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The Solarevolution: Much More with Way Less, Right Now—The Disruptive Shift to Renewables

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Abstract: Renewable energy resources and technologies are sufficient to meet all of humanity's energy requirements, provided that the transition to renewables is accompanied in parallel by intense, disciplined initiatives to design, fabricate, and distribute ubiquitously an emerging class of ultra-efficient energy consuming devices. Renewables can thereby power devices which are disruptively more energy-efficient in the delivery of fundamental energy services (food production, cooking, heating, cooling, mobility, logistics, lighting, industrial processes, information systems, etc.). Rather than substituting new energy sources to directly power legacy devices that were originally designed on the basis of fossil fuels, designers will develop these novel devices to deliver superior performance in all respects: cleaner, safer, more durable, more convenient, and more economical. This Solarevolution, like the Industrial Revolution two hundred years ago, is about transforming the artifacts of human society. Just as labor-saving machinery replaced manual and animal labor when James Watt invented the steam engine, so now energy-saving devices powered directly by non-polluting solar electricity are beginning to replace those inefficient brute force artifacts that still depend on the burning of fossil fuels. Building upon historic perspectives and the careful examination of key renewable energy qualities, four case studies will be highlighted, not to resolve all of the issues, but to instantiate the pivotal role of design science to avert the most severe impacts of global warming and strategic resources depletion. While great attention has been given to debating the net energy of renewable energy generation technologies, the stability of society depends just as much on redesigning energy-consuming technologies, overcoming the temptation, for example, of using biofuels to feed gas-guzzling energy hogs left over from the fossil fuel era—to run internal combustion engines that can't deliver more than 1% net efficiency. Applying the engineering principle of doing way more with way less, right now, humanity has the possibility of a bright, more secure future.

Keywords: solarevolution; renewables; design science; more with less; disruptive; energy chain; net energy; energy return on investment (EROI); energy return on energy invested (EROEI)

1. Introduction

It is time for moonshots, to achieve ten times (10×) more energy services with 10× less energy—there is no time to waste. The intense global climate change debate evokes calls to action, calls for restraint, truths, fictions, proposals, contradictions, opinions, bogus claims and misconceptions. The challenge, to discern fact from fiction and action from restraint, has intensified as a consequence of the United Nations Conference of the Parties (COP 21) in Paris in December 2015. A technological resolution has been put forward for which consensus is building: the burning of fossil fuels is the primary driving cause of climate change, and renewable energy is the solution.

Experts have asserted that renewable energy systems are reliable and nonpolluting, that deployment can be taken to a massive scale rapidly enough to stop the buildup of CO_2 emissions which threaten to take global temperatures above a survivable threshold.

Together with fire, over time, the three deadly Cs—cattle, cars and chainsaws [1]—have been exploited to dominate nature. These have now overtaken the land, making it necessary for humanity to let go of fire and the deadly Cs, to make a fresh start, designing 21st century artifacts based on electricity, not fire, abiding by the discipline of achieving more with less. It is necessary to use nonrenewable resources only to support the aggressive creation of disruptive renewable energy solutions [2].

This treatise is not about calculating the material resources or time it will take to secure the Solarevolution in order that, e.g., industrial processes, street lights and server farms might persist as now (others have devoted significant attention to that question). The objective here is rather to assert and demonstrate how society must redirect its engineering and manufacturing resources away from adapting biofuels and electricity to fossil fuel artifacts (e.g., the automated luxury electric car, still a car designed as a two-tonne military tank to protect its occupants) toward disrupting the very shape of energy services, configured from the outset to take advantage of renewable energy (e.g., the Solar Skyway, a new form of mobility that is solar-powered, automated, non-stop and elevated).

To achieve the societal transformation to renewable energy will require more than vast solar farms in the desert or offshore wind farms. While such initiatives are essential, more-with-less energy design disciplines at the micro-, meso- and macro-level are also key to the transition. For renewable energy technologies to accelerate and dominate the energy sector rapidly, key principles guiding the transition away from fossil fuels must be clarified, and the awareness of these principles must be strengthened.

Within the scientific community, there is an intense debate challenging the ability of renewable energy systems to highly leverage and supersede the prevailing fossil fuel energy sources. A key to the rapid expansion of renewables is leverage, the ability to generate over time a much larger amount of energy than the embodied energy required for fabrication and deployment, a measure of net energy that is labeled Energy Return on Energy Invested ("EROEI" or simply "EROI"). A corollary is that, although the energy content of fossil fuels was once large relative to the energy of extraction, the energy expended for extraction is increasing inexorably over time and will eventually become so high that extraction will be futile. Ultimately the net energy derived from fossil fuels will necessarily drop below unity.

Evidence is provided here to demonstrate that renewable energy deployment can indeed be accelerated rapidly, subject to these key principles:

- Renewable solutions must be reconfigured for the delivery of essential services. Reconfiguring is not the same as substitution; renewables will deliver energy services with forms that may be radically different from the forms that were originally invented on the premise of burning fossil fuels.
- Renewable energy sources directly coupled to services are generally more accessible than energy sources that must be transported great distances.
- For high leverage, application technologies must be hyper-efficient, e.g., more efficient by a factor of ten ("10×") in comparison to artifacts still lingering from the fossil fuel era.

Fossil fuels are not now and were not in the past as wondrous and effective as they have been characterized by the incumbency. Besides the disastrous impact of fossil fuels on climate, the tools of extraction and the artifacts that require the combustion of fuels have consistently been inefficient, dangerous, toxic, noisy, and expensive. The necessity of creating new technologies of all kinds to operate with renewable energy is a unique opportunity for redesign; those new technologies will serve humanity dramatically better than the technologies that burn fossil fuels today.

To assert and demonstrate the essential design principle of doing way more with way less, an important first step is to look at the lessons of history, beginning with the insights of thought leaders who have effectively addressed resource limits, and then highlighting the fundamental role of fire and the short history of electricity. The next step is to examine the challenges brought on by the power shift from fossil fuels to renewables. Then, the principle of designing to achieve more with less will be demonstrated with exemplary solutions, and finally, conclusions will be presented.

2. History

The myths surrounding energy resources have deep roots, and what might have seemed obvious in the past may now be interpreted differently. A brief excursion back a couple hundred years may shed some light on humanity's new standing with nature in light of technological advancements.

2.1. History of Limits

First, to understand where we have been (and thereby to guide our future), we can learn from thought leaders who have observed and called attention to the importance of comprehending and living within natural limits: Malthus, Jevons, Hubbert, Fuller, Boulding, and Daly.

Thomas Malthus (1766–1834): Of course the essential energy source for humans is food, and resources to produce food are the most fundamental. Since 1798, when Malthus made the obvious and logical observation that natural limits will constrain the population of humans on Earth, economists and other madmen have attempted to refute his observations by noting that the limit of the human population has not happened yet. That conclusion is not comforting. As Malthus observed, "Necessity ... restrains [the seeds of life] within the prescribed bounds .... And the race of man cannot, by any efforts of reason, escape from it [3]."

Postponing is not overcoming. The threat of runaway population growth limited by "subsistence" has remained in the human consciousness since Malthus first spoke his truth, in spite of protests from many sides.

Kenneth Boulding (1910–1993): Bringing the lessons of Malthus into a modern perspective, Boulding offered three theorems from economics (the "dismal" science), the first of which is "The Dismal Theorem."

First Theorem, The Dismal Theorem: "If the only ultimate check on the growth of population is misery, then the population will grow until it is miserable enough to stop its growth [4]."

Malthus lived in a time when perceived limits were being superseded by a series of technological miracles, one right after another, which temporarily relaxed such perceived limits. He could not see far enough ahead to realize that widespread use of coal (and later oil) would lead eventually to mechanized farming, liberating many humans from toiling on the land and leading to a much greater supply of food, with the subsequent great increase in human population. That energy revolution led to another insight in 1865, which also has had an important impact.

William Stanley Jevons (1800–1880): Based on what at the time seemed to be an unconstrained, open-ended natural ecosystem with its unending supply of coal, Jevons asserted that improvements to efficiency would surprisingly lead to greater use of a resource, not less. "Every improvement of the [steam] engine, when effected, does but accelerate anew the consumption of coal [5]."

Putting the Jevons paradox into perspective, Boulding offered a second theorem from the dismal science: "The Utterly Dismal Theorem."

Second Theorem, The Utterly Dismal Theorem: "Any technical improvement can only relieve misery for a while, for so long as misery is the only check on population, the improvement will enable population to grow, and will soon enable more people to live in misery than before. The final result of improvements, therefore, is to increase the equilibrium population which is to increase the total sum of human misery [4]."

M. King Hubbert (1903–1989): In the mid-twentieth century, noted geologist M. King Hubbert had unique access to comprehensive petroleum exploration and production data, enabling him to see the inevitable increase and subsequent decline of petroleum extraction. From his data-rich perspective, he could see far ahead. "The consumption of energy from fossil fuels is ... but a 'pip' ... thus representing but a moment in the total of human history .... It is upon our ability to ... evolve a culture ... in conformity with the limitations imposed upon us by the basic properties of matter and energy that the future of our civilization largely depends [6]."

Just like Malthus in his time, Hubbert encountered a storm of objections to his thesis. But his prediction in 1956 of the USA's peak of petroleum extraction in 1970 held, and that peak in turn precipitated the first energy crisis in 1973. His later prediction that global production would peak around 2000 also hit the mark. (Conventional crude oil peaked in 2005, a precursor of the 2008 recession. Subsequent increases have come from revised accounting practices, as much as from expensive, low net yield unconventional sources, a mad scramble to the bottom of the barrel.)

R. Buckminster "Bucky" Fuller (1895–1983): Into this perplexing mix came a message of hope from Bucky Fuller, a visionary who understood Hubbert's message well and offered a refreshing alternative view of humanity's future. "I seek through comprehensive anticipatory design science and its reductions to physical practices to reform the environment instead of trying to reform humans, being intent thereby to accomplish prototyped capabilities of doing more with less [7]."

"We now have about our Spaceship Earth more than ample capability to take care of all humanity . . . while concurrently phasing out all further human use of fossil fuels and atomic energy. We can live handsomely on our annual energy income from the sun and the many modes of its impoundment . . . . It can only be accomplished by a design revolution which produces so much higher technical performance per each unit of resource invested as to take care of all human needs [8]."

Some have misinterpreted Fuller's vision, suggesting that he proposed "increasing standards of living for an ever-growing population despite finite resources (building yet another argument against Malthus) [9]." However, Fuller understood limits. Boulding also understood, and he offered the world another theorem from the dismal science of economics to drive the point home:

Third theorem, the moderately cheerful form of the dismal theorem: "Fortunately, it is not too difficult to restate the Dismal Theorem in a moderately cheerful form, which states that if something else, other than misery and starvation, can be found which will keep a prosperous population in check, the population does not have to grow until it is miserable and starves, and it can be stably prosperous [4]."

Faced with the rapid depletion of natural resources and the existential threat of runaway climate change, what conceptual framework could humanity possibly embrace to fulfill Fuller's vision of a higher standard of living for everybody and Boulding's "moderately cheerful" view of human prosperity?

Herman Daly (1938–): The apparent contradictions between Malthus and Jevons, and between Hubbert and Fuller, cannot be resolved within the framework of an open-ended supply of ecosystem goods and services. Herman Daly noted that human activity ("the economy") is pushing the limits and beyond, but is nonetheless embedded within the environment: "Because of the exponential economic growth since World War II, we now live in a full world, but we still behave as if it were empty, with ample space and resources for the indefinite future. The founding assumptions of neoclassical economics, developed in the empty world, no longer hold, as the aggregate burden of the human species is reaching—or, in some cases, exceeding—the limits of nature at the local, regional, and planetary levels. The prevailing obsession with economic growth puts us on the path to ecological collapse, sacrificing the very sustenance of our well-being and survival. To reverse this ominous trajectory, we must transition toward a steady-state economy focused on qualitative development, as opposed to quantitative growth, and the interdependence of the human economy and global ecosphere. Developing policies and institutions for a steady-state economy will require us to revisit the question of the purpose and ends of the economy [2] . . . "

There it is: the big question. What are the purpose and ends of the human experiment? Is it to grow the global economy relentlessly, simply to maximize the number of miserable people on the planet (Boulding), or is it to create a new economy that works for "everybody at a higher standard of living than anybody has ever known" (Fuller) [10]?

Where does that put us today? The human experiment is being put to the test as never before. Only with a clear and widely embraced commitment to new priorities will humanity adapt to this finite planet. On a foundation of fossil fuels, a higher standard of living is patently impossible. The only option is to abandon fossil fuels rapidly, using only enough to bootstrap an economy based on renewable energy. How might that be achieved effectively and in a timely manner? What insights might be gained by examining the historic roles of fire and electricity?

2.2. A Brief History of Fire and Electricity

Our good old friend fire has inadvertently become our worst enemy; electricity is our very best, very new friend. It is a tall order for all members of society to recognize the existential danger of the continued use of fire and to accept the need to rapidly abandon that amazing phenomenon which was key to humanity's ascent along the evolutionary tree to become dominant on the planet.

Fire: For eons, fire has been at the very core of the human experience; there is evidence that early hominines used fire opportunistically 700,000 or possibly even more than a million years ago and systematically from 400,000 years ago [11].

Thus, it was natural to advance from burning wood (to cook food, which accelerated nutrition) to burning coal, oil and natural gas to extend humanity's reach. However, now, whether burning wood for warmth, logging and then burning down old growth forests for palm oil plantations or burning gasoline for faster travel, it has become essential, even existential, to extinguish fire.

Thankfully, there is a new option that has only recently become available to humanity, which has already transformed society and is the bridge to survival in a world beyond fire.

Electricity: Contrasted against fire, humanity's intimacy with electricity is incredibly recent. Electric shocks from fish and static electricity were encountered and documented over two thousand years ago. Though it is now the very essence of modern living, electricity was still little more than a curiosity only 250 years ago. Briefly, here are a few of the milestones achieved over that incredibly short time:

- Benjamin Franklin (1706–1790)—The nature of electricity, 1752: Benjamin Franklin, the most prolific early scientist in the New World, explored the nature of electricity, capturing electricity in a jar with a kite in a lightning storm.
- Alessandro Volta (1745–1827)—The battery, 1800: A breakthrough by Alessandro Volta in 1800 evolved into the primary device that was used to produce electricity for nearly a century.
- Samuel F B Morse (1791–1872)—The telegraph, 1844: Samuel Morse started a revolution in communication with the telegraph that revolutionized long-distance communication 172 years ago. It worked by transmitting electrical signals over a wire laid between stations.
- Alexander Graham Bell (1847–1922)—The telephone, 1876: Another communication revolution underpinned by electricity, the telephone, was perfected just 140 years ago.
- Thomas Edison (1847–1931)—The light bulb, 1879: Another profound early use of electricity was to produce light. Only 136 years ago, the wink of an eye in human history, Thomas Edison was finally successful after many failed tests to create an electric light that endured for many hours.

Significantly, Edison also envisioned a world beyond fire: "Sunshine is spread out thin and so is electricity. Perhaps they are the same, Sunshine is a form of energy, and the winds and the tides are manifestations of energy . . . . Do we use them? Oh, no! We burn up wood and coal, as renters burn up the front fence for fuel. We live like squatters, not as if we owned the property . . . . There must surely come a time when heat and power will be stored in unlimited quantities in every community, all gathered by natural forces [12]."

It is this vision which sustains humanity's hope for a breakthrough, predicated on altogether eliminating fire (the burning of coal, oil, natural gas or even biomass) to avert cataclysmic consequences (the loss of coastal cities and seaports with sea level rise and the potential overheating of global habitat beyond human survivability).

3. Power Shift: The Transition to Renewables

Does collapse of the fossil fuel era represent hindrance or gain? Can the transition to renewables actually improve civilization? Can greater well-being be achieved for all in a post-carbon world?

Such questions are addressed here through a series of assertions, with evidence to substantiate their validity. Though the assertions are far from comprehensive and the evidence is anecdotal, the intent here is to focus attention within the scientific and engineering communities on the necessity for a new design discipline predicated on the use of renewable energy and electricity, with a concomitant commitment to deliberately and rapidly eliminate fossil fuels, stopping the manufacture and deployment of artifacts dependent on fossil fuels and to avoid the temptation to maintain or expand infrastructure which hosts and depends on fossil fuel based artifacts.

3.1. Renewable Energy Can Actually Meet Humanity's Needs, as Thomas Edison Envisioned a Century Ago

At COP 21 in Paris in December 2015, renewable energy was declared to be the key to mitigating climate change. If this vision is to manifest, people must put aside many common misunderstandings, engage with the vision that was articulated by Edison and establish new priorities. In the following narrative, several such priorities are asserted and supported by evidence.

- Economics: Renewable energy is economical, here and now.
- Disruption not substitution: The emerging solar economy is fostering a design revolution. Designs configured for renewables will deliver energy services that yield well-being far beyond what was possible in the fossil fuels era.
- Intermittency: The Sun's energy is constant; fossil fuels are here today, gone tomorrow.
- Time to market: The Silicon Valley culture and its spinoff of crowdsourcing have enabled innovators to navigate around the incumbency.
- Net energy chain: Energy Return on Energy Investment (EROEI or simply EROI) and efficiency: The net energy of renewables is now higher than the net energy of fossil fuels and when combined with solar-based design is sufficient to leverage the Solarevolution.

3.2. Economics: Renewable Energy Is Economical, Here and Now

A primary question about renewable energy is whether solar and wind energy systems can be produced, installed and maintained at costs lower than fossil fuels. To find out, several factors are considered, which together form the metrics of economic activity:

a. Intrinsic costs: materials, energy, labor, overhead, profit, maintenance and decommissioning (in the context of fair trade).
b. Policy: modification of costs by government intervention.
c. Unaccounted costs: costs ignored, but experienced in the marketplace or the environment.
d. Theft: losses created by entities operating outside of existing accounting and policy boundaries.

a. Intrinsic costs: The cost to exploit fossil fuels increases with time. With each passing day, finite resources are exhausted, and therefore, new supplies necessarily become harder to discover and require more effort to extract. Though improvements in technology may temporarily reverse that trend, inevitably, costs will rise over time. Renewable energy technology, on the other hand, is less mature, and industry continues effectively to focus on doing more with less, e.g., solar cells become thinner, more efficient and easier to mass produce. The slow increase in oil and coal costs and the concomitant dramatic reduction in the cost of solar in the past decade can be seen in Figure 1.
b. Policy: Something may be deemed "uneconomical" and out of favor simply because of a hidden (or perhaps visible) subsidy to the advantage of competing forces. Market distortions that favor one stakeholder group over another are often justified by economic arguments, but underlying such distortions are policies based on value propositions, which bear scrutiny. Determining competitive advantages is challenging, because economic rationale invoked as an instrument of policy may favor outdated priorities. As can be seen in Figure 2, long-established policies based on plundering fossil fuels continue to blindly favor the energy incumbency and with few

exceptions have not yet been modified to reflect the policies initiated at Kyoto and reinforced at COP 21 to mitigate climate change.

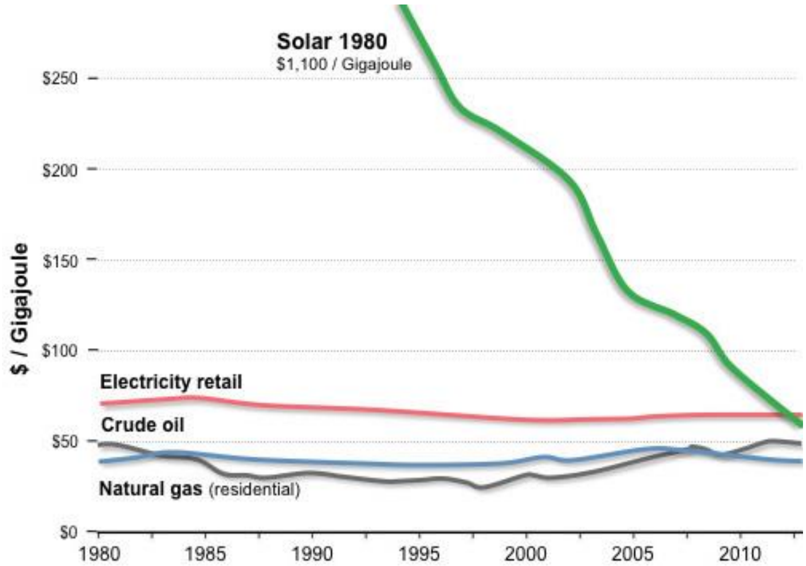

Figure 1. Solar prices in the U.S. have declined; fossil fuel prices (adjusted for inflation) have not [13].

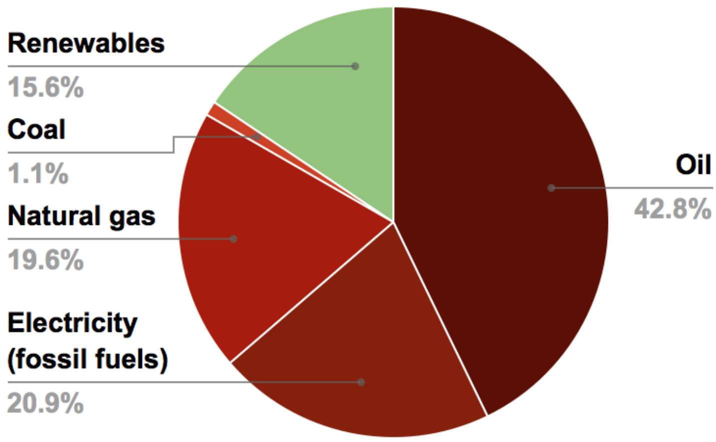

Figure 2. Global energy subsidies, 2012. Long-entrenched policies blindly favor fossil fuels [14].

c. Unaccounted costs: For one individual it might cost less to incinerate waste or toss garbage "out" than to pay for trash service, but over time, the cost to society will increase. Therefore, the originally ignored cost of garbage collection has become an accepted cost in modern society. On the other hand, when individuals or businesses start their engines (in cars or power plants) and push waste gases and particulates ("pollution") into the atmosphere, the cost of waste is externalized, not yet fully accounted. One of the most sophisticated judicial agencies in the world, the venerable U.S. Supreme Court, was conflicted on this question of cost allocation for pollution as recently as early 2016 [15].

d. Theft: "Fossil fuels" is a widely accepted misnomer for hydrocarbons (coal, oil, natural gas), a rhetorical classification which serves to justify relegating these intrinsically valuable materials to expediency, to one-time use, burned up and gone forever. Hydrocarbons in general, as precursors to key materials, such as cement, steel, plastics and other durable goods, have significant value to any economy, now and into the distant future. When arrangements of whatever stripe are made to transfer hydrocarbon wealth with no benefit to the citizenry of one country to others who burn that wealth, gone forever, to support their bloated economies, the difference between the value of that oil to create well-being for the people of an exporting country compared to the absurdly low price of oil in the global marketplace is theft. For example, oil exported per capita in Nigeria is 200 gallons/year, while consumption is 24 gallons, only 12% of exports, equal to 2.6% of U.S. per capita consumption of 900 gallons per year.

Hydrocarbons are also being massively stolen from youth (those who do not yet have a voice in policy) and future generations (those not yet born). Not only that, some countries have strong enough currency to incur massive debt and accumulate trade deficits sufficient to keep importing oil, delaying accountability for decades. Future generations will inherit the burden of that debt in their maturity, without a voice in the present.

In summary: The cost of renewable energy technologies continues to fall and the cost of fossil fuels continues to increase. Wherever policy and accounting practices are out of step with the realities of resource depletion (e.g., peak oil) and anthropogenic climate change, the economic advantage of renewables will be masked. While the trends are clear, it is treacherous to draw conclusions in the context of distorted metrics. As more nations reach toward 100% renewables, their observable competitive advantage will serve to resolve remaining uncertainties.

3.3. Disruption Not Substitution: The Emerging Solar Economy Is Fostering a Design Revolution; Designs Configured for Renewables Will Deliver Well-Being, Far beyond What Was Possible in the Fossil Fuels Era

Direct substitutes that would keep things the same as now are not necessary nor are they feasible; renewables need not compete to match fossil fuel functionality item by item across the spectrum of energy services and labor-saving devices.

Consider an imaginary conversation between John D Rockefeller and Henry Ford "at the club." John D says, "Look, Hank, I want you to try out my cheap new horse feed, kerosene! It is easy to transport as a liquid, with far greater energy density than oats. Your horses can run much faster and cheaper with it. Forget that silly contraption you have parked out there … "

Of course it was not like that. The urban horse was quickly abandoned when Ford's Model T was introduced, powered by Rockefeller's oil. In like fashion, the artifacts of the fossil fuel age will be indigestible as solar is embraced.

The U.S. Energy Flow Chart (Figure 3, also known as a Sankey diagram) from Lawrence Livermore National Laboratory demonstrates that nearly 80% of the fuel in transportation is converted directly into "rejected energy" (pollution) upon combustion. With the possible exception of aviation, which is likely to experience a drastic decline in response to peak oil anyway, a 5× improvement is possible by converting to renewables-generated electricity. Significant improvements (10× and more) in transportation may be realized when transportation infrastructure is deployed according to solar design principles with reduced mass and electric propulsion, while the automobile itself is relegated to race tracks and nostalgic expos.

The so-called "Rosenfeld effect" in Figure 4 demonstrates that California energy policy led by former Energy Commissioner Art Rosenfeld has kept per capita electricity consumption flat for decades with aggressive energy efficiency standards. Similarly, Europeans with a far harsher climate live with half the energy consumption of the U.S., sufficient evidence of the potential for a 2× reduction, at the least.

However, the U.S. and other high energy industrialized countries can cut energy consumption further to 5× or even an order of magnitude (10×) by moving away from fossil fuels and embracing the Solar Design Revolution. How to meet that challenge will be addressed in Section 4, Solutions.

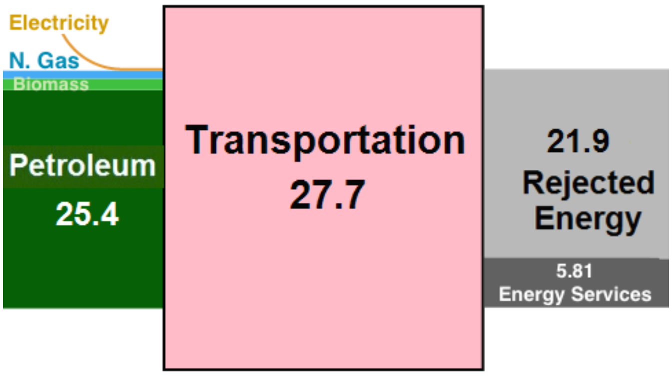

Figure 3. Extract from U.S. Energy Flow Chart shows that 79% of transportation fuel is lost as "Rejected Energy" [16].

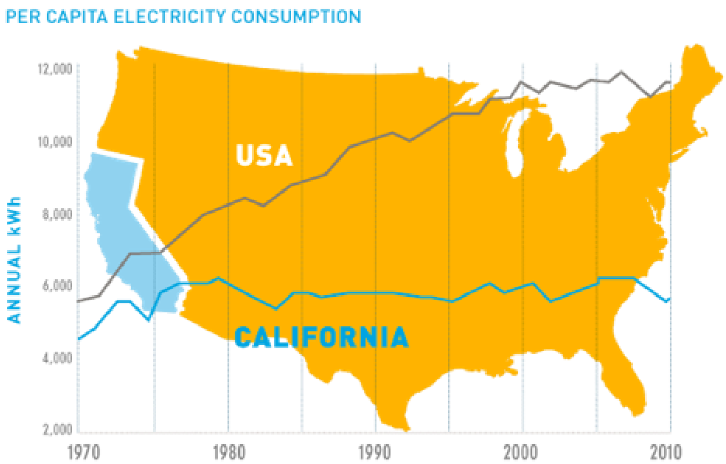

Figure 4. The Rosenfeld effect. California's aggressive energy policy led by Energy Commissioner Art Rosenfeld has kept per capita electricity consumption flat for decades [17].

3.4. Intermittency: The Sun's Energy Is Constant; Fossil Fuels Are Here Today, Gone Tomorrow

Since Nikolaus Copernicus published his treatise, *On the Revolutions of the Celestial Spheres*, in 1543, it has been known that the Sun does not switch off every evening and then return the next day: "What appear to us as motions of the sun arise not from its motion but from the motion of the earth and our sphere, with which we revolve about the sun like any other planet [18]."

Calling renewables intermittent is "the pot calling the kettle black." Constant sun, not always visible, is nearly infinite and a completely sufficient energy source. By contrast, any civilization dependent on resources that are "here today and gone tomorrow" will be gone tomorrow.

The industrial base of renewable energy is typically characterized as low compared to fossil fuels, even by renewable energy advocates. (Figure 5). *Au contraire*, the Sun provides about 99.95% of the planet's energy and the solar-powered ecosystem services essential to human survival. Fossil fuels (solar energy stored by nature millions of years ago) and nuclear energy produce approximately 77.9% $\times$ 16 TW $\div$ 23,000 TW = 0.05% of the energy on the planet (Figures 5 and 6). The Earth's total endowment of fossil fuels and uranium forever is less than 10% of the Sun's energy intersecting land, not counting sun upon the oceans in one year (Figure 6).

The variability of renewable energy flux, experienced due to the Earth's spin and weather patterns, justifies that attention be given to energy storage and grid management. In Germany and other countries where solar and wind energy generation have sometimes exceeded demand, grid scale energy storage and stabilization technologies are being developed, soon to be exported to countries that are lagging in the transition.

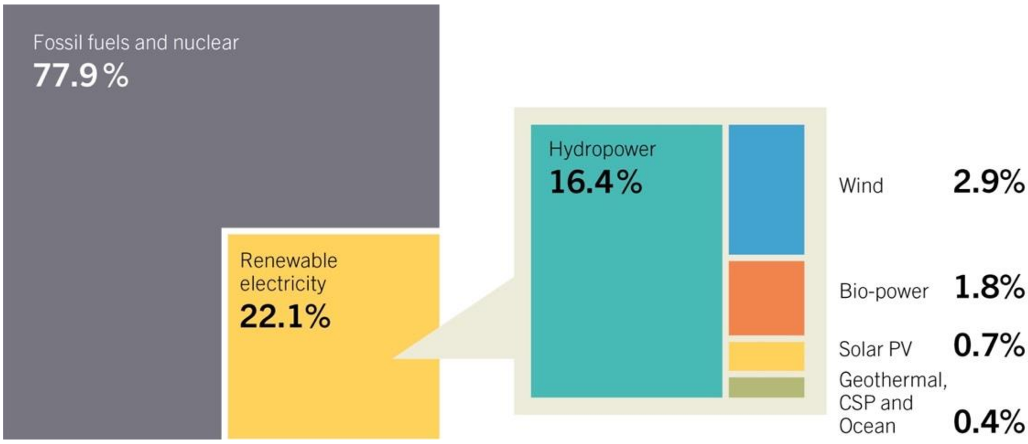

Figure 5. The industrial base of renewable energy is characterized as low compared to fossil fuels. (*CSP, Concentrated Solar Power) [19].

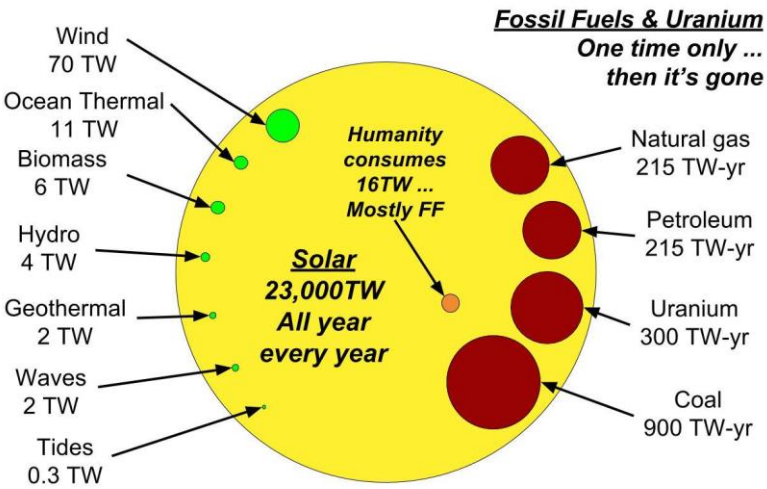

Figure 6. Fossil fuels and nuclear energy are transitory and deliver about 16 TW, only 0.05% of the energy on the planet [20].

At the grid scale, pumped hydro (developed substantially to absorb nighttime surplus of nuclear power) is a mature technology, but geographically limited to mountainous regions. Other innovative and robust grid-scale storage technologies are rapidly being introduced into the market. Examples are pumped thermal heat storage (hot water storage, hot rock storage), compressed air and underwater compressed air [21].

Grid stabilization with Demand Side Management (DSM) technologies are also becoming commonplace. As renewable energy systems proliferate and diversify, it will be possible to stabilize the grid by blending the diverse sources, as depicted in Figure 7.

Batteries will play an increasing role in small solar-powered point of use devices—personal lighting, cell phones, tablets, laptops, power drills, household appliances, etc. However, would the solar economy thrive if it were necessary to charge the batteries of seven billion automated electric cars (obscene luxuries in the first place)? No, there could be trouble if the challenge were to generate enough energy in renewables to directly match the world's obese lifestyle at 500 exajoules (≈500 quads) per year. Consider for example that the Sun's daily supply curve nearly matches the daily traffic demand curve (Figure 8), so storage (batteries or grid-scale reserves) can be minimized and real-time power transmitted directly to a grid-tied electric transit fleet that uses 5× to 10× less energy, 4× fewer materials and 10× less lithium than a luxury electric vehicle, and, instead of serving 1.3 passengers, is busy all day, serving 20–50 passengers. While a small, 1 kWh to 5 kWh battery pack is on board for load smoothing and emergencies, the primary storage is at the grid scale, at a small fraction of the cost of chemical batteries.

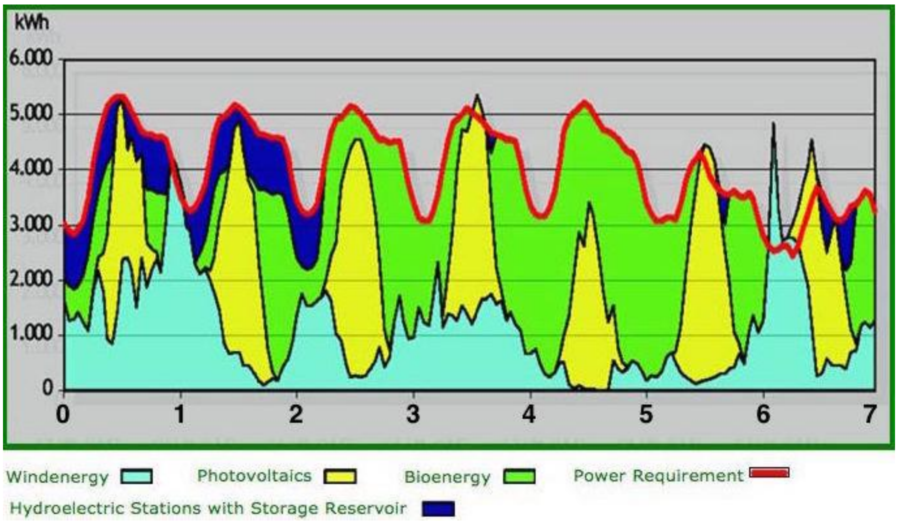

Figure 7. As renewable energy systems proliferate and diversify, the grid will stabilize by blending diverse sources. Simulated mixture of sources in one week [22].

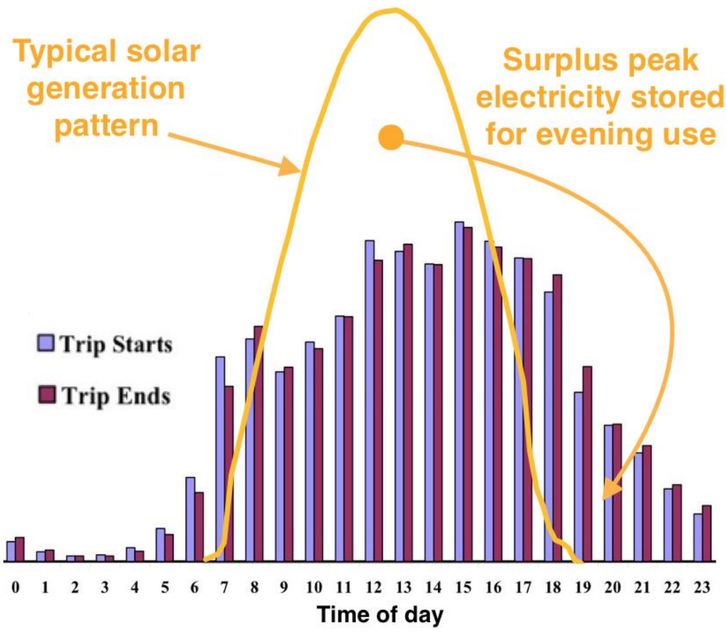

Figure 8. The sun's daily supply curve nearly matches a typical daily traffic demand curve [23].

Vehicle-to-Grid (V2G) schemes are promoted for grid stabilization, but such schemes assume the fossil-fuel-inspired vehicle with batteries taking the place of fuel tanks, while still sitting idle 23 h a day, still taking up 30% of the urban landscape just for parking. Instead of needing 100 EJ for a global fleet of automated electric cars, solar-powered public transit can operate on 20 EJ (globally), cutting mobility energy by 5× or better [24].

3.5. Time to Market: The Silicon Valley Culture and Its Spinoff of Crowdsourcing Have Enabled Innovators to Navigate around the Incumbency

The wholesale replacement of the global economy's reliance on fossil fuels is envisioned to take decades at a minimum, a vast undertaking to address climate change that may exceed human capability soon enough to matter. The risk of failure exists whether people sit on their hands or work 20 h per day. The good news is that the Silicon Valley culture encourages risk-taking, which propelled personal computing and the Internet, leading to mechanisms for innovation that ultimately fostered crowdsourcing, enabling innovators to navigate around the incumbency. Designers are highly motivated to create technologies that are disruptive 10× improvements over what exists. Consequently, it is simply not necessary nor attractive for smart designers to use solar technology to mimic products built around the inefficiencies of fossil fuels or to make incremental improvements. In other words, designing a more efficient internal combustion engine to improve U.S. Corporate Average Fuel Economy ("CAFÉ") standards is close to useless or even counterproductive, as it is a waste of critical talent and resources that would better serve if focused instead on electric propulsion and solar generation. Incremental efforts simply prolong the delusion that fuels could play a role in a post-carbon world, setting humanity on course to prove Boulding's second, utterly dismal theorem.

3.6. Net Energy (Energy Return on Energy Investment / EROEI / EROI) and Efficiency: The Net Energy of Renewables Is Higher than the Net Energy of Fossil Fuels and Is Sufficient to Leverage the Solarevolution

Net energy is a useful, but incomplete metric. Logically, for the benefit of scientists and policy makers, it would help to demonstrate that the net energy of renewables is higher than that of fossil fuels. To complete the picture, it is essential to also incorporate the metrics of engineering application systems, thereby coupling the relationship of energy sources (e.g., the net energy of generation) to energy sinks (e.g., the net energy efficiency of artifacts which consume energy). The entire energy chain matters, from source via extraction, refining, and manufacturing, through consumption via energy conversion.

a. Net energy of fossil fuels: In the early days of coal mining (the 1600s and earlier) and oil drilling (from 1859), extraction was relatively easy, and yields were bountiful. A gallon of oil invested in drilling and pumping would "return" 100 gallons (Figure 9). Then, as conventional easy oil was exploited fully, other forms of oil were pursued with increasingly costly methods (both financially and energetically). New fields today have low net energy yields; extraction is typically short lived and energy-intensive, with high carbon emissions.

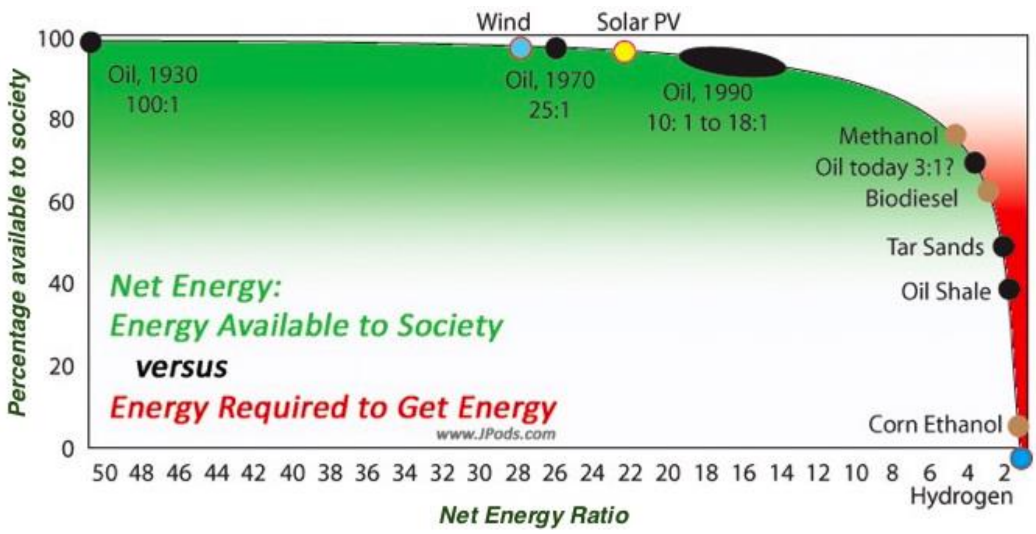

Figure 9. In the early days, extraction was easy, and yields for oil were bountiful [25].

b. Minimum net energy (EROI): In the context of ever lower net energy yields for fossil fuels, it is not surprising to hear the argument from Charles Hall that a minimum EROI of 10 is essential to the functioning of modern civilization [26]. It is easy to understand how that somewhat arbitrary guess came to be. When scientists first discovered the physics of heat and work and inventors created technology to exploit that understanding, engines were crude and fossil fuels were relatively easy to obtain. Engineering was inadvertently wasteful. Watt's early steam engines were less than 2% efficient. Steam locomotives (coal) reached only 6% efficiency in the U.S. around 1930 when they were superseded by diesel engines (oil). The very high EROI of early coal extraction was not coincidental; it was essential to the viable functioning of early steam engines with such low efficiencies.

The same applies to oil. A most revealing narrative is the sequence of losses seen in each step of extracting and processing petroleum, as depicted in Figure 10. Starting with 100 units of energy buried in an oil field, the remaining energy at a gasoline station is only 20.5 units. Putting those 20.5 units into an automobile with 13% average conversion yields 20.5% × 13% = 2.7%. Considering that less than 10% of a vehicle's mass is its passenger load, the entire energy chain drops down to a grotesque 2.7% × 10% ≈ 0.3% actual net efficiency. No wonder Hall claims the necessity of an EROI of 10 for a civilized world [27] instead of an EROI of 1.1 (say) that our ancestors needed to survive. Our fancy computerized burn-baby-burn artifacts are just glorified brute force.

Giving Hall the benefit of the doubt, is that minimum EROI of 10 for the fossil fuel economy applicable to the Solar Economy? No, even if the EROI of renewable energy generation turns out to be lower than anticipated, electric artifacts are becoming increasingly efficient. The complete renewable energy chain will outperform the fossil fuel energy chain. That is what the Solar Design Revolution is all about.

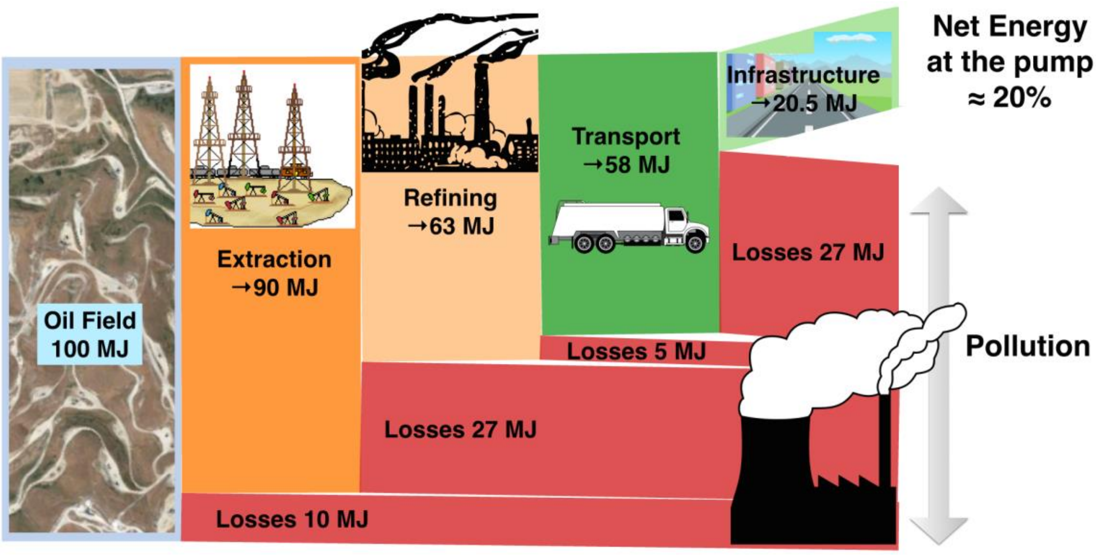

Figure 10. The sequence of losses in each step of petroleum processing is revealing [28].

c. Net Energy of Renewables: The success of the Solarevolution of course depends on the ability of solar/wind energy devices to produce significant net energy, that is, much more energy than is required to make them. An inconclusive debate has endured for a number of years, with high observed EROI asserted by, e.g., Raugei and Fthenakis [29] and others, versus low observed EROI asserted by solar energy specialist Pedro Prieto with support from Charles Hall, who first quantified the principle of net energy as EROI, building on the research of ecologist Howard Odum [30]. "Prieto and Hall conclude that the EROI of solar photovoltaics is only 2.45, very low despite Spain's ideal sunny climate. Germany's EROI is probably 20% to 33% less (1.6 to 2), due to less sunlight and efficient rooftop installations [31]."

A fundamental flaw of the Prieto-Hall analysis is the well-intentioned use of economic value as a proxy for energy. Noting a given country's aggregate energy consumption and its GDP, one can crudely approximate the energy embodied in any given purchase based on its price and the national energy use per dollar per year. Prieto and Hall calculated this for Spain to be 1.99 kWh per U.S. dollar of GDP generated [31].

Proxy energy is meaningful, for example, to distinguish between the embodied energy in a solar system installed on wooden racks by an impoverished electrician walking to work barefoot in Africa versus the same size system installed on aluminum racks by a California electrician who drives a long distance to work in a truck, earning enough for frequent vacations in Hawaii. This proxy, however, is flawed because economics is an instrument of policy, not a fundamental metric, e.g., BTUs or kilowatt-hours, leading to analysis which is inherently distorted and amplified by the "economic" framework (i.e., energy policy) in which any given project is embedded. Thus the Prieto-Hall proxy analysis based on Spain's economy, substantially dependent on imported fossil fuels, is questionable.

On the other end of the EROI debate, several others including Raugei and Fthenakis calculate a range of PV EROI between 20 and 40 (see Figure 9), and for comparison, they calculate the EROI of oil at 10–30 and coal, without Carbon Capture and Storage (CCS), at 40–80 [29].

Another survey, by Bhandari et al [32], indicates a lower range of values that render the levels in Figure 9 to be optimistic, except for high EROI Cadmium Telluride (CdTe) thin film modules (Figure 11), but nonetheless in the same range and superior to the values indicated for oil today. These disparate conclusions indicate wide discrepancies in methodology and underlying assumptions. However, might there be other fundamental principles of energy overlooked in the analysis that further distort the net energy debate?

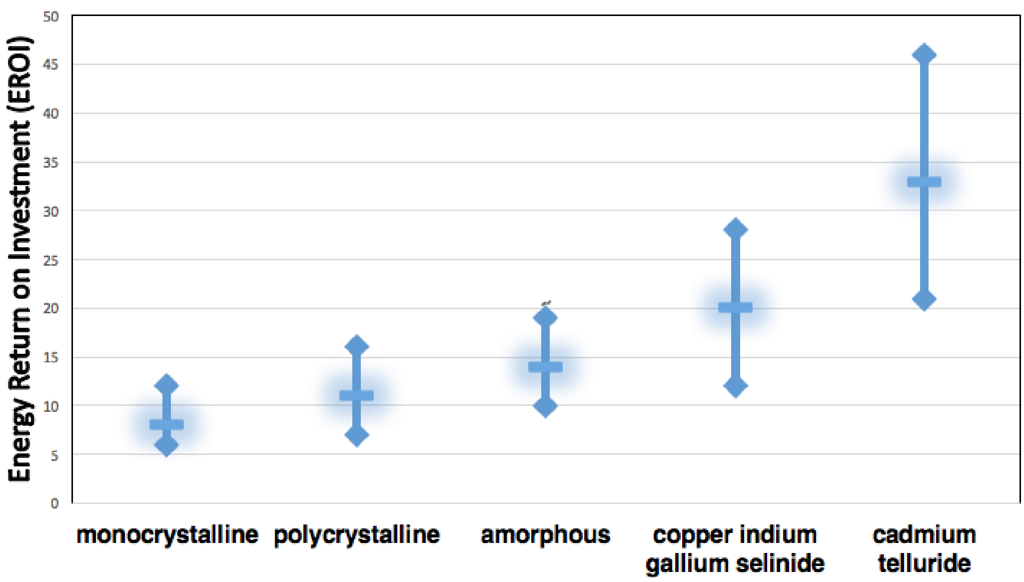

Figure 11. Mean harmonized EROI for photovoltaics with error bars representing one standard deviation for each module type [32].

d. Aperture efficiency and land efficiency: Aperture efficiency of solar is given significant attention in the media as a key indicator of potential cost savings. The aperture of a solar array is that portion of modules that directly face the Sun, in contrast to the efficiency of an entire system. By analogy, while the entire front of a camera receives light, it is only the lens that gathers the light to produce an image. Multiple rows of solar modules are separated to minimize self-shading while optimizing space allocation. For example, in Figure 12, the solar aperture "w" with row spacing "d" yields a "fill factor" of "w/d", which at mid-latitudes might be on the order of 1/3. Then, with a solar module at the high efficiency of 21%, the net efficiency to land would be 21% × 33% = 7%.

Optimizing this fill factor, balancing the cost of land and the cost of solar is important to installations of solar farms in open landscapes, but has little relevance whenever solar is installed on a mobile device, a solar race car, the pitched roof of a home or along an elevated transit guideway. In such cases, the fill factor can be considered to be close to 100%, as self-shading does not occur per se.

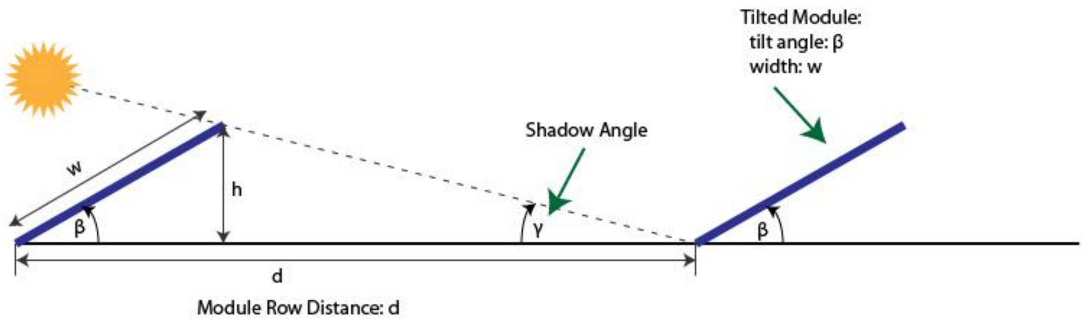

Figure 12. Illustration of PV module spacing [33].

e. Net energy of biofuels: The evident exception to high net energy (EROI) for renewables is the low net energy of liquid biofuels. This has been the source of much confusion because biofuels have been classified as renewable, whereas in fact, they are not. Photosynthesis is a natural process, and direct burning of biomass (e.g., firewood) has relatively high net energy yield and in moderation could be harvested in perpetuity. However, converting biomass into liquid fuels has burdensome inefficiencies (see Figure 9). To illustrate: with abundant water, about 1% of sunshine converts into biomass. Planting and harvesting (using fossil fuel-powered equipment) and the refining process (using coal-fired electricity) convert perhaps a third of the energy in biomass to a liquid form. Then, conversion in an internal combustion engine (with Carnot efficiency limits, friction and other losses) combines to exploit 13% for propulsion; the net result is 1% × 33% × 13% = 0.04% [34]. Fuels derived from algae may do better, but current algae producing machinery is material-intensive, and in spite of optimistic claims, hard data are elusive. Energy has to be used to pump water for irrigation, and if it were necessary to use the biomass itself to operate harvesters and the refining process, or to rejuvenate the soil, then the resulting EROI would be less than unity, i.e., non-renewable. These calculations are foreboding when farmers weigh their options for their fields. Since the process has little or no net energy yield, only misaligned government policy (subsidies) could possibly motivate the effort, which arguably could be rational for a farmer who has no children to inherit a depleted farm, but not otherwise.

4. Solutions

Having laid the groundwork to assess net energy at the source (generation), the next step is to illustrate how the solar economy will thrive with new artifacts that consume much less energy to provide far better energy services. Four applications shed light on the importance of measuring the entire energy chain to demonstrate the dramatic advantages of disruptive innovation versus incremental substitution. Obviously these examples are not comprehensive proof but they provide evidence that the transformation from fossil fuels can lead to a better quality of life. As the solar design discipline matures, additional superior energy services will emerge to validate the success of the Solarevolution.

- A Lighting: Solar-powered LED lights use 5× less energy than incandescent lights and 100× less energy per unit of light than kerosene lamps. Evidence: solar-powered LED D.Lights vs. kerosene lamps.
- B Communications: Tablets and smart phones use 10× to 100× less energy than desktop computers and are more accessible. Evidence: tablets and smart phones vs. desktop computers.
- C Architecture: Passive solar buildings use 10× less commercial energy than conventional buildings. The energy economics of the Living Building Challenge deliver remarkable improvements over time. Evidence: Bullitt Center, Seattle.
- D Transit: A 100% solar, net-zero-carbon transportation system is under development. It is elevated, making it more than just energy efficient; it is also faster and orders of magnitude safer than cars. (An EV powered by photovoltaics is not the answer. The laws of physics prevail; in accidents with cars, pedestrians lose; they are not equipped with air-bags.) Evidence: SANE (Solar, Automated, Nonstop, Elevated) transportation.

4.1. Example A, Lighting: Personal Energy Servers, the D.Light® Solar Lantern

A few years ago, compact fluorescent light bulbs were praised by politicians as the ultimate for energy efficient lighting. However, they contain toxic mercury and cannot be made tiny for specialized lighting applications. LED lights not only consume less energy, they can also be made smaller, to produce light better oriented to tasks, such as reading or walking in the dark, consuming even less energy.

A most impressive high leverage lighting device is the D.Light® S2 solar-powered LED lantern, which is daily replacing thousands of kerosene lanterns in Africa (Figure 13). Weighing only 120 grams, these tiny lights save liters of kerosene fuel (and money) every month.

Framed in the context of first world concerns, the familiar debate whether renewables can meet humanity's energy needs does not do justice to the billion people with limited or no access to modern energy services. "Power for ALL is committed to delivering access to energy to 85 percent of the 1.1 billion people living without reliable power before 2030 [35]." This commitment to the massive deployment of micro-solar devices is anything but modest.

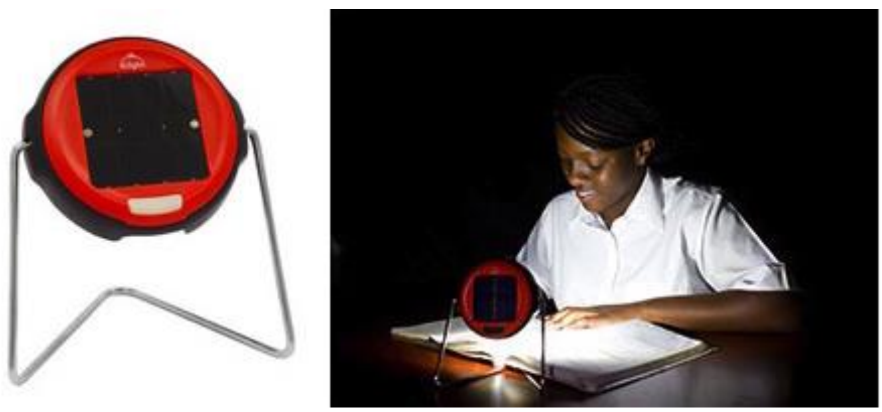

Figure 13. The D.Light® S2 solar LED lantern has replaced a million kerosene lanterns in Africa [36].

For Uganda, a poor non-electrified country with 37 million people and annual GDP of US$77 billion ($2100 per capita), that $20 is only 1% of GDP in one year, then it is free for several more years. What a blessing it is for children to be able to read at night and not be poisoned or burned by kerosene lanterns, which previously consumed 100× more energy, produced far less useful light and required burdensome ongoing monthly fuel costs.

Redundancy and responsibility are also important. Children with D.Light® S2s have their own personal solar devices. If there are five D.Lights in a family and one personal unit fails or is stolen, there are still four working units that the family can share until a replacement is acquired.

There is no need for stable and reliable local policy to implement renewable energy systems, and that is the beauty of it. Stability (even if heavily reinforced by sanctioned violence of official armies) is only necessary to maintain a 10,000-km supply chain from oil-producing nations to consuming nations. Meanwhile, the Sun delivers to everyone, everywhere (except the far north and Antarctica where very few people live), and basic solar devices can be completely personalized: networks of vulnerable copper cables or brutal armies are not required.

Thus, successful military intervention in the future will be when soldiers hand out solar lanterns to children. Small local solar businesses might not be able to succeed if an outsider is giving away what locals might otherwise be in a position to sell, but under conditions of war, refugee camps, extreme poverty or climate stress, this downside can be managed through various means of engaging local small businesses in distribution and maintenance.

4.2. Example B, Communications: From Desktops with CRT Monitors to Laptops to Tablets and Phones

Analogous to compact fluorescents is the personal computer. Stunning is the rapid revolution from desktops consuming 50 watts with CRT monitors consuming 80 watts for a total of 130 watts, compared to laptops at 20–50 watts, compared to tablets and smart phones, which consume 1 watt to 5 watts [37] (Figure 14).

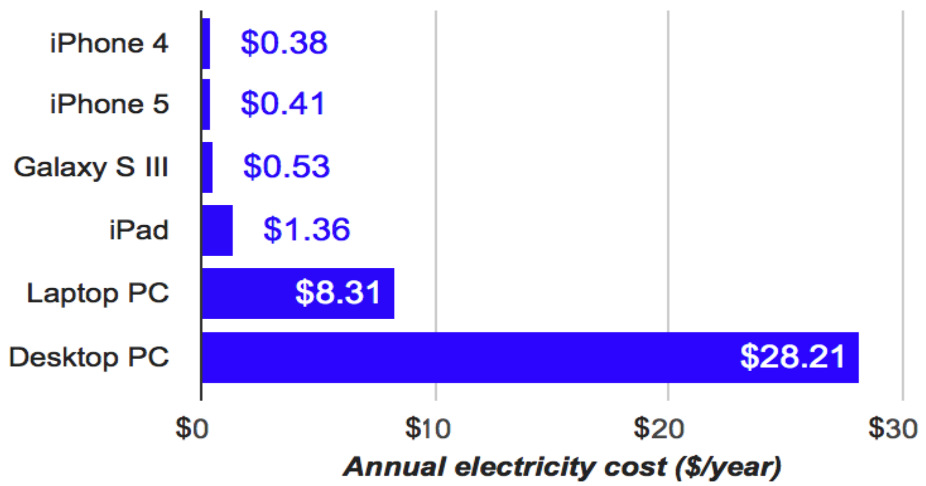

Figure 14. The rapid disruption—from desktops to laptops to tablets and smart phones [37].

In like fashion, solar-powered CB radios need only the air to link people together. In slightly more politically-stable environments, web-enabled solar-charged cell phones can provide network communications to the entire world. Additionally, if one can afford a cell phone, one will be able to afford a solar charger.

4.3. Example C, Architecture: The Living Building Challenge

Completed in 2012, the Bullitt Center is a commercial office building in Seattle, Washington, designed to be the greenest commercial building in the world, qualifying as a "Living Building" by the International Living Future Institute (Figure 15).

Figure 15. The Bullitt Center, designed to be the greenest commercial building in the world, qualified as a "Living Building" by the International Living Future Institute [38].

Features include:

- Building lifespan: 250 years.
- Energy: 1330 m^2 (14,300 ft^2) solar array generated 60% more electricity than the building used in 2014, 16 kBtu/sq.ft./year Energy Use Index (EUI) compared to 150 kBtu/sq.ft./year national median office building, extensive ground water heat pump system.
- Daylighting: 82% of the interior is infused with natural daylight.
- Water: 56,000 gallon (210,000 liter) cistern (with extensive filtering) for rainwater catchment.
- Transportation: 100 out of 100 WalkScore, bike racks, no automobile parking.

4.4. Example D, Transportation: SANE Mobility Systems

At San José State University, a Mechanical Engineering professor, over 150 engineering students, and several advisors (including the author) have been developing a SANE public transit system which demonstrates the Solarevolution assertions [39].

Consider the absurd notion of replacing every internal combustion engine in the global vehicle fleet with an electric motor. What a waste that would be. Cities are meant for people, not for machines. With over a million traffic deaths, 20–50 million seriously injured, and many more dying of air pollution every year, climate change is not the only reason for abandoning the artifacts of the fossil fuel era.

Applying solar energy as the new configuration driver, the San José State team demonstrates humanity's unique opportunity to revolutionize energy services (in this example, mobility) at the systems level, not just with a new mode of propulsion. Instead of crawling along in electric cars for hours in linear parking lots ("freeways") and then leaving them warehoused 23 h out of 24 in parking lots and garage structures costing more than the vehicles themselves, people will share SANE mobility with vehicles running all day long, each serving 20–50 people over the course of the day (Figure 16).

Compared to the energy efficiency of common transportation modes, the goal for SANE transit systems is to reduce energy consumption to 70 Watt-h/passenger-kilometer with (say) 1.6 average passengers/vehicle, about 5× or even 10× better than the automobile and other common public transportation options.

Figure 16. SANE transit (S = Solar, A = Automated, N = Nonstop, E = Elevated) [40].

5. Discussion

Achieving adequate net energy with renewables depends on the realization that solar flux by its very nature is conducive to producing electricity [12] and that, when coupled to electrical motors and electronic devices in a complete energy chain, renewables have already proven to be drastically more efficient than fossil fuel devices, and will continue to drive higher net efficiencies. The energy chain of fossil-fuel-coupled *pump jack-gas pump-car* will soon be relegated to the same role in society as the biofuel-coupled *hay-horse-and-buggy*—the next anachronistic novelty and nostalgic hobby.

Applying design science to this challenge requires the mindful integration of solar energy-consuming artifacts with solar energy generating artifacts, and decidedly not the adaptation of solar as an afterthought to existing fossil-fuel artifacts, *ergo*:

- The 10× Solar Design Revolution, embracing Boulding's Third Moderately Cheerful Theorem, a 10× invention of the solar-charged LED lamp to supersede the kerosene lantern; versus,
- Incremental 1.1× or 2× improvements to preserve the incumbency, serving only to validate Boulding's Second Dismal Theorem, the 1.1× "good money after bad" solution, to convert cars from gasoline to natural gas, or the 2× adaptation of the solar charged electric car to replace the gasoline powered car.
- Stated differently, we have arrived at this point in the human saga with a choice between (1) adhering to the dwindling net energy of fossil fuel sources (e.g., fracking, tar sands, deep offshore) coupled with incrementally more efficient artifacts (1.1× higher CAFÉ standards, 2× better hybrid electric cars), or (2) improving the net energy of solar sourcing devices (solar panels, micro-grid storage) coupled with appliances consuming 10× less energy (solar LED lanterns, solar charged smart phones, passive solar living buildings, SANE transit systems).

A significant portion of the human population continues to live as ever in a third world (legacy biomass solar) economy. These people can pull themselves away from the margin and thrive as their use of modern solar energy devices increases. The portion of the population now dependent on fossil-fuels will thrive in the solar economy with 10× less total energy in far safer, healthier communities.

- **Primitive** is living in balance with nature with net energy greater than 1 in the legacy solar economy (nomads, rainforest villagers) which was ubiquitous until perhaps ten thousand years ago, when animal husbandry and irrigation brought more energy into human society. The Solarevolution can provide access to modest energy services that will improve the lives of this population group.
- **Poverty** is living on the edge of a fossil fuel world, deprived of land for cultivation and lacking sufficient fossil fuels to thrive (slums, shanty towns). The Solarevolution can bring more energy services to this population without exacerbating climate change.
- **The climate refugee** is living where drought has overtaken the supply of basic nutrients, resulting in net energy less than 1, whereby survival depends upon imported nutrients. The Solarevolution may be the only way to restore stability within this population.
- **The Peak Oil refugee** is living in chaos, in a world of artifacts dependent on fossil fuels after fossil fuel supplies have dwindled or disappeared (Syria, Yemen). Fossil fuel subsidies will only postpone misery. The Solarevolution must be invoked to restore order within this population.
- **Overshoot** is living luxuriously in a fossil fuel economy which is destined to collapse; it's only a matter of time. This large community is especially vulnerable to resource shortages. The Solarevolution is critical to stability of energy-intensive urban communities.
- **Rebalance** is living lightly on the earth, in a solar economy with ultra-efficient novel devices, unencumbered by the burden of maintaining fossil fuel-hungry artifacts.

6. Conclusions: The 10× Solarevolution

Do we find ourselves mired in a straw-man argument about net energy on the supply side only, or do we navigate new energy pathways, building upon the assertion that we can achieve disruptive 10× improvements on the demand side too? With LED lighting, tablet computers, living buildings and SANE transit, yes we can. Can we perfect a direct coupling of high net energy solar/wind supplies, and lower electric demand by 10×? Embracing the Living Building Challenge, yes we can. Can we go beyond fire to jettison the entire fossil fuel chain "from well to wheels"? With SANE transit, yes we can.

The Solarevolution is the 21st century challenge. With design science and applied physics, we can further define and quantify the challenge we face; this is a starting point for further discovery.

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Conflicts of Interest: To instantiate the thesis of this article, the author has incorporated as a case study the Spartan Superway in which he is deeply involved, the results of which have built confidence in the potential of renewable energy in the challenging field of sustainable mobility. The professors, students, sponsors, and mentors had no role in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish this article.

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