CONTRIBUTED PAPER

Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?

Proposed solutions include: Sensible energy conservation; Solar thermal collection using parabolic reflectors; Hydrogen used as an energy carrier in combustion engines and for energy storage and transportation.

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ABSTRACT | We take a fresh look at the major nonrenewable and renewable energy sources and examine their long-term viability, scalability, and the sustainability of the resources that they use. We achieve this by asking what would happen if each energy source was a single supply of power for the world, as a *gedanken* experiment. From this perspective, a solar hydrogen economy emerges as a dominant solution to the world's energy needs. If we globally tap sunlight over only 1% of the incident area at only an energy conversion efficiency of 1%, it is simple to show that this meets our current world energy consumption. As 9% of the planet surface area is taken up by desert and efficiencies well over 1% are possible, in practice, this opens up many exciting future opportunities. Specifically, we find solar thermal collection via parabolic reflectors—where focussed sunlight heats steam to about 600 °C to drive a turbine—is the best available technology for generating electricity. For static power storage, to provide electricity at night, there are a number of viable options that are discussed. For mobile power storage, such as for fueling vehicles, we argue the case for both liquid and gaseous hydrogen for use in internal combustion engines. We outline a number of reasons why semiconductor solar cells and hydrogen fuel cells do not appear to scale up for a global solution. We adopt an approach that envisions exploiting massive economy of scale by establishing large arrays of solar collectors in hot desert regions of the world. For nonrenewable sources we argue that we cannot wait for them to be exhausted—we need to start conserving them imminently. What is often forgotten in the energy debate is that oil, natural gas, and coal are not only used as energy sources, but we also rely on them for embodying many crucial physical products. It is this fact that requires us to develop a solar hydrogen platform with urgency. It is argued that a solar future is unavoidable, as ultimately humankind has no other choice.

KEYWORDS | Consolidated utility time; economics of energy; electrolysis; energy; energy efficiency; energy generation; energy policy; energy supply; hydrogen; hydrogen liquefaction; hydrogen storage; hydrogen transfer; hydrogen transport; solar hydrogen economy; solar power; solar thermal; steam turbine; sustainability

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I. INTRODUCTION

> "I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."
>
> Thomas Edison (1931) in conversation with Henry Ford and Harvey Firestone [1].

The BP oil company currently uses the slogan "To make an energy fix, we need an energy mix." This encapsulates the idea that the solution to the global energy supply problem is to diversify with a mix of power sources, such as oil, solar, wind, biomass etc. This also appears to be the emerging energy policy of many governments around the globe.

In this vision paper, we consider the question differently from a large-scale perspective. The pertinent

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question to ask is, "is there a *single* technology that can supply the world's 15 terawatt (TW) power consumption[1] in a clean sustainable way?" Posing the problem in this way, we show that a solar hydrogen economy has a sustainable and vastly higher total power output potential than all other sources combined. Thus it pays to exploit economy of scale and focus on a dominant solution rather than a solution based on diversification of energy sources.

We argue that if we pose the above question, we obtain a clearer perspective on an workable solution. This then sets a vision that a solar hydrogen economy, should be the final goal of current energy policy. In the transition period towards such a sustainable energy cycle, the current approach promoting a mix of energy sources is required. However, having a dominant end vision can help to better analyze the most viable energy policy mix for the transitionary period.

In practice, due to economic forces and practicalities in the distribution of energy, it is unlikely that one type of energy source will supply the world. However, if there is a clear dominant solution, as we suggest, then perhaps one might envision a scenario where the dominant solution supplies 70% of the world's energy and where the remaining 30% is supplied via a mix of sources in the medium term. It can be argued that in the very long term, a 99% solar future is the only available option anyway. Therefore, the underlying methodology of this paper is to consider how various single sources hold up, for powering the whole world, as a means for identifying a dominant solution.

A number of key issues are examined in this paper using simple order-of-magnitude calculations, for clarity. The reader is referred to a number of reviews [2]–[12], as well as a Special Issue of the PROCEEDINGS OF THE IEEE on hydrogen for a recent debate of some of the issues [13]. In that Special Issue, under the assumption of finite resources, Bossel correctly shows that a hydrogen economy is uncompetitive due to the energy costs of storage, transportation, etc. [14]—this is treating the situation as a zero-sum game. However, in this paper we take a fresh approach where energy resources are considered virtually unlimited when electricity is derived from an efficient *solar thermal* collector scenario. As energy is freely supplied by the Sun, all Bossel's objections can be simply addressed via investing in the nonrecurring cost of low-maintenance solar collectors on a sufficient scale to drive the energy needs of a hydrogen economy. As this is a distinct shift in paradigm, we refer to this as the *solar hydrogen economy* in contradistinction to a *hydrogen economy*.

II. METHODOLOGY

> "That is the essence of science: ask an impertinent question, and you are on the way to a pertinent answer."
>
> Jacob Bronowski (1908–1974).

As there are a vast array of contending methods for supplying energy, our aim is to bring simplicity and clarity to the debate. We use the time-honored engineering approach of examining large-scale limiting cases—thus we consider each method individually and calculate which can supply the whole world's energy. Taking this approach enables us to identify if there is a clear leading solution or not. As the scales are large, it enables us to easily use a process of elimination using simple order-of-magnitude calculations based on first-order assumptions. If the results were closely bunched together, we would need to reexamine those assumptions. However, as we will see in the forgoing analyses, the assumptions are sufficient as a solution emerges that demonstrates viability orders of magnitude greater than competing methods. We shall see that this approach steers us away from all solutions based on digging up limited resources from the ground—also it steers us from renewable energy solutions that utilize exotic chemicals or rare elements as catalysts for downstream processing. In the following subsections, we motivate our approach showing simple examples of energy use and how order-of-magnitude calculations can easily identify if each scenario has long-term viability or not.

A. Example of Sustainability

As an illustration of the type of order-of-magnitude calculations we will perform in this paper, let us test if uploading photos on Facebook[2] is sustainable from a power consumption viewpoint. Let us assume in the limit that 5 billion people each upload one 50 kilobyte photograph every day. Conservatively, let each 500 W server at FaceBook control ten 1-terabyte hard disks for storage. As much as 3 million years would elapse for Facebook to start consuming the equivalent of our current total world power consumption of 15 TW. This demonstrates long-term viability, assuming the embodied energy of the servers themselves came from an unlimited source such as solar power. Notice that, as an order-of-magnitude calculation, we have assumed the power consumption of each server and the world population remain constant over million year timescales. The result is sufficiently far into the future that more sophisticated assumptions are unnecessary. We will be making similar first-order assumptions in the foregoing paper, to demonstrate which energy generation technologies are broadly viable and which are not.

[1] The total world consumption, in all forms, from gasoline through to electricity is roughly 15 TW.

[2] Facebook is the premier social networking website and is also used for sharing photographs.

B. Example of Nonsustainability

Assume 5 billion people drive a moderate car with a 50 kW engine for only 1 hour per day. On average, 10 TJ will be consumed in the world each second. This corresponds to 10 TW, which is two thirds the current world consumption. Therefore, in the limiting case of everyone on the planet driving a car this is clearly unsustainable, as gasoline is a limited resource. However, for example, if we now assume each car is fueled by liquid hydrogen, derived from solar energy, more than this level of power is cleanly available (Appendix B). This clearly demonstrates that for future expansion of transportation, movement away from oil dependency will be required. Perhaps in the Malthusian limit for transport, society will find a way to combine GPS, cell phone technology, and Facebook, with the science of *small world networks* [15], to efficiently share rides with friends. Also policies are needed to make GPS in vehicles compulsory, as the overall fuel savings due to finding the most efficient routes would be enormous.

C. Critical Importance of Energy Conservation

Before we begin to explore how to proactively supply the world's energy needs, we firstly highlight that any future solution must go hand in hand with continued measures to conserve energy. Supply of the world's energy has long-term viability if we take a two-pronged approach and put into place policies that create incentives to save energy. The importance of this cannot be overstressed, and we now motivate this with a simple example.

Suppose in the near future we have 1 billion domestic dwellings in the world. For simplicity, assume they are all average sized with a surface area of 500 m^2, and all have walls 0.1 m thick. Let us assume each house is a cube with no doors or windows, as a first-order approximation. Let the thermal conductivity of the brick[3] material be 1 $Wm^{-1}K^{-1}$, and let us assume that on average we are either heating or cooling each house to maintain as little as a 5 °C differential between the inside and the outside. The power consumed will then be 25 kW. If we now use wall insulation, so that we drop the thermal conductivity to 0.1 $Wm^{-1}K^{-1}$, we immediately save 22.5 kW. If we have 1 billion such houses in the world, without insulation, this will waste 22.5 TW, which is well over the current world power consumption. Thus, it is absolutely vital to responsibly conserve as well as to responsibly generate energy on large scales.

[3]The thermal conductivity of common brick is in the range 0.8 to 1.2 $Wm^{-1}K^{-1}$ [16] and plastic foam insulators are in fact 0.03 $Wm^{-1}K^{-1}$, but we have selected a higher value for illustration. While these figures overestimate our present average consumption, they dramatically illustrate how poor insulation strategy in the worst-case can rapidly lead to excessive waste.

Table 1 Orders of Magnitude for Power in Watts

Units	Scale	Item	Consumption
Watts	10^0	Flashlight	1 W
Kilowatts	10^3	Electric kettle	1 kW
Megawatts	10^6	Google	50 MW
Gigawatts	10^9	New York	13 GW
Terawatts	10^{12}	Total photosynthesis	90 TW
Petawatts	10^{15}	Sunlight absorbed by Earth	116 PW
Exawatts	10^{18}	Output of Sun's corona	3 EW
Zetawatts	10^{21}	Illuminance of Wolf 359	125 ZW
Yottawatts	10^{24}	Tsar Bomba	5 YW
-	-	Total output of the Sun	3.6×10^{26} W
-	-	Illuminance of our galaxy	5×10^{34} W
-	-	Planck power	3.63×10^{52} W

III. SCALE OF THE PROBLEM

Before we begin to critically examine the various energy generation methods, it is important to obtain an intuition for the size of the problem and put it in its context. The current population on the planet consumes 15 TW. Table 1 demonstrates this amount of power is equivalent to a trillion flashlights or a billion electric kettles. We can also visualize this as 150 billion 100 W light bulbs. The amount of power consumed by all of Google's computer servers is less than 0.0003% of world consumption. The peak power consumed by the whole city of New York is 13 GW. Interestingly, the total amount of solar energy utilized by all plant life is 90 TW—where, 65 TW [17] is from land plants and 25 TW [18] is from algae. The planet Earth reflects 30% of the incident 166 PW solar power back into space and therefore the total power our planet absorbs is 116 PW.

The illuminance of a red dwarf star, such as Wolf 359, is in the zetawatt range. In 1961, the Russian nuclear fusion bomb, dubbed *Tsar Bomba*, emitted a peak power of 5 yottawatts. The total power output of our Sun is enormous at 3.6×10^{26} W, and for our galaxy it is 5×10^{34} W. The largest power scale that physicists conceive is the Planck power, which lies at 3.63×10^{52} W. Reaching up to a quarter of the Planck power would create an event horizon and start a black hole.

The message here is that humankind's energy consumption of 15 TW is absolutely tiny when compared to the typical power levels in our cosmos. Thus for our future energy needs we need to look to our stars, with our nearest one being the Sun. Due to these enormous power levels at the scale of stars and galaxies, it should therefore not surprise us that the power incident on our planet from the Sun is 166 PW—this is more than 10 000 times our current global fuel consumption.

IV. FOSSIL FUELS

"All power corrupts, but we need the electricity."

Anon.

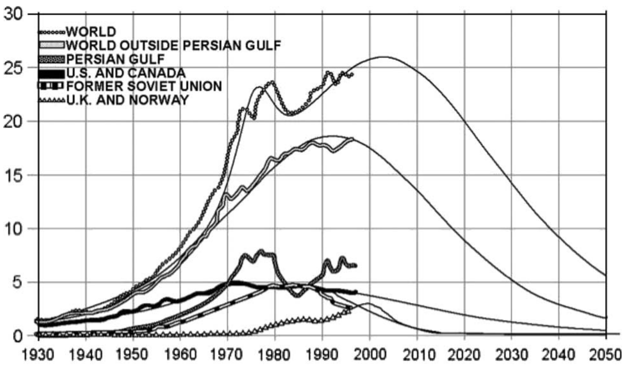

Fig. 1. ***This graph shows the classic Hubbert curve, indicating that world oil resources are on track to critically deplete within 40 years. While this figure is hotly debated, what is clear is that oil has a host of useful industrial applications and to irreversibly burn oil jeopardizes the future. The vertical scale is in arbitrary relative units, but to get an idea of scale, world production averaged at about 80 million barrels per day in 2008. Source: www.almc.army.mil.***

According to the World Coal Institute (www.worldcoal.org), at the current rate of consumption, reasonably recoverable coal reserves will run out in 130 years, natural gas in 60 years, and oil in 42 years. The Hubbert curve, in Fig. 1, shows in the very least that reasonably recoverable oil becomes critically low in 40 years. This means we must urgently begin transitioning to an alternative energy economy *now* and complete the task in a 20-year timeframe. We cannot afford to wait 40 years, as we cannot continue to burn oil—to secure long-term viability of our future, we need to conserve oil for lubricating the machines of the world for years to come, as well as to secure its continued use in the petrochemical industry.

Oil is a precious resource that humankind cannot afford to burn anymore. For similar reasons we also need to drastically slow down the consumption of coal and gas. For example, oil is used for lubricants, dyes, plastics, and synthetic rubber; natural gas is an important desiccant in industry and is used in ammonia, glass and plastics production; and coal products are used to make creosote oil, benzene, toluene, ammonium nitrate, soap, aspirin, and solvents. Thus we do need to sustain these fossil-based industries for their industrial applications, rather than as primary sources of energy. How can the burning of resources over the scale of decades be justified against their continued industrial need for many centuries to come?

We may someday discover currently unknown sources of fossil fuels, but it would be irresponsible to base today's energy decisions on such an uncertain gamble. Resources obtained by mining are ultimately finite and we cannot keep stretching the argument; especially when alternative clean, limitless, and viable resources await to be harnessed (Section VIII-B). The argument that stocks may replenish via abiotic oil generation is questionable on thermodynamic grounds [19], and has little scientific support.

V. NUCLEAR FISSION

> "Three Mile Island taught Wall Street... [that] a \$2 billion asset can turn into a \$1 billion cleanup job in about 90 minutes."
>
> Peter Bradford, U.S. Nuclear Regulatory Commission [20].

The economics of nuclear power plants are embedded with uncertainties and hidden costs [21], [22]. Nuclear power has hidden costs and risks that are not factored into its economics, and has poor public acceptance [23]—all these factors have been long debated [24]. The impact of accidents and impact of waste are all hidden costs.[4] Also when a reactor comes to the end of its 30–60 year lifetime, it has to be decommissioned in a safe manner [25]. It currently costs of the order of \$8000 per kilowatt to build a nuclear power station and then to decommission it.[5]

So, for a 750 MW nuclear plant, it costs \$6 billion to build and then a further hidden cost of another \$6 billion to decommission. The energy and financial cost in refining uranium ores and the expense of uranium enrichment are also important factors to consider when evaluating the economics of fission.

A. Does Nuclear Have Long Term Viability?

According to the World Nuclear Association (www.world-nuclear.org), at the current rate of consumption with conventional reactors, there are only 80 years of world uranium resources at reasonable recovery cost levels. Nuclear power currently only supplies about 5.7% of the world's total energy, thus if we hypothetically supplied the whole world's energy needs with nuclear power there would be only 5 years of supply. Why does it make sense for humankind to foot the risks and costs of nuclear power, for such a short-term return?

From the large-scale global energy picture, even if we could economically double uranium supply, nuclear fission only can supply a fraction of our needs. Given that renewable sources can supply many times our global energy needs, is it economically tenable to lock in our limited resources for improving nuclear power? Rather, should we ramp down nuclear power and invest in a dominant

[4] In the United States high insurance premiums for nuclear reactors are subsidized by the government, thus presenting another hidden cost that is not factored into the true economics.

[5] Note that low-end figures of \$4000/kW for nuclear construction and \$800/kW for decommissioning may be achievable, depending on local conditions. In reality, there is high uncertainty in cost and a final construction can blow out to three times the initial cost [22]. In this paper, we are looking at limits of scaling and, so if the whole world went nuclear, the \$8000/kW decommission cost used in our calculations is arguably on the low side as storage locations become scarce at these scales. Estimates as high as \$100 000/kW [22], for the decommissioning of the U.K.'s DFR reactor, are not appropriate for our calculations as the DFR is a very small reactor—at this size the cost vs. kW curve becomes nonlinear.

renewable source to build long-term energy viability for humankind?

Germany is a good case in point: it has relatively low levels of sunshine, a small coastline, and yet supplies 12.5% of its electricity[6] from renewable sources [3]—its *Atomausstieg* legislation has put a stop to the commissioning of any new nuclear power plants and existing ones are to be phased out [27].

B. Fast Breeder Reactors

Fast breeder reactors (FBRs) claim to extend the useful lifetime of uranium by a factor of about 60 times. However, since the first U.S. breeder in 1951, they have not met with commercial success—FBRs turn out not to be cost competitive, as well has having a number of safety issues [26]. The reactors use liquid sodium as a coolant and there have been safety issues with leakage. The U.S. Clinch River Breeder Reactor construction was abandoned in 1982. After a serious sodium leak and fire, during 1995, the reopening of Japan's Monju reactor has been stalled. France's Superphénix reactor closed down in 1997 due to its rate of malfunction and sodium leaks—during its 11-year lifetime there were 2 years of accumulated downtime, due to technical faults, at a total cost of $12 billion. There are many uncertainties with FBRs: their lifecycle efficiencies are unknown and how does one therefore compare their *energy return on investment* (EROI) with other energy generation methods?

C. Thorium Breeder Reactors

The key point is that thorium reactors are at an experimental stage and are commercially unproven. Thorium is claimed to be the answer to when uranium stocks run out, as it is a more 'abundant' element. However, its occurrence is only three times that of uranium, which is not significant. Moreover, the economically *recoverable* world reserves of thorium are only half of the world uranium reserves (www.world-nuclear.org). There are also uncertainties in the thorium cycle regarding safety and proliferation.

D. Uranium Recovery From Seawater

Another scheme that has been proposed for extending the viability time of uranium is to recover it from the sea. Total global seawater contains 4.5 billion tonnes of uranium. The downside is that the uranium concentration is 3 parts per billion (ppb) [28], and thus the rate of recovery and associated costs are questionable. Research on this in the 1960s stalled due to poor recovery efficiencies. Hydrated titanium oxide was used as the uranium absorbent, but was found impractical—for a review of the difficulties, see [28]. Recently, special polymer fiber membranes or chelating resins with various chemicals, in the amidoxime group, are being researched for absorbing uranium from seawater [29]. As well as questionable costs, practicalities, and recovery rates, it is unlikely that these materials would be sustainable for the sheer volumes of water that would need to be sifted. It is also unknown if uranium removal would be detrimental to aquaculture, where there is the possibility that marine life DNA mutation rates would drop and impact on long term survival adaptability.

E. Generation IV Reactors

Generation IV reactors are experimental, and far from commercial. They promise to not only burn nuclear fuel, but also waste products. This not only alleviates the waste problem, but will make our fuel last longer. However, an MIT study concludes the fuel cost would be very high at 4.5 times the cost of a traditional once-through fuel cycle—also, this advance in waste management does not outweigh the risks involved for the relatively short term gain [30].

F. Is Nuclear Scalable?

As with all nuclear reactors, nomatter how they are badged, they simply are not scalable for global power generation as reliability issues remain unsolved, e.g., neutron embrittlement of the nuclear vessel itself [31]. It is such embrittlement issues that lead to cracking, leaks, safety hazards, limited life-cycle, power plant downtime, and closure. Both FBRs and Generation IV proposals also suffer from issues with liquid sodium coolant—alternatives to sodium have been investigated, but these result in at least a threefold reduction in power density that results in higher fuel cycle costs [32]. In terms of scalability, FBRs are also limited by the fact they take 10 years to generate enough additional fuel in order to commission a new FBR [33].

Currently in 2009 there are about 440 commercially operational nuclear reactors throughout the world—there are about 70 reliability or safety incidents reported each year, which is an incident rate of 16% [34]. If we now hypothetically supply the world's 15 TW on nuclear power, it would require fifteen thousand 1 GW reactors. Thus even if we reduce this incident rate to 10% per year, five nuclear reliability incidents would happen every day somewhere in the world. This is clearly unsustainable and the fact is that the failure rate times the severity factor for nuclear accidents makes it a fundamentally unscalable technology. Moreover, with 15 thousand nuclear reactors in the world, if their construction were staggered over a 40-year period, there would have to be a decommissioning operation somewhere on the planet each day. Decommissioning is known to take up to 20 years for each reactor. The planet simply cannot sustain this decommission rate both in terms of cost and disposal management. Moreover, the level of investment in 15 000 reactors is not justified given the relatively low economically recoverable reserves of uranium (Section V-A).

[6]This is a 2006 figure and is now at about 15%.

VI. NUCLEAR FUSION

On the Sun, nuclear fusion involves the interaction of neutrons and protons generating deuteron (deuterium nuclei), helium-3 and then helium-4 (alpha particles), releasing photons in the process. However, this pathway is extremely slow, taking hundreds of million years, and thus is not viable for a fusion reactor on Earth. Thus nuclear fusion research is focussed on a faster pathway, namely, the fusion of deuterium and tritium. This reaction is faster because it involves the rearrangement of protons and neutrons, rather than the transformation of protons to neutrons that occurs in the solar scenario. However, this compromises the supposed 'clean' energy output.

A. Is Fusion Really Clean and Safe?

While deuterium is obtained from water, tritium is bred by reacting neutrons with lithium.[7] Tritium is sufficiently dangerous that nuclear licensing authorities limit its absorption by the walls of the reactor. Therein lies the problem with fusion: as reaction temperatures up to the order of 100 million Celsius[8] are required, the walls of the reactor must be made of carbon—but carbon readily absorbs tritium thus rapidly exceeding the allowed tritium limit. If the walls are made from exotic metals such as molybdenum, tungsten or beryllium, the problem of tritium retention is alleviated but then the reactor becomes commercially nonviable as it then simply cannot withstand many years of operation at such high operational temperatures.[9]

The International Thermonuclear Experimental Reactor (ITER) has the largest ever approved tritium retention limit of 350 g [35]. To put this into context, with carbon walls, ITER would reach this limit in about one week of commercial operation. It would then have to be powered down to allow access to clean the walls, for the removal of tritium. The carbon walls must be ablated to remove absorbed tritium, before fusion operation can be resumed. Exactly how to clean the walls, how to manage the resulting explosive dust, and the magnitude of the resulting reactor downtime are all uncertainties without any current solution. Thus, estimates of commercial fusion reactors by 2050 [35] are somewhat over-optimistic as they show no pathway to solving the tritium retention problem nor is the economic viability justified. Fusion reactors will still suffer from the large decommissioning costs that fission reactors are subject to—fusion does not circumvent this problem and reliability issues due to neutron embrittlement still remain. The issues of sustainability and environmental impact of nuclear fusion demand further debate.

The use of exotic materials also makes scalability questionable. For instance the solenoid coil in the ITER fusion reactor uses niobium alloys. To attain 15 TW would exhaust world niobium reserves, assuming 500 tonnes of niobium per 1 GW fusion reactor. Niobium has important applications in superalloys for engines and also in surgical medicine. This highlights the need for full analysis of the materials inventory of both fusion and fission reactors.

B. Sustainability of Lithium Fuel for Fusion

To produce 7 billion kilowatt hours of electricity by nuclear fusion has been estimated to require 100 kg of deuterium and 3 tonnes of lithium [35] as the fuel. Therefore, to supply the whole world's energy needs for 1 year would correspond to 1900 tonnes of deuterium and 56 000 tonnes of lithium. The world stock of lithium is estimated at 28 million tonnes, and thus the most optimistic case is that we have 500 years worth of nuclear fusion power. However, given the reality that lithium has many other competing industrial uses (e.g., battery technology, glass, ceramics, lubricants), this would bring down the viability of fusion power to about 100 years, which is marginally better than nuclear fission.

Given the usefulness of lithium (eg., its use in cell phones and laptops) if humankind irreversibly transmutes it into tritium, this raises serious questions. Seawater contains about 0.1 ppm of lithium [36], which is better than the case for uranium, however the recovery rates and sustainability of chemical membranes to sift the water both come into question again. It can be argued that lithium is too precious to transmute, and that it is a resource that should be reserved for our industrial needs. To irreversibly deplete the planet of a precious element is analogous to the extinction of a higher-order animal species and should be viewed in the same light. Maintaining our *elemental-diversity* is at the same level of fundamental importance as our *biodiversity*.

C. From Sunshine to Moonshine

The thought that the power of the Sun can be reproduced in a box on Earth caused Ernest Rutherford to famously comment that "anyone who expects a source of power from the transformation of the atom is talking moonshine" [37]. While we now know Rutherford was technically incorrect, if we preface his statement and specify "clean, reliable, and sustainable power," the thrust of his sentiment may indeed still prove to be correct. Two important questions remain unanswered [38]: i) why should fusing atoms be any more problem-free than splitting them? ii) in resource terms, will fusion be more or less costly?

While fusion as a resource may be debated, it is nevertheless an important frontier of fundamental science and builds our knowledge base in the understanding of the

[7]Tritium can be produced in small quantities when deuterium captures a neutron—however, as the capture cross-section is very small this pathway is questionable as a commercial route. The United States produced tritium using this method at Savannah River and closed down this site in 1988 for safety reasons. For fusion, breeding tritium from lithium is thus considered the preferred pathway.

[8]Fusion reactors are pulsed and thus this is a peak temperature.

[9]A D-D fusion cycle that uses no tritium requires five times the reaction temperature, hence current research is focussed on the D-T cycle to address containment issues.

Table 2 Power Available From Renewable Sources

Energy source	Max. power	% of Tot. Solar	Refs
Total surface solar	85,000 TW	100%	[40]
Desert solar	7650 TW	9%	-
Ocean thermal	100 TW	0.12%	[41]
Wind	72 TW	0.08%	[42]
Geothermal	44 TW	0.05%	[43]
River hydroelectric	7 TW	0.008%	[44]
Biomass	7 TW	0.008%	-
Open ocean wave	7 TW	0.008%	[45]
Tidal wave	4 TW	0.003%	[46]
Coastal wave	3 TW	0.003%	[47]

building blocks of matter. Thus, there is an imperative for fusion research to still continue, but the point here is that interesting fusion research cannot drive today's hard-nosed energy policy decisions. To do so would be like deciding today's healthcare policy based on an expectation that we will find a drug that cures all cancers someday—nevertheless, commitment to research such drugs remains.

In Appendix A we argue the case for viewing nuclear fuels as precious resources, and why it is better to preserve them to assist in the case of natural disasters.

VII. SELECTING THE DOMINANT RENEWABLE

The power outputs available from key renewable sources are shown in Table 2. The incident solar power on the planet is 166 PW; 30% of this is reflected back into space, and 19% is absorbed by clouds. This leaves a balance of 85 PW available for terrestrial solar collectors, as for this paper we shall not consider proposals to collect solar power using satellites [39]. There is no need to invoke this extra level of complexity, as 85 PW is more than adequate. This figure of 85 PW not only shows that solar power is well over *5000* times our current world 15 TW power consumption, but *all* other sources are less than 1% of solar. If we consider only the solar power that hits the desert regions of the world, all other renewables still only amount to less than 3% of this power.

This clearly demonstrates that solar is where humankind's effort must stay focussed for the future. Although alternative renewables only supply less than 1% of solar, they still can be justified for niche power in cold countries and also providing some backup security for critical utilities in case of natural disasters.

We will omit discussion of generating fuels from biomass, as Table 2 clearly shows that all biomass on the planet comes from 90 TW of solar photosynthesis and the 8% conversion efficiency[10] obtained, by burning all plant life in the world, would mean that we would only attain 7 TW in power at the needless expense of reintroducing hydrocarbons. For brevity, we will also omit discussion of wave energy as the contribution is relatively small—also the effort required for the amount of recoverable power is relatively high.

A. Wind Power

> "The wind blows wherever it pleases. You hear its sound, but cannot tell where it comes from or where it is going."
>
> *John 3:8* (c. 50–70 AD).

Wind power is an increasingly popular renewable source and produced as much as 100 GW world-wide in 2008—it is also a path to producing a renewable source of hydrogen for energy storage or as an energy carrier [48], [49]. As we see from Table 2, wind power can potentially generate a maximum of 72 TW in theory [42]. However, in practice, wind power is likely to only expand to a fraction of 72 TW and thus is not a dominant candidate for supplying the whole world's energy.

For example, a Californian study found that bird fatalities per MW per year, due to impact with wind turbine blades, are in the range of 0.8 to 2.0 birds per year [50]. If we optimistically take the low end and assume one fatal bird impact with turbine blades per MW per year, then if we supply the world's 15 TW of energy with wind power alone then this corresponds to 15 million deaths per year. Given that over 1000 bird species are approaching extinction, this means that the location of wind farms will be a sensitive issue. This can be managed by simply locating wind farms strategically away from avian migration pathways—in fact, in the United States it is illegal to kill a migrating bird, and thus such policies will drive location. Couple this with other restrictions on location such as keeping distance from high population densities, distance from sites of aesthetic beauty or cultural significance etc., and keeping proximity to windy areas, immediately narrows down the number of strategic locations—thus, the 72 TW maximum rapidly drops out of reach.

A question that is often overlooked, is to ask "where does wind come from?" It, of course, comes from the Sun that heats the ground creating massive convection currents. Thus wind power *is* solar power in extremely diluted form—it is solar power with a 99.9% conversion efficiency loss! Thus on this basis alone we can argue that the footprint of a wind farm can never compete with the obviously smaller footprint area of a solar farm, in the hot regions of Fig. 2.

Wind turbines have a number of problems such as noise, intermittency of supply, sudden surges, unpredictability of supply, turbine blades that snap off in gale force winds, and accumulation of ice on turbine blades. These can, of course, all be managed with appropriate

[10]This is assuming the most generous conversion efficiency of 8% that is true of sugarcane. In reality, for typical crops it can be anywhere from 0.1% to 2%.

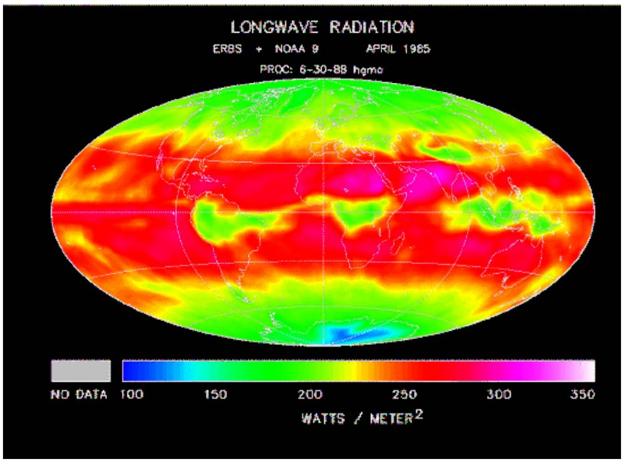

Fig. 2. ***This Erbe satellite image clearly identifies the strategic regions for solar collector farms. Actual insolation (solar power per unit area) levels are not obtained from this image, but it can be used to estimate which regions are relatively hotter. Note that in the hottest regions insolation levels can exceed 1 kW/m^2, whereas this image is showing outgoing thermal (longwave) power from the Earth in units of W/m^2. The wavelength band of the measurement is 0.5 to 50 μm. Notice that outgoing thermal power is reduced in regions of high humidity. Source: NASA.***

engineering, but in the hot regions of Fig. 2, where it makes sense that solar will dominate, economic forces may prevail against wind power.

It can be shown that wind power is economically competitive to solar power in cold regions with poor sun levels; see for example, a study carried out in the Newfoundland context where extremely cold conditions dominate [51].

Another point to note is that each wind turbine has bearings, gears, and oil seals that have to withstand enormous forces in high winds. Accordingly, for a typical 1.5 MW wind turbine, as much as of 20 gallons of lubricating oil is required, and often the conditions are so severe that the oil must be specially cooled. Thus if we were to hypothetically supply the world's energy needs with wind, we would require 40 million gallons of oil per year, assuming we need to replace the sump oil every 5 years. This is tenable with today's oil production, but will be costly in, say, 40 years time (see Fig. 1).

This calculation is also a warning signal as to why we must urgently replace oil with a suitable renewable source within the next 20 years, as we need the oil for lubricating all the engines of the world. We cannot afford to keep burning oil, as we need it in many diverse industrial applications from lubricants to plastics. For this reason, as wind power is oil-hungry, it is possibly only a medium-term solution—in cold countries geothermal and hydroelectric power will eventually dominate, and any deficit can be met by importing power from other countries (Section XIII-E).

B. Hydroelectric Power

Hydroelectric power is an excellent source of clean sustainable energy. The Hoover Dam alone provides 2 GW of power, and hydroelectricity currently provides 20% of the world's electricity. There is certainly room for growth, as only a quarter of the world's 45 000 dams are exploited for hydroelectricity [52]—however, as a candidate for supplying the whole world's power this option is limited by the availability of strategic waterways. There are also limitations imposed by the need to reduce effects on aquatic ecosystems—for example dams are known to interfere with the upstream spawning of river fish and are known to deleteriously affect salmon populations. If extra structures to bypass dams can be introduced, the restoration of salmon populations is possible [53].

An ambitious proposal to build a dam by the Red Sea estimates potential hydroelectric power of 50 GW [54]. This initiative would be detrimental to the local marine ecology and would adversely impact on tourism, fisheries, and transport. However, it is worth noting for comparison that its potential for 50 GW output is much greater than the largest nuclear station in the world: the U.S. Palo Verde nuclear power plant, has an output of only 3.2 GW. As the ultimate source of hydroelectric power is solar energy (via rain) this is a salient reminder as to the large power levels than can be obtained, compared to nuclear power, if we tap the Sun directly.

C. OETC Power

Ocean thermal gradients caused by the Sun, potentially contain up to 100 TW. Unfortunately, analysis of ocean thermal energy conversion (OETC) [55] shows poor performance—this is because practical temperature gradients are in the order of only 20°C, resulting in poor Carnot efficiency at around 6%.

D. Geothermal Power

Geothermal power involves heating a fluid or gas by pumping it below the Earth's crust and heating it by impact with hot rocks, which then can be used to run a turbine to generate electricity. Geothermal sources are cost-effective and do not have the intermittency problems of wind power. Currently geothermal power provides 1 GW, worldwide, and to put this into context it is only half of what is achieved by the Hoover Dam alone. While it is an increasingly popular and reliable source of energy, the catch in Table 2 shows that its maximum is 44 TW [43]. In practice, only a small fraction of 44 TW can be realized as much of the energy is very diffuse and thus unrecoverable. The total heat energy contained by the Earth is 10^{31} J, so if we hypothetically draw 1 TW it would last 3 trillion years and thus can be considered sustainable although rather small.

A drawback with geothermal: it is known to trigger unwanted seismic activity in some cases [56]. The fluids drawn from a geothermal bore contain hydrogen sulfide, arsenic, and mercury, and this unwanted toxicity has to be managed. Some techniques circumvent this problem by abandoning spent water in used bores, but this approach is not scalable as it raises the question of depleting water resources.

VIII. SOLAR POWER

> "The potential of solar energy is so great that developing means to tap it more efficiently and store it must be a priority."
>
> Sir Chris Llewellyn-Smith, chair of ITER council [33].

In the previous section we discussed the key renewable competitors to solar power, pointing out that they all supply less than 1% of available solar power. Solar is therefore clearly the dominant solution in terms of magnitude, and in terms of longevity it will supply all humankind's energy needs while the planet is inhabited. In this paper, we will focus solely on surface solar collection, and so the available solar power of 166 000 TW drops to half as 19% of this power is absorbed by clouds and 30% is reflected back into space. Thus the amount of available surface power is still 5000 times the current world energy needs!

This is why solar power ultimately makes economic sense. There is so much available power that any conversion inefficiencies can be more than compensated for by investing in the nonrecurring cost of more solar collectors. There is clearly so much solar power available that extra energy can be generated during the day for night use, by storing the power. The current trend in consumption patterns show a decrease in night consumption and an increase in the day—hence, losses due to storage will steadily decline and can also be compensated by more collectors. In the forgoing subsections, we identify the dominant collection technology. However, given that there are many methods of collecting solar power, in the following, we focus on two main contenders: *solar cells* and *solar thermal collectors*.

A. Solar Cells

Silicon photovoltaic (PV) solar cells are a convenient means of powering silicon microcircuits, such as pocket calculators. However, if we now pose the question of powering 15 TW with solar cells, we can identify their weaknesses in terms of efficiency and environmental impact as compared to the low-tech solution of solar reflector dishes driving steam turbines (Section VIII-B).

To calculate the solar panel area required to supply 15 TW, consider an average solar irradiance (insolation) of 300 W/m^2 and an optimistic average efficiency of 20% over the solar cell lifetime. This results in a total panel area of 100 km by 100 km in order to power total world consumption. For silicon semiconductor processing, it has been estimated that for each square centimeter of chip area it takes 20 kg of water and 4.5 g of chemicals during manufacture [57]. However, given that a solar cell is much simpler than a silicon microchip, requiring far fewer processing steps, let us optimistically reduce these figures to 10% giving 2 kg/cm^2 of water and 0.45 g/cm^2 of chemicals consumed during manufacture. This results in a total water consumption of 2×10^{17} g. This is equivalent to 3×10^{8} g of water consumed every second over the 20-year lifetime of the solar cells. This is not far off the same order of magnitude as the amount of water required for electrolysis per second in a world-scale hydrogen economy. However, in the case of solar cells, the figure of 0.45 g/cm^2 implies that the total water use is contaminated by 4.5×10^{14} g of chemicals at a concentration of 400 ppm. By contrast, a solar hydrogen economy burns hydrogen that produces water, which re-enters the environment in a clean way.

Each solar cell, for example, uses about 0.17 g/cm^2 of arsenic[11] during manufacture, and thus for a panel area of 100 km by 100 km we need 6 million tonnes of arsenic. Unfortunately, the world reserve base of arsenic lies at as little as 3 million tonnes [58]. Moreover, CdTe solar cells consume 6.5 g/m^2 of tellurium (Te), CIGS cells use 2.9 g/m^2 of indium (In), aSiGe cells use 0.44 g/m^2 of germanium (Ge), and dye sensitized cells use up 0.1 g/m^2 of rubidium (Ru) [59]—in all cases world reserves would be stretched, particularly if we take into account the finite lifetime of solar cells. This motivates the need for a more detailed viability analysis for all the chemicals used in solar cells. For an inventory of the toxic chemicals used in solar cell manufacture, and their hazards, see [60].

In terms of powering the world, a simple argument based on thermodynamics shows that PV solar cells are fundamentally unsuited for our aims. Consider the fact that the Sun's rays can be easily concentrated or focussed down, resulting in temperatures as high as 1000 °C. Simple thermodynamics tells us that it pays to exploit large temperature differences in order to approach ideal Carnot efficiency. This immediately tells us that a low-tech solution that involves boiling water and running a steam turbine, will fundamentally always be superior—PV solar cells simply do not exploit temperature. This tells us that solar cells are ideally suited to *energy harvesting* at lower powers and temperatures, thus are not ideal for heavy base-load energy demand.

The efficiency of PV solar cells can be increased by concentrating the light to create higher incident intensity. But focussing the Sun's rays also increases temperature. Because PV solar cells are a semiconductor technology there is a limit to the temperatures they can withstand. As

[11]Note that in semiconductor manufacture most of the dopant ends up as waste, and only a small fraction is implanted in the silicon.

temperature increases, semiconductor reliability dramatically drops and reversed biased leakage currents exponentially increase. Hence, cooled concentrated light PV cells achieve some gain, but fundamentally can never fully exploit the focussing power that solar-thermal collectors can withstand.

Concentrating the light can reduce the solar cell area required—but given that solar cells need replacement and that light concentration will cause a drop in cell lifetime, the consumption of chemical resources is still untenable. A factor that demands further analysis is *light-induced degradation* of solar cells [61], where performance drops with continued exposure of PV cells to light due to formation of semiconductor defects. This effect will be greatly accelerated in cases where light is highly concentrated providing around the equivalent of 500 suns incident on a PV cell. Thus claims that such concentrated solar cells can achieve > 40% efficiency must be tempered with realistic lifetime issues and consequent consumption of resources.

B. Solar Thermal Collectors

The previous subsection, argued against solar cells as they are not ideally suited for exploiting focussed sun. Therefore, in this subsection we cut to the chase by going straight to the method that optimally exploits this fact. This method is called *solar thermal*. The idea is to use a curved mirror to focus sunlight on a container of water to create steam. Due to the high temperatures, the steam is superheated and can efficiently run a turbine connected to a generator to produce electricity [62]–[68]. At present there are 340 million m^2 of solar hot water collectors in the world. In Appendix B we perform calculations that demonstrate that the planet has plenty of unused desert to supply the world's energy needs many times over, using solar thermal.

Fig. 3 shows a solar thermal system that has already demonstrated 20-year functioning performance in California's Mojave Desert, which currently outputs 354 MW of power [69]. This system illustrates long-term reliability with no signs of malfunction, over the last 20 years. The principle of operation is that a *trough* style reflector focusses sunlight down to a line and heats a pipe containing oil. The oil goes through a heat exchanger and is cycled back, and the heat is used to create steam. The resulting steam is used to drive Rankine cycle turbines, for producing electricity. The idea of the trough-shaped collector is that it makes tracking the sun simpler and eliminates shading along one axis.

However, other geometries turn out to provide better efficiency than the trough collector and modern control systems can be easily used to efficiently track the Sun. We will skip discussion of all the various geometries, and introduce the parabolic dish collector, in Fig. 4, which provides a more competitive efficiency [70]. Here the dish focusses the sunlight to heat a fluid or gas to thereby

Fig. 3. ***The Solar Energy Generating Systems (SEGS) solar trough farm at Kramer Junction, California. The concept is that the reflective troughs focus sunlight on a pipe containing oil in a closed-cycle, which heats water to create steam to turbines. In total there are nine SEGS farms, with two at Dagett, five at Kramer Junction, and two at Harper Lake; all in California's Mojave Desert. The total area occupied is 2.4 sq km, generating 354 MW of power. These figures scale up to a footprint of 320 km by 320 km, if we were to supply 15 TW with this method. The nine plants have gradually been installed from 1984 to 1990, demonstrating over 20 years of performance without malfunction. Source: Power Corp.***

Fig. 4. ***The Stirling Energy Systems (SES) SunCatcher solar dish farm being developed in California. Each 11.6 m (38 ft) diameter dish automatically tracks the sun and powers a 25 kW Stirling cycle generator. Source: Stirling Energy Systems.***

drive a Stirling engine. In this photo the dishes are 11.6 m in diameter and each drive a 25 kW Stirling engine connected to a generator. These dishes can be set up in arrays across large expanses of hot desert, cumulatively producing enormous quantities of power. Another possible configuration is to have a number of larger diameter dishes driving a high power Rankine cycle turbine—see Appendix B.

In terms of practicalities, current experience with solar thermal farms shows that they can be constructed to survive high winds, cleaning can be automated, sandstorms do not roughen the glass, and the replacement rate of mirrors is about 0.8% per year. By using 1 mm glass and supporting the mirrors in a way that allows them to flex, they surprisingly survive large hailstones.

In conclusion, assuming appropriate energy storage, solar thermal dishes have the potential to provide *base load* power—whereas the correct niche for solar cells is in *energy harvesting*.

IX. HYDROGEN VEHICLES

Given that vehicles based on any form of hydrocarbon (e.g., gasoline, natural gas, ethanol, etc.) raise both resource and emission issues, alternatives such as hydrogen or electric vehicles have generated much interest as clean alternatives. Electric vehicles appear attractive on a number of levels, particularly in that there is a large existing infrastructure for the distribution of electricity. However, vehicles based on liquid hydrogen combustion are far superior in terms of sustainability, as they do not create escalated consumption of extra chemical resources. The consumption of chemicals in the batteries of electric vehicles would place an enormous burden on our finite resources, leading also to high levels of toxic waste. For example, an average electric vehicle will typically require a battery containing about 20 kg of lithium. Given that our world reserves of lithium are estimated at 28 million tonnes, this would allow us a maximum of 1.4 billion electric vehicles. Assuming the current world-wide production rate of 60 million vehicles per annum, would leave us with only 23 years! Clearly, electric vehicles are not a viable long-term option—furthermore, this rapid depletion of our lithium reserves would be questionable given the increasing demand for lithium in mobile phones and laptop computers. Even taking into account the possibility of lithium recycling, the competition for lithium in other applications would escalate price.

A. Hydrogen Fuel Cell Vehicles

Fuel cells are essentially electric batteries fueled by hydrogen. This has a number of drawbacks: i) it leads to electric cars, whereas the world automobile industry is tooled-up with a combustion engine infrastructure; ii) fuel cells contain expensive membrane technology that leads to high cost and potential for catastrophic failure; and iii) fuel cells contain chemicals such as carbon-fluorine polymers with sulfonic side chains, leading to the issue of chemical sustainability.

Due to the disadvantages of membrane technology, it is difficult to argue for mass scalability of fuel cells as a dominant means for powering transport. In the context of vehicle transport, for every kilowatt, a fuel cell results in about a factor of 10 higher cost than gasoline [71]. Due to high cost, the economics of fuel cells has been critiqued [72]. Hydrogen internal combustion engines are accordingly considered more cost effective than fuel cell vehicles [7].

B. Hydrogen Internal Combustion Engine (ICE) Vehicles

In the same way that a combustion engine can be fueled by natural gas or gasoline, with suitable modifications it can also operate with either gaseous or liquid hydrogen. While hydrogen has an excellent energy to mass ratio, it has a poor energy to volume ratio. Accordingly, small vehicles such as cars will need to operate on liquid hydrogen, but larger vehicles such as buses have the tank space to utilize hydrogen gas. This is exactly the case at present, for example, the BMW Hydrogen 7 vehicle runs off liquid hydrogen, and currently 20% of Berlin's BVG (*Berliner Verkehrsbetriebe*) buses run on hydrogen gas. In the United States, for several years, Ford has been producing the E-450 shuttle bus featuring a hydrogen-fueled internal combustion engine (ICE). Also Mazda have produced a hydrogen ICE vehicle called the RX-8 Hydrogen RE.

The advantages of hydrogen vehicles that use internal combustion are that:

1) Gasoline engines can be retroffitted to run on hydrogen [73].
2) Hydrogen engines can potentially have higher efficiencies than those based in fossil fuels [74].
3) Hydrogen-fuelled engines do not need pollution control devices, and as a result conserve more energy [74].
4) Because hydrogen is so much lighter than jet fuel, it reduces the take-off weight of and consequently decreases the fuel consumption [74]–[77].
5) Combustion engines that burn hydrogen simply emit clean water vapor, so we can build further sustainable growth in the transport industry.
6) Burning pure hydrogen avoids the unsustainable use of specialized chemicals.
7) The automobile industry currently has the infrastructure to manufacture combustion engines, which is a significant economic resource advantage over electric cars.

In the next few sections we demonstrate how hydrogen can be handled, produced, stored, distributed, and how the resulting challenges can be addressed.

X. HYDROGEN SAFETY

Hydrogen has been safely manufactured, stored, and distributed by industry for a number of decades. If handled with the correct procedures, it is regarded as safe [78]. A key fact is that hydrogen is 14.4 times lighter than air, rises at 20 m/s (45 mph), and thus quickly dilutes and disperses. Thus it is difficult to contain hydrogen for a hazardous scenario. Hydrogen has a diffusivity in air of 3.8 times faster and rises 6 times faster than natural gas, thus rapidly escapes upwards if accidentally released. Hydrogen combustion produces water vapor and this, together with the absence of carbon, means that a tenth of the radiant heat is produced compared to a hydrocarbon fire—thus the risk of secondary fires is greatly reduced. For example, in air, a 9% hydrogen flame does not ignite a sheet paper even with a long exposure for 60 seconds [79]. The effect of hydrogen's high diffusivity and buoyancy on safety under different leakage scenarios has been extensively studied [80].

As seen in Fig. 5, hydrogen tanks have been tested under extreme conditions including firearm shots [81] and major mechanical damage—they have also been subjected to flames at 1000 °C for over an hour, without incident [82].

In Fig. 6 we see a study, carried out at the University of Miami, where a punctured hydrogen tank is compared with a punctured gasoline tank. In the test, both are deliberately ignited. As we see, the driver in the hydrogen car would be perfectly safe as a thin flame vertically rises due to the high buoyancy of hydrogen. However, in as little as 60 seconds, the driver of the gasoline vehicle would be in critical danger as the car is engulfed with flames—this is a consequence of the weight of gasoline.

Another issue is if there is a hydrogen leak in a confined space, hydrogen concentration may build up enough to become combustible. In a recent Japanese study, it was found that ceiling vents in enclosed parking lots are sufficient to maintain hydrogen safely below the flammability limit [83]. This promising result motivates further studies for rigorously developing ventilation standards for indoor parking lots.

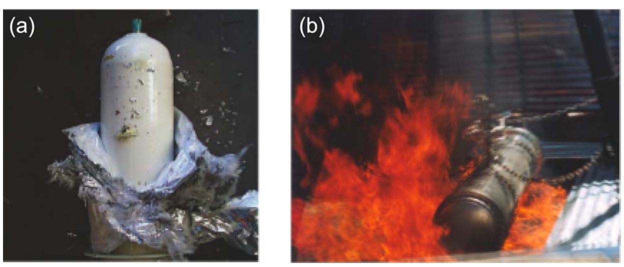

Fig. 5. ***Destructive tests on full hydrogen tanks. Under extreme conditions (a) piercing the tank with .30-caliber armor-piercing bullets, and (b) bathing the tank in flames for over 60 minutes at 1000 °C, no explosion occurred. Source: Lawrence Livermore Laboratories.***

Fig. 6. ***On the left is a vehicle with a hydrogen tank, and on the right a vehicle with a standard gasoline tank. Both tanks have been deliberately punctured and ignited. The top panel shows the two vehicles 3 seconds after ignition. We see that, due to the buoyancy of hydrogen, the flame shoots up vertically, whereas gasoline is heavy and spreads beneath the vehicle. The bottom panel shows the two vehicles 60 seconds after ignition. The hydrogen supply has burned off and the flame is diminished, whereas the gasoline fire has accelerated and has totally engulfed the vehicle on the right. Note that hydrogen flames are not intrinsically visible, but salt and particles in the ambient air burn off giving color to the flame as seen above. Source: University of Miami.***

XI. HYDROGEN PRODUCTION

There are a plethora of methods for producing hydrogen [84] but, when specifically asking the large-scale question of supplying the whole world's energy needs, many of these options can be eliminated. Take, for example, the electrolysis of ammonia (NH_4) leading to nitrogen and hydrogen—the obvious questions are: i) from where do we sustainably obtain all the ammonia, and ii) how do we manage the voluminous unused byproduct, in this case, nitrogen? By asking similar questions of every method it is easy to see weaknesses in their viability for world-scale operation.

The only option left that passes the test for large-scale viability is the splitting of water into hydrogen and oxygen [85]. The reasons are that: i) water is an option that requires no mining; ii) there are vast supplies of water; iii) the combustion of hydrogen creates water, and so we have a reversible cycle; iv) there are no significant byproducts; and v) the use of extraneous chemicals and exotic materials is minimized. This leads us to the question of how best to split water, and the various options are discussed in Appendix C.

XII. COMMON HYDROGEN MYTHS

Myth 1: "The Hindenburg exploded, killing everyone aboard." While there is much controversy over what caused the ignition, we know the airship did not explode apart, but it burned from the top surface in a fashion that enabled it to float down and allow 61 of 97 people aboard to walk to safety [74]. This is a much higher survival rate compared to a modern airline crash.

Myth 2: "Electrolysis of water to produce hydrogen drops in efficiency when gas bubbles collect around the electrodes, creating an insulating blanket layer." While this is true, it is a myth that there is no easy solution to the problem. Simple ultrasonic shaking of the fluid dislodges the bubbles and creates an energy saving of 10–25% in the electrolysis process [86].

Myth 3: "Production of hydrogen is costly as expensive compressors are needed to pressurize the gas, for handling and storage." This is a myth as electrolysis can take place under high pressure (10 000 psi), thus eliminating the need for hydrogen compressors [87] at higher electrolysis voltage while still making net power savings [88].

Myth 4: "Hydrogen internal combustion engines have dangerous nitrous oxide (NO_x) emissions." While it is true that the high combustion temperatures can cause nitrogen present in the air intake to form unwanted nitrous products, these are less than in conventional gasoline engines. Recent tests performed at Argonne National Laboratories have demonstrated NO_x emissions lower than 4% of the Super Ultra Low Emissions Vehicle (SULEV) standard [82]. The NO_x emissions are minimized [89], in practice, when the average relative air/fuel ratio, λ, is maintained around $2.5 < \lambda < 3.5$. Emissions peak at $\lambda = 1.3$, and this can be avoided by design. Also, concentration of carbon monoxide emissions (CO), due to reaction with engine lubricants, was found to be at the same low level that already exists in ambient air [82].

Myth 5: "Hydrogen internal combustion engines emit hydrogen peroxide (H_2O_2)." It has been shown that peroxide emissions in the range 400–1000 ppm are present only when a hydrogen engine is operating inefficiently—when the engine is designed to run efficiently, the peroxide emissions drop below measurable levels [90].

Myth 6: "There is no hydrogen infrastructure with experience in storage and transportation." Hydrogen is extensively used in industry, at present, for a number of chemical processes. Currently, 75 million tonnes of hydrogen are produced, stored, and shipped annually—the energy content of this amount of hydrogen is equivalent to well over half of the current U.S. annual gasoline consumption. Storage tanks and tanker trucks for road delivery exist. For distribution, there are also currently about 1500 km of hydrogen pipelines in the United States and about the same in Europe.

XIII. HYDROGEN CHALLENGES

A. The Platinum Question

A pertinent question is to ask how many tonnes of platinum we need for the electrolysis of water to produce hydrogen. Let us calculate the extreme case of producing hydrogen to supply all the 15 TW for world consumption. Firstly, we need to calculate the total surface area A of the electrodes required to do this. The ratio of power due to hydrogen combustion to the electrode area, P/A is given by,

$$\frac{P}{A} = \rho E R \tag{1}$$

where $\rho = 0.08988$ g/L is the density of hydrogen in grams per liter, $E = 1.43 \times 10^5$ J/g is the combustion energy[12] per gram of hydrogen, and R is the volume rate of hydrogen production per unit electrode area in units of liters per second per squared meters. Now, for electrolysis of water, R usually lies in the range of 4–10 $\mathrm{Lh^{-1}m^{-2}}$ [5], so let us select 4 $\mathrm{Lh^{-1}m^{-2}}$ for a rough worst-case analysis. Inserting these values into the above equation yields, $P/A = 14.3\ \mathrm{Wm^{-2}}$.

We need about a trillion times this amount of power to supply the world, and thus we need an electrode area of 10^{12} m^2. This corresponds to an area of 1000 by 1000 square kilometers, which is four times the land area required to supply the world's energy. If we assume that nickel electrodes are coated with platinum 1 μm thick, then the volume of platinum is 10^6 m^3. With a platinum density of 21.45 g/cm^3, this amounts to 2.15×10^5 tonnes. Unfortunately, the world platinum resource is only 9×10^4 tonnes and so we require 2.4 times more platinum present in world recoverable reserves.

Clearly, electrolysis via platinum electrodes is not sustainable. One possible solution that is being investigated are oxide electrodes embedded with platinum nanoparticles, in order to reduce the volume of platinum. However, platinum is nevertheless a precious resource and a platinum-free solution is preferable for world-scale use. While research is ongoing for suitable platinum substitutes, an interim solution is to simply compensate for the drop in efficiency by using alloys (e.g., nickel-chromium based alloys) by factoring in the nonrecurring cost of more solar dishes.

B. The Water Transport Question

Let us consider the extreme limiting case where we supply all the world's 15 TW from hydrogen—the mass of

[12] This is the HHV or gross calorific value for combustion that is used throughout this paper. It is an exercise for the reader to try the LHV net calorific value, which makes little difference to the order-of-magnitude results here.

water m required to produce this amount of hydrogen is given by

$$m = \frac{nPt}{E} \tag{2}$$

where $n = 18$ g is the molar mass of water and E is the combustion energy of hydrogen per gram as given before. If we put $t = 1$ s, this gives that the total mass of water consumed to power the world each second as $m = 1.9 \times 10^9$ g. The total mass of water on the whole planet is 1.36×10^{24} g, thus to power the planet requires less than a trillionth of a percent of our total water resource. Even if this amount was larger it would not concern us because, for every second this mass of water is electrolyzed, an equal quantity of water is recreated via hydrogen combustion in the same time. Therefore there is no net loss of water, and the balance of Nature is maintained.

However what might concern us is that we need to transport $m = 1.9 \times 10^9$ grams of water every second. The energy generated via hydrogen obtained from a mass m of water is $2mE/n$. Let us consider the extreme case that we use *all* our generated energy to transport the water with kinetic energy $(1/2)mv^2$, then the water travels at an average velocity v,

$$v = \sqrt{\frac{4E}{n}} \tag{3}$$

and inserting the values gives $v = 180$ m/s. Thus in one second the water travels 180 m, provided we consume all our energy. This simply means that when designing a large scale solar farm we must transmit the electricity by cable to a suitable source of water, rather than pumping the water to the solar farm. This is a clear design constraint. Water that is used in closed cycle to drive the steam turbines may, of course, be pumped to the solar farm as this is a small fraction. However, cables need to be brought to a suitable source of water (e.g., desalination plant) for performing large scale electrolysis.

C. The Hydrogen Balance Question

We have argued that solar hydrogen power is a sustainable cycle as no water is consumed, i.e., the generated hydrogen combusts and turns back to water in a repeatable cycle. While this is true to a first order approximation, it should be noted that in practice there will be some irreversible loss as a second order effect. The problem is that hydrogen is the lightest element and when it is released into the atmosphere it is so light that it escapes to the stratosphere, the troposphere, and a small fraction even escapes gravitational attraction and so it is permanently lost. If the whole world converts to a solar hydrogen economy, losing some free hydrogen to the upper atmosphere will be a practical consequence of handling and transportation. Thus over a long time scale we will deplete the planet of all its water.

However, we know that in 1 billion years all the water on the planet will be boiled off, anyway, as the Sun starts its progression towards becoming a red giant. Thus, if the end-game is zero water in a billion years anyway, then let us make a rough first-order calculation as to how much hydrogen leakage we can afford per second that results in total depletion of the world's water in a billion years time. If we electrolyze all the water on the planet, the resulting hydrogen mass would be 1.5×10^{23} g. Dividing this by the number of seconds in a billion years gives an allowable loss of 4.78×10^6 grams of hydrogen every second. Each second the world needs 15 TJ of energy, and a mass of 1.05×10^8 g of hydrogen is needed to supply this.

Thus in order to be sustainable over the next billion years we need policies in place that limit maximum hydrogen leakage to about 5% of total hydrogen production.[13] For the first hundred years, we can sustain a much higher leakage rate while adjusting to the economic transition. However, in the next century losses should be minimized for long-term survival of the planet. At present, the figure for industrial hydrogen leakage to the atmosphere is only at 0.1%, so in the long term we should be able to maintain this level and keeping below 5% is thus entirely feasible. At present, when hydrogen is stored, pressure is regulated by valves that bleed off hydrogen releasing it into a catalyst that turns it back to water, and thus maintaining the billion-year 5% limit appears to be tenable. A long-term approach might be to design hydrogen regulators that burn off the hydrogen back to water, in order to avoid chemical catalysts.

What are the long term effects of increased hydrogen leaked into the upper atmosphere? A recent study has shown that its affect on ozone (O_3) is negligible [91], but the affect of hydrogen on OH radicals in the stratosphere is still being debated and requires further research. However, if we maintain leakage levels less than 1% we will in fact be better off than the current situation with burning fossil fuels. To put this in context, current total fossil fuel emissions are 600 billion tonnes per year, and about 30 billion tonnes of this are NO_x emissions. In terms of hydrogen, the atmosphere contains 0.5 ppm, in volume, of hydrogen amounting to 175 million tonnes in total. About 20% of this hydrogen comes from the consumption fossil fuels [92], anyway; thus a hydrogen economy can improve the situation should future research confirm a deleterious effect on OH radicals.

[13] Note that we have not taken into account that Earth, in fact, *receives* an unsolicited 1×10^6 of water every second from small comets that disperse in our upper atmosphere. So a solar hydrogen economy is actually needed to prevent coastal cities flooding in 1 million years time.

D. The Hydrogen Embrittlement Question

As hydrogen is the smallest element it can be absorbed by metals and contained in interstitial sites of metal lattices—this can cause cracking and this challenge is referred to as *hydrogen embrittlement* [93]. In 1943, an early study by Armbruster [94] showed that the solubility of hydrogen in iron is a function of both temperature and pressure. Ferric steels and nickel superalloys are highly prone to embrittlement, whereas austenitic stainless steels, copper alloys, and low aluminum alloys are little affected [78].

Hydrogen only causes ferric steel embrittlement if it is roughly in the temperature range from -100 °C to $+200$ °C [95]. This is because at higher temperatures the hydrogen molecules are too energetic to be trapped, and at low temperatures they are not energetic enough to significantly diffuse into the steel. Thus, for liquid hydrogen vehicles there are no issues at liquid hydrogen temperatures and, at the combustion end of the engine, temperatures are well above $+200$ °C. Therefore, the only part that has to be addressed by special alloys is the transition region between the tank and intake into the engine. The BMW Hydrogen 7 vehicle has demonstrated that this is entirely feasible. The BMW tank is made of a glass fiber/aluminum composite so that is also free of embrittlement—this is necessary for cases where an almost empty tank warms up and has some residual hydrogen gas.

E. The Hydrogen Distribution Question

In Section XIII-B, we suggested that it would be more economical to take electricity by cable to a strategically located electrolysis plant, rather than pumping water to the solar collector farm. The next question is, should electrolysis be carried out in centralized plants or be distributed such that each refueling station performs electrolysis using grid electricity? The answer is clearly to exploit economy of scale and use centralized plants strategically located by appropriate water sources. A recent study of the economics of hydrogen distribution, in the context of Shanghai, shows that it is more economical to deliver hydrogen by truck to refueling stations in preference to on-site electrolysis [96]. Centralized plants, also make better sense in the long term—recall that electrolysis may be required to produce hydrogen for: i) energy storage to create grid power at night and ii) refueling of vehicles. Thus further economic analysis needs to account for the fact that vehicle fuel is not the only demand for hydrogen production.

Hydrogen pipelines currently operate in Germany, Northern France, the United States, South Korea, and Thailand [52].

F. The Hydrogen Storage Question

For temporary storage of hydrogen for supplying electricity at night, the simplest option would be underground storage. Large quantities of hydrogen have been stored in underground caverns by ICI for a number of years without any problem. However, a possible criticism is that it is hard to see how the 1-billion year 5% leakage limit (see Section XIII-C) can be maintained with such storage.

There are numerous forms of chemical storage, where hydrogen is converted to a compound and then recovered for later use—refer to the review in [97]. In this category, conversion of hydrogen to a metal hydride is regarded as one of the most promising options. In particular, schemes based on magnesium hydride appear to be the most competitive [98]. However, the downside is that hydrogen recovery requires heating the hydride to 300 °C, the kinetics are slow, and the cycle life is finite [98].

An approach adopted, in this vision paper, is to select options that minimize the use of chemicals and have virtually unlimited cycle lifetimes. From this viewpoint, the most straightforward approach is to simply liquefy the hydrogen. While this comes at an energy cost, no additives are necessary. Composite aluminum-glass fiber double-walled fuel tanks that can store liquid hydrogen have been demonstrated to perform well in the BMW Hydrogen 7 vehicle. Moreover, in the area of space flight, liquid hydrogen was used to safely power, for example, the Space Shuttle and Saturn V. While the energy density per weight of liquid hydrogen is excellent compared to gasoline, its energy per volume is lower. However, the concern that this will lead to vehicles with poor range is unwarranted. The BMW Hydrogen 7 has a range of 200 km on a full liquid hydrogen tank, which is adequate for metropolitan driving. With tremendous public support for renewable energy, the inconvenience of refueling a little more often than with gasoline is tolerable. In the medium term, BMW are working on advanced energy management to increase the range to 600 km—while this is complicated to optimize, implementation will be easy as modern car engines are electronically controlled. For larger vehicles such as trucks and public transportation, larger tanks can be easily accommodated. Refueling pump technology that can be safely operated by the public has been developed [99]. For an analysis on refueling safety, see [100].

The question of meeting the extra energy demand for liquefying the hydrogen, should not be mistaken for a zero-sum game as is the case with fossil fuels. In our scheme, we have a more than enough energy supplied freely from the Sun, and the solution is to factor in the nonrecurring cost of extra low-maintenace solar dish collectors to provide energy for liquefaction. The calculations in Section XVI include liquefaction, and yet suggest the cost of a solar collector farm is much lower than a nuclear station of equivalent power.

G. The Transition Rate Question

Is the number of solar thermal collectors we need to power the world so large that we could never build them in time? To answer this, let us select the case of transitioning to a total world solar hydrogen economy within 20 years. If the world needs 1.7×10^9 collectors in total (see Appendix B), in a 20-year period, this would mean 2.5 collectors must be built in every second somewhere in the world. This is tenable given that the planet already builds an automobile every two seconds, comprising a much more complicated set of parts.

H. The Geolocation Question

In Appendix B, we suggest a total footprint of 500 km by 500 km can supply the whole world's energy needs. But where should this be located? Australia has expansive stable dry deserts and could potentially supply the whole world's energy needs. Due to known geopolitical stresses caused by uneven distribution of oil in the world, we know from experience that solar farms should be widely distributed throughout the world to avoid such situations. Furthermore, this would be more economical in terms of energy distribution. Thus, solar dish farms around 4×4 square kilometers in size are ideal for both economy of scale and wide distribution. Many regions such as the Americas, Africa, Australasia, Asia, and the Middle East all have hot desert regions ideal for solar farms.

In Europe, Spain has ideal hot locations, but cold industrial countries such as Germany have to seek creative solutions. Currently, Germany is establishing a solar farm in Algeria and running an HVDC cable to Aachen. There are other European initiatives along similar lines, and one of the criticisms is the perceived stability of hosting countries for the solar dishes. This should not be a problem as such deals cement good will, mutual prosperity, internationalization, and hence stability. If a country really wanted to be isolationist, it only costs \$50 million/km^2 to reclaim land from the sea and this is a relatively low-cost solution. Other possibilities are floating platforms at sea or table mountain tops.

Some countries will, of course, be in a position to export solar energy to their neighbors. This might be carried out either by transporting liquid hydrogen, or by direct transmission of electricity via HVDC cable. Underwater electric cable links are possible—for example, there are existing underwater cables between New Jersey and Long Island, as well as between Tasmania and mainland Australia. However, at present, the longest undersea cables are only in the order of hundreds of kilometers.

I. The Infrastructure Question

To answer the objection that there is no current network of liquid hydrogen refueling stations, Fig. 7 reminds us that exactly the same situation existed when the gasoline car was first manufactured. The intense demand for these vehicles stimulated coevolution of the relevant infrastructure. When the Model T Ford was introduced there were no sealed roads and users initially purchased gasoline, by the can, at local pharmacies. It did not take long, however, for the infrastructure to rapidly develop.

Fig. 7. *Henry Ford with his Model T, circa 1908. When the gasoline car was first introduced there was no infrastructure, were no sealed roads, and were no refueling stations. Typically a vehicle owner would purchase a can of gasoline at the local pharmacy. This is a salient reminder that the growth of infrastructure can coevolve with demand.*

J. The Transition Implementation Question

The opinion here is that local governments can easily stimulate growth of the infrastructure in a stepwise approach. The first step is for governments, along with industry partners, to build solar dish farms around 4×4 square kilometers in size and connect them to supplement the local electricity grid. Then in conjunction with a desalination plant, electricity is used to electrolyze water finally resulting in liquid hydrogen. The next step is to then power public transport, such as buses and trams, using liquid hydrogen. The public can then purchase liquid hydrogen cars, and refuel at public transport depots. This will then stimulate the conversion of existing gasoline stations to also begin in providing liquid hydrogen refueling.

A possible transitionary phase step towards solar farms is to use them to supply grid power and hydrogen for cars during the day, while burning fossil fuels at night. Then overnight solar storage techniques can be gradually phased in after careful trials of the many possible options.

XIV. HIGH-TECH VERSUS LOW-TECH SOLUTIONS: AN ENTROPY BASED ARGUMENT

As humankind has evolved, tools and instruments have become increasingly sophisticated inexorably climbing the high-tech ladder of complexity. This has been achieved by mastering energy and directing it towards manipulating matter at finer scales: the microscale, the nanoscale, and the atomic scale. The progression of science appears to always evolve towards increasingly high-tech scenarios.

Following this trend, it is therefore easy to fall into the trap of thinking that the solution to providing the world's energy must necessarily lie in high-tech solutions such as nuclear fusion or increasingly sophisticated semiconductor solar cells. We have grown accustomed to thinking that high-tech is the way ahead, and we therefore tend to be automatically attracted to this type of solution space.

Therefore it comes as a surprise to find that when seeking how to supply the word's energy, we have arrived at a solution involving simple mirrors and steam—one cannot get lower-tech than this. Why is this and is there a physical principle that can explain this?

A simple entropy-based argument can help us to clearly see that when it comes to energy generation one must *necessarily* use a low-tech solution. On one hand, we *expend* energy when we direct it towards creating sophisticated ordered structures at the micro- and nanoscales. However, when we *generate* energy the situation is reversed, where arrangements of matter become disordered: in our case, to approach Carnot efficiency, steam is unavoidably heated to a high state of disorder. This argument tells us that, for heavy energy demand, a high-tech solution will never give both optimal reliability and efficiency—ordered structures are not suited for surviving the unavoidable by-product of disorder when generating large quantities of energy. Therefore the high-tech paradigm has no place, at the front-end, when it comes to generating the world's energy needs. We must proactively focus on simple low-tech solutions, due to the very nature of the problem.

XV. FUTURE VISION

> "We are continually faced with a series of great opportunities brilliantly disguised as insoluble problems."
>
> John W. Gardner (1912–2002).

Given that we have demonstrated a solar hydrogen economy has a billion-year viability and that it has the potential to produce many times our world's current energy consumption, this stimulates discussion of a number of possible future visions.

A. Emerging Townships

In Section XIII-H, we discussed the desirability of having many solar hydrogen sites of reasonable size around 4 × 4 square kilometers, distributed throughout the hot deserts of the world for reasons of i) geopolitical stability, ii) distributed security, and iii) economics of energy distribution, as opposed to building one large vulnerable solar farm at one site in the world. One can therefore envision that in the same way that new townships emerged in the 19th century, where steam locomotives stopped for water and fuel, we will see the emergence of new city oases developing around desert solar farm sites. The solar farms will bring employment, virtually limitless energy, and prosperity to remote regions. It will become economically tenable to build extra solar dishes specifically for providing the energy to pump water to service these regions.

B. Recycling

An impending global problem is that of sustainability of our mineral resources [58]. Many precious elements are increasingly being used up in high-technology. To sustain our future viability in the age of IT and personal computing, we will need vast amounts of energy to extract and recycle exotic materials from used semiconductors and circuit boards. In order to sustain our need for oil to lubricate the engines and machines of the world, we will need energy to purify and recycle used sump oil. Scarce metals such as lithium and platinum will need to be recovered from waste products. The increasing need for recycling may require humankind to, in effect, double the world energy production. To double our energy output within a few decades, for the luxury of recycling, would be unthinkable in a fossil fuel economy. However, doubling the world's solar farm footprint is entirely feasible given that it is low-tech and occupies only a fraction of the surface area of the world's deserts.

XVI. NEW ECONOMICS

The vision in this paper highlights the imperative to question the way we carry out applied energy economics. In-built into economics are short-term processes that lead to waste and policies that are not in the interests of the common good. Economics is myopic in that it is mostly focussed on returns in less than 5-yr cycles and does not factor in the long term. Current economic thinking leads to anomalies, hidden costs that are not always transparent, and analyses vulnerable to cherry picking.

A. Hidden Costs Versus Hidden Savings

In nuclear power there are hidden costs (Section V), whereas in a solar hydrogen economy there are hidden savings. The production of clean water from the combustion of hydrogen can be harnessed as a cost-saving resource. The environmental cleanliness of solar hydrogen is also a hidden saving. Also we need to view the cost of *embodied energy* differently for solar hydrogen—as solar farms expand, more solar dishes can be made from the energy produced by the existing dishes and thus there is a favorable 'bootstrap' effect that needs to be taken into account.

An interesting 'hidden saving' in the use of liquid hydrogen (Section IX-B), for powering automobiles, is that the energy invested into liquefying the hydrogen can be partially recovered. For example, the liquid hydrogen can be warmed just before combustion and this heat can be drawn from the engine, via a secondary heat exchanger, to improve engine efficiency—this is akin to Robert H. Goddard's work in the 1930s on *regeneratively cooled engines*. Similarly, the available *cold sink* can be put to good use for cooling the exhaust and recovering clean water. Managed via RFID technology, an enthused public can be rewarded with fuel discounts every time they deposit recovered water at approved roadside locations.[14] The recovery of water eases the throughput of desalination plants for the production of hydrogen, and this needs to be favorably factored into the economics of hydrogen.

A massive solar-collector farm has savings due to economy of scale, and the fact it is *modular*. For example, when a nuclear power plant has a catastrophic failure or meltdown a country loses 1−3 GW of power and it is on the scale of years before a replacement takes effect. By contrast, when a solar dish fails the power loss is insignificant and it can be repaired within a day. Thus modularity has significant downstream economic benefits in terms of maintenance costs and downtime cost incurred by malfunction.

B. Consolidated Utility Time

Table 3 shows what we call the *consolidated utility time* (CUT), which is the time it would take for each resource to run down reasonably recoverable reserves if it individually had to supply the whole world's energy needs, in isolation. The figures generously assume that consumption remains at the current level, so in reality the figures are much more pessimistic for nonrenewables. In the case of nuclear fusion (Section VI) we have assumed only 100-yrs availability of lithium due to competing interests for this resource.

As we see in the table, there is only enough good quality uranium ore to last 5 years (Section V) if we power the world only on fissile nuclear power. Extending this out to 500 years by using breeder reactors is questionable in terms of costs and risks, compared to a solar hydrogen economy with a 1-billion year viability. Thus the long term return on humankind's investment is virtually zero in the case of nuclear power and virtually infinite in the case of solar hydrogen! Moving to fusion makes little difference on these scales. To a rational player, solar hydrogen is clearly the winner and yet our system of accounting the

[14]Recovering water from hydrogen combustion also counters the objection that excessive water vapor is a greenhouse gas.

Table 3 Consolidated Utility Time (CUT)

Energy source	Utility time
Solar-hydrogen	1-billion years
Nuclear fusion	100 years
Coal	35 years
Gas	14 years
Oil	14 years
Nuclear fission	5 years

economic costs anomalously confers nuclear power as viable. There is a game-theoretic element in here that needs careful thought, and calls for a new form of economics that transparently accounts for all the relevant factors.

The problem is how do we truly quantify the economic utility of two resources that have vastly different time scales? What is clear is that we need a shift in thinking from a short-term to a long-term mindset when determining the future of the world's energy requirements. Energy must not be treated in the same way as a minor commodity subject to short-term trading—energy is the foundation on which we build our whole economy and thus fundamentally demands a long-term perspective.

C. Case Example: Nuclear Versus Solar

Consider a case such as in the U.K., where there are 11 aged nuclear reactors that are closing for decommissioning for a total cost of \$110 billion [102]. For simplicity, let us assume ten 750 MW reactors at a decommissioning cost of \$8000/kW—this amounts to a total clean-up cost of \$60 billion, which is not unusual in the nuclear industry. Now, on a massive world-supply scale, solar dishes with 25 kW Stirling cycle generators could eventually cost \$1000 each. But let us assume \$50 000 each on a medium-term scale. This means that \$60 billion can buy us 1.2 million solar dish engines. In Appendix B we calculate conservatively that we would need 1.7 billion dishes to supply 15 TW, and this averages at 8.8 kW each. Thus, 1.2-million dishes would generate 10.5 GW—in comparison, ten nuclear plants at 750 MW each amounts to 7.5 GW. Thus solar gives us more power for only the closing down costs of nuclear stations.

D. Vendor Lock-In

Another economic problem is that of *vendor lock-in* where it becomes costly to exit from a scheme in order to switch to another. Given that nuclear power is of almost zero significance, on a 1-billion year timescale, one has to weigh the economic cost of locking in too much investment into something of short-term utility, at the expense of investment in solar hydrogen that has 1-billion year utility.

Perhaps, the way forward is to combine the science of economics with engineering methods for simulating *complex systems*. Some of these economic questions maybe easier to analyze in computer simulation using *agent-based modeling* methods.

E. Fuel Sources Versus Fuel Carriers

Often in the literature a distinction is made between fuels that are *sources* of energy and those that are *carriers* of energy. The current literature claims it is a mistake to consider hydrogen as an energy source, because it does not exist freely in Nature such as coal, oil, or natural gas. Due to this prevailing viewpoint, hydrogen is often disparagingly downgraded to the status of an energy carrier, on the basis that some other source of energy is required to generate it.

It is the opinion here that this distinction between carriers and sources is specious because *all* fuels come at the expense of an external energy source. The fact is that *all* fuels are carriers of energy and all fuels obtained their energy from another source at their point of creation. The only distinction is one of timescale—for example, coal was created in the distant past, whereas in the case of a solar hydrogen economy we generate hydrogen in real-time as we need it. In both cases the prime source of the energy is the Sun, which ultimately came from the Big Bang.

The false dichotomy between carriers and sources hides a number of economic factors—for example, all fuels require us to apply varying degrees of external energy to obtain and process them for practical use. The real question is by how much. Thus it is far more useful to call *all* fuels carriers and focus on the real issue, which is to fully quantify the costs and extra energy that are required to process the fuel. In the case of uranium, for example, one has to count the cost of mining, purification, and enrichment—then there is also the embodied energy of the mining equipment and the enrichment plant itself. Whereas, in the case of hydrogen we have to count the cost of electrolysis, desalination, and the embodied energy of those plants.

Take also, for example, the so-called *shale oil economy*. About a further 2 trillion barrels of oil exists in these sand deposits [103]. Let us generously assume it is all economically recoverable. Given that we use 80 million barrels a day, this means we have 68 years of shale oil. But given that 40% its energy is used up to recover shale oil, we are only left with 41 years. The reality is less than 20 years as demand increases, and not all of it is recoverable anyhow. Is this long enough to justify the large infrastructure required? On the other hand with solar hydrogen, no matter how pessimistically we calculate the energy required, to generate the hydrogen, it still lasts 1 billion years and still only takes up a fraction of the world desert area. This is what is meant when it is said that energy comes 'freely' from the Sun. Thus investment in a solar hydrogen infrastructure is absolutely justifiable and gives a much longer-term return than any new fossil fuel resource.

This motivates future economic analysis that carefully compares all the costs in detail. In such an analysis, the cost in energy of producing the fuel is meaningless in isolation from the cost of generating power from that fuel. The whole process from production of fuel to the delivery of power to the final end user must be fully examined in order to make a proper analysis.

XVII. CONCLUSION

There are three take-home messages from this paper: i) a sound energy policy must first begin by promoting sensible energy conservation, e.g., insulation for buildings; ii) a solar hydrogen cycle has the potential to provide much more than our current energy needs; and iii) solar thermal technology with suitable storage has the potential to provide *centralized* base-load power, whereas PV solar cell technology is better suited to *distributed* energy harvesting applications.

The bottom line is that 7.6 PW in solar power is incident on our desert regions around the world, and if we only tap 10% of it at an energy conversion efficiency of 10%, we generate five times the current world's energy requirement. With suitable engineering this figure can be significantly increased, but in the worst-case we can obtain many times our current world energy requirement even at low efficiency. Moreover, for a world solar hydrogen economy, with a conservative efficiency, we use up less than 8% of the world's desert area.

Regarding the use of hydrogen as an energy carrier, it is the most sustainable option as it becomes part of the natural water cycle. In terms of sustainability and massive scalability, hydrogen combustion engines are preferable to fuel cell engines. The potential of hydrogen motivates further research into improving efficiency of hydrogen combustion engines, storage, and transportation. These are achievable engineering challenges that are not as daunting as sending man to the moon—current efficiencies are sufficient to begin building pioneering solar hydrogen plants, begin the process of converting public buses, and pursuing further hydrogen combustion vehicle demonstrators.

Another key conclusion is that, while some mix of energy sources in the medium-term is inevitable, in the longer term humankind has no choice but to move to a solar power future. There are no other viable options, and we have demonstrated this using the concept of consolidated utility time (CUT). Also, in practice we have shown that competing renewable sources produce less than 1% of that achievable with solar. Therefore solar must be adopted as the dominant focus for research and investment, and large-scale approaches that build economy of scale are vital. While some energy diversity is useful, the order-of-magnitude analyses in this paper now motivate more detailed studies in order to place each energy source in its proper perspective.

Energy sources such as fossil fuels and nuclear power (fission or fusion) all rely on finite resources, generating waste end products in an *irreversible* cycle. The elegance of the solar hydrogen cycle is that it is *reversible*, i.e., the combustion of hydrogen generates clean water that is ultimately fed back for solar-powered electrolysis to produce hydrogen again and so on. Of course, the ultimate source of this energy is generated in an irreversible cycle on the Sun, but the trick is that by adopting a hydrogen cycle we harness this energy in a reversible manner on Earth, and the irreversible end products are rather conveniently contained on the Sun out of harm's reach. The bottom line is that the Sun is Nature's nuclear fusion reactor that is at an arguably safe distance from Earth, it generously affords us 5000 times our current world energy needs, and will run reliably over the next billion years with zero downtime. It is uncertain if man-made fusion reactors will ever become commercially viable, and if they do why does it make sense to take on uncertainty in terms of resource and safety issues when the Sun already provides us with a virtually limitless natural nuclear fusion resource? ■

APPENDIX A
WHY SAVE NUCLEAR RESOURCES?

In the same way that oil, for example, is too precious to burn as it has many uses in the petrochemical industry, we can argue that nuclear resources are too precious to burn. For example, asteroids that are 10 km or more in diameter, whose impacts have the capacity to create mass extinctions, hit our planet about once every 100 million years [104]. It might be argued that we need to reserve our nuclear resources for large-scale future catastrophic events. A nuclear detonation may possibly be needed to intercept such asteroids while they are still deep in space.

There are as many as 4000 Near-Earth Objects (NEOs) that have been detected so far, and 10% of these are over 100 m in diameter. Our next intercept will be in 2036, where the asteriod called 99942 Apophis is estimated at present to have a 1/3000 to 1/6000 chance of hitting Earth [104]. If Apophis strikes Earth, it will have the capacity to wipe out a city as large as New York or create tsunamis with the power to wipe out many coastal cities on hitting an ocean.

To contextualize this risk, Cartlidge has suggested [104] that it can be compared with foreknowledge that a nuclear plant has a 1/3000 chance in wiping out a major city in 30 years. How would a government respond to such a situation?

Another point is that humankind will need to leave the planet in as little as half a billion years time. This is because the planet will get too hot as the Sun expands in its progression to becoming a red giant. It is arguable that we may need to preserve our nuclear resources in order to migrate life to other planets.

To put this in context, the solar energy incident on the planet in only *one year* is an order magnitude greater than all the energy contained within the world's total estimated fuel resources (i.e., recoverable uranium, oil, coal, gas, etc., in total). Thus we can more than afford to conserve these resources by moving to solar power.

APPENDIX B
SOLAR THERMAL COLLECTOR FOOTPRINT

What is the land area or footprint required to supply the world's energy needs? The methodology we will adopt is to make some conservative assumptions so that we arrive at a worst-case footprint—this then sets an upper bound from which engineering ingenuity can always improve upon. Let us select a hot desert of the world, and conservatively select an average[15] insolation of $I = 300\ \mathrm{W/m^2}$. For simplicity, let us assume 10 m diameter dishes each occupying a plot of 12 m by 12 m to allow room for maintenance vehicles and cleaning equipment, giving an area fill factor of $\eta_a = 0.54$. Let the efficiency of the electricity production from a Stirling engine driven generator be $\eta_g = 0.3$. Let us electrolyze water at an overall efficiency of $\eta_e = 0.5$, for generating hydrogen to fuel cars. In practice, for night time energy storage either pumped hydro or compressed air [105], closed cycle ammonia storage [106] or molten salt heat storage [107] are regarded as cost effective alternatives, however, let us be pessimistic and supply all the world's energy needs with hydrogen at $\eta_e = 0.5$ for this worst-case exercise. Let us then liquefy all the hydrogen with an efficiency $\eta_l = 0.7$. Bossel estimates that taking into account all the inefficiencies of storage and transportation of hydrogen, requires that 1.6 to 2 electrical energy units must be harvested for every unit of hydrogen energy taken up by the end-user [14]—so let us use a worst-case Bossel factor of $\eta_b = 0.5$. If the world's power requirement is $P = 15$ TW, then the solar farm footprint area is,

$$A = \frac{P}{I\eta_a\eta_g\eta_e\eta_l\eta_b}, \tag{4}$$

which corresponds to an area of $1.76 \times 10^{12}\ \mathrm{m^2}$ that is equivalent to a plot of size of 1330 km by 1330 km—this is only 8% of the land area of all the hot deserts of the world. In reality, with less pessimistic assumptions we can easily bring down the required total area to 500 km by 500 km. This would correspond to an array of 1.7 billion solar dishes that are each 10 m wide. For these large numbers, economy of scale comes into play and production of Stirling generator dishes would be tenable at $1000 each.[16]

[15]Note that the use of average insolation is acceptable for our order-of-magnitude calculations, but when actually designing a solar collector the calculations are more complicated as efficiency increases with insolation.

[16]This is, of course, the base cost. For the installed cost with labor, apply an appropriate factor depending on local conditions.

This would make the total world cost only \$1.7 trillion dollars, which is less than the going rate of a war these days. For the pessimistic footprint area, we obtain an upper cost of \$12 trillion.

Let us in the worst case assume all the resulting energy is used to electrolyze water, forming hydrogen, as indicated in Fig. 8. The energy required by a desalination plant per volume of water processed is conservatively, 4.3 kWhr/m^3. In total, this energy is equivalent to 0.2% of the energy generated by combusting the hydrogen and thus is reasonable. This demonstrates the viability of linking solar farms by cable to desalination plants for electrolysis [108].

An interesting alternative to having small 10 m diameter dishes, each driving a small Stirling engine, would be to have many dishes simultaneously driving a large turbine. For example, one could envisage over 1000 larger 25 m diameter dishes powering a 500 MW Rankine cycle turbine that drives a generator. An example of a working experimental dish about this size is shown in Fig. 9. There would be heat losses in transferring steam from the dishes to the Rankine engine, but these could be minimized if the connecting pipe is well insulated and maintained at a small diameter. This results in only a 500 km by 500 km footprint, for the worst case of supplying the world's power all as liquid hydrogen. Thus this motivates the need for future study that performs a careful economic trade-off analysis between the two approaches. The large Rankine turbine approach possibility has higher set-up costs, but with the advantage of lower running and maintenance costs. It also has the advantage that the current power industry already uses large Rankine turbines, and thus we would be riding on current infrastructure.

Fig. 9. ***The SG3 Big Dish prototype was built in Australia in 1994 and is the world's largest solar dish for generating electrical power, with an average diameter of roughly 23 m. It achieves a solar concentration of 1500 suns, and heats water in the range 400 °C–700 °C at 4.2–6.8 MPa. It has a design output of 320 kW. Source: Australian National University (ANU).***

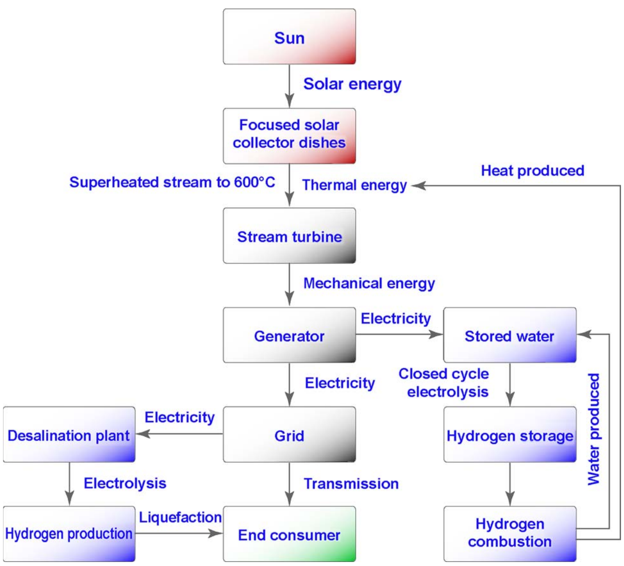

Fig. 8. ***Flow diagram showing solar energy conversion steps to get to the end user. These are the steps assumed for our solar footprint calculation. We generate electricity from steam heated via solar dish reflectors. The electricity is transmitted to the end user via the grid and is also transmitted to a remote desalination and electrolysis plant. Hydrogen is then produced via electrolysis and is supplied to the end user for mobile storage, i.e. for use in vehicles. A fraction of electricity is also used to electrolyze water in a closed cycle for local solar farm static storage, i.e. for power generation at night and on cloudy days. To create a worst-case upper limit, the footprint calculation assumed all the electricity is converted to hydrogen.***

What about the volume and footprint taken up by the requirement for overnight energy storage? Let us take the example of a 1 GW solar farm that might take up a footprint of 4 km by 4 km just for the solar dishes. In the context of hot Australian desert, the worst case weather pattern is a sequence of 10 cloudy days with poor power output. So let us say that storage has to be designed for a worst-case scenario of supplying 1 GW for 10 days. Let us use liquid hydrogen as the storage medium to provide a worst case analysis, as it has a fairly low density at 6.78 kg/m^3. About 7 kg of hydrogen is required to produce 1 GJ, but we need that amount of energy every second for 10 days. Thus the total amount of liquid hydrogen storage we need is a volume of 45 cubic meters, which is tenable.

In practice, this figure would be smaller as in the near-term some load balancing will be achieved via other power sources supplying the grid. In the longer term, countries such as the United States and Australia would have many 1 GW solar farms at different locations around each country all supplying the grid. Thus a cloudy day in one location, can be balanced by bright days at many other locations—given that we are focussing on hot desert regions.

APPENDIX C
TECHNIQUES FOR SPLITTING WATER

Thermochemical splitting [109] uses heat to split water into hydrogen and oxygen. The drawback is that temperatures around 2500 °C are needed and there are no suitable low-cost materials for containing fluids at that temperature. The operating temperature can be reduced if additives such as sulfuric acid or zinc are introduced, however, efficiencies of only around 50% have been acheived [84] and this is not sufficient to justify the environmental burden of an extra chemical pathway. A recent study of thermal separation of water, using solar energy as the heat source, with thermoacoustics as the means of separating the resulting gases, shows this is 30 times more costly than a solar-driven Stirling generator simply electrolyzing water [101]. Thermal splitting at 800 °C using simple iron oxides has recently been proposed, though extensive experimentation has not been carried out as yet [110].

Photoelectrolysis [84] can be eliminated as a possibility, as it is essentially a semiconductor solar cell configured to directly produce hydrogen by splitting water, and we have already argued the case against solar cell technology in Section VIII-A. Photocatalytic water splitting is possible [111], though its potential for global scalability is questionable due to the need for exotic transition element catalysts.

This leads us to the final remaining option, namely, electrolysis. Commercial water electrolysis systems, at room temperature and pressure, have efficiencies of 56%–73% [112]. Proton exchange membrane (PEM) electrolysis, can be ruled out, for our purposes as its efficiency is in the 55%–70% range, which is not dramatic enough to justify the use of expensive membrane technology and exotic elements such as iridium, ruthenium, and rhodium as catalysts [113]. Solid oxide electrolysis cells (SOEC) have been demonstrated with efficiencies up to 69%, but again use exotic materials such as yttria stabilized zirconia (YSZ) electrolyte and metal doped lanthanum metal oxides [84], [114].

Thus we are left with the final option: alkaline electrolysis that does not use expensive membrane technology, but has about a 10% lower efficiency [84] than PEM electrolysis. The slightly lower efficiency can be compensated by factoring in the nonrecurring cost of more solar dishes, rather than sustaining the recurring cost of continually replacing membranes. Alkaline electrolysis is a current commercial technology, using a ceramic microporous separator and an aqueous KOH or NaOH electrolyte that, in principle, can be recovered and re-used. The electrodes are usually made of nickel, with the cathode coated in platinum and the anode coated in manganese oxide or tungsten oxide [84]. Platinum is a precious resource, and perhaps the best way forward might be to use a more common metal or alloy instead, and compensate the resultant drop in efficiency (by 10%–20%) with more solar dishes. We can reduce this efficiency drop in not using platinum, with an increase in efficiency by performing electrolysis on heated water. An increase in water temperature by 50 °C can increase efficiency by 10% [115]. Ganley has demonstrated high temperature and pressure electrolysis using cobalt plated anodes [116]. A *pinch analysis* can be performed to analyze the possiblity of heating the water at no extra cost, using available heat from existing solar collectors.

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