build-outs of renewable technologies including wind, photovoltaics (PVs), concentrating solar power (CSP), geothermal, wave, and tidal power. This paper seeks to determine how the temporal characteristics of electric power demand, the variability of renewable resources, and the controls employed by renewable technologies influence the potential for a renewable portfolio to displace carbon-based generation and to reduce carbon dioxide emissions at very high penetrations. Furthermore, we seek to understand which of these factors has the strongest influence on the carbon abatement potential of a given technology, and in the case that a limit to the carbon abatement potential of intermittent renewables exists, what technologies are needed to achieve complete decarbonization of the electricity grid.

In the past, economic analyses of the carbon abatement potential of renewables have tended to assume that renewable

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/c2ee03490e

Broader context

The reliable integration of renewable resources on to the electricity grid represents an important step toward decarbonizing the electric power sector and mitigating global climate change. This step is complicated by both the variability and the uncertainty associated with power output from renewable resources, like wind and solar power. Analyses that seek to quantify system reliability, reserve requirements, and the carbon dioxide emissions associated with operating these reserves have historically relied on simulations with high temporal resolution (typically an hour or less) and with stochastic treatments, both of which increase the computational complexity significantly. However, energy-economic models capable of analyzing the costs and economic impacts of different decarbonization strategies or policies typically use time scales of one year and cannot accurately resolve the phenomena associated with intermittent renewables. In this paper, we develop a parameterization of the results from higher temporal resolution simulations that can be implemented in large-scale energy-economic models. This effort contributes to the improved economic treatment of renewable power sources in analyses used by policymakers and may provide additional insight regarding technological cost targets for innovators.

Energy Policy 57 (2013) 585–601

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight

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HIGHLIGHTS

- New York State's all-purpose energy can be derived from wind, water, and sunlight.
- The conversion reduces NYS end-use power demand by ~37%.
- The plan creates more jobs than lost since most energy will be from in state.
- The plan creates long-term energy price stability since fuel costs will be zero.
- The plan decreases air pollution deaths 4000/yr ($33 billion/yr or 3% of NYS GDP).

ARTICLE INFO

Article history:
Received 14 September 2012
Accepted 18 February 2013
Available online 13 March 2013

Keywords:
Renewable energy
Air pollution
Global warming

ABSTRACT

This study analyzes a plan to convert New York State's (NYS's) all-purpose (for electricity, transportation, heating/cooling, and industry) energy infrastructure to one derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen. Under the plan, NYS's 2030 all-purpose end-use power would be provided by 10% onshore wind (4020 5-MW turbines), 40% offshore wind (12,700 5-MW turbines), 10% concentrated solar (387 100-MW plants), 10% solar-PV plants (828 50-MW plants), 6% residential rooftop PV (~5 million 5-kW systems), 12% commercial/government rooftop PV (~500,000 100-kW systems), 5% geothermal (36 100-MW plants), 0.5% wave (1910 0.75-MW devices), 1% tidal (2600 1-MW turbines), and 5.5% hydroelectric (6.6 1300-MW plants, of which 89% exist). The conversion would reduce NYS's end-use power demand ~37% and stabilize energy prices since fuel costs would be zero. It would create more jobs than lost because nearly all NYS energy would now be produced in-state. NYS air pollution mortality and its costs would decline by ~4000 (1200–7600) deaths/yr, and $33 (10–76) billion/yr (3% of 2010 NYS GDP), respectively, alone repaying the 271 GW installed power needed within ~17 years, before accounting for electricity sales. NYS's own emission decreases would reduce 2050 U.S. climate costs by ~$3.2 billion/yr.

1. Introduction

This is a study to examine the technical and economic feasibility of and propose policies for converting New York State's (NYS's) energy infrastructure in all sectors to one powered by wind, water, and sunlight (WWS). The plan is a localized microcosm of that developed for the world and U.S. by Jacobson and Delucchi (2009, 2011) and Delucchi and Jacobson (2011). Recently, other plans involving different levels of energy conversion for some or multiple energy sectors have been developed at national or continental scales (e.g., Alliance for Climate Protection, 2009; Parsons-Brinckerhoff, 2009; Kemp and Wexler, 2010; Price-Waterhouse-Coopers, 2010; Beyond Zero Emissions, 2010; European Climate Foundation (ECF), 2010; European Renewable Energy Council (EREC), 2010; World Wildlife Fund, 2011).

Limited plans are currently in place in New York City (PlaNYC, 2011) and NYS (Power, 2011) to help the city and state, respectively, provide predictable and sustainable energy, improve the

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0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.02.036

Energy 73 (2014) 875–889

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A roadmap for repowering California for all purposes with wind, water, and sunlight

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A R T I C L E I N F O

Article history:
Received 16 December 2013
Received in revised form
21 June 2014
Accepted 26 June 2014
Available online 22 July 2014

Keywords:
Renewable energy
Air pollution
Global warming

A B S T R A C T

This study presents a roadmap for converting California's all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructure to one derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen. California's available WWS resources are first evaluated. A mix of WWS generators is then proposed to match projected 2050 electric power demand after all sectors have been electrified. The plan contemplates all *new* energy from WWS by 2020, 80–85% of existing energy converted by 2030, and 100% by 2050. Electrification plus modest efficiency measures may reduce California's end-use power demand ~44% and stabilize energy prices since WWS fuel costs are zero. Several methods discussed should help generation to match demand. A complete conversion in California by 2050 is estimated to create ~220,000 more 40-year jobs than lost, eliminate ~12,500 (3800–23,200) state air-pollution premature mortalities/yr, avoid $103 (31–232) billion/yr in health costs, representing 4.9 (1.5–11.2)% of California's 2012 gross domestic product, and reduce California's 2050 global climate cost contribution by $48 billion/yr. The California air-pollution health plus global climate cost benefits from eliminating California emissions could equal the $1.1 trillion installation cost of 603 GW of new power needed for a 100% all-purpose WWS system within ~7 (4–14) years.

1. Introduction

This paper presents a roadmap for converting California's energy infrastructure in all sectors to one powered by wind, water, and sunlight (WWS). The California plan is similar in outline to one recently developed for New York State [39], but expands, deepens, and adapts the analysis for California in several important ways. The estimates of energy demand and potential supply are developed specifically for California, which has a higher population, faster population growth, greater total energy use, and larger transportation share of total energy, but lower energy-use per capita, than does New York. The California analysis also includes originally-derived (1) computer-simulated resource analyses for both wind and solar, (2) calculations of current and future rooftop and parking structure areas and resulting maximum photovoltaic (PV) capacities for 2050, (3) air-pollution mortality calculations considering three years of hourly data at all air quality monitoring stations in the state, (4) estimates of cost reductions associated

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http://dx.doi.org/10.1016/j.energy.2014.06.099
0360-5442/

Energy 72 (2014) 443–458

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Features of a fully renewable US electricity system: Optimized mixes of wind and solar PV and transmission grid extensions

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ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form
15 May 2014
Accepted 17 May 2014
Available online 18 June 2014

Keywords:
Energy system design
Large-scale integration of renewable power generation
Wind power generation
Solar PV power generation
Power transmission

ABSTRACT

A future energy system is likely to rely heavily on wind and solar PV. To quantify general features of such a weather dependent electricity supply in the contiguous US, wind and solar PV generation data are calculated, based on 32 years of weather data with temporal resolution of 1 h and spatial resolution of 40×40 km^2, assuming site-suitability-based and stochastic wind and solar capacity distributions. The regional wind-and-solar mixes matching load and generation closest on seasonal timescales cluster around 80% solar share, owing to the US summer load peak. This mix more than halves long-term storage requirements, compared to wind only. The mixes matching generation and load best on daily timescales lie at about 80% wind share, due to the nightly gap in solar production. Going from solar only to this mix reduces backup energy needs by about 50%. Furthermore, we calculate shifts in FERC (Federal Energy Regulatory Commission)-level LCOE (Levelized Costs Of Electricity) for wind and solar PV due to differing weather conditions. Regional LCOE vary by up to 29%, and LCOE-optimal mixes largely follow resource quality. A transmission network enhancement among FERC regions is constructed to transfer high penetrations of solar and wind across FERC boundaries, employing a novel least-cost optimization.

1. Introduction

CO_2 and air pollution emission reduction goals as well as energy security, price stability, and affordability considerations make renewable electricity generation attractive. A highly renewable electricity supply will be based to a large extent on wind and solar photovoltaic (PV) power, since these two resources are both abundant and either relatively inexpensive or rapidly becoming cost competitive [1]. Such a system demands a fundamentally different design approach: While electricity generation was traditionally constructed to be dispatchable in order to follow the demand, wind and solar PV power output is largely determined by weather conditions that are out of human control. We therefore collectively term them VRES (variable renewable energy sources).

Spatial aggregation has a favorable impact on generation characteristics, as was found both for wind and solar PV power in numerous studies [2–9]. Especially for wind, smoothing effects are much more pronounced on large scales, as can be seen from the comparison of the US East coast (about 3000×500 km^2), discussed in Ref. [8], to Denmark (about 200×300 km^2), cf. Ref. [9]. In spite of the leveling effects of aggregation, there is still a considerable mismatch between load and generation left, which is partly due also to load variability.

This paper aims to identify general design features for the US power system with a high share of wind and solar PV. While several studies have demonstrated the feasibility of high penetrations of VRES generators in the regional or nationwide US electric system [11–14], these have only evaluated one individual US region and/or have only considered a small set of hours for their analysis. This paper is based on data for the entire contiguous US of unprecedented temporal length and spatial resolution. Relying on 32 years of weather data with hourly time resolution and a spatial resolution of 40×40 km^2, potential future wind and solar PV generation time

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http://dx.doi.org/10.1016/j.energy.2014.05.067
0360-5442/

Energy 81 (2015) 437–445

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Renewable build-up pathways for the US: Generation costs are not system costs

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ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form
15 December 2014
Accepted 21 December 2014
Available online 27 January 2015

Keywords:
Energy system design
Large-scale integration of renewable power generation
Renewable power generation
Optimal mix of wind and solar PV
Levelized cost of electricity

ABSTRACT

The transition to a future electricity system based primarily on wind and solar PV is examined for all regions in the contiguous US. We present optimized pathways for the build-up of wind and solar power for least backup energy needs as well as for least cost obtained with a simplified, lightweight model based on long-term high resolution weather-determined generation data. In the absence of storage, the pathway which achieves the best match of generation and load, thus resulting in the least backup energy requirements, generally favors a combination of both technologies, with a wind/solar PV (photovoltaics) energy mix of about 80/20 in a fully renewable scenario. The least cost development is seen to start with 100% of the technology with the lowest average generation costs first, but with increasing renewable installations, economically unfavorable excess generation pushes it toward the minimal backup pathway. Surplus generation and the entailed costs can be reduced significantly by combining wind and solar power, and/or absorbing excess generation, for example with storage or transmission, or by coupling the electricity system to other energy sectors.

1. Introduction

We investigate highly renewable electricity scenarios for the contiguous US. In this paper, the main focus is placed on the optimization of the mix of wind and solar PV power during the renewable build-up. While numerous studies investigate regional or nationwide fully renewable power systems [1–7], they usually focus on detailed single scenarios or pathways and/or only cost-optimal installations. Here, a simplified and computationally lightweight description based on high-resolution wind, solar PV, and load data is used to survey a large number of possible renewable scenarios and derive systematic insights from the spatio-temporal characteristics of the generation-load mismatch.

In our model of the electricity system, the supply is largely reliant on the variable renewable energy sources wind and solar PV power, which we abbreviate as VRES (variable renewable energy sources). CSP (concentrated solar power) is not implemented yet. The rest of the electricity generation is assumed to be dispatchable, and it is implied that it is used to cover the residual demand that remains after VRES generation has been subtracted from the load. From this point of view, the dispatchable part of the power system will be referred to as the backup system, and correspondingly, the energy from this system will be termed backup energy. Examples for backup power plants in a fully renewable setting are hydroelectric power, geothermal power, and to some extent CSP with thermal storage. In general, any other form of dispatchable generation can be used. The share of VRES in the system is measured as gross share, i.e. the total VRES generation divided by the total load. Due to temporal mismatches in generation and load, the VRES net share, i.e. the amount of VRE (variable renewable energy) actually consumed in the electricity system at the time of their generation is generally lower. Even in a system with a VRES gross share of 100%, the load will partly be covered from backup. This renders contributions from dispatchable renewable sources crucial to a fully renewable system.

To get an impression of the dimensions of the installations, current and extrapolated renewable installations are shown in

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http://dx.doi.org/10.1016/j.energy.2014.12.056

Energy & Environmental Science

PAPER

Cite this: *Energy Environ. Sci.*, 2015, **8**, 2093

100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States†

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This study presents roadmaps for each of the 50 United States to convert their all-purpose energy systems (for electricity, transportation, heating/cooling, and industry) to ones powered entirely by wind, water, and sunlight (WWS). The plans contemplate 80–85% of existing energy replaced by 2030 and 100% replaced by 2050. Conversion would reduce each state's end-use power demand by a mean of ∼39.3% with ∼82.4% of this due to the efficiency of electrification and the rest due to end-use energy efficiency improvements. Year 2050 end-use U.S. all-purpose load would be met with ∼30.9% onshore wind, ∼19.1% offshore wind, ∼30.7% utility-scale photovoltaics (PV), ∼7.2% rooftop PV, ∼7.3% concentrated solar power (CSP) with storage, ∼1.25% geothermal power, ∼0.37% wave power, ∼0.14% tidal power, and ∼3.01% hydroelectric power. Based on a parallel grid integration study, an additional 4.4% and 7.2% of power beyond that needed for annual loads would be supplied by CSP with storage and solar thermal for heat, respectively, for peaking and grid stability. Over all 50 states, converting would provide ∼3.9 million 40-year construction jobs and ∼2.0 million 40-year operation jobs for the energy facilities alone, the sum of which would outweigh the ∼3.9 million jobs lost in the conventional energy sector. Converting would also eliminate ∼62 000 (19 000–115 000) U.S. air pollution premature mortalities per year today and ∼46 000 (12 000–104 000) in 2050, avoiding ∼$600 ($85–$2400) bil. per year (2013 dollars) in 2050, equivalent to ∼3.6 (0.5–14.3) percent of the 2014 U.S. gross domestic product. Converting would further eliminate ∼$3.3 (1.9–7.1) tril. per year in 2050 global warming costs to the world due to U.S. emissions. These plans will result in each person in the U.S. in 2050 saving ∼$260 (190–320) per year in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ∼$1500 (210–6000) per year and ∼$8300 (4700–17 600) per year, respectively. The new footprint over land required will be ∼0.42% of U.S. land. The spacing area between wind turbines, which can be used for multiple purposes, will be ∼1.6% of U.S. land. Thus, 100% conversions are technically and economically feasible with little downside. These roadmaps may therefore reduce social and political barriers to implementing clean-energy policies.

Received 25th April 2015,
Accepted 27th May 2015

DOI: 10.1039/c5ee01283j

www.rsc.org/ees

Broader context

This paper presents a consistent set of roadmaps for converting the energy infrastructures of each of the 50 United States to 100% wind, water, and sunlight (WWS) for all purposes (electricity, transportation, heating/cooling, and industry) by 2050. Such conversions are obtained by first projecting conventional power demand to 2050 in each sector then electrifying the sector, assuming the use of some electrolytic hydrogen in transportation and industry and applying modest end-use energy efficiency improvements. Such state conversions may reduce conventional 2050 U.S.-averaged power demand by ∼39%, with most reductions due to the efficiency of electricity over combustion and the rest due to modest end-use energy efficiency improvements. The conversions are found to be technically and economically feasible with little downside. They nearly eliminate energy-related U.S. air pollution and climate-relevant emissions and their resulting health and environmental costs while creating jobs, stabilizing energy prices, and minimizing land requirements. These benefits have not previously been quantified for the 50 states. Their elucidation may reduce the social and political barriers to implementing clean-energy policies for replacing conventional combustible and nuclear fuels. Several such policies are proposed herein for each energy sector.

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/c5ee01283j

1. Introduction

This paper presents a consistent set of roadmaps to convert each of the 50 U.S. states' all-purpose (electricity, transportation,

PNAS

Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes

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Edited by Stephen Polasky, University of Minnesota, St. Paul, MN, and approved November 2, 2015 (received for review May 26, 2015)

This study addresses the greatest concern facing the large-scale integration of wind, water, and solar (WWS) into a power grid: the high cost of avoiding load loss caused by WWS variability and uncertainty. It uses a new grid integration model and finds low-cost, no-load-loss, nonunique solutions to this problem on electrification of all US energy sectors (electricity, transportation, heating/cooling, and industry) while accounting for wind and solar time series data from a 3D global weather model that simulates extreme events and competition among wind turbines for available kinetic energy. Solutions are obtained by prioritizing storage for heat (in soil and water); cold (in ice and water); and electricity (in phase-change materials, pumped hydro, hydropower, and hydrogen), and using demand response. No natural gas, biofuels, nuclear power, or stationary batteries are needed. The resulting 2050–2055 US electricity social cost for a full system is much less than for fossil fuels. These results hold for many conditions, suggesting that low-cost, reliable 100% WWS systems should work many places worldwide.

energy security | climate change | grid stability | renewable energy | energy cost

Worldwide, the development of wind, water, and solar (WWS) energy is expanding rapidly because it is sustainable, clean, safe, widely available, and, in many cases, already economical. However, utilities and grid operators often argue that today's power systems cannot accommodate significant variable wind and solar supplies without failure (1). Several studies have addressed some of the grid reliability issues with high WWS penetrations (2–21), but no study has analyzed a system that provides the maximum possible long-term environmental and social benefits, namely supplying all energy end uses with only WWS power (no natural gas, biofuels, or nuclear power), with no load loss at reasonable cost. This paper fills this gap. It describes the ability of WWS installations, determined consistently over each of the 48 contiguous United States (CONUS) and with wind and solar power output predicted in time and space with a 3D climate/weather model, accounting for extreme variability, to provide time-dependent load reliably and at low cost when combined with storage and demand response (DR) for the period 2050–2055, when a 100% WWS world may exist.

Materials and Methods

The key to this study is the development of a grid integration model (LOADMATCH). Inputs include time-dependent loads (every 30 s for 6 y); time-dependent intermittent wind and solar resources (every 30 s for 6 y) predicted with a 3D global climate/weather model; time-dependent hydropower, geothermal, tidal, and wave resources; capacities and maximum charge/discharge rates of several types of storage technologies, including hydrogen (H_2); specifications of losses from storage, transmission, distribution, and maintenance; and specifications of a DR system.

Loads and Storage. CONUS loads for 2050–2055 for use in LOADMATCH are derived as follows. Annual CONUS loads are first estimated for 2050 assuming each end-use energy sector (residential, transportation, commercial, industrial) is converted to electricity and some electrolytic hydrogen after accounting for modest improvements in end-use energy efficiency (22). Annual loads in each sector are next separated into cooling and heating loads that can be met with thermal energy storage (TES), loads that can be met with hydrogen production and storage, flexible loads that can be met with DR, and inflexible loads (Table 1).

Most (50–95%) air conditioning and refrigeration and most (85–95%) air heating and water heating are coupled with TES (Table 1). Cooling coupled with storage is tied to chilled water (sensible-heat) TES (STES) and ice production and melting [phase-change material (PCM)-ice] (*SI Appendix*, Table S1). All building air- and water-heating coupled with storage uses underground TES (UTES) in soil. UTES storage is patterned after the seasonal and short-term district heating UTES system at the Drake Landing Community, Canada (23). The fluid (e.g., glycol solution) that heats water that heats the soil and rocks is itself heated by sunlight or excess electricity.

Overall, 85% of the transportation load and 70% of the loads for industrial high temperature, chemical, and electrical processes are assumed to be flexible or produced from H_2 (Table 1).

Six types of storage are treated (*SI Appendix*, Table S1): three for air and water heating/cooling (STES, UTES, and PCM-ice); two for electric power generation [pumped hydropower storage (PHS) and phase-change materials coupled with concentrated solar power plants (PCM-CSP)]; and one for transport or high-temperature processes (hydrogen). Hydropower (with reservoirs) is treated as an electricity source on demand, but because reservoirs can be recharged only naturally they are not treated as artificially rechargeable storage. Lithium-ion batteries are used to power battery-electric vehicles but to avoid battery degradation, not to feed power from vehicles to the grid. Batteries for stationary power storage work well in this system too. However, because they currently cost more than the other storage technologies used (24), they are prioritized lower and are found not

Significance

The large-scale conversion to 100% wind, water, and solar (WWS) power for all purposes (electricity, transportation, heating/cooling, and industry) is currently inhibited by a fear of grid instability and high cost due to the variability and uncertainty of wind and solar. This paper couples numerical simulation of time- and space-dependent weather with simulation of time-dependent power demand, storage, and demand response to provide low-cost solutions to the grid reliability problem with 100% penetration of WWS across all energy sectors in the continental United States between 2050 and 2055. Solutions are obtained without higher-cost stationary battery storage by prioritizing storage of heat in soil and water; cold in water and ice; and electricity in phase-change materials, pumped hydro, hydropower, and hydrogen.

Author contributions: M.Z.J. designed research; M.Z.J. and M.A.D. performed research; M.Z.J., M.A.D., M.A.C., and B.A.F. contributed analytic tools; M.Z.J., M.A.D., and M.A.C. analyzed data; and M.Z.J., M.A.D., M.A.C., and B.A.F. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data available upon request (from M.Z.J.).

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1510028112/-/DCSupplemental.

Renewable Energy 86 (2016) 75–88

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State

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ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form
31 July 2015
Accepted 1 August 2015
Available online xxx

Keywords:
Renewable energy
Air pollution
Global warming
Wind
Solar
Energy cost

ABSTRACT

This study analyzes the potential and consequences of Washington State's use of wind, water, and sunlight (WWS) to produce electricity and electrolytic hydrogen for 100% of its all-purposes energy (electricity, transportation, heating/cooling, industry) by 2050, with 80–85% conversion by 2030. Electrification plus modest efficiency measures can reduce Washington State's 2050 end-use power demand by ~39.9%, with ~80% of the reduction due to electrification, and can stabilize energy prices since WWS fuel costs are zero. The remaining demand can be met, in one scenario, with ~35% onshore wind, ~13% offshore wind, ~10.73% utility-scale PV, ~2.9% residential PV, ~1.5% commercial/government PV, ~0.65% geothermal, ~0.5% wave, ~0.3% tidal, and ~35.42% hydropower. Converting will require only 0.08% of the state's land for new footprint and ~2% for spacing between new wind turbines (spacing that can be used for multiple purposes). It will further result in each person in the state saving ~$85/yr in direct energy costs and ~$950/yr in health costs [eliminating ~830 (190–1950)/yr statewide premature air pollution mortalities] while reducing global climate costs by ~$4200/person/yr (all in 2013 dollars). Converting will therefore improve health and climate while reducing costs.

1. Introduction

This paper analyzes a roadmap for converting Washington State's all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructure to one powered by wind, water, and sunlight (WWS). Existing energy plans in Washington State are largely embodied in the 2012 Washington State Energy Strategy and Biennial Energy Reports [48]. Both address the need to reduce greenhouse gas emissions, keep energy prices low, and foster jobs. However, the goals in those reports are limited to emission reductions based on a 2008 state law that requires reducing statewide greenhouse gas emissions to 1990 levels by 2020, to 25% below 1990 levels by 2035, and to 50% below 1990 levels by 2050. The plan proposed here outlines not only how to achieve Washington State's current goals but also how to achieve much more aggressive goals: eliminating 80–85% of present-day greenhouse-gas and air-pollutant emissions by 2030 and 100% by 2050.

Several previous studies have analyzed proposals for near 100% WWS penetration in one or more energy sectors of a region (e.g. Refs. [23,24,19,5,3,31,2,30]). The plan proposed here is similar in outline to ones recently developed for New York State and California [25,26]. However, the estimates of energy demand, potential supply, and proposed policy measures here are developed specifically for Washington State, which has greater installed hydropower and thus more built-in storage for matching power supply

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http://dx.doi.org/10.1016/j.renene.2015.08.003
0960-1481/

Energy 101 (2016) 65–78

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Flexibility mechanisms and pathways to a highly renewable US electricity future

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ARTICLE INFO

Article history:
Received 17 April 2015
Received in revised form
22 January 2016
Accepted 25 January 2016
Available online xxx

Keywords:
Renewable energy integration
Energy system analysis
Aggregation
Storage
Transmission
Electric vehicle charging

ABSTRACT

This study explores various scenarios and flexibility mechanisms to integrate high penetrations of renewable energy into the US (United States) power grid. A linear programming model – POWER (Power system Optimization With diverse Energy Resources) – is constructed and used to (1) quantify flexibility cost-benefits of geographic aggregation, renewable overgeneration, storage, and flexible electric vehicle charging, and (2) compare pathways to a fully renewable electricity system. Geographic aggregation provides the largest flexibility benefit with ~5–50% cost savings, but each region's contribution to the aggregate RPS (renewable portfolio standard) target is disproportionate, suggesting the need for regional-and-resource-specific RPS targets. Electric vehicle charging yields a lower levelized system cost, revealing the benefits of demand-side flexibility. However, existing demand response price structures may need adjustment to encourage optimal flexible load in highly renewable systems. Two scenarios with RPS targets from 20% to 100% for the US (peak load ~729 GW) and California (peak load ~62 GW) find each RPS target feasible from a planning perspective, but with 2× the cost and 3× the overgeneration at a 100% versus 80% RPS target. Emission reduction cost savings for the aggregated US system with an 80% versus 20% RPS target are roughly $200 billion/year, outweighing the $80 billion/year cost for the same RPS range.

1. Introduction

Electric utilities, load balancing areas, and transmission providers across the US are increasingly managing larger penetrations of renewable energy and engaging in greater regional coordination. This is driven by (1) policy, such as RPS (renewable portfolio standard) targets, FERC (Federal Energy Regulatory Commission) orders, and emission regulations, (2) reliability requirements, and (3) economics, such as declining wind and solar costs. As the electric sector continues in this transformation, there is a growing need for inter-regional analyses to determine the most cost-effective plan for interconnecting large geographic areas with high penetrations of renewable energy generators. Such power system planning studies have been completed for various spatial extents in the US, e.g., PJM using the RREEOM model [1], western US using the SWITCH model [2], and contiguous US using the ReEDS model [3], as well as in Europe, e.g., ENTSO-E grid with the URBS-EU model [4] and broader European extent including portions of Asia and Africa [5]. Other studies have focused on the operation of the system, such as NREL's Eastern [6] and Western [7] Integration studies, as well as more specialized operational studies that look at finer temporal resolutions (e.g., frequency response and transient stability in the western US [8]).

Throughout these planning, grid integration, and detailed operational studies, various flexibility mechanisms have been identified to help mitigate the variability and uncertainty challenges arising from an increasing penetration of variable renewable generation. These include aggregation of supply, demand, and reserves through transmission interconnections; storage technologies; flexible generation, such as flexible natural gas turbines and the improved used of hydroelectric assets; demand flexibility, such as "smart grid" technologies and other demand-side mechanisms

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http://dx.doi.org/10.1016/j.energy.2016.01.079
0360-5442/

Energy 117 (2016) 198–213

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model

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ARTICLE INFO

Article history:
Received 13 May 2015
Received in revised form
28 September 2016
Accepted 19 October 2016

Keywords:
Renewable energy
Linear programming
Computational requirements
Model accuracy
Aggregation
Energy system analysis

ABSTRACT

As the number and complexity of power system planning models grows, understanding the impact of modeling choices on accuracy and computational requirements becomes increasingly important. This study examines empirically various temporal and spatial tradeoffs using the POWER planning model for scenarios of a highly renewable US system. First, the common temporal simplification of using a representative subset of hours from a full year of available hours is justified using a reduced form model. Accuracy losses are generally ≤6%, but storage is sensitive to the associated model modifications, highlighting the need for proper storage balancing constraints. Cost tradeoffs of various temporal and spatial adjustments are then quantified: four temporal resolutions (1- to 8-h-average time blocks); various representative day subset sizes (1 week–6 months); two spatial resolutions of site-by-site versus uniform fractional buildout across all solar and wind sites; and multiple spatial extents, ranging from California to the contiguous US. Most tradeoffs yield <15% cost differences, with the effect of geographic aggregation across increasing spatial extents producing the largest cost reduction of 14% and 42% for the western and contiguous US, respectively. These results can help power system modelers determine the most appropriate temporal and spatial treatment for their application.

1. Introduction

As the US electricity sector transforms to meet regulatory and reliability requirements in an aging and increasingly renewable system, numerous optimization studies are being conducted to explore the economic and power system impacts under different generator and transmission scenarios. These studies span a range of spatial scales, from regional, state, and balancing areas, e.g., PJM using the RREEOM model [1] and the Western US using the SWITCH model [2], to country-wide analyses, e.g., contiguous US using the ReEDS model [3], US-REGEN model [4], NEWS model [5], and POWER model [6]. Many of these studies utilize a specific multi-decade capacity expansion model or shorter-term planning model. Table 1 summarizes the relevant features of several US-based electricity sector planning models at the national scale (POWER, ReEDS, US-REGEN, NEWS, NEMS EMM, ReNOT) and at the regional scale (SWITCH, RREEOM). Each of these models deterministically optimizes for the least-cost system. A review of these model can be found in Section 4.1 of [7]; a broader review of optimization, simulation, and equilibrium capacity expansion models is provided in Ref. [8].

At a high level, the differences among these models can be characterized by tradeoffs in temporal resolution and extent, spatial resolution and extent, and model complexity. Temporal resolution is the time step size (hourly, sub-hourly, etc.); temporal extent is the time horizon over which the model solves (1 week, 1 month, 1 year, etc.); spatial resolution reflects the handling of the wind/solar/other devices included in the model (e.g., solve site-by-site, or solve as an aggregated unit across all sites/devices uniformly); and spatial extent is the geographic coverage of the model (state, region, country, etc.). System complexity refers to the representation of different power system components, such as resource adequacy, reliability, intra-regional transmission, distribution system impacts, variability and uncertainty of renewables, and storage chronology. These "levers" can be adjusted to suit the research objective(s) and computational resources available. For instance, temporal and spatial resolution can be reduced in order to capture a greater system complexity. Most models in Table 1 have adjusted the temporal lever to include a representative subset of hours or "time slices" across a full year due to computational limits.

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http://dx.doi.org/10.1016/j.energy.2016.10.074
0360-5442/

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100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World

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SUMMARY

We develop roadmaps to transform the all-purpose energy infrastructures (electricity, transportation, heating/cooling, industry, agriculture/forestry/fishing) of 139 countries to ones powered by wind, water, and sunlight (WWS). The roadmaps envision 80% conversion by 2030 and 100% by 2050. WWS not only replaces business-as-usual (BAU) power, but also reduces it ~42.5% because the work: energy ratio of WWS electricity exceeds that of combustion (23.0%), WWS requires no mining, transporting, or processing of fuels (12.6%), and WWS end-use efficiency is assumed to exceed that of BAU (6.9%). Converting may create ~24.3 million more permanent, full-time jobs than jobs lost. It may avoid ~4.6 million/year premature air-pollution deaths today and ~3.5 million/year in 2050; ~\$22.8 trillion/year (12.7 ¢/kWh-BAU-all-energy) in 2050 air-pollution costs; and ~\$28.5 trillion/year (15.8 ¢/kWh-BAU-all-energy) in 2050 climate costs. Transitioning should also stabilize energy prices because fuel costs are zero, reduce power disruption and increase access to energy by decentralizing power, and avoid 1.5°C global warming.

INTRODUCTION

The seriousness of air-pollution, climate, and energy-security problems worldwide requires a massive, virtually immediate transformation of the world's energy infrastructure to 100% clean, renewable energy producing zero emissions. For example, each year, 4–7 million people die prematurely and hundreds of millions more become ill from air pollution,[1,2] causing a massive amount of pain and suffering that can nearly be eliminated by a zero-emission energy system. Similarly, avoiding 1.5°C warming since preindustrial times requires no less than an 80% conversion of the energy infrastructure to zero-emitting energy by 2030 and 100% by 2050 (Timeline and Section S10.2). Lastly, as fossil-fuel supplies dwindle and their prices rise, economic, social, and political instability may ensue unless a replacement energy infrastructure is developed well ahead of time.

As a response to these concerns, this study provides roadmaps for 139 countries for which raw energy data are available.[3] The roadmaps describe a future where all energy sectors are electrified or use heat directly with existing technology, energy demand is

Context & Scale

For the world to reverse global warming, eliminate millions of annual air-pollution deaths, and provide secure energy, every country must have an energy roadmap based on widely available, reliable, zero-emission energy technologies. This study presents such roadmaps for 139 countries of the world. These roadmaps are far more aggressive than what the Paris agreement calls for, but are still technically and economically feasible. The solution is to electrify all energy sectors (transportation, heating/cooling, industry, agriculture/forestry/fishing) and provide all electricity with 100% wind, water, and solar (WWS) power. If fully implemented by 2050, the roadmaps will enable the world to avoid 1.5°C global warming and millions of annual air-pollution deaths, create 24.3 million net new long-term, full-time jobs, reduce energy costs to society, reduce energy end-use by 42.5%, reduce power disruption, and increase worldwide access to energy.

Renewable Energy 123 (2018) 236–248

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes

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ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form
11 January 2018
Accepted 2 February 2018
Available online 3 February 2018

Keywords:
Wind-water-solar
Electric and thermal grid
Electricity and thermal storage
Transmission
Demand response

ABSTRACT

Matching electricity, heat, and cold demand with supply at low cost is the greatest concern facing countries seeking to provide their all-purpose energy with 100% clean, renewable wind, water, and sunlight (WWS). Implementing WWS worldwide could eliminate 4–7 million annual air pollution deaths, first slow then reverse global warming, and provide energy sustainably. This study derives zero-load-loss technical solutions to matching demand with 100% WWS supply; heat, cold, and electricity storage; hydrogen production; assumed all-distance transmission; and demand response for 20 world regions encompassing 139 countries after they electrify or provide direct heat for all energy in 2050. Multiple solutions are found, including those with batteries and heat pumps but zero added hydropower turbines and zero thermal energy storage. Whereas WWS and Business-As-Usual (BAU) energy costs per unit energy are similar, WWS requires ~42.5% less energy in a base case and ~57.9% less in a heat-pump case so may reduce capital and consumer costs significantly. Further, WWS social (energy + health + climate) costs per unit energy are one-fourth BAU's. By reducing water vapor, the wind turbines proposed may rapidly offset ~3% global warming while also displacing fossil-fuel emissions. Thus, with careful planning, the world's energy challenges may be solvable with a practical technique.

1. Introduction

Globally averaged temperatures in 2016 were over 1 °C higher than at the end of the 19th century [1]. To avoid 1.5 °C warming and eliminate the 4–7 million worldwide premature air pollution deaths occurring annually, the world must rapidly replace fossil fuels with zero-emissions energy sources. To help accomplish this goal, 139 individual country roadmaps were recently developed to transition all energy sectors (electricity, transportation, heating/cooling, industry, and agriculture/forestry/fishing) to use electricity and direct heat powered by 100% wind, water, and sunlight (WWS) by 2050, with 80% conversion by 2030 [2]. Only WWS technologies were used in that study, as they provide greater air pollution health and climate benefits than do bioenergy or fossil fuels with carbon capture and sequestration (CCS) [3]; use less land than crop-based bioenergy [3]; and result in less catastrophic risk, weapons proliferation risk, waste, and delays than nuclear power [3,4].

Whereas, the 139-country roadmaps estimate the numbers of WWS generators needed for each country to match annually-averaged electricity, heat, and cold power demand with WWS supply, they do not provide a detailed analysis of matching supply with demand over shorter time scales (e.g., minutes, hours, months, or seasons). Such an analysis is necessary, as the concern for load loss (supply shortfall) due to the variability of WWS resources and associated costs of mitigating such uncertainty is the greatest barrier facing the large-scale, worldwide adoption of WWS power [5].

Previous advanced studies have examined matching time-dependent demand with supply for up to 100% renewable energy by replacing conventional generators with WWS, or WWS plus bioenergy in either the electric power sector alone, or in the electric sector plus one or two other sectors after they have been electrified

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https://doi.org/10.1016/j.renene.2018.02.009
0960-1481/

Sustainable Cities and Society 42 (2018) 22–37

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

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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ARTICLE INFO

Keywords:
Sustainable cities
Renewable energy
Wind
Solar
Urban air pollution
Climate change

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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https://doi.org/10.1016/j.scs.2018.06.031
Received 10 January 2018; Received in revised form 17 May 2018; Accepted 24 June 2018
Available online 30 June 2018
2210-6707/

Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries

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https://doi.org/10.1016/j.oneear.2019.12.003

SCIENCE FOR SOCIETY The Earth is approaching 1.5°C global warming, air pollution kills over 7 million people yearly, and limited fossil fuel resources portend social instability. Rapid solutions are needed. We provide Green New Deal roadmaps for all three problems for 143 countries, representing 99.7% of world's CO_2 emissions. The roadmaps call for countries to move all energy to 100% clean, renewable wind-water-solar (WWS) energy, efficiency, and storage no later than 2050 with at least 80% by 2030. We find that countries and regions avoid blackouts despite WWS variability. Worldwide, WWS reduces energy needs by 57.1%, energy costs from $17.7 to $6.8 trillion/year (61%), and social (private plus health plus climate) costs from $76.1 to $6.8 trillion/year (91%) at a capital cost of ~$73 trillion. WWS creates 28.6 million more long-term, full-time jobs than are lost and needs only 0.17% and 0.48% of land for footprint and space, respectively. Thus, WWS needs less energy, costs less, and creates more jobs than current energy.

SUMMARY

Global warming, air pollution, and energy insecurity are three of the greatest problems facing humanity. To address these problems, we develop Green New Deal energy roadmaps for 143 countries. The roadmaps call for a 100% transition of all-purpose business-as-usual (BAU) energy to wind-water-solar (WWS) energy, efficiency, and storage by 2050 with at least 80% by 2030. Our studies on grid stability find that the countries, grouped into 24 regions, can match demand exactly from 2050 to 2052 with 100% WWS supply and storage. We also derive new cost metrics. Worldwide, WWS energy reduces end-use energy by 57.1%, aggregate private energy costs from $17.7 to $6.8 trillion/year (61%), and aggregate social (private plus health plus climate) costs from $76.1 to $6.8 trillion/year (91%) at a present value capital cost of ~$73 trillion. WWS energy creates 28.6 million more long-term, full-time jobs than BAU energy and needs only ~0.17% and ~0.48% of land for new footprint and spacing, respectively. Thus, WWS requires less energy, costs less, and creates more jobs than does BAU.

INTRODUCTION

The world is beginning to transition to clean, renewable energy for all energy purposes. However, to avoid 1.5°C global warming, we must stop at least 80% of all energy and non-energy fossil fuels and biofuel emissions by 2030[1] and stop 100% no later than 2050.[1,2] Air pollution from these same sources kills 4–9 million people each year (Figure 1),[3] and this damage will continue unless the sources of air pollution are eliminated. Finally, if the use of fossil fuels is not curtailed rapidly, rising demand for increasingly scarce fossil energy will lead to economic, social, and political instability, enhancing international conflict.[3,4]

In an effort to solve these problems, studies among at least 11 independent research groups have found that transitioning to 100% renewable energy in one or all energy sectors, while keeping the electricity and/or heat grids stable at a reasonable cost, is possible.[1,5–26] The reviews of Brown et al.[27] and Diesendorf and Elliston[28] further find that critiques of 100% renewable systems are misplaced. The latter study, for example, concludes, "the main critiques published in scholarly articles and books contain factual errors, questionable assumptions, important omissions, internal inconsistencies, exaggerations of limitations and irrelevant arguments."

Among the studies that find that 100% renewable energy is cost effective, many have been of limited use to policy makers because they considered only private cost and not social cost, did not compare business-as-usual (BAU) with wind-water-solar