Hydrogen Without Tears: Addressing the Global Energy Crisis via a Solar to Hydrogen Pathway

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The total world power consumption by humans currently lies at about 15 TW—this figure includes power in all its forms from electricity through to gasoline combustion. Given our finite fossil-fuel resources and growing world population, our current patterns of energy supply and usage are clearly unsustainable.

Imagine, for example, that everyone in the world boils water in an electric kettle only once a day to make a hot drink. If each person overfills their kettle with as little as 100 ml of water, this amounts to an enormous wastage equal to the whole power output of the Hoover Dam. With prospects of developing countries seeking to rapidly industrialize, it is clear that energy consumption and production as we know it must drastically change.

But what is the way ahead? How do we sort through the complexity of multiple possible energy-supply proposals? Where are we heading and what is our long-term vision for energy policy as a planetary community? Are we forced to precariously juggle a mix of energy sources, hoping that a winner will emerge and save the day? Or is it possible to identify a dominant future solution, where we can begin to plan our strategy now, invest, and build massive scale over the next few decades?

If a dominant solution with long-term sustainability can be identified now, this will help mankind to build an energy policy roadmap so that investment and focus is not overly locked in to solutions that are not globally scalable or that have short-lived utility times. A clear end-vision provides a fixed point from which we can plan out an energy policy mix for the transitionary phase toward a sustainable future.

In a forthcoming issue of the PROCEEDINGS OF THE IEEE [1], it will be shown that order-of-magnitude calculations are sufficient to identify a solar-hydrogen economy as the

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dominant solution. The key conclusions are foreshadowed as follows.

I. THE NEGATIVE PICTURE

The picture at present is a poor one, as our current pattern of energy supply simply does not scale. Fossil fuels such as oil, coal, and natural gas do not scale. Regardless of carbon emission debates and regardless of the debate over whether oil will be critically low in 40 years, we can argue that we cannot continue to burn these resources, as they are critical for embodying industrial products such as plastics, paints, tires, and a host of petrochemicals. We need oil to lubricate engines and machines for many centuries to come. Thus without any green agenda, we can argue that fossil fuels are resources that are too valuable to burn, and thus energy alternatives are urgently needed.

If we met the world's present 15 TW demand with nuclear fission, it would require the building of 15 000 nuclear power stations at 1 GW each. The decommissioning costs at $8 billion each would alone exceed the world's gross national product. Also, at this rate of consumption, we only have economically recoverable uranium reserves to last five years, and thus global-scale investment is not justified. Even extension of fuel lifetimes with breeder cycles does not justify this level of investment given the costs and risks. Leaving aside issues of safety, storage of waste, and proliferation, nuclear fission simply does not scale, and the high decommissioning costs render it uneconomical on a global scale.

We cannot formulate energy policy based on nuclear fusion, as it is a technology that does not exist yet. We have no guarantee that fusion will be both safe and economically viable—any claims are far too premature. Even if we hypothetically consider fusion, the fact is the reactor still becomes irradiated with neutrons and the decommission costs will still apply. Furthermore, there is the issue that fusion irreversibly transmutes lithium. Lithium is a scarce resource that has a host of industrial uses and is used in every laptop computer and mobile phone. Reclaiming lithium from seawater is questionable in terms of recovery rates and scalability, given that it is dispersed at a concentration of 0.1 ppm.

This leaves us with renewables such as wave, wind, hydroelectric, biomass, geothermal, and solar power. Wind, wave, biomass, and hydroelectric power are all indirect forms of solar energy with enormous conversion efficiency losses. So this leads us to ask: why not go direct to solar? The fact is there is about 350 times more solar power available than all other renewables put together. In terms of recoverable power, renewables perform poorly and do not scale to provide the world's power needs—with the exception of solar that can provide many times our needs.

However, solar power looks bleak when we calculate the PV silicon solar cell area required to supply the world's power consumption—the semiconductor manufacture would require on the order of 10^{17} g of water and 10^{14} g in toxic chemicals. Given that the cells would have to be replaced every 20 years, or less if we consider efficiency drop over the lifetime, this level of chemical use is unsustainable. For example, the arsenic dopant alone would exceed world reserves. Even if we reduce solar cell area by using solar concentrators, the rate of chemical usage is still not tenable.

In terms of mobile energy storage for cars, electric vehicles appear attractive but are unscalable as the world reserves of lithium for batteries would rapidly become exhausted. Running cars off biomass derivatives—even if we ignore the hydrocarbon issue—does not scale due to the large effective land area required to grow the required biomass.

The most sensible option for cars appears to be hydrogen, as it can be obtained from splitting water and turns back to water on combustion. Thus it is infinitely sustainable and mimics the Earth's natural water cycle. However, the density of hydrogen is low, and hydrogen fuel cells simply do not scale for a global solution due to the use of expensive membrane technology and exotic chemicals that would stretch the world reserves inventory. Moreover, Bossel has shown that if we assume standard production techniques for hydrogen, the inefficiencies simply render the costs of storage and transportation too high [2].

II. THE SCALABLE VISION

So far, the only truly scalable power source in Section I is solar; however, the primary collection method using semiconductor technology does not scale. Thus the solution lies in finding an alternative collection method. However, in order for solar power to properly scale with population, our profligate energy consumption patterns must first be addressed.

A. Energy Conservation

If everyone on the planet drove a car for one hour a day, we would use two thirds of our present world power consumption. If there were a billion domestic dwellings on the planet, without double glazing, wall insulation, and roof insulation, we would exceed our present world power consumption alone if each house was attempting to cool or heat to maintain a 5 °C difference from the outside temperature. Thus the cornerstone of all energy policy is, first, conservation. Governments need policies and incentives to ensure every building is fully insulated in both hot and cold climates. Public education programs are required to better manage energy waste in the kitchen and bathroom and to encourage shared rides. Advances in global positioning systems, cell phone technology, and Web-based social networking sites could be combined to usher us into a modern age of scheduling shared rides.

B. Energy Production

In tandem with sensible conservation schemes, we need a scalable source of power, which is sunlight. This is clear as the Sun's power warms the surface of our planet, delivering 5000 times our present global power needs. A solar economy is desirable, as it has plenty of room for growth and expansion. A scalable vision is to step back from semiconductor solar cells and go low-tech. Using either large trough-shaped or parabolic-shaped mirrors, it has been demonstrated that focused sunlight can viably superheat water for generating electricity via a conventional steam turbine (e.g., Rankine cycle engine) [3]–[7]. This technique is called *solar thermal*. As little as a 500 by 500 km^2 footprint is needed to supply the world's energy needs—this is a tiny fraction of the world's desert area.

To create economy of scale, large solar farms at least 4 by 4 km^2 in size in hot deserts, on top of table mountains, on reclaimed land, or on floating ocean platforms are preferable to piecemeal collectors on rooftops. There are a range of possible energy storage options for storing energy during the day for nighttime use [8]–[10].

In Section I, we argued that hydrogen fuel cells and electric batteries for cars are not scalable. So how do we power vehicles? The solution has already been demonstrated by BMW, Ford, and Mazda, where vehicles are powered by internal combustion engines on hydrogen. This solution is inherently scalable, as hydrogen combusts to form water, and cars then become part of the natural water cycle. In principle, if we introduce combustion engines that run on hydrogen, we can continue to operate for a billion years. Hydrogen can be obtained from splitting water—here, electricity from a given solar collector farm can be connected via the grid to a desalination plant for electrolysis.

But as Bossel points out, there are efficiency losses in liquefying and delivering hydrogen. However, as the available solar power is so expansive, the solution is to invest in the nonrecurring cost of the correct quantity of solar thermal dishes to drive a solar-hydrogen economy at whatever efficiency at which it happens to sit. We show in [1] that—even taking into account all the inefficiencies—to meet present consumption, the total solar footprint required is 500 by 500 km^2 and the low-tech collector technology would cost less than all the decommission costs of all the nuclear power stations needed to generate an equivalent energy.

III. LOW-TECH IS THE KEY

Notice the solution of using steam and mirrors to harness solar power is extremely low-tech. High-tech solar cells are so ordered that they simply cannot reliably withstand very high solar concentrations that would significantly heat them. Low-tech solar collecting dishes, driving steam turbines, can survive higher temperatures and thus can exploit the Carnot cycle. In principle, reflectors can focus sun to 3000 °C and even higher. However, at these temperatures, even a steam turbine is too ordered (i.e., too high-tech) and would be unable to reliably operate. We cannot even fully exploit the awesome power of focused sunlight, as all containment materials simply melt at these temperatures. This questions the viability of commercial nuclear fusion: if we cannot even reliably harness solar power at 3000 °C, how can we expect fusion stations to have viable reliability where much higher temperatures are generated? The embrittlement of the reactor vessel due to the enormous neutron fluence will also be a critical reliability issue.

IV. CONCLUSION: EVERYONE WINS

In summary, the dominant scaleable vision is a solar-hydrogen economy, where solar thermal collectors are preferred to solar cells. Also for mobile storage, pure hydrogen (liquid and/or gas) is preferred to both electric batteries and hydrogen fuel cells. Placing this form of a solar-hydrogen economy as an end vision on our energy policy roadmap is a situation where everyone wins.

The end consumer wins, as energy supply together with sensible conservation scales with our increasing reliance on electricity-driven technology. Governments win, as they can build solar farms on a grand scale, with high levels of public acceptance, building stability and economy of scale.

The fossil-fuel industry wins, as its resources become increasingly valued in the petrochemical industry rather than being irreversibly burned—then together with recycling, the long-term survival of these industries is secured. Oil will always be fundamentally important for providing lubrication to engines. The nuclear fission industry wins, as it can continue to provide boutique energy, without pressure to unsustainably scale up operations that would inevitably lead to its downfall. Nuclear fusion research can still continue to explore the frontiers of matter interaction, without long-range fundamental science having to prematurely be the tail wag of a commercial dog.

The non-solar-sector renewable industries, such as wind, geothermal, etc., still win. Although they only represent a small fraction of what can be obtained from solar power, they nevertheless have an important niche. While they do not present the dominant scalable vision, they nevertheless provide a level of power diversity. Some level of diversity is always important to provide backup power and security in times of natural disaster and unforeseen future events.

The power generation industry wins, as its present infrastructure already relies on steam turbines supplying the grid—a solar thermal dish farm rides on the backbone of this infrastructure. The car manufacturing industry wins, as its infrastructure is set up to make combustion engines—the use of liquid and gaseous hydrogen exploits the present combustion engine infrastructure.

The solar cell industry still wins—while solar thermal dish farms will provide the main base load power of the future, solar cells will always have an enormous demand for *energy harvesting* from handheld devices through to boutique power using conformal panels on large buildings.

A solar-hydrogen economy is therefore no threat to any existing industry—in fact, it is the bedrock upon which existing industries can anchor their long-term survival. Every energy source has its niche, and placing each in its correct perspective is the way forward to a viable energy policy roadmap. ■

REFERENCES

[1] D. Abbott, "Keeping the energy debate clean: How do we supply the world's energy needs?" *Proc. IEEE*, to be published.

[2] U. Bossel, "Does a hydrogen economy make sense?" *Proc. IEEE*, vol. 84, no. 10, pp. 1826–1837, 2006.

[3] W. B. Stine and R. B. Diver, "A compendium of solar dish/stirling technology," Sandia National Labs., Albuquerque, NM, Tech. Rep. SAND-93-7026, 1994.

[4] S. Kaneff, "Viable distributed dish central plant solar power: Status, new developments, potential," *J. Phys. IV*, vol. 9, no. P3, pp. 195–200, 1999.

[5] L. C. Spencer, "A comprehensive review of small solar-powered heat engines: Part I.I. Research since 1950—'Conventional' engines up to 100 kW," *Solar Energy*, vol. 43, pp. 197–210, 1989.

[6] B. Kongtragool and S. Wongwises, "A review of solar-powered Stirling engines and low temperature differential Stirling engines," *Renew. Sustain. Energy Rev.*, vol. 7, pp. 131–154, 2003.

[7] H. Müller-Steinhagen and F. Trieb, "Concentrating solar power: A review of the technology," *Quart. Royal Acad. Eng.*, vol. 18, pp. 43–50, 2004.

[8] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progr. Natural Sci.*, vol. 19, pp. 291–312, 2009.

[9] A. Luzzi, K. Lovegrove, E. Fiippi, H. Fricker, M. Schmitz-Goeb, M. Chandapillai, and S. Kaneff, "Techno-economic analysis of a 10 MW solar thermal power plant using ammonia-based thermochemical energy storage," *Solar Energy*, vol. 66, no. 2, pp. 91–101, 1999.

[10] U. Herrmann, B. Kelly, and H. Price, "Two-tank molten salt storage for parabolic trough solar power plants," *Energy*, vol. 29, no. 5–6, pp. 883–893, 2004.