CONTRIBUTED PAPER

Smart Grids Versus the Achilles' Heel of Renewable Energy: Can the Needed Storage Infrastructure Be Constructed Before the Fossil Fuel Runs Out?

This paper summarizes the need for large-scale investments in energy storage with a view on the long term wherein significant energy needs of the world are met by renewable energy sources.

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ABSTRACT | In this paper, *prima facie* evidence is presented to demonstrate that, by the close of this century: 1) the world will be approaching exhaustion of its supply of recoverable fossil fuel; 2) the energy shortages engendered thereby can reliably be avoided only if immediate massive steps are taken to actualize the development and manufacture of important, as yet unproven, components of a global smart energy system; and 3) the world over, there is little evidence (as measured by funding committed for development and demonstration) that the key governments are seriously concerned.

KEYWORDS | Massive energy storage; renewable energy; smart grid

I. INTRODUCTION

> "The problem of the commercial utilisation, for the production of power, of the energy of solar radiation, the wind and other intermittent natural sources is a double one. The energy of the sources must first be changed so as to be suitable in form; it must next be stored so as to be available in time"—Reginald A. Fessenden, 1910 [1].

This truism was beautifully illustrated in a recent modeling exercise by Budischak *et al.* [2] who analyzed four operating years of a 72-GW American grid system and showed that, with rare exceptions, it could have been powered solely by a mix of photovoltaics, offshore wind, and inland wind if: 1) the renewable generation was sized to be approximately 200 GW_{peak}; and 2) the grid was buffered by approximately 875 GWh of energy storage capacity. That is, each gigawatt of generating capacity had to be backed by 12 GWh of storage capacity; and, even so, there were five brief periods when the renewable generation would have required significant fossil backup. Nevertheless, this exercise did show that a renewably powered grid, which made no pretense of being "smart," could be successfully operated given massive energy storage. It is only reasonable to assume that a smart grid could be operated even better. This is good news for ordinary citizens, for pundits who comment on energy questions, and also for fossil-fuel geologists who keep predicting imminent supply shortages. But it leaves policy makers a bit up in the air.

First, a grid (smart or otherwise) that requires fossil backup for its reliable performance is neither renewable nor sustainable. And a nation that opts also for essential fossil-fuel backup while claiming to make a green

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Table 1 Predicted World Production of Fossil Fuel. Seven Independent Research Groups Were Selected for Inclusion; They Presented Their Predictions Differently

Predictions → / Predictors ↓	Peak Coal	Coal Droop	Peak Oil	Oil Droop	Peak Gas	Gas Droop
Mohr SH & Evans GM. 2009. *Fuel* **88**, 2059-2067.	2030	2100[a]				
Patzek TW & Croft GD. 2010. *Energy* **35**, 3109–3122.	2011	2047[b]				
Höök M, et al. 2010. *Fuel* **89**, 3546-3558.	2025	2090[c]				
Heinberg R & Fridley D. 2010. *Nature* **469**, 367-369.	~2030	?[d]				
Rutledge D. 2011. *International Journal of Coal Geology* **85**, 23-33.	?	2070[e]				
Wang J, et al. 2011. *Energy Policy* 39, 7616-7621.			2011	2050[f]		
Maggio G & Cacciola G. 2012. *Fuel* **98**, 111-123.	2052	2117[g]	2015	2052[g]	2035	2070[g]

[a] By 2100 coal production is predicted to have declined to 50% of peak and to be dropping precipitously. "Best Guess" scenario, measuring production in energy units.

[b] By 2047 coal production is predicted to have declined irreversibly to 50% of peak.

[c] By 2100 coal production is predicted to have declined to 50% of peak and to be dropping sublinearly.

[d] This source is more qualitative than quantitative, but supply challenges are clearly expected in the latter half of the century.

[e] By 2070, 90% of the economically recoverable coal will have been recovered.

[f] By 2050, oil production is predicted to have declined to 50% of peak.

[g] These are the dates by which produced energy is predicted to have dropped to half of peak. Values from Fig. 15.

transition, may not be taking its task seriously enough. If the fossil backup is not CO_2 neutral, then employing it may simultaneously drive climate change and invalidate the model used to predict the renewable generation. If the fossil backup is assumed to come with carbon capture and storage (CCS), then a major development effort for CCS will be needed; and this could negatively impact the resources available to develop the massive energy/electricity storage (MES) that will be essential to match intermittent renewable generation to variable consumer demand.

Second, no one knows for sure when fossil-fuel production will have dropped catastrophically and a switch to renewable energy become unavoidable.[1] However, in the past several years, there have been made a number of independent scholarly studies of anticipated depletion scenarios: seven of these are summarized in Table 1. The clear message of these projections is that annual world outputs of coal, oil, and natural gas are now nearing their peaks but that really serious constrictions in supply may not occur until the latter half of the century. By contrast, industrial or agency projections seem more optimistic: 1) BP's "Energy Outlook 2030" [3] foresees increasing world production of petroleum liquids (p. 34), natural gas (p. 44), and coal (p. 56) over the period 2010–2030; 2) the U.S. Energy Information Agency's "Annual Energy Outlook" [4] foresees monotonically increasing production of petroleum liquids (Fig. 19) over the period 2010–2035; and 3) the International Energy Agency's (IEA's) "World Energy Outlook" [5] foresees modest production increase in petroleum liquids (Fig. 3.15), modest production increase in natural gas (Table 4.4), and, barring CO_2 amelioration, a significant increase in coal production (Table 5.4) by 2035. These two sets of predictions are not in blatant contradiction because the first focuses on the latter half of this century while the second worries only about the next 20 or so years. In fact, virtually everyone agrees that fossil fuel's days are numbered, and even the IEA's guarded optimism is qualified by a realistic "the rate of oil production has exceeded that of discoveries by a wide margin for many years" [5, p. 105].[2] What uncertainty there is lies in knowing the precise date by which a switch to renewables should have been completed. Section II discusses the obligations this uncertainty places upon grid planners.

[1]Nuclear energy will not, in this contribution, be considered renewable even though, with reprocessing and breeder reactors, it might prospectively become partially so and provide many centuries of base-load power. This decision was based upon the failure of the United States to develop tested, functioning, permanent repositories for civilian nuclear waste—despite the facts that the need has been clear for more than 60 years and that, under the guidelines of the International Atomic Energy Agency, it is supposed to do so. Additionally, barring as yet prospective output-agile fission generators, matching generator output to consumer demand could still require vast MES.

[2]Where appropriate, pointers will be given to page (p.), section (Sec.), chapter (Ch.), equation (eq.), figure (Fig.), table (Table), appendix (App.), or experiment (Exp.) of the pertinent reference.

Third, massive electricity/energy storage (MES) does not at present exist on the scale needed. To begin with, the scale needed is unclear. Will it entail, as envisioned by Armaroli and Balzani [6], a world largely powered by electricity? Or will it instead, as envisioned by Ahlgren [7], leave transportation largely powered by synthetic combustibles? And will it be a world of low energy intensity and a modest total population or an overcrowded world characterized by profligate energy use? To be optimistic, let us assume that it will it be an affluent but frugal society in which 10 k€ y^{-1} of gross domestic product (GDP) requires a metric tonne of oil equivalent energy (toe), rather like what might be the case for the European Union in 2035 [5, Fig. 2.4].[3] Then, a 50 k€ y^{-1} per person GDP must be backed by an average per-person renewable generation of 5 toe $y^{-1} \Rightarrow 6.6$ kW $\sim$ 5 kW. And, as the results of Budischak *et al.* reveal [2], this should be buffered at a rate somewhat above 12 kWh of storage per kilowatt of average generation to compensate for source intermittency. However, in the United States, lengthy grid outages are rather more frequent than the public grasps [8]; so simple caution might suggest storing at least 48 kWh of energy for each kilowatt of average generation used, just in case. This then means that each affluent member of an equitable world society could need direct-plus-indirect underpinning by as much as 5 kW_{avg} of steady energy supply plus its backup at 48 kWh/kW_{avg} [8] for perhaps 240 kWh = 10 kWd of energy storage.[4] In Section III, this assertion will be discussed in much greater detail and illustrations given of just how daunting this task promises to be.

Today, a grid labeled "smart" can shed load, encourage conservation, protect critical uses, make sensible choices, and inform the public of less obvious consequences of their energy choices. But it does not, in its present incarnations, provide truly massive quantities of energy storage the way the coal pile behind the generating plant used to. When a brief outage occurs today: 1) uninterruptible power supplies come online and protect data systems for minutes to hours; and 2) emergency generators come to life and keep a home, or a hospital, or even the cooling pumps at a nuclear power plant running until the grid returns or their diesel fuel runs out. Currently, however, the many days of backup that a major catastrophe merits are unavailable. Nor do present-day grids fragment gracefully into smart microgrids, each with its own robust supply of massive energy/electricity storage (MES).

In the envisioned smart grid of the future, supply and demand will be matched by balancing renewable generation, consumer demand, and colossal MES.

1) Renewable generation is unlike fossil-fuel generation. Once its generators are in place, they do not have to be fueled by the utility. Sunshine, wind, tidal flow, and their ilk are fluxes of energy not produced by man, but rather intercepted by man. If man does not intercept them and capture their energy, that energy passes on and becomes opportunity lost. Because in-place renewable generation has but minor operating costs yet yields valuable energy, its operator has a strong motive for capturing and selling as much as possible given the available generating capacity.
2) Consumer demand has some flexibility. To be sure, the consumer has preferences; but he can be bribed/coerced by suitable pricing options to shift that demand in time, and even to install personal energy storage or to do without the desired energy. Commonly viewed as intolerable, however, are power outages that take down hospitals or police communications or a major semiconductor fabrication facility and do so independently of the consumers' momentary willingness to pay. That is, smart control seems likely to compensate for a host of minor mismatches, but not for essential demands that do not abate during prolonged shortfalls of renewable generation.
3) Massive energy/electricity storage[5] for backstopping renewable generation is only somewhat like the huge pile of coal behind the power station [9]. When the MES is exhausted, then we have to await the natural resumption of renewable generation, whereas, to date, diminished coal piles have always been replenished with cheap shipments from the mines, and natural processes have endowed the mines with years (even decades) of reserves, exploitation of which can generally be accessed by emergency measures. Coal piles behind power stations are only simple heaps of crushed rock on bare ground, are cheap to construct compared to the cost of the coal, and

[3]The reader is reminded that long tradition within the energy industry makes free use of many non-SI energy units, and that these units are not always precisely defined. A good introduction to this uncertainty of conversion is provided by the American Physical Society at their Web site http://www.aps.org/policy/reports/popa-reports/energy/units.cfm. The "quad" is one quadrillion British thermal units or 1.055×10^{18} J. The "tonne of oil equivalent" ("toe") is 1010 calories or 41.868×10^{9} J. The "barrel of oil equivalent" ("boe") is $\sim$6.12 GJ. The "standard cubic foot (of natural gas)" ("SCF") is 1000 Btu or 1.055×10^{6} J.

[4]The reader is reminded that, by the First Law of Thermodynamics, energy is always conserved. However, by the Second Law of Thermodynamics, not all forms of energy are equally useful for powering all tasks. For example, the portion of the energy in a system that can be converted into mechanical work is frequently referred to as the "exergy" of the system, and is regarded as energy of high quality. The 5 kW_{avg} per person figure given above pessimistically assumes that high-quality pure-exergy electricity would be needed, and thus errs on the side of caution.

[5]MES as defined in connection with the smart grid commonly refers to the storage and discharge capabilities of the local smart grid as a whole rather than the average 5 kW_{avg} of power and 10 kWd of storage needed by each person using that grid. Official thresholds for MES have not yet been established for MES on a grid scale. However, a credible estimate can be obtained by studying the limitations of present pumped hydro storage facilities in the United States: these top out around 1 GW_{peak} with 1 GWd maximum capacity [19, Table 1], but none have been built in recent years. A serviceable lower bound on "massive" might therefore be 1 GW_{peak} ($\sim$0.5 GW_{avg}) and 1 GWd; such a facility could service $\sim$100 000 people.

can, at little cost, be generously sized to outlast probable supply disruptions, such as strikes or delivery postponement due to severe weather. In contrast, development of MES infrastructure is expected to be significantly more expensive per kilowatt hour than the simple piling of pulverized coal. Both MES and coal piling are gambler's ruin problems in which the gambler's pockets must be deep enough to outlast a run of bad luck. The difference between them is the construction costs, which assure that the MES gambler will almost always have the shallower pockets. Of course, when the coal runs out, the MES gambler will have the only pockets—a thought which those who might wish to put off MES would do well to contemplate.

In a smart grid future, the smart grid, however sophisticated, will not work unless undergirded by both ample renewable generation and ample massive energy storage. The balance among abundance of generation, flexibility of demand, and massiveness of storage remains to be worked out. That will be a function of economic realities not yet comprehensible because the technologies that determine them have yet to be developed, much less evolved to maturity.

II. THE OBLIGATIONS OF UNCERTAINTY

It was argued above that each resident of an equitable sustainable society would have to be the recipient of primary energy equivalent to as much as 5 kW of steadily supplied renewable power. This is in no way an outlandish estimate, because already the Earth's population of about 7.1 billion people is consuming a gross primary energy of roughly 14 Gtoe $y^{-1} \Rightarrow$ 2.0 toe person^{-1}y$^{-1} \Rightarrow$ 84 GJ person^{-1}y^{-1} [5, Table 2.1]; and this leads to an average current power consumption of 2.7 kW person^{-1}.

If we make it a humanity-wide goal to grow coupled generation and consumption to reach the 5.0 kW person^{-1} goal in 50 years, that is a net growth of 1.25% a year in the available *per capita* power. If population growth is figured in, then the growth in total power generated could probably be closer to $3\frac{1}{2}$%–4%; and growth at such a rapid pace has, in fact, been envisioned by the U.S. Energy Information Administration [9, Ch. 5]. However, it is by no means certain that mankind absolutely positively must have any particular *per capita* supply of renewable power by any particular date. What is difficult to deny are the propositions: 1) that the supply of fossil fuels is finite; 2) that the problem of permanent CO_2 disposal has not yet been resolved unequivocally; 3) that the supply of fissionable materials is finite; 4) that the permanent disposal of massive quantities of fission waste has not yet been resolved unequivocally; 5) that adequate sustainable power supplied from renewable sources is not yet available; 6) that no one knows for sure when the inevitable crunch on nonrenewable energy supplies will occur; and 7) that, if the necessary renewable energy supplies are not yet available when the crunch does occur, severe societal dislocations could well result. Because all seven of the recent studies summarized in Table 1 predict significantly constricted supplies of fossil fuels by the end of the present century, it seems only prudent to commence an immediate reconfiguration of the world's energy infrastructure to a sustainable renewable basis.

Mistakes will be made during this restructuring; and resources will be wasted. This is only to be expected because mankind has never before made a comparably extreme transition on such short notice. For example, the period required for coal to go from 1% of America's supply of primary power to 50% was on the order of 50 years, and the same was true as coal was displaced by oil/gas [10]. Now, as Table 1 reveals, mankind has as little as 50 years to switch energy sources. Only this time the switch will not be voluntary: this time mankind will have no choice. And the new technology needed, though envisioned, is not yet well developed. In such circumstances, society's leaders have an obligation to behave proactively rather than hoping for the best while letting matters take their course. It is a simple matter of intergenerational equity: the present does not have a right knowingly to beggar the future [11].[6]

A cautionary tale of costly proactive preparation is the following. In the 1920s and the early 1930s, the distribution of armaments among the industrialized nations was loosely regulated by international treaties, in no small measure to avoid the destabilizing effects of a renewed arms race such as that which preceded the Great War. As former allies, Japan and the United States were allowed rough parity in aircraft carriers. However, shortly after the onset of the Great Depression, the rise of Nazi Germany in Europe and Japan's territorial ambitions on the Chinese mainland provoked international unease. The subsequent action–reaction, shown in Table 2, then occurred between the United States and Japan [12]. In the middle 1930s, the Japanese ramped up a carrier building program, while the United States focused upon its massive internal economic catastrophe and did not react obviously until 1941. Even then isolationism was rampant within the American electorate, and rearmament was far from popular. World War II achieved full scale in late 1941, with Japan and the United States having rough parity in carriers. 1942 was a tough year, and it ended with Japan enjoying two-to-one superiority in carriers. Fortunately for the United States, it had a lot of underutilized production potential and turned things around. But, if it had not started laying down carrier keels in 1941, World War II could have had a rather different course. Naturally this analogy from history is not

[6]This last statement is obviously a moral or philosophical judgment that cannot be falsified by replicable experiment. Rawls [11] discusses in detail the "veil of ignorance" test that might be used to support it. Presumably, most readers would prefer not to find themselves in a beggared future.

Table 2 Anatomy of an Arms Race. The Number of Major Aircraft Carriers Laid Down, Launched, and Deployed in the Run-Up and Prosecution of World War II. Data Are for Year's End

Year	Carriers under Construction		Carriers Actually Deployed	
	Japan	USA	Japan	USA
1932	1	1	3	3
1933	1	1	3	3
1934	3	2	3	4
1935	4	2	3	4
1936	5	3	3	4
1937	5	2	4	5
1938	6	1	4	6
1939	7	2	5	6
1940	7	1	6	7
1941	6	11	8	7
1942	4	18	6	3
1943	3	13	7	19
1944	0	5	2	26
1945	0	0	2	32

Only major carriers commissioned and subsequently deployed prior to 1946 are included in this tabulation; 'major' is defined as carrying at least 30 planes and designed for combat rather than escort service. Data from Chesneau [12].

all that similar to the present energy challenges because every nation on the planet had a lot of experience with war and the United States knew how to build weapons of war that worked. Whereas, today, nobody has had experience with a catastrophic exhaustion of fossil-fuel reserves, nobody knows what the correct trajectory is to achieve renewable fueling, and nobody knows which massive energy storage strategies are the correct ones.

Therefore, it seems prudent to invoke some sort of precautionary principle[7] and mandate remedial action: precaution is, after all, a standard response to uncertainty [13]–[15]; and it was enjoined upon us from earliest youth in such aphorisms as "an ounce of prevention is worth a pound of cure" or fables such as The Ant and the Grasshopper.

III. THE MONSTROUS SIZE OF THE MES

In an imagined affluent world of the future, each resident (cf. Section I above) could need as much as 5 kW of continuous energy buffered by 10 kWd of energy storage. The 5 kW is by no means a farfetched estimate because, in 2011, ~312 million residents of the United States consumed 97.30 quads (102.7×10^{18} J) of primary energy [4] or 10.4 kW person^{-1}: the presumption of 5 kW person^{-1} in fact assumes significant energy conservation. Neither does the 10 kWd person^{-1} (240 kWh person^{-1}) of energy storage seem out of line because it backs up the resident for only two days, and because outages of two or more days in length are part of the memories of most adults, middle-aged and older [8].[8]

Remembering that the chemical energy in combustibles must be heavily discounted if it is to be converted into useful work, approximately what does 10 kWd (= 864 MJ ~1 GJ) of exergy storage look like in practical terms? In the following, four simple illustrations will be provided for the case in which the captured renewable energy is immediately converted into electricity for distribution or storage.[9]

A) Iso-octane has a higher heat value of approximately 32.9×10^9 Jm^{-3} [16]. If it can be turned back into exergy with an efficiency of 1/3, about 79 L will be needed for each citizen. Thus, a storage tank with the volume of the Great Pyramid of Giza (2.48×10^6 m^3 [17, p. 456]) should suffice for 31.5×10^6 people.

B) A large industrial battery (GNB model GX6000) was arbitrarily selected [18]. Nominal specifications are: voltage, 4 V; capacity, 6000 A h $\Rightarrow$ 86.4 MJ; volume, 417 L; mass, 894 kg. Ten such massive batteries will be needed for each citizen, a total volume of 4.17 m^3. But a Great Pyramid of such batteries should suffice for only 0.59×10^6 people.

C) 250 m^3 of dry air, isothermally compressed to a volume of only 1 m^3, holds a mechanical energy of 140 MJ; therefore, 6.17 m^3 of such compressed air will be needed. And a pressure chamber the volume of a Great Pyramid would suffice for but 0.40×10^6 people.

D) A cubic meter of water elevated 750 m at standard gravity has a potential energy of 7.35 MJ; therefore, 118 m^3 per person will be needed. But, since two reservoirs are needed in a pumped storage scheme (one upper and one lower [19]), a Great Pyramid of reservoir would handle only 10.5×10^3 people.

The reader will observe that these per-person energy storage volumes span the range 0.079–236 m^3, a ratio of roughly 1 : 3000. Moreover, the absolute quantities that ultimately will be required are unknown because future population growth is unknown. Nevertheless, current predictions of world population in 2100 call for roughly

[7]In modern ecological or political thinking, a precautionary framework makes it a social responsibility of policy makers to protect the public from significant harm when there is credible scientific evidence of such harm being apt to arise from a particular course of action, whether that course is optional, mandatory, or quite unpredictable. Moreover, it is common to regard as unwise the postponement of proactive precaution because there is not yet full scientific certainty of that harm.

[8]Take note that the 10 kWd person^{-1} takes cognizance only of "normal" short-term weather variations and grid failures. It does not factor in trans-seasonal load shifting for winter heating or summer cooling.

[9]For simplicity, the only storage modes discussed are a typical hydrocarbon and those modes that the Electricity Storage Association currently recommends for decoupling from energy use the generation and stationary storage of massive quantities of electrical energy (http://www.electricitystorage.org/technology/storage_technologies/technology_comparison). If none of these come close to sufficing, then slim are the chances of mankind exiting this century in control of its energy future. It should be noted that the four have been roughly ordered by the per-person volume of energy storage required.

ten billion people, give or take a factor of two.[10] The author, who has been much impressed by the huge drops in birthrate that frequently follow universal education and readily available contraception, will use 5.00×10^9 people for population projections in this document. But "only" five billion is still a huge number whose energy needs will have to be met with renewables once fossil fuels and other nonrenewables have been exhausted.

IV. ARE THESE FOUR OBVIOUS STORAGE STRATEGIES ADEQUATE FOR THE WORLD'S NEEDS?

What will now be shown is that each of these strategies offers some prospect of being able to surmount the intermittency challenge (i.e., the task of storing sufficient energy to match capriciously varying renewable generation to mankind's changing needs). This disconnect between supply and demand has justly been described as the Achilles' heel of renewable energy [20]. Yet, it has still not been unequivocally neutralized. And research related to it has been quietly neglected.[11]

Case A). This possibility depends upon using renewably generated electricity to drive the synthesis of inorganic and organic fuels from water (provides H) and air (provides C, N, and O). This could yield gaseous hydrogen [21], ammonia [7], methane [7], [22]–[24], simple alcohols [7], [22], [23], and liquid hydrocarbons [7], [22], [23], [25], [26]. Because the atoms constituting the fuels are continuously recycled, the supplies of synthesizing constituents are sustainable. And the feasibility of the process should depend largely 1) upon the sustainability of catalysts for the syntheses; and 2) upon the realities of both energy economics and financial economics. Until synthetic fuel synthesizing systems are scaled up enormously and their technology allowed to mature, accurate economic predictions about this form of storage are unlikely.

Case B). This possibility depends upon using renewably generated electricity to manufacture and charge batteries, of which there is a plethora of types. It has already been shown that the planet's lead reserves are seemingly inadequate to sustain massive electricity storage with lead acid batteries for a world population of even five billion [27], [28]. If batteries are to be used, today's familiar families of secondary batteries will, for a number of reasons, probably never suffice for massive energy storage: first, they have been subjected to intense incremental improvement for over a century without a major breakthrough in energy density and may have "hit the wall"; second, they tightly couple together storage capacity and maximum power output; and third, they may not deliver the long and robust service lives that utility customers expect.[12] Thinking "outside the box" seems called for.

Outside the box is, for example, redox flow batteries, wherein output current is intrinsically decoupled from total energy stored [29], [30]. Such batteries are now in a phase of intense development.

Outside the box is metal–air batteries, which offer seductively large theoretical (as contrasted with currently practical) energy densities [31].

Outside the box is new electrolytes, such as are found in the burgeoning field of metal-based ionic liquids (MetILs), e.g., [32] and [33].

"Outside the box," as illustrated above, also means "under development." And "under development" is of little use for massive electricity storage until the new technologies have been field tested, the bugs wrung out of their production, robustness demonstrated, end-of-life issues resolved, and the new batteries are flooding into the market by the boxcar.

Case C). Compressed air energy storage (CAES), whether adiabatic or isothermal, has been recently figured prominently in the energy policy literature, e.g., [34]–[38]. Moreover, there also seems to be a respectable literature on the physical and engineering underpinnings of CAES, e.g., [39]–[44]. What seems to be missing is evidence for a single major instance in which CAES was actually built and successfully used for operation of an expander train to generate electricity directly. The commonly cited plants in Huntorf, Germany and McIntosh, AL, USA [43] use compressed air as a way of reducing compressor costs in natural-gas-fired power plants; such use is not sustainable because natural gas is an unsustainable, finite, fossil resource. No major new plants have been built in decades; and few are being widely touted as "under construction." If built, for example, advanced adiabatic CAES might prove a viable storage solution. But until designed, built, tested, debugged, and reliably operated at reasonable cost, it ought not be counted upon to meet future MES needs.

Case D). Pumped hydro storage works well and is backed by generations of experience [45], [46]. Indeed, approximate calculations of various strategies that might be employed have already been made [19], [47], [48] and will be adapted here to the problem as posed by Murphy [47] for the United States: roughly, store enough gravitational potential in elevated water to provide 2 TW of electric power for 7 days $\Rightarrow$ 336 TWh $\Rightarrow 336 \times 10^9$ kWh $\Rightarrow 1.21\times 10^{18}$ J $\sim$ 1 EJ.

[10] A search of the Web yields many interesting charts, all of which point to this outcome and most of which are based on the 2010 revision of the United Nations' Probabilistic Population Projections http://esa.un.org/unpd/ppp/index.htm.

[11] Modern science is so vibrant that somewhere someone is diligently exploring almost any topic of possible concern. What matters is whether effective action is being taken on those rare problems whose predicted onsets 1) are relatively soon; 2) could well be catastrophic as opposed to merely inconvenient; 3) are not already being circumvented; and 4) do not yet have well tested and verified solutions.

[12] This is memorably described in the recent scathing essay "Battery performance deficit disorder" by Prof. Thomas W. Murphy of the University of California at San Diego (http://physics.ucsd.edu/do-the-math/2012/08/battery-performance-deficit-disorder/)

Murphy [47] proposed damming valleys in mountainous terrain to provide the upper and lower reservoirs and estimated that: 1) 170 stations each storing $\sim 7 \times 10^{15}$ J would be needed; 2) in aggregate, an area rather larger than Lake Erie (only deeper) would be drowned; and 3) a stupendous quantity of concrete would be required.

By contrast, Pickard [19] favored many smaller modular facilities built upon non-arable flatland, each with a hydraulic head of 750 m, an excavated underground reservoir of roughly 25×10^6 m^3, and an upper reservoir roughly 1 km^2 in area and 30 m deep, formed on the surface and ringed by spoil from the excavation; each such module would store roughly 0.2×10^{15} J. In all, roughly 5000 of these smaller units would be needed; but they could be placed, largely unnoticed, on land of low agricultural, commercial, and scenic value.

Last, Slocum *et al.* [48] have proposed storing the energy in partially evacuated hollow spheres resting on the seabed near offshore wind-turbine generators. When there is a shortage of electric power, seawater would be admitted to the sphere by way of a Francis turbine driving a suitable generator; and the resulting electricity would be fed into the grid. When there is a surplus of electric power, the Francis turbine would be run backwards by some of that surplus, and the water inside the sphere would be pumped into the sea.

Obvious though these three pumped hydro schemes may appear, they are all outside the boundaries of tried and tested technology. They should work, except that the history of technology is littered with the ruins of major projects that failed because of unanticipated contingencies.

Economic feasibility and turnaround efficiency. The reasonableness of an energy project's cost is situationally determined [49], as is the cost itself. Here, buffering the renewable generation is presumed essential: what remain to be determined are the magnitude of the buffering and the timing of its addition to the project. Both are influenced by the anticipated (though unpredictable) gyrations of the cost.

Turnaround efficiency of a storage system over a specified interval of time is the ratio {total amount of energy of a particular type extracted from the system}/{total amount of energy of the same type added to the system}, it being assumed that the initial and final states of the system are the same. Normally, higher efficiencies are preferred strongly.

Summary. There are lots of clever, though untried, strategies that might meet the world's rapidly approaching need for energy storage in stupendously massive quantities. Some of them, perhaps most of them, may ultimately fail to work satisfactorily. And those that finally do prove out, may fail to do so in a timely fashion. Presumably, the most prudent path to success in massive energy storage lies in testing straightway all of the above schemes in full-scale demonstration projects.

V. CAN THE NECESSARY INFRASTRUCTURE BE CREATED IN THE TIME REMAINING?

A. Introduction

The take home message of Section I was that recent projections of fossil-fuel supplies are strongly pessimistic: by 2070, mankind will probably be well beyond peak fossil fuel.

The claim of Section II was that, if mankind expects serious energy shortages in a generation or so, then it has an obligation to protect future generations by moving forthwith to counter those shortages, even if doing so is devilishly inconvenient. It is just not right to place the burden of our life styles upon the shoulders of our descendents.

In Section III, it was shown that dauntingly large is the amount of massive energy storage needed to smooth out all of the intermittencies that characterize common renewable sources.

In Section IV, it was asserted that none of the likely technologies needed to make such massive storage a reality can today be obtained off the shelf at known specifications, cost, reliability, and lifetime.

In this section, it will be argued that revising the world's energy infrastructure to run reliably with a mix of largely intermittent renewable sources is apt to take at least 50 years [10], [50], [51].

B. Previous Transitions in Primary Energy Sources

What we will here focus upon is stored energy that can be transformed to do useful work. The history of such energy in the service of man can be summarized in the nine transitions of Table 3.

Until coal was added to the energy mix, primary energy was neither conveniently nor infinitely dispatchable; cf., [52] and [53]. Humans could work only so hard and then only so many hours a day: you either accepted this and lived with it or you worked people to death, in which case you lost a most useful source of intelligent energy; moreover, humans tended to be stubbornly diurnal. The environment, like humans, could be exploited only so vigorously; and therefore the supply of biomass, whether gathered or farmed, was limited and perhaps seasonal. Animals, like humans, could be worked only so many hours a day, and provided dispatchable energy only if employed in shifts. Wind is notoriously fickle; and its users, whether sailors or millers, accepted this intermittency because intermittent wind was a lot better than rowing a boat or pushing on a capstan mill. Hydro, whether by falling water or by flowing water or by waves, was only somewhat dispatchable, and was apt to be seasonal. Coal opened a whole new energy terrain: it stored energy densely, could be accumulated locally in enormous piles, and yielded as much energy as needed by the simple expedient of shoveling harder. Oil was a lot like coal. And gas is a lot like coal

Table 3 Nine Energy Transitions That Characterize the Development of Mankind. The Last Two Are Still Under Way; and, From Food Through Solar; Each of the Primary Energy Sources Employed by Mankind Waxes and Wanes With Human Development

Human + Food
Human + F + Biomass
Human + F + B + Animals
Human + F + B + A + Wind
Human + F + B + A + W + Hydro
Human + F + B + A + W + H + **Coal**
Human + F + B + A + W + H + **C** + **Oil**
Human + F + B + A + W + H + **C** + **O** + **Gas**
Human + F + B + A + W + H + **C** + **O** + **G** + Nuclear
Human + F + B + A + W + H + **C** + **O** + **G** + N + Solar

and oil: it is conveniently stored; and its energy can, with some forward planning, be dispatched on demand in virtually any quantity desired.

Nuclear energy, although stored at a far higher energy density than the chemical energy of oil, may have represented a step backward in three ways First, it is not, as presently configured, dispatchable because of the slow thermal response times of presently available plants; generation IV nuclear plants, now in the planning stage, might possibly circumvent this [54]. Second, it is not, *sensu stricto*, renewable because the available resources of fissile nuclei (though large) are limited; however, fertile nuclei are in much greater supply and could perhaps extend greatly an age of fission fuel; cf., [49]. Third, despite being two generations into its nuclear future, mankind has yet to produce a demonstrably effective method of storing the nuclear waste from power reactors [55]; but, here too, generation IV reactors might be of help; cf., [54]. The difficulty is that delivery of generation IV reactors is not envisioned until the 2030s, and could well be delayed by unforeseen difficulties. Therefore, one should not count too heavily upon nuclear powering the postcarbon world: because, despite our being 60 years into the touted Atomic Age, nuclear has yet to fulfill the hopes once vested in it.

Before being accumulated and stored by man, solar energy must first be anthropogenically captured and transformed [1]. The good news about solar is that there is a great deal of it

What does seem likely as the century progresses is: 1) that Earth's dowry of those three bulwarks of nonrenewable (but highly dispatchable) stored energy (C + O + G) will soon be greatly depleted; and 2) that the dispatchable energy we take for granted will become something of a golden legend from bygone days—unless, that is, massive energy storage grows in synchrony with energy generation by intermittent renewables.

C. Massive Energy Storage Is Different

It is different because dispatchability of massive powers has become possible only since mankind gradually became dependent upon fossil fuels and developed life styles that dispatchability made possible. And only when fossil fuels become scarce is dispatchability likely to become recognized as the daunting desideratum that it is. Without dispatchability, our technical civilization could well transform into an under-resourced variety of global refugee camp.

Putting it differently, mankind has always been dependent upon energy derived from the environment. This has, however, been sharply recognized only recently. The history of civilization can now be regarded as one long story of extracting greater absolute quantities of energy, of employing energies of higher quality, and of employing those energies more effectively [52]. Migration to follow food resources (i.e., edible fuel) is prehuman. Storage of food surpluses is prehuman. The origins of stockpiling nonfood chemical fuels are lost in history; and our present day proficiency at it is the result both 1) of gradual unremarked trial and error, and, more recently, 2) of premeditated scientific design. Where mankind comes up short, however, is on massively and efficiently storing energy in nonfood noncombustible forms. Therefore, when supplies of fossil fuels become meager, our technical civilization enters uncharted waters.

D. What History Tells Us About the Rapidity of Previous Transitions in the Supply of Primary Energy and What We Should Expect During the Transition From Fossil Fuels to Renewable Ones

Historically, such transitions have taken generations, several decades to centuries [52], [53]; and 50 years should be considered a rough lower limit for transitions that were driven by economic considerations of a free market within a stable social milieu [10]. Hence, technically, it should be possible to shift to renewables before 2070, the putative exhaustion milestone for fossil fuels (cf., Table 1). But this time could be different.

First, what are the immediate benefits that might entice a nation hastily to change its primary sources of energy before it has to? Probably none, whereas past switches were motivated by the prospect of near-term gain. Within the ambit of the Organization for Economic Co-operation and Development (OECD): 1) the economies of its member nations are today mostly delicate, so that any major reallocation of priorities/expenditures might pit immediately baleful consequences against major but prospective gains in a distant future; 2) today, right now, governmental units are having a hard time balancing their budgets and government financial obligations are becoming more difficult to honor; 3) even cherished social programs are becoming stressful to sustain; and 4) today, right now, civil infrastructure is in need of costly repair, refurbishing, and replacement. Therefore, there will be relentless temptation to let renewable technology develop quietly, to avoid rocking the energy boat, and to await more propitious economic times before trying to switch sources of primary energy.

Anyway, second, is the growth of renewable generation really in a tight race with the exhaustion of fossil fuels? Is a sense of urgency about switching fuels truly justified? Renewable generation clearly is becoming better every year; meanwhile, the jury is out on just when the supplies of fossil fuel will get really, really tight. Moreover, in light of the Free World's production miracle during World War II, does it not seem likely that a "fossil-fuel exhaustion crunch" would simply motivate mankind to belt-tighten and, in only a few years, build the renewable energy generation, actualize the low-loss immensely-flexible smart grid, and provide all the massive energy storage such a grid will need to operate flawlessly? Arguably, maybe.

But, third, remember that the technology to accomplish much of the above has thus far only been envisioned and conceptualized. Call up any energy-relevant industrial organization and ask for firm price, delivery, and specifications on several gigawatts of immediately connected sustainable concentrated-solar-power (CSP) generation or a gigawatt-week of turnkey flow battery MES. The author presumes that you will be told that this is not off-the-shelf technology and that lengthy development will be necessary; also, the ultimate price may be painfully less attractive than envisioned. Indeed, engineering history is littered with technical marvels that did not quite work out as confidently (even reasonably) expected. The Maginot Line was built more or less on schedule, except that its designers failed to get it right the first time, and there was no second chance [56]. The Atomic Age, with its envisioned "electrical energy too cheap to meter [57]," never came to pass; while the safe and permanent disposal of its toxic waste remains an unresolved problem to this day [55]. Likewise, antiballistic missile defense systems have been under development by the United States since 1945, with the first of many major efforts commencing in 1957 [58]; despite periodic publicity and significant expenditures, these programs have limped along for over 50 years [59], with modest interception success occurring only in the past five [60], [61].

E. Can the Envisioned Smart Grid Be Afforded?

Whereas we have but little experience with large-area full-blown multigigawatt smart grids, whereas examples of their ancillary low-loss robust transmission backbones are not yet available for study, and whereas copious hard data on gigawatt-week energy storage do not exist, be it therefore recognized that entrepreneurially reassuring cost estimates cannot be made. At best, analysts must make do with Fermi calculations; cf., [62].

Suppose, as a concrete example, that the United States reduces its primary energy demand to only $\sim$50 quad $y^{-1} \Rightarrow \sim 52.8 \times 10^{18}$ $Jy^{-1} \Rightarrow \sim 1.67 \times 10^{12}$ W_{avg}. Currently, wind energy averages about \$2 per nameplate watt, installed [63]; or, at a cautious capacity factor of 1/4, roughly \$8 per average watt. Thus, the raw generation to take the United States green could cost $\sim$\$13 trillion.[13] Suppose, as presumed above, that this power flow should be backed up by one week of MES; then on the order of $\sim 1.01 \times 10^{18}$ J $= 281 \times 10^9$ kWh $=$ 1670 gigawatt-weeks will be needed. It has been estimated that underground pumped hydro MES would cost about a third of lead-acid battery MES and come in around \$4 per watt-day $=$ 167 \$/kWh [16], [19], [64];[14] this works out to a storage investment by the United States of $\sim$\$47 trillion, which suggests trying to make do with two days rather than a week of MES. Finally, a crude ballpark figure is needed for the cost of 200 000 km of $\pm$750-kV HVDC backbone for a nation-spanning smart grid; because the cost per kilometer of such a structure is so highly dependent upon the local circumstances of each link, a pessimistic flat cost of \$2 million km^{-1} will be assumed (cf., [65]), thereby yielding a total cost of $\sim$\$0.4 trillion and emphasizing that the installation costs of transmission will be minor compared to those of generation and storage.

If then the decision is made to dial back storage capability to only two days, the total cost will be $\sim$\$28 trillion (give or take a factor of 2), slightly less than two years of America's recent Gross Domestic Product (GDP) of $\sim$\$15 trillion. Spread over 50 y between now and 2070, this would require $\sim$\$0.6 trillion y^{-1}. This is only 4% of the GDP, roughly twice what was spent building railroads and canals in the decades immediately preceding the Civil War; only America's economy is much more mature now than then. More importantly, that 4% is markedly less than the 7.6% of GDP that America's businesses allocated to capital expenditures in the peri-recession year of 2010 [66], [67]; and, if it were to be phased in over a few years, the economy would probably adjust unremarkably. But it bears noting that the longer the United States dithers on the renewable energy issue, the bigger will be the fraction of the GDP required: 4% will become 6%, will become 8%, etc.; and, before you know it, the fraction needed will be disastrously large.

F. A Somewhat Pessimistic Interpretation

Although the United States may not today have in place as appropriate a STEM and manufacturing complex as it had in place at the start of World War II, there still may be

[13]In fact, recent data from the National Renewable Energy Laboratory (Michigan Wind Working Group, "New wind maps and resource potential estimates for the United States," March 31, 2010) indicate that the wind from only prime locations within the United States ought to be able to deliver three times the 50 quad needed.

[14]If this seems insanely expensive, please note that this is equivalent to about 46 \$/MJ of turnkey MES. By comparison, a typical 12-V storage battery (as for an automobile) turns out to cost around 50 \$/MJ, but one then has to expend much money buying and installing the electronics for monitoring and recharging. The reputed cost of battery storage to be installed on Hokkaido (Japan) is approximately \$204 million for 60 MWh, or about 950 \$/MJ.

time for it to react to the approaching end of the Age of Fossil Fuel. With the time available, it might yet be possible to clarify the technical issues and create a sustainable smart grid with renewable generation, robust and deftly managed transmission, and ample MES. And it does seem as if the economic demands of the task, though onerous, could be met—by the United States.[15] This accords with other recent studies, e.g., [6] and [68]–[71], but is at variance with the rarer more pessimistic ones, e.g., [72]–[74].

However, despite an infectious gee-whiz enthusiasm for smart grids, there is little compelling evidence for the political will needed actually to put in place policies likely to result in the final development and deployment of the building blocks that might be used in a nation-spanning smart grid.[16] Unfortunately, once the oil shocks of the 1970s had passed, funding for energy research, development, and demonstration fell sharply in the United States and has not yet recovered [75]. Currently, similar underinvestment in energy, especially renewable energy, is widespread throughout the world [76]–[78]. Yet, without real test data from real large-scale demonstration projects, neither the United States nor the world can make sensible strategic decisions on our energy future. And without those sensible decisions, the world will risk terrible economic harm when fossil fuel becomes scarce and a bidding war ensues for that which is left.

[15]How well the burdens of going green could be borne by less affluent nations is a matter of speculation, as is what will happen to those nations that neglect to so much as try.

[16]Public perception of the present energy situation was evaluated on April 4, 2014, by a Google search of the following terms for items updated during the past month: "fuel price," 69×10^3 hits; "smart grid," 139×10^3 hits; "massive energy storage," 31 hits.

VI. CONCLUSION

The data and derivations set forth in this contribution constitute at least several scintillae of evidence, probably a preponderance of evidence, and possibly even *prima facie* evidence that, by the close of this century: 1) the world will be approaching exhaustion of its recoverable fossil-fuel supplies; 2) the energy shortages engendered thereby can reliably be avoided only if immediate massive steps are taken to actualize the development and manufacture of the many unproven components of a global smart energy system; and 3) the world over, there is precious little evidence (as measured in G\$ y^{-1} of new funding for development and demonstration) that world governments are seriously concerned. ■

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