Summary: A Path to Sustainable Energy by 2030

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Executive Summary

The plan below demonstrates how the world can feasibly produce 100% of its energy by 2030 from sources with near-zero lifetime (including construction, operation and decommissioning) emissions of greenhouse gases and air pollutants. Only technologies available and scalable today are included. These include wind, water, and solar (WWS) for power, and battery and fuel cell vehicles (including airplanes) powered by WWS electricity and hydrogen split from water, respectively, for transportation. The obstacles to a clean-energy future are largely political, not technical.

Highlights:

1. Switching to WWS power worldwide by 2030 will require 5.4 TW less power than maintaining a traditional fuel mix, and 1 TW less than used today. This is due to the greater power efficiency of electricity. For example, only 17-20% of the energy in gasoline is used to move a vehicle (the rest is wasted as heat), whereas 75-86% of electricity delivered to an electric vehicle goes into motion.
2. Total estimated worldwide costs of this plan are $100 trillion over 20 years, not including transmission. This money would be spent anyway for new fossil fuel plants plus their lifetime fuel costs, and avoids tens of trillions in health, environmental and security costs. Switching to WWS now will save money!
3. Mass-produced electric vehicles could have lower lifetime cost per mile (including battery replacements) than a gasoline vehicle when gasoline costs more than $2 a gallon.
4. Though the plan calls for 3.8 million new 5 MW turbines to be installed, the world manufactures 73 million cars and light trucks in a *single year.*

Technical Summary

The Plan:

Across the whole surface of the Earth, 1,700 terawatts (TW) of wind, 6,500 TW of solar, and 2 TW of water power are available. Subtracting areas not likely to be developed (middle of the ocean, high mountain passes, protected regions, etc.) 40-85 TW of wind, 580 TW of solar, and 1.1 TW of water are practically available. We need only 11.5 TW!

WATER	*WIND*	*SOLAR*
1.1 TW (9% of supply)	5.8 TW (51% of supply)	4.6 TW (40% of supply)
- 490,000 **1 MW** tidal turbines (< 1% in place). - 5,350 **100 MW** geothermal plants (2% in place). - 900 **1.3 GW** hydroelectric plants (70% in place).	- 3,800,000 **5 MW** wind turbines (1% in place). - 720,000 **0.75 MW** Wave converters* (1% in place)	- 1,700,000,000 **0.003 MW** rooftop photovoltaic systems** (< 1% in place). - 40,000 **300 MW** PV power plants (< 1% in place). - 49,000 **300 MW** concentrated solar power plants (< 1% in place).

Table 1: A Plan to get 11.5 TW. Underlined numbers indicate the number of units needed. **Bold** indicates the size of each unit. 1 megawatt (MW) = 1 million watts; 1 gigawatt (GW) = 1 billion watts; 1 terawatt (TW) = 1 trillion watts. *Wind drives waves **Sized for a modest house;

a commercial roof might have dozens of systems.

Enough Space?

The worldwide footprint of the 3.8 million turbines, accounting for the required space between them, would be ~1% of the Earth's land. But not all the turbines need to be on land, and the empty space among turbines could be used for agriculture, ranching, or as open land or ocean. The nonrooftop PV and concentrated solar plants would occupy ~0.33% of the planet's land. Of course, space for the rooftop systems is already allocated! By contrast, making up the extra power we'd need by 2030 would require about 13,000 large new coal plants, which themselves would occupy a lot more land, as would the mining to supply them.

Intermittency

Concerns about power intermittency are easily addressed by interconnecting dispersed wind farms, utilizing on-site energy storage methods, using complementary and gap-filling power sources, using "smart" demand-response management, routing spare WWS energy to make hydrogen, and perhaps using vehicle to grid or centralized energy storage. Any of these strategies can go a long-way towards addressing intermittency. For example, if 19 wind farms in a 850x850 km area of the midwest were interconnected, 33% of their annual energy production could be supplied with the same reliability as coal!

Furthermore, WWS technologies generally suffer less downtime than traditional sources. The average U.S. coal plant is offline 12.5% of the year for scheduled and unscheduled maintenance. Compare this to 2% downtime for turbines on land, less than 5% for turbines at sea, and 2% for PV. Finally, when a coal, nuclear or natural gas plant goes offline, a large chunk of generation is lost. With wind and solar, only a small fraction of production is affected.

Current and projected costs for technologies included in the plan

Power source	2005-2010 (¢/kWh)	2020 (¢/kWh)	Power source	2005-2010 (¢/kWh)	2020 (¢/kWh)
Conventional	7	8	*Wind offshore*	10 to 17	<4
Geothermal	4 to 7	4 to 7	*Wave*	≥11	4
Hydroelectric	4	4	*Concentrated solar*	10 to 15	8
Wind onshore	4 to 7	<4	*Solar PV*	>20	10

Table 2: Costs. For each WWS technology listed, the numbers include the annualized cost of capital, land, operations, maintenance, and energy storage to help offset intermittent supply and transmission. When externalities (damage to human health, environment, climate, etc.) of fossil-fuel generation are taken into account, WWS technologies become even more cost-competitive.

Problem materials

There is plenty of steel and concrete to make get to 100% renewable power by 2030, and these two materials are easily recycled. But, what about the rarer elements required by these technologies?

Rare Material	Needed for	Solution to tight supply
Neodymium	Wind turbine gear boxes	Manufacturers already moving to gearless turbines
Tellurium and	Thin-film PV	Only some thin-film cells. Other types may pick

Indium		up.
Silver	PV	More and better recycling. A big step towards this, which the industry is aware of, will be designing equipment with easy recycling of rare materials in mind.
Rare Earth Metals	Electric motors	
Lithium	Batteries	
Platinum	Fuel Cells	

Table 3: Enough material? Deploying so many renewable resources would require a lot of rare materials. This chart specifies the rarest materials, and how we might still manage.