Running the World on Renewables:
Alternatives to Electricity for Gathering and Transmission, Annual-scale Firming Storage, and Integration of Diverse, Stranded, Renewable Energy (RE) Resources

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A. Our present energy system inflicts several socio-economic challenges upon humanity:

a. Depletion of non-renewable energy resources, depriving future generations of hydrocarbons
b. Lack of access to any affordable, high-quality energy, for many people
c. Competition for fresh water
d. Costly resource wars

Several dangers have become emergencies:

a. Rapid climate change, generally warming
b. Ocean acidification
c. Rapid sea level rise
d. Species extinctions

These dangers apparently result from increasing concentrations of greenhouse gases (GHG's) in Earth's atmosphere, including CO_2 from fossil fuel combustion.

Public opinion and governments are drifting in inadequate response, wasting precious time. JREF, engineers, and other professionals need to lead now, with a compelling and encouraging vision, strategy, and plan for a benign, equitable, and affordable energy future for humanity's total energy needs.

We must transform humanity's largest industry -- energy -- from primarily fossil-source to primarily renewables-source energy, as rapidly as we prudently can.

Our goal must be nothing less than "running the world on renewables" -- plus probably some degree of nuclear, now very hard to predict. This will require a combination of "distributed" and "centralized" renewable energy (RE) generation and other infrastructure. We should not try to do this with electricity systems alone, because the necessary total energy system resilience, reliability, and dispatchability will be very costly to achieve thereby, and because better options may be available.

Therefore, we must now think beyond:

a. Advocating subsidy preservation and a few hundred GW of new electricity transmission;
b. Electric wires as "transmission", to include renewables-source fuels via pipelines;
c. "Power", to include all energy, for all purposes, from all sources.

We must expand our definition of "transmission" from electric wires, and of "storage" from adjuncts to the electricity system, as we may advance it, in order to conceive and optimize complete RE systems.

B. This conversion is a very large technical, economic, and social task and opportunity, requiring conceiving and optimizing complete RE systems -- from photons and moving air and water molecules and biologic processes to delivered energy services. This will synergistically affect all RE system components, including the generators. Electricity systems will always serve us, especially as we advance their design, but may be inadequate or suboptimal for this task, thus losing market share to other RE systems. Progress toward "running the world on renewables" presents three grand systems challenges:

a. Gathering and transmission

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b. Annual-scale firming storage, rendering "dispatchable" the time-varying output, at scales of seconds to seasons, of many RE resources

c. Integration: distribution, end-use, and synergy with other energy systems

As RE generation equipment advances in technology, in lower long-term cost of energy (COE), and in public and industry acceptance and desirability, these challenges become severe constraints.

Distributed generation (DG) requires on-site RE natural resources and conversion equipment to capture them, and / or a firm and dispatchable supply of fuel; in humanity's "run the world on renewables" scenario, that must be RE-source, C-free or C-neutral fuel.

C. Two alternatives to electricity systems seem especially attractive, whereby the costly connection of RE generation to deliver quality electricity to the grid is replaced by conversion of RE, within the plant gate, to:

a. Gaseous hydrogen (GH_2) fuel for transmission in underground pipelines, with low-cost bulk storage in deep, solution-mined salt caverns if the geology is available, and / or

b. Liquid anhydrous ammonia (NH_3) fuel for transmission in underground pipelines, with low-cost bulk liquid storage in small and large carbon-steel tanks.

These GH_2 and NH_3 fuels are distributed at market centers for C-free stationary combined-heat-and-power (CHP), for transportation fuels, and for all other energy services. Systems other than hydrogen and ammonia may also be attractive or superior.

These alternatives must be considered as complete, integrated, optimized RE systems, not as adjuncts to the electricity system, or "grid", as we know it, or as we may advance it. Both hydrogen and ammonia systems and fuels have unique advantages, disadvantages, and dangers -- as all fuels and electricity have. Other energy carriers and systems have been proposed and should also be considered in the context presented in this paper. The NH_3 Fuel Association has sponsored ten annual conferences; all presentations available. [i]

Hydrogen (H_2) from biological, quasi-biological, and photochemical sources may complement or exceed hydrogen produced from RE-source electricity, synergistically feeding gaseous hydrogen (GH_2) gathering and transmission pipelines. Examples: [ii] , [iii] , [iv]

D. We cannot now say that either hydrogen or ammonia RE systems will be advantageous, at any scale. But, given the urgent energy system challenges and dangers before us, these alternatives deserve investment now in thorough, competent, and unbiased technical and economic systems analysis as complete, integrated, optimized systems. If we find these alternatives limited, or unattractive, we may confidently set them aside for demonstrated good cause, refocusing our systems engineering where it is most promising. We will need resources and expert collaboration for this analysis.

Complete and competent exploration, discussion, and presentation of the comparative systems analysis topic proposed herein will require both in-kind and funded effort. The work may be embraced by established budgets and work plans in many established organizations. For example, NREL and other national labs, EPRI, IEEE, ASME. Consultants will require cash funding. Organizing and leading this effort will require talent and the sponsors' endorsement and imprimatur.

The Japan Renewable Energy Foundation (JREF) goal and role should be motivating and recruiting interest in pursuing this "alternatives to electricity" topic as a collaboration of diverse interests, perhaps under patronage of NEDO, METI, the World Energy Council (WEC), International Energy Agency (IEA), and / or perhaps as a separate entity with a budget to enable professional consulting contracts. The collaboration should be global.

APPENDIX A Assumptions and further considerations

1. We must think of and plan for all energy, for all purposes, from all sources. NREL is pursuing this via its Energy Systems Integration program: http://www.nrel.gov/esi/
RE-source energy may be transmitted and delivered as C-free or C-neutral fuel, as well as by electricity. Our modeling must anticipate carbon taxes, eventually global. We must prevent realizing the consensus global energy scenarios which show, by mid-century, total energy consumption increasing ~ 80%, with fossil fuel contribution of > 60%. [v], [vi], [vii], [viii]

2. Running the World on Renewables: Hermann Scheer (1944-2010), Bundestag, Germany, published in 2010, "Der Energethische Imperativ" (energy ethics demands), subtitled "100% Now: How the Complete Switch to Renewable Energies Can Be Realised": his passionate conviction that it is technically and economically feasible for renewable energy to fully replace fossil and nuclear energy within just a few years, if the political will existed, essentially "running the world on renewables." [ix]

M. Jacobson and M. Delucchi show that humanity's entire energy demand could now be supplied from wind, water, and solar (WWS) sources. [x], [xi], [xii], [xiii]

3. Electricity systems, with inherent short time constants, are fundamentally not well suited to gathering and delivering the time-varying output -- at scales of seconds to seasons -- of most RE sources, as annually "firm" and "dispatchable". System economics and capital component design suffer as we attempt to "stuff a square peg into a round hole". As RE penetration increases, to supply all energy for all purposes, we may simply be "barking up the wrong tree" to expect electricity systems to perform optimally and exclusively.

4. "Smart Grid" is primarily a demand side management (DSM) strategy, with limited value because it:

a. Results in no increase in physical transmission and storage capacity, and in only marginal increases in virtual and effective capacities;
b. Will require large capital investments;
c. Diverts resources from potentially superior investments in other RE systems;
d. May make the electricity grid more vulnerable to cyberattack, via more nodes and code; [xiv]
e. Does not adequately lengthen electricity system time constants to make dispatchable diverse, time-varying-output RE resources as they approach supplying all humanity's energy.

5. Net metering and high-penetration distributed generation (DG) force the electric utilities to supply firming storage and dispatchability for which they may not be technically competent nor adequately financially compensated. GH_2 and NH_3 systems may better accommodate a large percentage of total large-scale energy supply from RE, from DG backfeed, via their distribution pipelines. The "utility of the future" must respond wisely to the DG challenge via new technology and business models. [xv], [xvi]

6. Energy storage, as adjuncts to the electricity grid, is too costly to deploy at adequate annual-firming scale, to render renewables "dispatchable". The capital cost of large-scale chemical energy storage is about:

- $ 0.10 per kWh for liquid NH_3 in typical 30,000 ton steel tanks ubiquitous in the USA Corn Belt;
- $ 0.20 per kWh for GH_2 storage in large salt caverns; two such caverns operate now in Texas, USA.

We haven't enough valleys to dam for pumped hydro. Batteries remain too costly. But, we have enough deep salt formations in the Gulf of Mexico coast and northern Germany to firm at least North America's and Europe's total energy supply as GH_2. We can afford to buy enough large, above-ground, mild steel, "atmospheric" liquid NH_3 storage tanks to firm the global energy supply. Round trip efficiency is relevant only if we must deliver RE-source energy as electricity This concept delivers RE-source fuel(s), not electricity, intended for applications capturing and using the byproduct heat from CHP, and for transport.

7. "Power To Gas": On 13 June 13, Hydrogenics, Toronto, activated the world's largest (2 MW) electrolysis plant converting otherwise-curtailed wind-generated electricity to GH_2 for direct injection into the E.ON natural gas transmission pipeline system at Falkenhagen, Germany, receiving only the natural gas wholesale energy value, but enjoying essentially free storage and transmission, and avoiding generation curtailment. Germany now allows 5% H_2 in pipeline gas. [xvii]

Enbridge Pipelines intends to do the same in Canada. [xviii]

EU's "NaturalHY" project studied metallurgical and other implications of up to ~ 20% (volume) concentration of H_2 in pipeline gas, concluding that > 10% is safe, but requires volumetric price adjustment to customers for H_2 concentration. [xix]

EU's "HyUnder" project studies RE storage as GH_2 in deep salt caverns. [xx]

These developments presage increased transmission and storage of a very large quantity of stranded RE as GH_2 in pipelines and caverns, perhaps eventually in RE systems optimized for 100% high-purity GH_2 fuel, via dedicated national-scale and continental-scale GH_2 pipeline networks connecting RE sources -- both centralized and distributed -- with cavern storage and widespread markets.

8. Transportation fuel is a very big market for RE: the ICE, CT, and fuel cell operate well on GH_2 and NH_3 fuels, with only H_2O and N_2 (in the NH_3 case) emissions. Battery electric vehicles (BEV's) are no panacea, and have significant disadvantages. [xxi]

The world's major automakers plan to introduce series-production hydrogen fueled, fuel cell hybrid electric vehicles (FCHEV's) in about 2015, if adequate fueling is available, in competition with the BEV's they are introducing now. NH_3 is easily reformed to H2 on-board-vehicle; NH_3 costs less to store on-board than GH_2.

9. Capital cost of GH_2 and NH_3 transmission pipelines, and HVDC electric lines, per GW-km of transmission service capacity, is comparable; pipelines may cost less. Underground pipeline O&M cost is generally lower than for overhead electric transmission lines. Polymer-metal composite linepipe may solve the hydrogen embrittlement (HE) problem for GH_2 systems.

10. "Packing" GH_2 pipelines, compressing to store and decompressing to deliver, as the natural gas industry does, provides low-cost storage. A 1 m diameter GH_2 pipeline, 1,600 km long, packed to 100 bar and unpacked to 35 bar, stores ~ 190,000 MWh as the chemical energy in H2. GH_2 viscosity is low, so that optimized transmission pipelines might be built with no midline compression; transmission loss is thus low. Liquid NH_3 pipelines cannot be packed. NH_3 pumping energy is significant, but low.

11. A "Power To Ammonia" limited infrastructure is already in place, via ~ 3,000 miles of liquid ammonia pipelines and storage terminals, from New Orleans to and throughout the Corn Belt, moving ~ 12 million tons of NH_3 per year as nitrogen fertilizer, ~ 60% of which is imported. With the pipeline owners' agreement, this infrastructure could distribute "green" NH_3 made from RE, mixed with "brown" NH_3 made from fossil fuels, as we now mix "green" and "brown" electrons in electricity systems, with comparable economic incentives for customers buying the green products. Presentations from ten years of Ammonia Fuel Association conferences are available. [xxii]

12. Fresh water use: Supplying all 100 Quads of total annual energy used in USA today, from all sources for all purposes, requires ~ 17,000 billion liters (about 1.7 trillion gallons) of fresh water per year. Some is "withdrawn", returned to the source water body, usually warmer. Some is "consumed", usually evaporated, and lost by the host water body. If all 100 Quads were generated as RE-source electricity, converted to GH_2

and / or NH_3 fuels at the source, for pipeline transmission and delivery as C-free fuels, total annual fresh water consumption would be ~ 7,000 billion liters. The H_2O would be dissociated; H becomes the energy carrier; the O_2 byproduct is released to Earth's atmosphere or sold to adjacent gasification plant markets.

13. Transmission and other infrastructure permitting in USA: The Federal Energy Regulatory Commission (FERC) has jurisdiction over interstate oil and natural gas pipelines and perhaps over interstate GH_2 and NH_3 energy transmission pipelines. Siting and construction of electricity transmission facilities is not within FERC's public utility related statutory authority under FPA Parts II and III. "Not In My Back Yard" (NIMBY) may always be a problem for new overhead electric transmission lines, while historically it has been less impeding for underground transmission pipelines. [xxiii]

APPENDIX B

Distribution: I will distribute this widely**,** requesting comments and corrections and interest in collaboration. Please FWD this, as you wish.

Corrections, comments, and revisions are welcome: I offer this draft as an MSWord file, for your convenience in critique and comment, in revision and propagation. Please request it via email. Thank you for your consideration. wleighty@earthlink.net

Candidate titles for future committee, working group, or conference topic:

- GW-scale Renewable Energy Systems: Alternatives to Electricity for Transmission, Storage, and Integration to Supply Total Energy Demand
- Running the World on Renewable: Can We Do It Entirely with Electricity Systems?
- Renewable Energy Storage at < $1.00 / kWh Capital Cost Requires Alternatives to Electricity, for Integrated Renewables-source Energy Systems

Other resources: Please consider my co-authored work on this subject at:
http://www.leightyfoundation.org/earth.php
See especially: http://www.leightyfoundation.org/files/ASME-IMECE-12-87097-FINAL-30Jul12-C.pdf
http://www.leightyfoundation.org/files/ASME-IMECE-2012-A.pdf
http://www.leightyfoundation.org/files/Poster_R3.2_press-quality.pdf

U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather
http://energy.gov/downloads/us-energy-sector-vulnerabilities-climate-change-and-extreme-weather

Hermann Scheer (1944-2010), Germany Bundestag
http://www.theguardian.com/world/2010/oct/18/hermann-scheer-obituary
http://www.youtube.com/watch?v=8fCfdo6h7l8
http://www.hermannscheer.de/de/

A Republican Case for Climate Action
http://www.nytimes.com/2013/08/02/opinion/a-republican-case-for-climate-action.html?hp&_r=0

Global collaboration on strategies and energy systems by which to "run the world on renewables" should include at least these RE interests in USA and many others internationally:

- International Energy Agency (IEA) http://www.iea.org
- Canadian Hydrogen and Fuel Cell Association http://www.chfca.ca/
- World Energy Council
- Japan: METI and NEDO, Japan Renewable Energy Foundation (JREF)

Engineering associations: IEEE, ASME, ASCE
USA Industry groups: ACORE, AWEA, ASES, EPRI, UVIG, CHBC, CHFCP
USA government: DOE and its National Laboratories; DOT; DOD; EPA
Universities and their Institutes
Charitable foundations
Capital equipment manufacturers
Energy and Economics Consultants
Research Institutes and Advocacy Organizations

Renewables energy integration on electricity grid:
Resnick Institute, CalTech: "Grid 2020: Towards a Policy of Renewable and Distributed Energy Resources" 2012,

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[iv] http://www.guardian.co.uk/science/blog/2013/jul/19/sweet-hydrogen-sugar-energy-needs

[v] http://www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/Energy_Outlook_2035_booklet.pdf

[vi] http://www.bp.com/content/dam/bp/pdf/Energy-economics/Energy-Outlook/Energy_Outlook_2035_booklet.pdf

[vii] http://www.worldenergy.org/documents/p000616.pdf

[viii] http://www.shell.com/global/future-energy/scenarios.html?gclid=CK2_z62v2bwCFUiGfgodvwoA9g

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[xii] http://www.scientificamerican.com/article/a-path-to-sustainable-energy-by-2030/

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[xvi] http://articles.latimes.com/2013/dec/02/nation/la-na-grid-renewables-20131203

[xvii] http://www.hydrogenics.com/products-solutions/energy-storage-fueling-solutions/power-to-gas

[xviii] http://www.enbridge.com/DeliveringEnergy/AlternativeTechnologies.aspx

[xix] http://www.naturalhy.net/

[xx] http://www.iphe.net/docs/Events/Seville_11-12/Workshop/Posters/IPHE%20workshop_HyUnder_poster.pdf

[xxi] http://spectrum.ieee.org/energy/renewables/unclean-at-any-speed

[xxii] http://nh3fuelassociation.org/events-conferences/

[xxiii] http://www.ferc.gov/about/ferc-does/ferc101.pdf (slide 12)