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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).

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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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quality of life, and reduce climate-relevant emissions. NYS also has a renewable portfolio standard requiring 30% of its electric power to come from renewable sources by 2015 (NYSERDA (New York State Energy Research and Development Authority), 2012). Although current plans for NYS and other states, countries, and continents are visionary and important, the plan here goes further by proposing a long-term sustainable energy infrastructure that supplies *all* energy from wind, water, and solar power, and provides the largest possible reductions in air pollution, water pollution, and global warming impacts. This study represents the first effort to develop a plan for an individual state to provide 100% of its all-purpose energy from WWS and to calculate the number of WWS energy devices, land and ocean areas, jobs, and policies needed for such an infrastructure. It also provides new calculations of air pollution mortality and morbidity impacts and costs in NYS based on multiple years of high-resolution air quality data.

In brief, the plan requires or results in the following changes:

(1) Replace fossil-fuel electric power generators with wind turbines, solar photovoltaic (PV) plants and rooftop systems, concentrated solar power (CSP) plants, solar hot water heater systems, geothermal power plants, a few additional hydroelectric power plants, and a small number of wave and tidal devices.
(2) Replace all fossil-fuel combustion for transportation, heating and cooling, and industrial processes with electricity, hydrogen fuel cells, and a limited amount of hydrogen combustion. Battery-electric vehicles (BEVs), hydrogen fuel cell vehicles (HFCVs), and BEV–HFCV hybrids sold in NYS will replace all combustion-based passenger vehicles, trucks, buses, non-road machines, and locomotives sold in the state. Long-distance trucks will be primarily BEV-HFCV hybrids and HFCVs. Ships built in NYS will similarly run on hydrogen fuel cells and electricity. Today, hydrogen-fuel-cell ships, tractors, forklifts, buses, passenger vehicles, and trucks already exist, and electric vehicles, ferries, and non-road machinery also exist. Electricity-powered air- and ground-source heat pumps, heat exchangers, and backup electric resistance heaters will replace natural gas and oil for home heating and air conditioning. Air- and ground-source heat pump water heaters powered by electricity and solar hot water preheaters will provide hot water for homes. High-temperatures for industrial processes will be obtained with electricity and hydrogen combustion. Petroleum products may still be used for lubrication and plastics as necessary, but such products will be produced using WWS power for process energy.
(3) Reduce energy demand beyond the reductions described under (2) through energy efficiency measures. Such measures include retrofitting residential, commercial, institutional, and government buildings with better insulation, improving the energy-out/energy-in efficiency of end uses with more efficient lighting and the use of heat-exchange and filtration systems; increasing public transit and telecommuting, designing future city infrastructure to facilitate greater use of clean-energy transport; and designing new buildings to use solar energy with more daylighting, solar hot water heating, seasonal energy storage, and improved passive solar heating in winter and cooling in summer.
(4) Boost economic activity by implementing the measures above. Increase jobs in the manufacturing and installation industries and in the development of new and more efficient technologies. Reduce social costs by reducing health-related mortality and morbidity and reducing environmental damage to lakes, streams, rivers, forests, buildings, and statues resulting from air and water pollution. Reduce social costs by slowing the increase in global warming and its impacts on coastlines, agriculture, fishing, heat stress, severe weather, and air pollution (which otherwise increases with increasing temperatures). Reduce long-term macroeconomic costs by eliminating exposure to future rises in fossil fuel prices.
(5) The plan anticipates that the fraction of new electric power generators as WWS will increase starting today such that, by 2020, all new generators will be WWS generators. Existing conventional generators will be phased out over time, but by no later than 2050. Similarly, BEVs and HFCVs should be nearly the only new vehicles types sold in NYS by 2020. The growth of electric vehicles will be accompanied by a growth of electric charging stations in residences, commercial parking spaces, service stations, and highway rest stops.
(6) All new heating and cooling technologies installed by 2020 should be WWS technologies and existing technologies should be replaced over time, but by no later than 2050.
(7) To ensure reliability of the electric power grids, several methods should be used to match renewable energy supply with demand and to smooth out the variability of WWS resources. These include (A) combining geographically-dispersed WWS resources as a bundled set of resources rather than as separate resources and using hydroelectric power to fill remaining gaps; (B) using demand-response grid management to shift times of demand to match better with the timing of WWS power supply; (C) oversizing WWS peak generation capacity to minimize the times when available WWS power is less than demand and to provide power to produce heat for air and water and hydrogen for transportation and heating when WWS power exceeds demand; (D) integrating weather forecasts into system operation to reduce reserve requirements; (E) storing energy in thermal storage media, batteries or other storage media at the site of generation or use; and (F) storing energy in electric-vehicle batteries for later extraction (vehicle-to-grid).

2. How the technologies were chosen

The WWS energy technologies chosen for the NYS plan exist and were ranked the highest among several proposed energy options for addressing pollution and public health, global warming, and energy security (Jacobson, 2009). That analysis used a combination of 11 criteria (carbon-dioxide equivalent emissions, air-pollution mortality and morbidity, resource abundance, footprint on the ground, spacing required, water consumption, effects on wildlife, thermal pollution, water chemical pollution/radioactive waste, energy supply disruption, and normal operating reliability) to evaluate each technology.

Mined natural gas and liquid biofuels are excluded from the NYS plan for the reasons given below. Jacobson and Delucchi (2011) explain why nuclear power and coal with carbon capture are also excluded.

2.1. Why not natural gas?

Natural gas is excluded for several reasons. The mining, transport, and use of conventional natural gas for electric power results in at least 60–80 times more carbon-equivalent emissions and air pollution mortality per unit electric power generated than does wind energy over a 100-year time frame. Over the 10–30 year time frame, natural gas is a greater warming agent relative to all WWS technologies and a danger to the Arctic sea ice due to its leaked methane and black carbon-flaring emissions (discussed more below). Natural gas mining, transport, and use also produce carbon monoxide, ammonia, nitrogen oxides, and organic gases.

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Natural gas mining degrades land, roads, and highways and produces water pollution.

The main argument for increasing the use of natural gas has been that it is a "bridge fuel" between coal and renewable energy because of the belief that natural gas causes less global warming per unit electric power generated than coal. Although natural gas emits less carbon dioxide per unit electric power than coal, two factors cause natural gas to increase global warming relative to coal: higher methane emissions and less sulfur dioxide emissions per unit energy than coal.

Although significant uncertainty still exists, several studies have shown that, without considering sulfur dioxide emissions from coal, natural gas results in either similar or greater global warming-relevant-emissions than coal, particularly on the 20-year time scale (Howarth et al., 2011, 2012a, 2012b; Howarth and Ingraffea, 2011; Wigley, 2011; Myhrvold and Caldeira, 2012). The most efficient use of natural gas is for electricity, since the efficiency of electricity generation with natural gas is greater than with coal. Yet even with optimistic assumptions, Myhrvold and Caldeira (2012) demonstrated that the rapid conversion of coal to natural gas electricity plants would "do little to diminish the climate impacts" of fossil fuels over the first half of the 21st Century. Recent estimates of methane radiative forcing (Shindell et al., 2009) and leakage (Howarth et al., 2012b; Pétron et al., 2012) suggest a higher greenhouse-gas footprint of the natural gas systems than that estimated by Myhrvold and Caldeira (2012). Moreover, conventional natural gas resources are becoming increasingly depleted and replaced by unconventional gas such as from shale formations, which have larger methane emissions and therefore a larger greenhouse gas footprint than do conventional sources (Howarth et al., 2011, 2012b; Hughes, 2011).

Currently, most natural gas in the U.S. and NYS is not used to generate electricity but rather for domestic and commercial heating and for industrial process energy. For these uses, natural gas offers no efficiency advantage over oil or coal, and has a larger greenhouse gas footprint than these other fossil fuels, particularly over the next several decades, even while neglecting the climate impact of sulfur dioxide emissions (Howarth et al., 2011, 2012a, 2012b). The reason is that natural gas systems emit far more methane per unit energy produced than do other fossil fuels (Howarth et al., 2011), and methane has a global warming potential that is 72–105 times greater than carbon dioxide over an integrated 20-year period after emission and 25–33 times greater over a century period (Intergovernmental Panel on Climate Change (IPCC), 2007; Shindell et al., 2009). As discussed below, the 20-year time frame is critical.

When used as a transportation fuel, the methane plus carbon dioxide footprint of natural gas is greater than for oil, since the efficiency of natural gas is less than that of oil as a transportation fuel (Alvarez et al., 2012). When methane emissions due to venting of fuel tanks and losses during refueling are accounted for, the warming potential of natural gas over oil rises further.

When sulfur dioxide emissions from coal are considered, the greater air-pollution health effects of coal become apparent, but so do the lower global warming impacts of coal versus natural gas, indicating that both fuels are problematic. Coal combustion emits significant sulfur dioxide and nitrogen oxides, most of which convert to sulfate and nitrate aerosol particles, respectively. Natural gas also emits nitrogen oxides, but not much sulfur dioxide. Sulfate and nitrate aerosol particles cause direct air pollution health damage, but they are "cooling particles" with respect to climate because they reflect sunlight and increase cloud reflectivity. Thus, although the increase in sulfate aerosol from coal increases coal's air-pollution mortality relative to natural gas, it also decreases coal's warming relative to natural gas because sulfate offsets a significant portion of coal's CO_2-based global warming over a 100-year time frame (Streets et al., 2001; Carmichael et al., 2002). Coal also emits "warming particles" called soot, but pulverized coal in the U.S. results in little soot. Using conservative assumptions about sulfate cooling, Wigley (2011) found that electricity production from natural gas causes more warming than coal over 50–150 years when coal sulfur dioxide is accounted for. The low estimate of 50 years was derived from an unrealistic assumption of zero leaked methane emissions.

Thus, natural gas is not a near-term "low" greenhouse-gas alternative, in absolute terms or relative to coal. Moreover, it does not provide a unique or special path to renewable energy, and as a result, it is not bridge fuel and is not a useful component of a sustainable energy plan.

Rather than use natural gas in the short term, we propose to move to a WWS-power system immediately, on a worldwide scale, because the Arctic sea ice may disappear in 20–30 years unless global warming is abated (e.g., Pappas, 2012). Reducing sea ice uncovers the low-albedo Arctic Ocean surface, accelerating global warming in a positive feedback. Above a certain temperature, a tipping point is expected to occur, accelerating the loss to complete elimination (Winton, 2006). Once the ice is gone, regenerating it may be difficult because the Arctic Ocean will reach a new stable equilibrium (Winton, 2006).

The only potential method of saving the Arctic sea ice is to eliminate emissions of short-lived global warming agents, including methane (from natural gas leakage and anaerobic respiration) and particulate black carbon (from natural gas flaring and diesel, jet fuel, kerosene burning, and biofuel burning). The 21-country Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants recognized the importance of reducing methane and black carbon emissions for this purpose (UNEP (United Nations Environmental Program), 2012). Black carbon controls for this reason have also been recognized by the European Parliament (Resolution B7–0474/2011, September 14, 2011). Jacobson (2010a) and Shindell et al. (2012) quantified the potential benefit of reducing black carbon and methane, respectively, on Arctic ice.

Instead of reducing these problems, natural gas mining, flaring, transport, and production increase methane and black carbon, posing a danger to the Arctic sea ice on the time scale of 10–30 years. Methane emissions from the natural-gas system and nitrogen-oxide emissions from natural-gas combustion also contribute to the global buildup of tropospheric ozone resulting in additional respiratory illness and mortality.

2.2. Why not liquid biofuels?

This study also excludes the future use of liquid biofuels for transportation and heating. In addition to their creating more air pollution than gasoline for transportation, their tank-to-wheel efficiency of combustion is 1/4th to 1/5th the plug-to-wheel efficiency of electricity for transportation. This tends to make the energy cost-per-distance much higher for biofuel vehicles than electric vehicles. In addition, the land required to power a fleet of flex-fuel vehicles on corn or cellulosic ethanol is about 30 times the spacing area and a million times the footprint area on the ground required for wind turbines to power an equivalent fleet of electric vehicles (Jacobson, 2009).

Liquid biofuels are partially renewable with respect to carbon since they remove carbon dioxide from the air during photosynthetic growth. However, liquid biofuels require energy to grow and, in some cases (e.g., corn for ethanol) fertilize crops, irrigate crops (although not in NYS), distill the fuel (in the case of ethanol), transport crops to energy production plants, and transport the liquid fuel to its end use locations. For transportation, the resulting environmental costs of liquid biofuels are high, particularly for air and water quality (Delucchi, 2010), and greenhouse gas emissions are at best only slightly less than from using fossil fuels, and may be far worse when indirect land-use changes due to using land for fuel instead of food are fully considered (Searchinger et al., 2008). Moreover, carbon emissions from an advanced biofuel, cellulosic ethanol for flex-fuel vehicles, are about 125 times those from wind energy powering electric vehicles without considering indirect land use changes (Jacobson, 2009) and higher if indirect land use changes are accounted for (Searchinger et al., 2008). For these reasons alone, reviews by international agencies have recommended against the use of liquid biofuels for transportation (Bringezu et al., 2009; Howarth and Bringezu, 2009).

Ethanol combustion, regardless of the source, increases average air pollution mortality relative to gasoline due to the aldehyde and unburned ethanol emissions from ethanol fuel combustion (Jacobson, 2009; Anderson, 2009), and the effect increases at low temperature (Ginnebaugh et al., 2010, 2012). Ethanol and biodiesel fuel also increase air pollution from their upstream production more than do gasoline or diesel fuel, respectively (Delucchi, 2006). By contrast, electric and hydrogen fuel cell vehicles eliminate nearly all such pollution (Jacobson et al., 2005).

Much less analysis of the impacts of liquid biofuels for heating has been done than for transportation, but the fundamental issues remain the same. Namely, liquid biofuels for heating produce air pollution because they are combusted; require energy to grow, produce, and transport thus result in more emissions, and require much more land than solar power for the same energy output.

2.3. Temporary role of solid biofuels

The NYS plan allows for the temporary heating use of certain solid biofuels, such as wood pellets, energy crops grown on unused farmland, and agricultural waste and of biogas extracted from landfills and derived from anaerobic digestion of organic wastes. The use of such solid biofuels and biogas will be phased out by 2030–2050.

Solid biofuels combusted for cogeneration of electric power and heat are more efficient than liquid biofuels for transportation and are widely used in this way across northern Europe (Campbell et al., 2009; Howarth and Bringezu, 2009; Bringezu et al., 2009). Much of NYS is rural, with large expanses of old abandoned agricultural land, much of it now second-growth forest. Such land can produce large quantities of biomass. For example, the 8-county (Broome, Chemung, Chenango, Delaware, Schulyer, Steuben, Tioga, and Tompkins) Southern Tier economic development region of NYS is estimated to be able to produce 1.9 million dry tons annually of biomass for energy, with half of this coming from wood-chip harvest and the rest from dedicated energy crops such as switchgrass or willow (Woodbury et al., 2010). This is equivalent to 3 tons per year for every resident of this area, more than enough to alone supply all domestic heating needs.

Using biomass for heat allows farmers and forest owners to produce an energy crop on land that would not otherwise be used and to make use of low-value wood, increasing economic productivity and producing agricultural and forestry jobs. However, solid biomass should be used carefully so as not to over-harvest forestlands or use high-quality agricultural land. The scale of use is important as well, as moving and processing solid biomass takes substantial energy and carbon; the biomass should be used near the point of harvest to reduce this energy cost and the resulting environmental pollution. Using landfill biogas allows methane that would otherwise escape to the air to be used for energy. Similarly, converting organic waste to biogas allows the use of material for energy that would be processed biologically and released to the air in any case.

For two reasons, the use of solid biofuels and biogas in our plan is only temporary. First, biomass or biogas for energy requires much more land than solar power producing the same electricity and heat. For example, the growth of switchgrass for electric power requires about 115 times more land area than the use of solar PV to provide the same electric power based on biomass data from Kansas Energy Report (2011). If biomass combustion is used for both electricity and heat, switchgrass still requires 70 times more land area than does solar PV. Thus, one acre of land growing switchgrass for electricity produces 1/70th to 1/115th the usable energy of the same land with PV on it. Since electricity can run (a) air-source heat pumps very efficiently, (b) electric-resistance backup heating to produce heat, and (c) electrolyzers to produce hydrogen that can be used safely for home and building heat (KeelyNet, 2009), the use of solar PV for electricity and electricity-derived heat is more efficient than is the use of biomass for the same purpose in terms of land use and reducing air pollution,

Second, the use of solid biofuels or biogas for electricity and heat is still a combustion process, resulting in similar air pollution health and mortality impacts as fossil fuel combustion. Because solid biofuels for energy would be grown and processed in NYS, NYS “upstream” air pollution emissions from such processing will likely increase compared with current fossil fuel upstream emissions, most of which occur out of state (Woodbury et al., 2010). Because feedstock will be transported primarily by truck, road congestion, erosion, and pollution emissions will also likely increase (Woodbury et al., 2010). For these reasons, solid biofuels and biogas are to be phased out during 2030–2050 in the NYS plan.

3. Change in NYS power demand upon conversion to WWS

Table 1 summarizes the changes in global, U.S., and NYS end-use power demand between 2010 and 2030 upon a conversion to a 100% WWS infrastructure (zero fossil fuels, biofuels, and nuclear

Table 1
Contemporary (2010) and projected (2030) end-use power demand (TW) for all purposes by sector, for the world, U.S., and NYS if conventional fossil-fuel and wood use continue as projected and if all conventional fuels are replaced with WWS technologies.
Source: Jacobson and Delucchi (2011) for the world and U.S., NYS values are calculated with the same methodology but using EIA (Energy Information Administration, U.S.), 2012a end-use demand data. The U.S. and NYS populations in 2010 were 307,910,000 and 19,378,000, respectively. Those in 2030 are estimated to be 358,410,000 (USCB (United States Census Bureau), 2011) and 19,795,000 (Cornell Program on Applied Demographics, 2011), respectively, giving the U.S. and NYS population growths as 16.4% and 2.15%, respectively.

Energy sector	Conventional fossil fuels and wood 2010			Conventional fossil fuels and wood 2030			Replacing fossil fuels and wood with WWS 2030		
	World	U.S.	NYS	World	U.S.	NYS	World	U.S.	NYS
Residential	1.77	0.38	0.026	2.26	0.43	0.025	1.83	0.35	0.020
Commercial	0.94	0.28	0.023	1.32	0.38	0.025	1.22	0.35	0.022
Industrial	6.40	0.86	0.009	8.80	0.92	0.009	7.05	0.74	0.007
Transportation	3.36	0.97	0.036	4.53	1.10	0.037	1.37	0.33	0.011
Total	12.47	2.50	0.094	16.92	2.83	0.096	11.47	1.78	0.060
Percent change							(−32%)	(−37%)	(−37%)

energy). The table was derived on a spreadsheet from annually-averaged end-use power demand data as in Jacobson and Delucchi (2011). All end uses that feasibly can be electrified will use WWS power directly, and remaining end uses (some heating, high-temperature industrial processes, and some transportation) will use WWS power indirectly in the form of electrolytic hydrogen (hydrogen produced by splitting water with WWS power). As such, electricity requirements will increase, but the use of oil and gas for transportation and heating/cooling will decrease to zero. The increase in electricity use will be much smaller than the decrease in energy embodied in gas, liquid, and solid fuels because of the high efficiency of electricity for heating and electric motors.

The power required in 2010 to satisfy all end use power demand worldwide for all purposes was about 12.5 trillion watts (terawatts, TW). (End-use power excludes losses incurred during production and transmission of the power.) About 35% of primary energy worldwide in 2010 was from oil, 27% was from coal, 23% was from natural gas, 6% was from nuclear power, and the rest was from biofuel, sunlight, wind, and geothermal power. Delivered electricity was about 2.2 TW of all-purpose end-use power.

If the world follows the current trajectory of fossil-fuel growth, all-purpose end-use power demand will increase to ~17 TW by 2030, U.S. demand will increase to ~3 TW, and NYS power demand will increase to ~96 GW (Table 1). Conventional power demand in NYS will increase much less in 2030 than in the U.S. as a whole because the NYS population is expected to grow by only 2.15% between 2010 and 2030, whereas the U.S. population is expected to grow by 16.4% (Table 1, footnote).

Table 1 indicates that a conversion to WWS will reduce world, U.S., and NYS end-use power demand and power required to meet that demand by ~32%, ~37%, and ~37%, respectively. The reductions in NYS by sector are 21.0% in the residential, 12.3% in the commercial, 20.0% in the industrial, and 69.5% in the transportation sectors. Only 5–10 percentage points of each reduction are due to modest energy-conservation measures. Some of the remainder is due to the fact that conversion to WWS reduces the need for upstream coal, oil, and gas mining and processing of fuels, such as petroleum or uranium refining. The remaining reason is that the use of electricity for heating and electric motors is more efficient than is fuel combustion for the same applications (Jacobson and Delucchi, 2011). Also, the use of WWS electricity to produce hydrogen for fuel cell vehicles, while less efficient than the use of WWS electricity to run BEVs, is more efficient and cleaner than is combusting liquid fossil fuels for vehicles (Jacobson et al., 2005). Combusting electrolytic hydrogen is slightly less efficient but cleaner than is combusting fossil fuels for direct heating, and this is accounted for in the table.

4. Numbers of electric power Generators needed

How many WWS power plants or devices are needed to power NYS for all purposes assuming end use power requirements in Table 1 and accounting for electrical transmission and distribution losses?

Table 2 provides one of several possible future scenarios for 2030. In this scenario, onshore wind comprises 10% of New York's

Table 2
Number of WWS power plants or devices needed to provide New York's total annually-averaged end-use power demand for all purposes in 2030 (0.061 TW from Table 1) assuming the given fractionation of demand among plants or devices and accounting for transmission, distribution, and array losses. Also shown are the footprint and spacing areas required to power NYS as a percentage of New York's land area, 122,300 km^2.

Energy technology	Rated power of one plant or device (MW)	Percent of 2030 power demand met by plant/device	Number of plants or devices needed for NYS	Nameplate capacity of all devices (MW)	Footprint area (percent of NYS land area)	Spacing area (percent of NYS land area)
Onshore wind	5	10	4020	20,100	0.000041	1.46
Offshore wind	5	40	12,700	63,550	0.00013	4.62
Wave device	0.75	0.5	1910	1435	0.00082	0.039
Geothermal plant	100	5	36	3600	0.010	0
Hydroelectric plant	1300	5.5	6.6[a]	8520	3.50[a]	0
Tidal turbine	1	1	2600	2600	0.00061	0.0095
Res. roof PV system	0.005	6	4.97 million[b]	24,900	0.15[c]	0
Com/gov roof PV system	0.10	12	0.497 million	49,700	0.30[c]	0
Solar PV plant	50	10	828[b]	41,400	0.25	0[c]
CSP plant	100	10	387	38,700	0.60	0[c]
Total		100		254,000	4.82	6.13
Total new land required					0.96[d]	1.46[e]

Rated powers assume existing technologies. Percent power of each device assumes wind and solar are the only two resources that can power NYS independently (Section 5) and should be in approximate balance to enable load matching (Section 6) but that wind is less expensive (Section 7) so will dominate more. The number of devices is calculated by multiplying the NYS end use power demand in 2030 from Table 1 by the fraction of power from the source and dividing by the annual power output from each device, which equals the rated power multiplied by the annual capacity factor of the device. The capacity factor is determined for each device as in the Supplementary Information spreadsheet of Jacobson (2009), except that onshore wind turbines are assumed here to be located in mean annual wind speeds at hub height of 7.75 m/s and offshore turbines, 8.5 m/s (Dvorak et al., 2012a). From that study, 9200 km^2 of NYS land area has mean wind speeds >7.75 m/s at 90 m, and the average wind speed in those areas is 8.09 m/s. From the present table, only 1786 km^2 of onshore wind is needed. Land and spacing areas are similarly calculated as in the Supplementary Information of Jacobson (2009).

[a] NYS already produces about 89% of the hydroelectric power needed for the plan (Section 5). See Jacobson (2009) for a discussion of apportioning the hydroelectric footprint area by use of the reservoir.

[b] The solar PV panels used for this calculation were Sun Power E20 panels. The average capacity factor for solar assumed was 18%.

[c] For central solar PV and CSP plants, nominal "spacing" between panels is included in the plant footprint area.

[d] The total footprint area requiring new land is equal to the footprint area for onshore wind and geothermal, plus 2.75% of the footprint area for hydroelectric, plus the footprint area for solar PV and CSP plants. Offshore wind, wave and tidal are in water, and so do not require new land. The footprint area for rooftop solar PV does not entail new land because the rooftops already exist and are not used for other purposes (that might be displaced by rooftop PV). Only 2.75% of the hydropower requires new land because 89% of hydroelectric capacity is already in place and, of the remaining 11%, three-quarters will come from existing reservoirs or run-of-the-river.

[e] Only onshore wind entails new land for spacing area. The other energy sources are either in water or on rooftops, or do not use additional land for spacing. The spacing area for onshore wind can be used for multiple purposes, such as open space, agriculture, grazing, etc.

supply; offshore wind, 40%; residential solar rooftop PV, 6%; commercial/government solar rooftop PV, 12%; PV power plants, 10%; CSP plants, 10%; hydroelectric power, 5.5% (of which 89% is already in place), geothermal power, 5%; tidal power, 1%; and wave power, 0.5%.

Rooftop PV in this scenario is divided into residential (5-kW systems on average) and commercial/government (100-kW systems on average). Rooftop PV can be placed on existing rooftops or on elevated canopies above parking lots and structures without taking up additional undeveloped land. PV power plants are sized, on average, relatively small (50 MW) to allow them to be placed optimally in available locations.

Wind (50%) and solar (38%) are the largest generators of electric power under this plan because they are the only resources sufficiently available to power NYS on their own, and both are needed in combination to ensure the reliability of the grid. Wind is currently less expensive than solar, particularly at latitudes as high as in NYS, so wind is proposed to play a slightly larger role.

Since most wind and all wave and tidal power will be offshore under the plan, most transmission will be under water and out of sight. Transmission for new onshore wind, solar power plants, and geothermal power plants will be along existing pathways but with enhanced lines to the greatest extent possible, minimizing zoning issues. Four methods of increasing transmission capacity without requiring additional rights of way or increasing the footprint of transmission lines include the use of dynamic line rating equipment; high-temperature, low-sag conductors; voltage up-rating; and flexible AC transmission systems (e.g., Holman, 2011). To the extent existing pathways need to be expanded or new transmission pathways are required, they will be applied for using regulatory guidelines already in place.

Footprint is the physical space on the ground needed for each energy device, whereas spacing is the space between some devices, such as wind, tidal, and wave power. Spacing area can be used for open space, agriculture, grazing, etc. Table 2 provides footprint and spacing areas required for each energy technology. The table indicates that the total new land footprint required for this plan is about 0.96% of New York's land area, mostly for solar PV and CSP power plants (as mentioned, rooftop solar does not take up new land). Some additional footprint is proposed for hydroelectric as well, but that portion may not be needed if run-of-the-river hydro, imported hydro, or hydro from existing reservoirs that do not currently produce electric power is used. Additional space is also needed between onshore wind turbines. This space can be used for multiple purposes and can be reduced if more offshore wind resources are used than proposed here. The total additional land footprint needed (0.96% of the state) is minimal compared with the footprint of agriculture in the state (23.8%) and the footprint of house lots, ponds, roads, and waste-land used for agriculture (1.9%) (USDA (United States Department of Agriculture), 2011). Fig. 1 shows the relative footprint and spacing areas required in NYS.

The number of devices takes into account the availability of clean resources as well as of land and ocean areas. NYS has more wind, solar, geothermal, and hydroelectric resources than is needed to supply the state's energy for all purposes in 2030. These resources are discussed next.

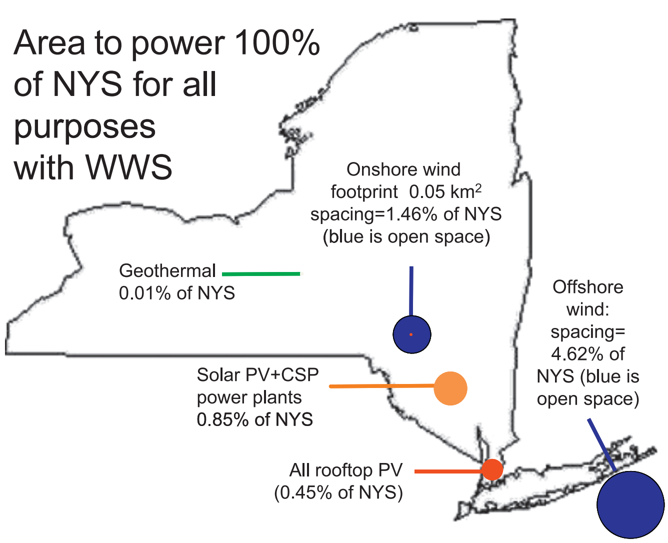

Fig. 1. Spacing and footprint areas required to implement the plan proposed here for NYS, as derived in Table 2. Actual locations would differ. The dots are only representative areas. For wind, the small red dot in the middle is footprint on the ground and the blue is spacing. For the others, the footprint and spacing are similar to each other. In the case of rooftop PV, the dot represents the rooftop area to be used. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. WWS resources available

This section discusses raw WWS resources available in NYS. Fig. 2 shows NYS's onshore and offshore annual wind resources from Dvorak et al. (2012a) in terms of a wind turbine's capacity factor, which is the annual average power produced divided by the rated power of a turbine. If only half the high-wind-speed land (capacity factor > 30%) in NYS were used for wind development, 327 TWh of wind energy would be harnessed, enough to provide more than 60% of NYS's 2030 WWS end-use power demand for all purposes. However, this plan proposes that only 10% of NYS's 2030 power demand come from onshore wind.

Dvorak et al. (2012a) mapped the East Coast offshore wind resources and Dvorak et al. (2012b) proposed locations for an efficiently interconnected set of offshore East Coast wind farms, one of which would be off of Long Island's coast. Offshore resources significantly exceed those onshore. The U.S. has not yet built an offshore wind farm, and some have expressed a concern over their potential environmental impacts. However, a study of over a decade of experience of offshore wind in Denmark by the International Advisory Panel of Experts on Marine Ecology found little damage to wildlife (Dong Energy, Vattenfall Danish Energy Authority, and Danish Forest and Nature Agency, 2006).

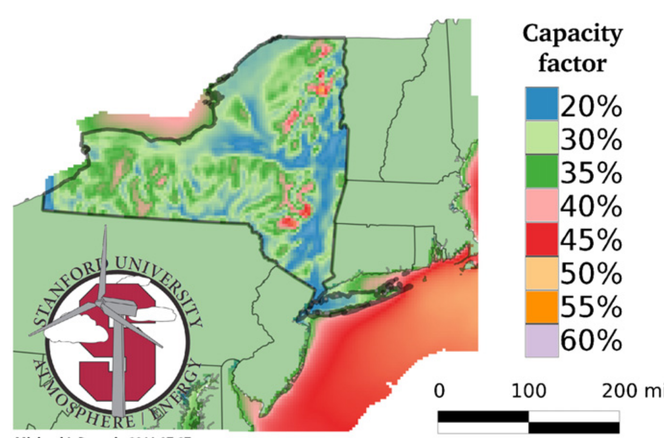

Fig. 2. Capacity factors at 90-m hub height in NYS and offshore in Lake Ontario, Lake Erie, and the Eastern seaboard, as calculated with a 3-D computer model evaluated against data assuming 5-MW RE-Power wind turbines with rotor diameter $D = 126$ m from simulations run in Dvorak et al. (2012a, 2012b). Capacity factors of 30% or higher are the most cost-effective for wind energy development.

Despite NYS's high latitude, solar resources in the state are significant. NREL (National Renewable Energy Laboratory) (2008) estimates NYS's solar resources as 4–4.5 kWh/m^2/day. Based on these numbers, only 0.85% of additional land (beyond existing rooftops) is needed to provide 38% of the state's energy for all purposes in 2030 in the forms of CSP plants, PV power plants, and rooftop PV. This assumes that 18% of the state's new energy comes from rooftop PV on existing urban structures (Table 2).

Geothermal resources in NYS (NREL (National Renewable Energy Laboratory), 2009) are also abundant. Geothermal energy production requires little land area (Table 2) and is proposed to provide only 5% of NYS's total energy in 2030.

NYS has a hydroelectric potential of 38.6 kW/km^2 (5 GW, or 43.8 TWh/yr) of delivered power (DOE (Department of Energy), 2004). It can currently produce about 60% of this. For example, in 2009, hydroelectric supplied about 26.1 TWh/yr (3 GW delivered power), or 21% of NYS's electric power consumption of 131 TWh/yr. Under the plan, hydro will produce about 3.3 GW, or 5.5% of the total delivered power for all purposes in NYS in 2030. Hydro currently produces 89% of this amount. Sufficient in-state and, if necessary, imported hydroelectric power is available to provide the difference. Most additional in-state hydro may be obtainable from existing dams that do not have turbines associated with them.

Tidal (or ocean current) and wave power are proposed to comprise a combined 1.5% of NYS's overall power in 2030 (Table 2). Tidal and wave resources off the East Coast are both modest. However, tidal power has already been used to generate electricity in the East River through the Verdant Power Roosevelt Island Tidal Energy Project.

6. Matching electric power supply with demand

An important concern to address in a clean-energy economy is whether electric power demand can be met with WWS supply on a minutely, daily, and seasonal basis. Previous work has described multiple methods to match renewable energy supply with demand and to smooth out the variability of WWS resources (Delucchi and Jacobson, 2011). Such methods include (A) combining geographically-dispersed WWS resources as a bundled set of resources rather than separate resources and using hydroelectric or stored concentrated solar power to balance the remaining load; (B) using demand-response management to shift times of demand to better match the availability of WWS power; (C) over-sizing WWS peak generation capacity to minimize the times when available WWS power is less than demand and provide power to produce heat for air and water and hydrogen for transportation and heating when WWS power exceeds demand; (D) integrating weather forecasts into system operation; (E) storing energy in batteries or other storage media at the site of generation or use; and (F) storing energy in electric-vehicle batteries for later extraction (vehicle-to-grid). Here, we discuss updated information on only a couple of these methods since Delucchi and Jacobson (2011) discuss the other methods.

Several studies have examined whether up to 100% penetrations of WWS resources could be used reliably to match power demand (e.g., Jacobson and Delucchi, 2009; Mason et al., 2010; Hart and Jacobson, 2011, 2012; Connolly et al., 2011; Elliston et al., 2012; NREL (National Renewable Energy Laboratory), 2012; Rasmussen et al., 2012; Budischak et al., 2013). Using hourly load and resource data and accounting for the intermittency of wind and solar, both Hart and Jacobson (2011) and Budischak et al. (2013) found that up to $>99.8\%$ of delivered electricity could be produced carbon-free with WWS resources over multiple years. The former study obtained this conclusion for the California grid over 2 years; the latter, over the PJM Interconnection in the eastern U.S., adjacent to NYS, over 4 years. Both studies accounted for the variability in the weather, including extreme events. Although WWS resources differ in NYS compared with these other regions, the differences are not expected to change the conclusion that a WWS power system in NYS can be reliable. NYS has WWS resources not so different from those in PJM (more offshore wind and hydroelectric than PJM but less solar).

Eliminating remaining carbon emission is challenging but can be accomplished in several ways. These include using demand response and demand management, which will be facilitated by the growth of electric vehicles; oversizing the power grid and using the excess power generated to produce district heat through heat pumps and thermal stores and hydrogen for other sectors of the energy economy (e.g. heat for buildings, high-temperature processes, and fuel-cell vehicles); using concentrated solar power storage to provide solar power at night; and storing excess energy at the site of generation with pumped hydroelectric power, compressed air (e.g., in underground caverns or turbine nacelles), flywheels, battery storage packs, or batteries in electric vehicles (Kempton and Tomic, 2005).

Oversizing the peak capacity of wind and solar installations to exceed peak inflexible power demand can reduce the time that available WWS power supply is below demand, thereby reducing the need for other measures to meet demand. The additional energy available when WWS generation exceeds demand can be used to produce hydrogen (a storage fuel) by electrolysis for heating processes and transportation and to provide district heating. Hydrogen must be produced in any case as part of the WWS solution. Oversizing and using excess energy for hydrogen and district heating would also eliminate the current practice of shutting down (curtailing) wind and solar resources when they produce more energy than the grid can accommodate. Denmark currently uses excess wind energy for district heating using heat pumps and thermal stores (e.g., Elsman, 2009).

7. Costs

An important criterion in the evaluation of WWS systems is to ensure that the full costs per unit energy delivered, including capital, land, operating, maintenance, storage, and transmission costs, are comparable with or better than costs of conventional fuels.

Table 3 presents estimates of 2005–2012 and 2020–2030 costs of electric power generation for WWS technologies, assuming standard (but not extra-long-distance) transmission and excluding distribution. The table also shows the average U.S. delivered electricity cost for conventional fuels (mostly fossil) under the same assumptions. For fossil-fuel generation, the externality cost, which includes the hidden costs of air pollution morbidity and mortality and global warming damage (e.g., coastline loss, agricultural and fish losses, human heat stress mortality, increases in severe weather and air pollution), is also shown. Table 4 breaks down the externality costs.

Table 3 indicates that the 2005–2012 costs of onshore wind, hydroelectric, and geothermal plants are the same or less than those of typical new conventional technologies (such as new coal-fired or natural gas power plants) when externality costs of the conventional technologies are ignored. Solar costs are higher. When externality costs are included, WWS technologies cost less than conventional technologies.

The costs of onshore wind, geothermal, and hydroelectric power are expected to remain low (4–8.8 cents/kWh) in 2020–2030. Costs of other WWS technologies are expected to decline to 5–11 cents/kWh (Table 3). These estimates include the costs of local AC transmission. However, many wind and solar farms may be sufficiently far from population centers to require long-distance transmission.

For long-distance transmission, high-voltage direct-current (HVDC) lines are common because they result in lower transmission

Table 3
Approximate fully annualized generation and short-distance transmission costs for WWS power (2007 U.S. cents/kWh-delivered), including externality costs. Also shown are generation costs and externality costs (from Table 4) of new conventional fuels. Actual costs in NYS will depend on how the overall system design is optimized as well as how energy technology costs change over time.

Energy technology	2005–2012*	2020–2030*
Wind onshore	4[a]–10.5[b]	≤ 4[a]
Wind offshore	11.3[c]–16.5[b]	7[b]–10.9[c]
Wave	> 11.0[a]	4–11[a]
Geothermal	9.9–15.2[b]	5.5–8.8[g]
Hydroelectric	4.0–6.0[d]	4[a]
CSP	14.1–22.6[b]	7–8[a]
Solar PV (utility)	11.1–15.9[b]	5.5[g]
Solar PV (commercial rooftop)	14.9–20.4[b]	7.1–7.4[h]
Solar PV (residential rooftop)	16.5–22.7[e]	7.9–8.2[h]
Tidal	> 11.0[a]	5–7[a]
New conventional (plus externalities)[f]	**9.6–9.8 (+5.3)=14.9–15.1**	**12.1–15.0 (+5.7)=17.8–20.7**

* $0.01/kWh for transmission was added to all technologies as in Delucchi and Jacobson (2011) except for distributed generation projects (i.e. commercial and residential solar PV).

[a] Delucchi and Jacobson (2011).

[b] Lazard (2012).

[c] Levitt et al. (2011).

[d] REN21 (Renewable Energy Policy Network for the 21st Century) (2010).

[e] SEIA (Solar Energy Industries Association) (2012). Residential LCOE: Calculated by multiplying the Lazard (2012) Commercial LCOE by the ratio of the Residential PV $/Watt to the Commercial PV $/Watt=$0.149 ($5.73/$5.16)–$0.204($5.73/$5.16).

[f] The current levelized cost of conventional fuels in NYS is calculated by multiplying the electric power generation by conventional source in NYS (EIA (Energy Information Administration, U.S.), 2012b) by the levelized cost of energy for each source (Lazard, 2012 for low estimate; EIA (Energy Information Administration, U.S. (2012c) for high estimate) and dividing by the total generation. The future estimate assumes a 26.5% increase in electricity costs by 2020 (the mean increase in electricity prices in NYS from 2003 to 2011, EIA (Energy Information Administration, U.S.), 2012d), and twice this mean increase by 2030. Externality costs are from Table 4.

[g] Google (2011), 2020 projection.

[h] The ratio of present-day utility PV to present-day commercial and residential PV multiplied by the projected LCOE of utility PV.

Table 4
Mean (and range) of environmental externality costs of electricity generation from coal and natural gas (Business as Usual—BAU) and renewables in the U.S. in 2007 (U.S. cents/kWh). Water pollution costs from natural gas mining and current energy generation are not included. Climate costs are based on a 100-year time frame. For a 20-year time frame, the NG climate costs are about 1.6 times those of coal for the given shale:conventional gas mixes.
Source: Delucchi and Jacobson (2011) but modified for mean shale and conventional natural gas carbon equivalent emissions from Howarth et al. (2011) assuming a current shale:conventional NG mix today of 30:70 and 50:50 in 2030 and a coal/NG mix of 73%/27% in 2005 and 60%/40% in 2030. The costs do not include costs to worker health and the environment due to the extraction of fossil fuels from the ground. (These estimates apply to the U. S. Section 8 estimates external costs specifically for NYS.)

	2005			2030		
	Air pollution	Climate	Total	Air pollution	Climate	Total
Coal	3.2	3.0	6.2 (1.2–22)	1.7	4.8	6.5 (3.3–18)
Natural gas (NG)	0.16	2.7	2.9 (0.5–8.6) [a]	0.13	4.5	4.6 (0.9–8.9) [a]
Coal/NG mix	2.4	2.9	5.3 (1.0–18)	1.1	4.6	5.7 (2.7–15)
Wind, water, and solar	< 0.01	< 0.01	< 0.02	< 0.01	< 0.01	< 0.02

[a] McCubbin and Sovacool (2013) estimate slightly higher air pollution-plus-climate-change costs for natural-gas fired power plants in California: 1.4–9.5 cents/kWh for 1987–2006, and 1.8–11.8 cents/kWh projected for 2012–2031 (2010 dollars).

losses per unit distance than alternating-current (AC) lines. The cost of extra-long-distance HVDC transmission on land (1200–2000 km) ranges from 0.3 to 3 U.S. cents/kWh, with a median estimate of ~1 U.S. cent/kWh (Delucchi and Jacobson, 2011). A system with up to 25% undersea transmission would increase the additional long-distance transmission cost by less than 20%. Transmission costs can be reduced by considering that decreasing transmission capacity by 20% reduces aggregate power among interconnected wind farms by only 1.6% (Archer and Jacobson, 2007). The main barrier to long distance transmission is not cost, but local opposition to the siting of lines and decisions about who will pay the costs. These issues must be addressed during the planning process.

In sum, even with extra-long-distance HVDC transmission, the total social costs of all WWS resources in 2020–2030, including solar PV, are expected to be less than the 17.8–20.7 cents/kWh average direct plus externality cost of conventional electricity.

WWS will provide a stable, renewable source of electric power not subject to the same fuel supply limitations as fossil fuels and nuclear power. Due to the eventual depletion of coal, oil, natural gas, and uranium resources, their prices should ultimately rise although technology improvements may delay this rise. Table 5 projects fuel costs from 2009 to 2030 of selected conventional fossil fuels used for transportation, heating, and electricity production in NYS. The table indicates a 19–37% anticipated increase in the cost of natural gas and a 109% increase in the cost of gasoline during this period. A benefit of WWS is that it hedges NYS against volatility and rises in long-term fossil fuel prices by providing energy price stability due to zero cost of WWS fuel.

Table 5
Projected unit costs of selected conventional fossil fuels over the period 2009–2030 in NYS.
Source: NYSEPB (New York State Energy Planning Board) (2009), Energy Price and Demand Long-Term Forecast (2009–2028). Annual growth rate factors provided in reference document have been extrapolated for the period 2029–2030.

Fuel type	Projected changes in fuel cost, 2009–2030 (2009 dollars/ MMBTU)		Percent change (%)
	2009	2030	
Gasoline—all grades	$19.30	$40.39	109
Natural gas—electric	$6.30	$10.14	27
Natural gas—residential	$13.58	$16.19	19
Natural gas—commercial	$10.27	$13.06	27
Natural gas—industrial	$8.73	$11.98	37

8. Air pollution and global warming cost Reductions in NYS due to WWS

Conversion to a WWS energy infrastructure will reduce air pollution mortality and morbidity, health costs associated with mortality and morbidity, and global warming costs in NYS. These impacts are quantified here.

Air pollution mortality in New York is estimated in two ways, a top-down approach and a bottom-up approach. The top-down approach is described first. The premature mortality rate in the U.S. due to cardiovascular disease, respiratory disease, and complications from asthma due to air pollution has been calculated conservatively to be at least 50,000–100,000 per year by several sources. From Braga et al. (2000), the U.S. air pollution mortality rate was estimated at about 3% of all deaths. The all-cause death rate in the U.S. is about 804 deaths per 100,000 population and the U.S. population in 2011 was 308.7 million. This suggests an air pollution mortality rate in the U.S. of ~75,000 per year. Similarly, from Jacobson (2010b), the U.S. death rate due to ozone and particulate matter was calculated with a three-dimensional air pollution-weather model to be 50,000–100,000 per year. These results are consistent with those of McCubbin and Delucchi (1999), who estimated 80,000–137,000 due to all anthropogenic air pollution in the U. S. in 1990, when air pollution levels were higher than today.

The population of NYS in 2011 was 19.5 million, or 6.3% of the U.S. population. A simple scaling of population to the U.S. premature mortality rate from Jacobson (2010b) yields at least 3000–6000 annual premature deaths in NYS. Since a large segment of New York's population lives in cities, this estimate is likely conservative since the intake fraction of air pollution is much greater in cities than in rural areas.

Mortalities from airborne inhalation of particulate matter ($PM_{2.5}$) and ozone (O_3) are next calculated with a bottom-up approach. This involves combining measured countywide or regional concentrations of each pollutant with a relative risk as a function of concentration and U.S. Census Bureau population by county or region. From these three pieces of information, low, medium, and high mortality estimates of $PM_{2.5}$ and O_3 are calculated with a health-effects equation (Jacobson, 2010b).

Tables 6 and 7 show the resulting low, medium, and high 2006 premature mortalities estimates in NYS due to $PM_{2.5}$ and ozone respectively. The medium values for the state as a whole were about 3300 $PM_{2.5}$ mortalities/yr, with a range of 800–6500/yr and ~710 O_3 mortalities/yr, with a range of 360–1100/yr. Thus, overall, the bottom-up approach gave ~4000 (1200–7600) premature mortalities per year for $PM_{2.5}$ plus O_3. The top-down estimate falls within this range.

Table 6
NYS annually-averaged 2006 $PM_{2.5}$ concentrations and resulting estimated annual premature mortalities. Appendix Table A1 contains details and data by county.

New York State	2006 $PM_{2.5}$ ($\mu g/m^3$)	Population (thousands)	Total 2006 Mortalities from $PM_{2.5}$		
			Low estimate	Medium estimate	High estimate
Total	**9.3**	**19,380**	**820**	**3260**	**6480**

Concentration data were from NYSDH (New York State Department of Health) (2011). The methodology is described in the text.

Table 7
Average Annual 2009–2011 premature mortalities due to ground-level ozone by New York region.

	Annual premature mortalities due to ground-level ozone		
	Low estimate	Medium estimate	High estimate
Region 1	55.1	110	164
Region 2	103	205	306
Region 3	37.7	75.1	112
Region 4	10.7	21.4	32.0
Region 5	26.5	52.8	78.9
Region 6	8.4	16.8	25.1
Region 7	18.9	37.7	56.4
Region 8	15.8	31.5	46.8
Region 9	80.8	164	244
Total	**356**	**713**	**1070**

Hourly ozone data at individual monitoring stations were obtained for January 2009–October 2011 from NYDEC (New York State Department of Environmental Conservation (2011). The 1-h maximum ozone for each day was determined from all hourly values during the day. Monitoring stations were then grouped by regions defined by the NYS Department of Environmental Conservation. Region 1=Western New York, Great Lakes Plain; Region 2=Catskill Mountains and West Hudson River Valley; Region 3=Southern Tier; Region 4=New York City and Long Island; Region 5=East Hudson and Mohawk River Valleys; Region 6=Tug Hill Plateau; Region 7=Adirondack Mountains. Mortalities were calculated each day for each region based on ozone relative risks and a health-risk equation, as in Jacobson (2010b). The low-threshold for ozone premature mortality referenced in this study was 35 ppbv.

USEPA (United States Environmental Protection Agency) (2006) and Levy et al. (2010) provided a central estimate to the value of a statistical life at $7.7 million in 2007 dollars (based on 2000 GDP). The value of life is determined by economists based on what people are willing to pay to avoid health risks as determined by how much employers pay their workers to take additional risks (Roman et al., 2012). With this value of life, 4000 (1200–7600) premature mortalities (both adult and infant) due to air pollution cost NYS roughly $31 ($9–$59) billion/yr.

Additional costs due to air pollution result from increased illness (morbidity from chronic bronchitis, heart disease, and asthma), hospitalizations, emergency-room visits, lost school days, lost work days, visibility degradation, agricultural and forest damage, materials damage, and ecological damage. USEPA (United States Environmental Protection Agency), 2011 estimates that these non-mortality-related costs comprise an additional ~7% of the mortality-related costs. These are broken down into morbidity (3.8%), recreational plus residential visibility loss (2.8%), agricultural plus forest productivity loss (0.45%), and materials plus ecological loss (residual) costs. These estimates are conservative, as other studies in the economics literature indicate considerably higher non-mortality costs. McCubbin and Delucchi's (1999) detailed, comprehensive analysis of air-pollution damages at every air quality monitor in the U.S found that the morbidity cost of air pollution

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(mainly chronic illness from exposure to particulate matter) is 25–30% of the mortality costs. Delucchi and McCubbin (2011) summarize studies that indicate that the cost of visibility and agriculture damages from motor-vehicle air pollution in the U.S. is at least 15% of the cost of health damages (including morbidity damages) from motor-vehicle air pollution. Thus, the total cost of air pollution, including morbidity and non-health damages, is at the very least ~\$8.2 million/death, and probably over \$10 million/death.

Given this information, the total social cost due to air pollution mortality, morbidity, lost productivity, and visibility degradation in NYS is conservatively estimated to be \$33 (10–76 [using \$10 million/death for the upper end]) billion per year. Reducing these costs represents a savings equivalent to ~3% of NYS's gross 2010 domestic product of \$1.1 trillion.

One set of cost estimates for global warming (in 2006 U.S. dollars) to the U.S. alone is \$271 billion/yr by 2025, \$506 billion/yr by 2050, \$961 billion/yr by 2075, and \$1.9 trillion/yr by 2100 (Ackerman et al, 2008). That analysis accounted for severe-storm and hurricane damage, real estate loss, energy-sector costs, and water costs. The largest of these costs was water costs. It did not account for increases in mortality and illness due to increased heat stress, influenza, malaria, and air pollution or increases in forest-fire incidence; thus, it may be conservative.

Averaged between 2004 and 2009, NYS contributed to 3.39% of U.S. and 0.636% of world fossil-fuel CO_2 emissions (EIA (Energy Information Administration, U.S.), 2011). Since the global warming cost to the U.S. is caused by emissions from all states and countries worldwide, it is necessary to multiply the cost of global warming to the U.S. by NYS's fraction of global CO_2 emissions to give the cost of global warming to the U.S. due to NYS's greenhouse gas emissions. The result is \$1.7 billion/yr by 2025, \$3.2 billion/yr by 2050; \$6.1 billion/yr by 2075; and \$12 billion/yr by 2100. NYS's emissions are also increasing the health and climate costs to other countries of the world.

In sum, the current fossil-fuel energy infrastructure in NYS causes ~4000 (1200–7600) annual premature mortalities, which together with other air-pollution damages cost the state ~\$33 billion/yr (~3% of its annual GDP). Fossil fuels emitted in the state will also result in ~\$1.7 billion/yr in global warming costs to the U.S. alone by 2025. Converting to WWS in the state will eliminate these externalities and their costs.

Since every 1 MW of installed WWS capacity costs ~\$2.1 million averaged over all generation technologies needed, the \$33 billion annual air-pollution cost is equivalent to ~16 GW of installed WWS power every year. Since the state needs ~271 GW of installed WWS power to deliver the 60 GW needed (Table 1) to power the state for all purposes in 2030, the payback time to convert the state as a whole to WWS, is ~16 years from the mean air-pollution-cost savings alone. The payback time accounting for air-pollution plus global-warming-cost savings is ~15 years; that accounting for air-pollution plus warming-cost benefits plus electricity sales at no profit is 10 years; that accounting for these plus 7% profit is ~9.8 years.

9. Jobs and earnings due to new electric power plants and devices

This section discusses job creation and earnings resulting from implementing the WWS electric power infrastructure described in Table 2. The analysis is limited to the electric power generation sector to provide an example. Additional jobs are expected in the electricity transmission industry, electric vehicle and hydrogen fuel cell vehicle industries, in the heating and cooling industries, and with respect to energy use for high-temperature industrial processes, but estimates for these sectors are not provided here due to the large undertaking such a calculation requires.

9.1. Onshore and offshore wind

The job creation and revenue stream resulting from generating half of NYS's all-purpose power in 2030 from onshore plus offshore wind (Table 2) were estimated with the Jobs and Economic Development Impact (JEDI) wind model (DOE (Department of Energy), 2012).

Scenarios were run assuming the development by 2025 of 200 onshore wind farms containing 4020 5-MW turbines with a total nameplate capacity of 20,100 MW and 400 offshore wind farms containing 12,700 turbines with a total nameplate capacity of 63,550 MW.

The development of the onshore wind farms is calculated to create ~61,300 full-time jobs and >\$4 billion in earnings in the form of wages, services, and supply-chain impacts during the construction period. It is also estimated to create ~2260 annual full-time jobs and >\$162 million in annual earnings in the form of wages, local revenue, and local supply-chain impacts post-construction.

The development of the offshore wind farms is estimated to create 320,000 full-time jobs and >\$21.4 billion in earnings during construction and 7140 annual full-time jobs and >\$514 million in annual earnings post-construction. (Section 9.5 discusses the extent to which WWS jobs merely displace jobs in the current energy sector.)

9.2. Concentrated solar power plants, solar PV power plants, and rooftop solar PV

The job creation and revenue stream resulting from generating 38% of NYS's all-purpose energy in 2030 with concentrated solar power (CSP, 10%) and solar PV plants and residential rooftop devices (PV, 28%), were estimated with the JEDI Concentrated Solar Power Trough and PV models (DOE (Department of Energy), 2012).

Scenarios were run assuming the development by 2025 of 38,700 MW in nameplate capacity of CSP projects, 41,400 MW of solar PV plant projects, and 75,000 MW of residential, commercial, and government rooftop PV projects.

The CSP projects are estimated to create ~401,000 full-time jobs and >\$41 billion in earnings during construction and ~15,700 full-time jobs and >\$2 billion in annual earnings post-construction.

Solar PV plants are estimated to create ~1,160,000 full-time jobs (>\$83 billion in earnings) during construction and ~5690 full-time jobs (>\$390 million in annual earnings) post-construction.

Rooftop PV systems are estimated to create ~2,420,000 full-time jobs (~\$159 billion in earnings) during construction and ~9620 full-time jobs (>\$676 million in annual earnings) post-construction.

9.3. Hydroelectric, tidal, and wave

In line with the guidelines of PlaNYC, nearly 7% of NYS's total energy in 2030 will be generated from hydroelectric, tidal, and wave power (Table 2). At most, about 944 MW of additional installed hydroelectric will be needed for the present plan, since 89% of hydroelectric is in place (Table 2). This translates into 2360 additional post-construction full time jobs assuming 2–3 full time jobs are created per MW of hydropower generated in 2025 (Navigant Consulting, 2009). Temporary construction and other supply chain jobs are not included in this projection. Temporary construction jobs for hydroelectric are estimated as 6.5 full-time equivalent (FTE) jobs/MW. FTEs are jobs during the life of the construction phase (Navigant Consulting, 2009). This gives 6200 construction jobs for hydroelectric. With the approximate ratio of

$70,000 per job (based on the ratios determined here for wind and solar), the earnings during construction of hydroelectric plants are estimated as ~$430 million during construction and $165 million/yr after construction.

For wave power (1430 MW needed) and tidal power (2600 MW needed) the same number of construction and permanent jobs per installed MW as offshore wind power are assumed, giving 7200 construction jobs and 161 annual permanent jobs for wave power and 13,100 construction jobs and 292 annual permanent jobs for tidal power. Earnings during the construction period of wave farms are estimated as ~$504 million, and those during operation, ~$11 million/yr. Earnings during construction of tidal farms are estimated as ~$920 million, and those during operation, ~$20.5 million/yr.

9.4. Geothermal

The construction of 5635 MW of geothermal capacity in the western United States has been estimated previously to create 90,160 construction and manufacturing jobs plus 23,949 full time jobs after construction (Western Governor's Association, 2010). Assuming the same relationship holds for NYS in 2025, the 3600 MW of geothermal energy (5% of total) needed for NYS will amount to the creation of ~57,600 construction and manufacturing jobs and ~15,300 post-construction jobs. With the approximate ratio of $70,000 per job, the earnings during construction of geothermal plants will be ~$4 billion during the construction period and $1 billion/yr thereafter.

9.5. Summary of jobs and earnings

Summing the job production from each sector above gives ~4.5 million jobs created during construction and ~58,000 permanent annual jobs thereafter for the energy facilities alone developed as part of this plan. Total earnings during the construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) are estimated as ~$314 billion and permanent annual earnings during operation of the facilities, ~$5.1 billion/yr

Additional jobs and earnings are associated with the enhancement of the transmission system and with the conversion to electric and hydrogen fuel cell vehicles, electricity-based appliances for home heating and cooling, and electricity and hydrogen use for some heating and high-temperature industrial processes.

The number of permanent jobs created by the electric power sector alone is expected to exceed significantly the number of lost jobs in current fossil-fuel industries. The reason is that nearly all energy for NYS with the proposed plan will be produced within the state, whereas currently, most oil, natural gas, and coal used in the state is mined out of the state or country, so jobs in those industries are not in NYS. In fact, the total number of mining jobs (for all natural resources combined) in NYS in 2011 was approximately 5700 (NYSDL (New York State Department of Labor), 2011). The total number of workers in the NYS utility industry in 2011 was about 37,100 (NYSDL (New York State Department of Labor), 2011). Even if the current electric utility industry plus mining jobs were lost due to a conversion with the present plan, they would be more than made up by with the 58,000 permanent jobs resulting from the present plan. The present plan would also result in the replacement of gas stations with electric charging and hydrogen fueling stations, likely exchanging the jobs between the industries. Similarly, the plan will require the growth of some appliance industries at the expense of others, resulting in job exchange between industries.

The increase in the number of jobs due to WWS versus the current fossil fuel infrastructure is supported independently by Pollin et al. (2009), who determined from economic modeling that, for each million dollars spent on energy production in the United States, oil and gas create 3.7 direct and indirect jobs, whereas wind and solar create 9.5 and 9.8 jobs, respectively. The difference in relative numbers of jobs created in NYS is likely to be larger than this due to the fact that many oil and gas workers and suppliers come from out of state. Since WWS resources are generated in state, their capture will provide more jobs to NYS residents. In addition, even though some of the jobs in NYS might come at the expense of jobs in other states, Pollin et al. (2009) indicate that for the U.S. as a whole, the wind and solar power industry will employ many more people than will an energy-equivalent fossil-fuel industry.

In addition, the development of the large-scale energy infrastructure proposed here should motivate research and development of new technologies and methods of improving efficiency. Much of this research will come from higher education and research institutes in NYS, creating jobs in these sectors. Demands created by infrastructure development should similarly motivate inner-city job training programs in the energy-efficient building and renewable energy industries.

10. State and local tax revenue and other cost considerations

The implementation of this plan will likely affect NYS's tax revenue and may require tax policy changes to ensure that state revenue remains at the level needed. Some revenues will increase and others will decline.

The increase in the number of jobs due to the plan over the current energy infrastructure is expected to increase personal income tax receipts. In addition, as more of NYS's infrastructure is electrified under the plan, revenues from the Utility Tax, which currently accounts for slightly less than 1.5% of state tax revenue, will increase.

NYS may experience higher property tax revenues than under an alternative, natural gas, infrastructure. Property values may decrease with shale gas drilling due to the increases in noise, conflicts with neighbors, lawsuits with gas companies, health complaints, and increases in crime in previously sparsely populated rural areas. In addition, banks may be unwilling to issue residential-rate mortgages on residential properties in gas drilling areas since industrial activity and the storing of hazardous material on the property violate residential mortgage requirements. Similarly, some insurance companies may not issue policies on such properties. Property tax revenues are expected to increase with some WWS technologies, such as rooftop PV and solar thermal due to the higher home values that result from installation of these local energy technologies. A study of the effects of 24 existing wind farms within 10 miles of residential properties in 9 states found no effect on property values (Hoen et al., 2009). Thus, a conversion to WWS should result in higher property values and tax revenues than should a fossil fuel-based infrastructure.

Finally Delucchi and Murphy (2008) show that in 1991 and 2000, the effective U.S. federal corporate income tax rate (tax paid divided by taxable income) in the oil industry was half that of all other industries, resulting in a tax "subsidy" in the year 2000 of $9.4 billion. Replacing fossil fuels with WWS energy in NYS alone could result in higher corporate income-tax revenues to the nation and may set an example for other states.

Revenues directly associated with the sale of petroleum fuels, such as the Motor Fuel Tax and the Petroleum Business Tax, will diminish as the vehicle fleet is made more efficient and ultimately transitions away from petroleum altogether. These tax revenues currently account for less than 2.5% of state tax revenue; however, they are sources of funds for the Highway and Bridge Trust Fund, the Dedicated Mass Transportation Trust Fund, and the

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Mass Transportation Operating Assistance Fund. Another potential loss in tax revenue will be from the ad valorem tax on shale gas development.

As diesel fuel is phased out, goods will increasingly be transported by means other than commercial freight, and revenue from the Highway Use Tax will diminish. This tax accounts for less than 0.2% of state tax revenue at present, but is also a large contributor to transportation infrastructure and operation funds (NYSA (New York State Assembly), 2011).

Other tax revenues associated with passenger vehicle use are not expected to decrease significantly. These include Motor Vehicle Fees, Taxi Surcharge fees, and Auto Rental Tax. These collectively account for approximately 2% of State tax revenue and contribute to the state's dedicated mass transportation and highway and bridge funds.

Some lost revenues can be regained by applying a mileage-based road use tax on noncommercial vehicles similar to the Highway Use Tax levied on commercial vehicles in NYS. This has been considered at the Federal level (NSFIFC (National Surface Transportation Infrastructure Financing Commission), 2009) and piloted in Oregon (ODT (Oregon Department of Transportation), 2007).

There are other cost considerations. For example, the conversion from fossil fuels to WWS will likely reduce environmental externality costs, thereby possibly preserving some jobs that would otherwise be lost under future fossil fuel development in NYS. Some industries that are vital to upstate NY economies and require clean water and air include agriculture, tourism, organic farming, wine making, hunting and fishing, and other outdoor recreation industries. WWS development is unlikely to adversely impact these industries, whereas future shale gas development may negatively impact these industries.

It is expected that costs to communities in NYS will increase with shale gas development, and these costs will likely be much lower or not exist with WWS development. Such costs include increased demand on police, fire departments, first responders, social services, and local hospitals. Damage to roads and resulting repair and maintenance costs have been substantial where shale gas development has taken place, especially in Texas and Arkansas. WWS development is unlikely to cause such extensive long-term damage to roads and infrastructure.

Thousands of miles of natural gas pipelines represent an opportunity cost to NYS, as future building and economic development will not be possible on or adjacent to the pipelines. The tradeoff for these pipelines with WWS is an increase in transmission lines. However, transmission lines, while resulting in some similar issues, do not carry the risk of gas leakage or explosive fires, such as the $5 billion fire that destroyed a residential neighborhood in San Bruno, California, on September 10, 2010.

Finally, extractive industries, including fossil fuels, are known for their boom and bust cycles. Renewable energy industries, and in particular WWS, are long-term sustainable industries, unlikely to be subject to boom and bust cycles.

11. Reducing energy use in Buildings, Neighborhoods, and commercial complexes

The proposed plan will continue existing efforts to improve energy efficiency in residential, commercial, institutional, and government buildings to reduce the demand for electric power in NYS. It will also encourage the conversion of buildings, neighborhoods, and commercial complexes to sustainable ones that use and store their energy more efficiently.

First, energy efficiency measures in buildings, appliances, and processes have the potential to reduce end-use power demand in the U.S. by up to 23% by 2020 (McKinsey and Company, 2009). Such a demand reduction exceeds the modest reduction of 5–10% proposed in Table 1 of the present study. The NYS demand reduction is conservative to ensure that it does not underestimate the number of energy devices and plants needed for NYS. If demand reduction is larger than 5–10%, then the NYS plan will be easier to implement. Efficiency measures include improving wall, floor, ceiling, and pipe insulation, sealing leaks in windows, doors, and fireplaces, converting to double-paned windows, using more passive solar heating, monitoring building energy use to determine wasteful processes, performing an energy audit to discover energy waste, converting to LED light bulbs, changing appliances to those using less electricity, and using hot water circulation pumps on a timer, among others.

Historically, efficiency programs targeting multifamily households have resulted in overall energy savings of approximately 20% (Falk and Robbins, 2010). For such households, the NYSERDA Home Performance with Energy Star program reportedly achieved annual savings of approximately 15% of average household electricity usage and over 50% of heating fuel savings for natural gas-heated homes (NYSERDA (New York State Energy Research and Development Authority), 2011).

Second, designing new buildings, neighborhoods and commercial complexes or retrofitting existing ones to use and store energy more efficiently has the potential to reduce significantly building energy required from the grid, transmission needs, and costs. Four methods of improving energy use and storage in buildings include: (1) extracting heat in the summer and cold in the winter from the air and solar devices and storing it in the ground for use in the opposite season, (2) recovering heat from air conditioning systems and using it to heat water or air in the same or other buildings, (3) extracting heat (or cold) from the ground, air, or water with heat pumps and using it immediately to heat (or cool) air or water, and (4) using solar energy to generate electricity through PV panels, to recover heat from water used to cool the panels, and to heat water directly for domestic use (e.g., Tolmie et al., 2012). The Drake Landing solar community is a prototype community designed primarily around the first method, that of seasonal energy storage (Drake Landing, 2012).

12. Timing of plan

This plan anticipates that the fraction of new electric power generators as WWS will increase starting today such that, by 2020, all new generators will be WWS generators. Existing conventional generators will be phased out gradually, but no later than 2050. Similarly, all new heating and cooling technologies will be WWS technologies by 2020 and existing technologies will be replaced over time, but by no later than 2050.

For transportation, the transition to BEVs and HFCVs has potential to occur rapidly due to the rapid turnover time of the vehicle fleet (~15 years) and the efficiency of BEVs and HFCVs over fossil-fuel combustion vehicles. However, the actual rate of transition will depend on policies put in place and the resulting vehicle and energy costs. BEVs and HFCVs exist today, but due to their efficiency over combustion, they are proposed to be the only new vehicles sold in NYS by 2020. Several electric vehicles are currently available (e.g., Tesla Model S, 499 km (310 mile) range; Tesla Roadster, 391 km (243 mile); Renault Fluence Z.E., 185 km (115 mile); Citroen C-Zero, 177 km (110 mile); Mitsubishi I MiEV, 177 km (110 mile); Tazzari Zero, 140 km (87 mile); Ford Focus, 129 km (80 mile); Nissan Leaf, 117 km (73 mile)). The growth of electric vehicles will be accompanied by an increase in electric charging stations in residences, commercial parking spaces, and service stations. Most charging will be done with 220 V chargers over several hours, but 440 V chargers are now available for faster charging. For example, the Tesla Model S includes 440 V, 160 A charging capability that will allow sufficient power for a 310 mile range in about 1 h.

13. Recommended first Steps

Below are recommended short-term policy steps to start the conversion to WWS in NYS.

13.1. Large energy projects: offshore/onshore wind; solar PV/CSP, geothermal, hydro

- Direct the New York State Energy Research and Development Authority (NYSERDA) to issue a new main tier solicitation to meet its existing renewable portfolio standard (RPS) commitments through 2015, selecting and contracting with sufficient wind and solar projects to do so.
- Extend the RPS in NYS. The 30% RPS currently sunsets in 2015. Propose to ramp up the RPS each year to get to 50% by 2025 (2% per year).
- Set a goal of at least 5000 MW offshore wind by 2020. Direct the New York Power Authority (NYPA) and the Long Island Power Authority (LIPA) to issue requests for proposals (RFPs) for new power generation from offshore wind as part of their generation and procurement budgets.
- Set up a Green Bank, which is a vehicle for public–private financing in conjunction with long-term contracts for large wind and solar development projects in NYS. An example Green Bank exists in Connecticut. The Green Bank would include a statewide version of the Department of Energy Loan Guarantee Program that focuses specifically on WWS energy generation projects. Such a program will reinvigorate private lending activity.
- Lock in upstate coal-fired power plants to retire under enforceable commitments. At the same time, streamline the permit approval process for WWS power generators and the associated high-capacity transmission lines and eliminate bureaucratic hurdles involved in the application process. Promote expanding transmission of power between upstate and downstate and between onshore and offshore, in particular.
- Work with regions and localities, and the federal government (in the case of offshore wind) to reduce the costs and uncertainty of projects by expediting their physical build-out by managing zoning and permitting issues or pre-approving sites.
- Encourage regulators to require utilities to obtain permission for a certain capacity of electric power to be installed before auctioning off projects to lowest-bidding developers. Currently, a pre-approved Power Purchase Agreement between a utility and particular project developer is required before permission from the regulators can be obtained. This change will ensure end-users obtain electricity at the lowest price.

13.2. Small energy projects: residential commercial, and government rooftop solar PV

- Extend the New York Sun (NY Sun) program to a multi-year program to finance rooftop and on-site solar projects in the state.
- Implement virtual net metering (VNM) for small-scale energy systems. The following recommendations will render utility-scale wind and solar power net metering conducive to corporate clients, and pave the way for a more widespread subscription to off-site generating project for the public at large.

(1) Remove the necessity for subscribers to have proprietorship in the energy-generating site.
(2) Expand or eliminate the capacity limit of renewable power under remote net-metering for each utility.
(3) Remove the barrier to inter-load zone transmission of net-metered renewable power.
(4) Expand Public Service Law 66.j to reduce red tape and enable off-site virtual net-metering from upstate to downstate, and from the outer boroughs to Manhattan.

- Streamline the small-scale solar and wind installation permitting process. Currently, each municipality has its own permitting process and fee structure. Creating common codes, fee structures, and filing procedures across a state would reduce a barrier to the greater implementation of small-scale solar and wind.
- Develop community renewable energy facilities, whereby a community buys power from a centralized generation facility. The facility feeds power into the grid, and the utility credits the kilowatt-hours to the accounts of individuals, businesses, and any other electricity customer that sign up. The facility may be located anywhere in the utility's service territory, since all that is required is a bill crediting arrangement by the utility. This brings many advantages: economies of scale of the facility, siting in an ideal location, and broader inclusiveness. Many electricity users cannot install a renewable energy system, because they are renters or because their property is not suitable for a system. Community renewable energy is inclusive because it enables anyone, whether living in rural New York or an apartment building in Manhattan, to buy the power without having to host the system. New York already has a community renewable energy program, but it is restrictive. A simple legislative fix would enable this approach to be used widely.
- Encourage clean-energy backup emergency power systems rather than diesel/gasoline generators. For example, work with industry to implement home energy storage (through battery systems) accompanying rooftop solar to mitigate problems associated with grid power losses.
- Implement feed-in tariffs (FITs) for small-scale energy systems. FITs are financial incentives to promote investment in renewable power generation infrastructure, typically by providing payments to owners of small-scale solar PV systems to cover the difference between renewable energy generation cost (including grid connection costs) and wholesale electricity prices.

13.3. Energy efficiency in buildings and the grid

- The current target for energy efficiency is 15% less energy use below forecasted levels by 2015. Expand the target significantly beyond 2015 and increase investment fivefold from both public and private sources. This requires the New York State Public Service Commission (NYSPSC) to increase NYSERDA and utility requirements and budgets for efficiency.
- Promote, through municipal financing, incentives, and rebates, energy efficiency measures in buildings, appliances, and processes. Efficiency measures include improving wall, floor, ceiling, and pipe insulation, sealing leaks in windows, doors, and fireplaces, converting to double-paned windows, using more passive solar heating, monitoring building energy use to

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determine wasteful processes, performing an energy audit to discover energy waste, converting to LED light bulbs, changing appliances to those using less electricity, and using hot water circulation pumps on a timer, among others.

- Encourage conversion from natural gas water and air heaters to heat pumps (air and ground-source) and rooftop solar thermal hot water pre-heaters. Incentivize the use of efficient lighting in buildings and on city streets.
- Encourage utilities to use demand-response grid management to reduce the need for short-term energy backup on the grid. This is a method of giving financial incentives to electricity users to shift times of certain electricity uses to times when more energy is available.
- Institute, through Empire State Development Corporation, a revolving loan fund to pay for feasibility analyses for commercial Energy Services Agreements. The revenues from these retrofits are amortized as a majority percentage of the Energy-Cost Savings realized as direct result of these retrofits. ROI's can be realized in 5–10 years with 10–20 year Energy Services Contracts. Allocating some of these revenues back to the fund will render it sustainable.
- Extract heat in the summer and cold in the winter from the air and solar devices and store it in the ground for use in the opposite season. The Drake Landing solar community is a prototype community designed primarily around seasonal energy storage (Drake Landing, 2012).
- Recover heat from air conditioning systems and use it to heat water or air in the same or other buildings at the same time.
- Extract heat (or cold) from the ground, air, or water with heat pumps and use it immediately to heat (or cool) air or water.
- Recover heat from water used to cool solar PV panels to heat water directly for domestic use.

13.4. Vehicle electrification

- Coordinate items below so that vehicle programs and public charging stations are developed in sync. Create a governor-appointed EV Advisory Council, as has been done in states such as Illinois and Connecticut, to recommend strategies for EV infrastructure and policies. Council members should include representatives from state agencies, environmental groups, utilities, auto companies, and EV charging infrastructure companies.
- Leverage and augment the technical and financial assistance of the U. S. Department of Energy's "Clean Cities Program" activities, focusing on the deployment of EVs.
- Adopt legislation mandating the transition to plug-in electric vehicles for short- and medium distance government transportation and encouraging the transition for commercial and personal vehicles through purchase incentives and rebates.
- Encourage fleets of electric and/or hydrogen fuel cell/electric hybrid buses starting with a few and gradually growing the fleets. Electric or hydrogen fuel cell ferries, riverboats, and other local shipping should be encouraged as well.
- Encourage and ease the permitting process for the installation of electric charging stations in public parking lots, hotels, suburban metro stations, on streets, and in residential and commercial garages.
- Ensure that new charging infrastructure is vehicle-to-grid (V2G)-capable, and integrated into a statewide "smart grid" system.
- Set up time-of-use electricity rates to encourage charging at night.
- Provide electric vehicle drivers access to high-occupancy vehicle (HOV) lanes.
- Use excess wind and solar produced by WWS electric power generators to produce hydrogen (by electrolysis) for transportation and industry and to provide district heating (as done in Denmark) instead of curtailing the wind and solar.

13.5. Industrial processes

- Provide incentives for industry to convert to electricity and electrolytic hydrogen for high temperature and manufacturing processes where they are not currently used.
- Encourage industries to use WWS electric power generation for on-site electric power (private) generation.

14. Conclusions

This study examined the technical and economic feasibility of and proposed policies for converting New York State's energy infrastructure for all purposes into a clean and sustainable one powered by wind, water, and sunlight producing electricity and hydrogen. Such a conversion is estimated to improve the health and welfare of NYS residents, thereby lowering their medical, insurance, and related costs, and is expected to create jobs to manufacture, install, and manage the infrastructure.

The study found that complete conversion to WWS in NYS will reduce end-use power demand by ~37%, due mostly to the efficiency of electricity versus combustion, but also due partly to energy efficiency measures.

If complete conversion to WWS occurs, the 2030 NYS power demand for all purposes (not only electricity) could be met by 4020 onshore 5-MW wind turbines (providing 10% of NYS's energy for all purposes), 12,770 off-shore 5-MW wind turbines (40%), 387 100-MW concentrated solar plants (10%), 828 50-MW solar-PV power plants (10%), 5 million 5-kW residential rooftop PV systems (6%), 500,000 100-kW commercial/government rooftop systems (12%), 36 100-MW geothermal plants (5%), 1910 0.75-MW wave devices (0.5%), 2600 1-MW tidal turbines (1%), and 7 1300-MW hydroelectric power plants (5.5%), of which 89% are already in place. The onshore wind capacity installed under this plan (~20.1 GW) would be less than twice the 2012 installed capacity of Texas.

Several methods exist to match renewable energy supply with demand and to smooth out the variability of WWS resources. These include (A) combining geographically-dispersed WWS resources as a bundled set of resources rather than as separate resources and using hydroelectric power to fill in remaining gaps; (B) using demand-response grid management to shift times of demand to match better with the timing of WWS power supply; (C) over-sizing WWS peak generation capacity to minimize the times when available WWS power is less than demand and to provide power to produce heat for air and water and hydrogen for transportation and heating when WWS power exceeds demand; (D) integrating weather forecasts into system operation to reduce reserve requirements; (E) storing energy in thermal storage media, batteries or other storage media at the site of generation or use; and (F) storing energy in electric-vehicle batteries for later extraction (vehicle-to-grid).

The additional footprint on land for WWS devices is equivalent to about 0.96% of New York's land area, mostly for CSP and PV. An additional on-land spacing area of about 1.46% is required for on-shore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land, for example.

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The land footprint and spacing areas (open space between devices) in the proposed scenario can be reduced by shifting more land based WWS generators to the ocean, lakes, and rooftops.

2020–2030 electricity costs are estimated to be 4–8.8 cents/kWh for most WWS technologies and 5–11 cents/kWh for others (including local transmission and distribution), which compares with about 17.8–20.7 cents/kWh for fossil-fuel generators in 2030, of which 5.7 cents/kWh are externality costs. Long-distance transmission costs on land are estimated to be 1 (0.3–3) cent/kWh for 1200–2000 km high-voltage direct current transmission lines.

Although the cost of WWS electricity is expected to be lower than that of fossil fuels and all energy in a WWS world will be transformed to electricity, infrastructure conversion will result in other cost tradeoffs not quantified here. For example, conversion from combustion vehicles to electric and hydrogen fuel cell vehicles and from current combustion-based heating technologies to electricity based technologies may result in large initial cost increases to consumers, when relatively low levels of vehicles are being manufactured. However, as production of new vehicles increases and technology matures, manufacturing costs will decline, and this, combined with the lower energy and operating costs of electric vehicles, may result eventually in electric vehicles having a total lifetime cost comparable with that of conventional gasoline vehicles (Delucchi and Lipman, 2010),

The plan is estimated to create ~4.5 million jobs during construction and ~58,000 permanent annual jobs thereafter for the proposed energy facilities alone. Total earnings during the construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) will be ~$314 billion and permanent annual earnings during operation of the facilities will be ~$5.1 billion/yr

The implementation of this plan will likely increase personal income, property, and utility tax revenues in NYS relative to the current infrastructure. At the same time, it will reduce fuel-tax revenues. These can be made up from either the utility taxes or mileage-base road fees.

The plan effectively pays for the 100% WWS energy generation infrastructure to power NYS for all purposes over 15 years solely by the reduction in air-pollution costs to the state and global warming costs to the U.S. from state emissions. Annual electricity sales equal to the cost of the plant divided by its expected life (~30 years) reduce the payback time to ~10 years. The current fossil-fuel infrastructure does not provide the air-quality benefits to NYS, so it's payback time with annual electricity sales equal to the cost of the plant and fuel divided by the expected plant life is ~30 years; assuming a 7% profit, it is ~28 years.

This plan may serve as a template for plans in other states and countries. Results here suggest that the implementation of plans such as this in countries worldwide should reduce global warming, air, soil, and water pollution, and energy insecurity.

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Appendix A1

See Appendix Table A1.

Table A1
NYS annually-averaged 2006 $PM_{2.5}$ concentrations and resulting estimated annual premature mortalities by county.

County	2006 $PM_{2.5}$ ($\mu g/m^3$)	Population (thousands)	Total 2006 Mortalities from $PM_{2.5}$		
			Low estimate	Medium estimate	High estimate
Albany	9.4	304	8.4	33.4	66.5
Alleghany*	8.2	49	0.9	3.5	6.9
Bronx	13.9	1385	88.4	351	695
Broome**	10.3	201	7.0	27.8	55.4
Cattaraugus*	9.6	80	2.3	9.3	18.6
Cayuga*	8.3	80	1.5	5.9	11.8
Chautauqua	8.3	135	2.5	10.0	20.0
Chemung*	8.2	89	1.6	6.3	12.6
Chenango*	10.3	50	1.8	7.0	13.9
Clinton*	5.5	82	0.9	3.6	7.3
Columbia*	9.4	63	1.7	6.9	13.8
Cortland*	8.3	49	0.9	3.7	7.3
Delaware*	10.3	48	1.7	6.7	13.2
Dutchess**	10.7	297	11.3	45.1	89.7
Erie	10.9	919	36.4	145	289
Essex	5.5	39	0.4	1.7	3.5
Franklin*	6.0	52	0.6	2.5	4.9
Fulton*	11.5	56	2.5	9.8	19.6
Genesee*	10.3	60	2.1	8.3	16.5
Greene*	9.4	49	1.4	5.4	10.8
Hamilton*	6.0	5	0.1	0.2	0.5
Herkimer*	6.4	65	0.8	3.3	6.6
Jefferson*	6.4	116	1.5	6.0	12.0
Kings	12.8	2505	138	547	1090
Lewis*	6.4	27	0.4	1.4	2.8
Livingston*	8.9	65	1.5	6.0	12.0
Madison*	8.3	73	1.4	5.5	10.9
Monroe	9.5	744	21.1	84.1	168
Montgomery*	11.5	50	2.2	8.9	17.7
Nassau	10.8	1340	52.0	207	412
New York	14.4	1586	108	427	845
Niagara	10.4	216	7.7	30.7	61.2
Oneida**	10.5	235	8.5	34.1	67.8
Onondaga	8.3	467	8.7	34.7	69.1
Ontario*	8.9	108	2.5	9.9	19.8
Orange	9.7	373	11.2	44.5	88.7
Orleans*	10.0	43	1.4	5.5	10.9
Oswego*	8.3	122	2.3	9.1	18.1
Otsego*	10.5	62	2.3	9.0	18.0
Putnam*	10.4	100	3.5	14.0	27.9
Queens	11.6	2231	101	402	800
Rensselaer*	9.4	159	4.4	17.5	34.9
Richmond	12.2	469	23.5	93.5	186
Rockland*	10.4	312	11.0	43.7	87.1
St. Lawrence	6.4	112	1.4	5.8	11.5
Saratoga*	11.5	220	9.8	38.9	77.3
Schenectady**	11.5	155	6.9	27.4	54.5
Schoharie*	9.4	33	0.9	3.6	7.2
Schuyler*	8.2	18	0.3	1.3	2.6
Seneca*	8.2	35	0.6	2.5	5.0
Steuben**	8.2	99	1.8	7.0	14.0
Suffolk	10.4	1493	53.1	212	422
Sullivan*	9.7	78	2.3	9.3	18.4
Tioga*	10.3	51	1.8	7.1	14.1
Tompkins*	9.4	102	2.8	11.0	21.9
Ulster*	9.7	182	5.5	21.8	43.4
Warren*	5.5	66	0.7	2.9	5.8
Washington*	5.5	63	0.7	2.8	5.6
Wayne*	9.5	94	2.7	10.6	21.1
Westchester	11.0	949	38.4	153	304
Wyoming*	10.9	42	1.7	6.7	13.2
Yates*	8.7	25	0.5	2.2	4.3
Total	**9.3**	**19,380**	**820**	**3260**	**6480**

Concentration data were from NYSDH (New York State Department of Health) (2011). The methodology is described in the text.

* 2006 data for these counties were not available, so an average of data from adjacent or nearby counties was used.

** 2006 data for these counties were not available, so 2003 values were used.

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