Clean and Doable Liquid Fission (LF) Energy Roadmap For Powering Up Our World

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Introduction

This essay responds to an article by Stanford Professor Mark Z. Jacobson et al, 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. Their controversial WWS roadmap has several interesting features and benefits.

- Coal, natural gas, and petroleum energy sources are replaced by WWS.
- Electricity from WWS becomes the universal energy source.
- Everything is electrified, including transportation, industry, and heating.
- Electricity demand grows from 2,400 GW in 2012 to 11,800 GW by 2050.
- Fossil-sourced combustion heat drops to zero from 9,700 GW.
- Clean air ends premature deaths of 3.5 million people per year.
- CO2 emissions drop to zero.

However WWS implementation issues are controversial.

- Solar and wind energy sources are intermittent.
- Energy storage cost assumptions of 0.8 cents/kWh are an order of magnitude too low.
- From 59% to 85% of energy demand must be "flexible" to adjust to supply availability.
- New electric generation nameplate capacity needs are 49,900 GW.
- Over 2.5 million wind turbines plus billions of rooftop solar systems must be built.
- Capital investments are $125 trillion.
- Electricity will cost 11 cents/kWh.
- New global public policies are needed to force adoption of expensive WWS power.

Many authors have pointed out the impossibility of this Stanford WWS roadmap, including Jesse Jenkins and Samuel Thernstrom: Deep Decarbonization of the Electric Power Sector, Mathijs Beckers wrote The Non-Solutions Project of Mark Z. Jacobson. Misled by Jacobson, climate activists such as Bill McKibben of 350.org calls for world war-like mobilization of nations to effect the $125 trillion WWS roadmap.

This present essay describes a doable, affordable liquid fission (LF) power roadmap to solve the multiple issues of climate change, air pollution, and poverty reduction.

Liquid Fission

Advanced, demonstrated liquid fission technology provides an energy source alternative that can economically address a wide scope of global needs:

- Reducing energy poverty and enabling prosperity in developing nations.
- Cutting combustion-sourced air pollution causing millions of premature deaths annually.
- Ending CO2 emissions from burning fossil fuels.

Current light water reactor (LWR) nuclear power plant technology, which generates dependable, emission-free electric power, now provides 11% of world electricity. Liquid fission (LF) power was demonstrated at Oak Ridge National Laboratory in the last century, then politically sidelined. LF technology uses energy-rich thorium and/or uranium fuel dissolved in molten salt. This liquid transfers fission heat energy via heat exchangers to steam turbine electric generators. In contrast to LWRs, LF power plants operate at high temperature and low pressure. LF achieves low electricity costs because of high power conversion efficiency, simplicity of handling liquid fuel, and low-pressure coolant. High safety comes from passive reactivity control and cooling, radioactive materials at low pressure, and high temperature tolerance of materials using molten fuel salt 700°C below its boiling point.

Developing Nations

Electricity from both WWS and new LWR power plants is more expensive than electricity from new coal-fired plants, which costs about 6 cents/kWh. Coal power plants generate 1400 of 2400 GW of today's global electric power. Advised by climate scientists and international organizations, governments have unsuccessfully strived to reduce global carbon dioxide emissions. CO2 in the atmosphere is now rising at the fastest rate ever recorded. Developing nations have plans to build yet another 1400 GW of coal-fired power plants by 2040. They choose coal plants because these now generate the cheapest, ample, reliable power.

Low-emission WWS sources are intermittent and more expensive electricity generators than coal-fired power plants. Liquid fission can provide energy even cheaper than coal. Simple economic self-interest will induce developing nations, then all nations, to adopt this least expensive, least environmentally harmful energy source. LF is emission-free, reducing deadly particulate air pollution and the heat-trapping atmospheric CO2 contributing to global warming.

WWS and LF Roadmap Similarities

The WWS and LF energy roadmaps agree on the future importance of electrification and conversion of industrial, commercial, residential, and transportation services to use electric energy rather than thermal energy from fossil fuels.

Jacobson's WWS Table 1 aggregates thermal and electric power as Total, but it's useful to distinguish them. Here BAU means business as usual.

Table 1: Electric and thermal power demand			
Roadmap	Total end-use (GW)	Electric (GW)	Thermal (GW)
BAU 2012	12,105	2,400	9,705
BAU 2050	20,604	4,085	16,519
WWS 2050	11,840	11,840	0

The WWS 2050 roadmap table projects that (11,840 - 4,085) 7755 GW additional electric power can replace 16,519 GW of thermal power. This is consistent with LF roadmap projections in Figure 2 that converting all energy use to electricity will triple electric power consumption.

Powering Prosperity

The opportunity to improve human prosperity with electric power is immense. Developing economies typically improve their GDP by $4 per kWh additional. In this Figure 1 projection per capita power grows to about half that of US persons. Though this projection is timeless, the resulting 5000 GW is roughly consistent with Jacobson's 4085 GW for 2050 BAU.

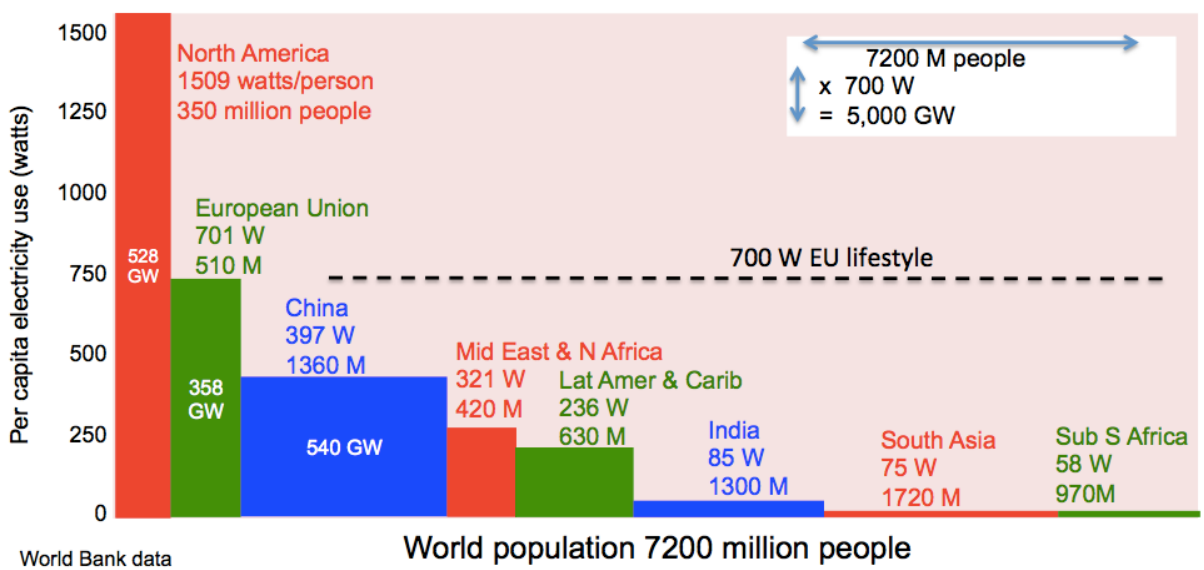

Figure 1. Prosperity: world wide prosperity demands 5,000 GW of electric power.

Liquid Fission Roadmap

Liquid fission power is being developed by several innovative companies. The ThorCon objective is to manufacture power plants at less capital cost than coal-fired plants. Fuel costs for thorium and uranium are much less than for coal, so generated electricity will cost less. ThorCon's web site projects capital costs of $1.2B per GW of generating capacity, leading to electricity that should cost 3 cents/kWh or less.

These plants are designed to be manufactured in 50 to 500 ton modular blocks by existing shipyards, using proven high-quality steel-fabrication technologies. Complete fitted-out blocks will be barged to excavated shore-side locations and welded together. After achieving mass production, time from firm order to operation will be 2 years. How?

Steel for such a 1-GW LF underground power plant is 36,000 tons. The world's single largest shipyard can fabricate 2.5 million tons of steel into ships, annually; industry capacity exceeds 15 million tons/year, enough to manufacture more than 400 1-GW power plants per year. Moreover this manufacturing capacity already exists and is underutilized, so production can start soon.

ThorCon International is planning to build LF power plants starting in Indonesia. The first few rows of Table 2 reflect the plans shared with the power company and potential investors. In this extended illustration, as mass production is achieved, LF power plant deployment rates rise progressively to 10, 20, 50, 100, then 200 GW per year after 2040.

Table 2: Liquid Fission Roadmap

Year	Annual Production Rate (GW)	New LF Additions (GW)	Cumulative New LF Power Supply Additions (GW)
2022		1	1
2026	3	3	4
2027	5	5	9
2028-2029	10	20	29
2030-2031	20	40	69
2032-2033	50	100	169
2034-2040	100	700	869
2041 - 2050	200	2,000	2,869
2051 - 2100	200	10,000	12,869

Electric Power Sector Decarbonization

By 2050 the LF roadmap additions of 2,869 GW could avoid adding the planned 1400 GW of coal-fired electric generation and then retiring the 1400 GW of existing coal-fired generators. This meets Jenkins' expert consensus that "Power sector CO2 emissions must fall nearly to zero by 2050 to achieve climate policy goals." and "There is no disagreement on the question of prioritizing the power sector in decarbonization scenarios."

Realistically, operating fossil-fueled power plants will likely run to the end of their economic lives. The world is now building more of them at 100 GW per year. Their fires might be extinguished early if LF power costs drop below coal plant incremental operational costs. Coal fuel costs about 2.3 cents/kWh. A carbon tax might incentivize retirement of operating fossil fuel power plants.

Electrification Can End CO_2 of Burning Oil, Gas, Coal.

Electrify everything! Many processes and applications based on heat from burning fossil fuels can be replaced with electric-powered ones. Immediate electrification opportunities in other sectors are:

- *Transportation*. Electric cars and trains can cut use of gasoline and diesel fuels.

- *Heating and cooling*. Electricity can heat and cool buildings with heat pumps. Air conditioning in the mid East and Africa provides a productivity growth opportunity.

- *Desalination*. Electricity used to desalinate seawater can provide fresh water to arid regions, enabling increased food production, important as climate change progresses.

- *Aluminum*. Over half the valued added in manufacturing aluminum comes from electricity. Aluminum is substituting for heavier steel in trucks, for example.

By 2050 electrification of transportation and industrial sectors will be feasible. The transportation sector now depends on hydrocarbon fuels such as gasoline and diesel, which are as big a source of CO_2 as electric power plants. Future carbon-neutral onboard liquid fuels may be based on hydrogen from splitting water. Electrolyzing technology such as CuCl catalysis at 530°C will be able to use LF heat and LF electricity to make hydrogen at a conversion efficiency near 50%. At 3 cents/kWh for LF electricity, future hydrogen would cost 1.6 cents per megajoule — the same as energy from $2/gallon gasoline. However the fuel efficiency of a hydrogen-fuel-cell powered electric car is twice that of a gasoline-engine powered car, cutting the fuel cost per mile in half. Trucking ventures such as Nikola are already exploring hydrogen fuel.

Synfuels such as gasoline-substitute methanol (CH_3OH) and diesel-substitute dimethyl ether (CH_3OCH_3) are compatible with today's internal combustion engines. Their carbon might be recycled from flue gas, or derived from climate-neutral sources such as bio-waste, or CO_2 from the atmosphere or dissolved in the ocean, which contains 50 times as much as the air. Future electrification opportunities arising from inexpensive LF electric power include:

- *Ammonia*. Ammonia (NH_3) is used for fertilizer that feeds a third of the world's people. Today it is made from natural gas methane (CH_4), releasing CO_2 in the process. It is also a proven alternative vehicle fuel.

- *Synfuels*. The US navy demonstrated extraction of CO_2 dissolved in seawater, with hydrogen from dissociation of water, to synthesize JP-5 jet fuel at $5/gallon.

- *Hydrogen*. LF-electrolyzed hydrogen itself is a possible on-board vehicle fuel, demonstrated in fuel cell cars.

- *Steel.* Direct reduction process with electricity and possibly hydrogen may replace coal-fired blast furnaces.

- *Cement*. Plasma-arc electric heating might reduce the huge quantities of fossil fuel burned to sinter limestone and sand to make cement.

Universal Electrification, Prosperity, and Population Growth

World population is growing, with best guess estimates of perhaps 9.5 billion people by 2100. This Electrified Growth LF roadmap projection below illustrates

- doubling electric consumption as developing nations achieve prosperity,
- tripling of electric consumption to 2100 W/person as it substitutes for fossil fuel burning, and
- increasing world population to 9.5 billion people.

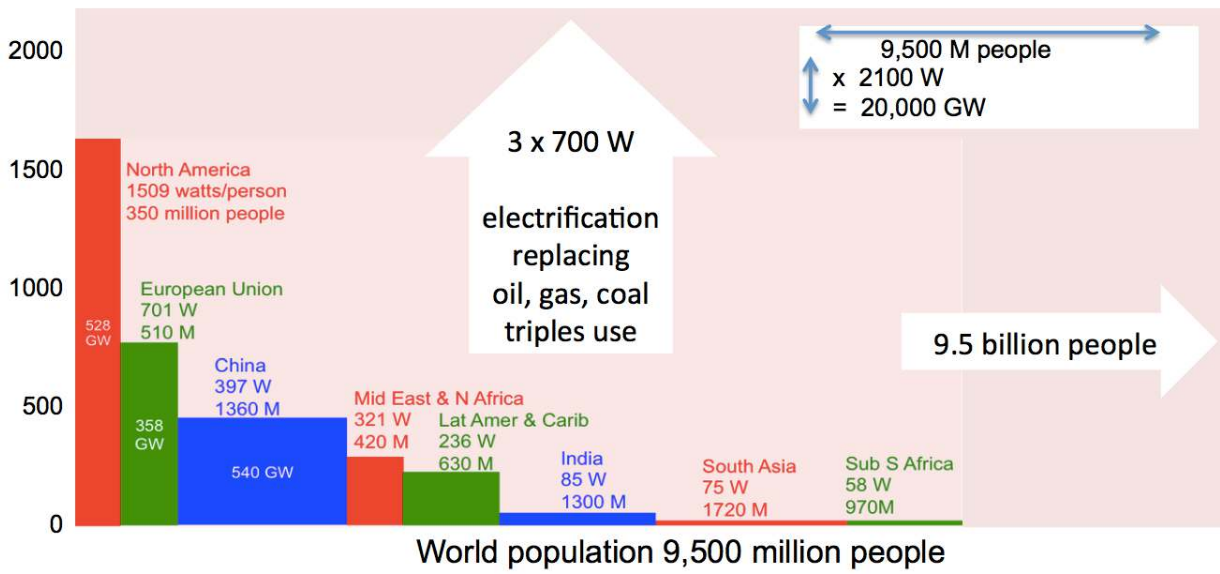

Figure 2. Electrified Growth: an electrified, crowded planet demands 20,000 GW.

This LF roadmap Electrified Growth demand of 20,000 GW exceeds the WWS 11,840 GW, which projects energy consumption of 1200 watts per person in 2050.

LF and WWS Roadmaps Compared

This LF roadmap has many advantages compared to Jacobson's WWS roadmap.

- Capital required for the LF roadmap to 2100 is $15 trillion rather than $125 trillion for WWS.

- LF electricity at 3 cents/kWh is much less expensive than WWS electricity at 11 cents/kWh.

- There is no need for most energy demand to be "flexible" to adapt to WWS availability.

- Subsidies are not needed for LF. Economic self interest drives demand for carbon-free electricity because it's cheaper than coal.

- Jacobson's WWS roadmap claims to achieve 100% clean energy generation of 11,840 GW by 2050, while the LF roadmap passes that mark in 2095.

Spending $125 trillion for 2.5 million wind turbines and nearly 2 billion solar plants would unnecessarily consume vast amounts of the planet's resources — metal, concrete, precious minerals, water and energy that would be far better used to build homes, water and sewage systems, hospitals, and transportation systems for the poor of the world. The WWS scale would be massive. China is the world's largest industrial producer at $4.5 trillion per year. WWS demands would consume the entire industrial production of China for 38 years.

Enabling Liquid Fission Power

Confidence. Many people needlessly fear nuclear power, which has been shown to be the safest energy source, by far. Liquid fission is advanced nuclear power, even safer. Jacobson's WWS paper starts off with outrageous false claims about nuclear power, designed to exclude from consideration any advanced nuclear power such as liquid fission.

Jacobson WWS roadmap claim	**ThorCon LF roadmap plan**
"nuclear plants require 10-19 years between planning and operation"	Shipyard production enables a 2-year construction cycle.
"nuclear now costs 2.5-4 times more per unit energy than onshore wind or utility scale photovoltaics"	LF capital $15 trillion < WWS capital $125 trillion LF energy @ 3 cents/kWh < WWS @ 11 cents/kWh
nuclear "produces 3.4-25.4 times more carbon and pollution per unit energy than wind"	EIA: lifecycle emissions for nuclear/wind/solar are 40/23/42 g-CO_2/kWh. LF plants even less than LWR.
"expanding the use of nuclear to countries where it doesn't exist will increase weapons proliferation and meltdown risks"	No proliferation ever from LWR power plants; even less likely with LF technology compliant with IAEA protocols. LF can't melt down; it's already melted.

Proponents of fossil fuels and renewables have long spread groundless fear of possible health effects of low level radiation associated with nuclear power and successfully created excessive government protection bureaucracies, specifically to raise costs of nuclear power to make it uncompetitive.

Enabling liquid fission power is simply a matter of permitting it. Existing nuclear power regulations developed for LWRs are not applicable to LF. New regulatory rules should be implemented based on demonstrated safety testing and modern radiation biology science.

Money. Capital for electric power plants already exists and flows into construction of fossil-fuel-burning plants to satisfy the developing nations' demands for 1400 GW of new power. As LF power plants prove to be cheaper than coal, that capital will divert to fund LF rather than coal and natural gas power plants.

Suppliers. Existing shipyard capacity exceeds 400 GW per year. It is now possible to build LF power plants at rates of 100 GW per year. That is about the rate of new fossil fuel power plant additions. Supercritical high-temperature steam turbine-generators are a major component of LF power plants. These are available from a half dozen companies already supplying such equipment for coal and natural gas power plants. Turbine-generator destinations can be diverted.

Fuel. Uranium fuel is ample for 20 years of building 100 GW of LF power plants. Fuel recycling will double uranium utility. Doubling prices paid will likely reveal an order of magnitude more reserves. Even resorting to extracting uranium from seawater would only add 1 cent/kWh to LF electricity costs. Thorium is ample.

Liquid Fission and Economics Can Lead Deep Decarbonization of World Energy.

- LF electric power cheaper than coal can displace fossil fuel combustion to satisfy the world's growing needs for electricity for human development.
- In future, battery electric vehicles, electrification of railroads, and fuels from LF-electrolyzed hydrogen may power the transportation sector even more cheaply than petroleum.
- Using LF power for heating and cooling, desalination, and industrial processes can complete the transition from fossil fuels.
- Economic self-interest can motivate the transition to deep decarbonization.
- Favorable economics will attract existing capital to create the new LF energy sources.
- LF decarbonization is doable. Technology and manufacturing capacity already exist.
- Permission is the only roadblock.