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Massive Electricity Storage for a Developed Economy of Ten Billion People

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ABSTRACT Presently, America's average electrical power consumption is ∼1.3 kW/p; in the world as a whole, it is ∼0.33 kW/p. If, for 2050, a world goal of 1 kW/p is adopted, this implies an average electric power draw of 1 GW for each population cohort of 1 000 000 residents; and the Earth will have ∼10 000 such cohorts. Multi-hour outages are already common; demand peaks daily; and renewable generation is intermittent. Hence, as a hedge against rare supply failures, each cohort would profit from local backup storage of electricity/energy in the order of 1–2 GWd. For comparison, the biggest electrochemical storage scheme yet seriously proposed will contain ∼240 MWh, while most of the largest pumped hydro storage reservoirs are <50 GWh. In approximately 50 years, when fossil fuels have become scarce, we should already have constructed this bulk storage. This review argues that the principal contenders for the storage of electricity in bulk are: 1) electrochemical storage in flow batteries; 2) chemical storage in agents, such as ammonia, hydrogen, methanol, or light hydrocarbons; 3) compressed air energy storage; and 4) underground pumped hydro. Finally, it will argue that not one of these four contenders has yet been built, tested, and perfected, while virtually none of the needed storage capacity exists today.

INDEX TERMS Energy storage, exhaustion of fossil fuels, intermittency challenge, massive electricity storage, underground pumped hydro.

I. INTRODUCTION

Mankind is on a trajectory towards exhaustion of our planet's supply of economically recoverable fossil fuels [1]. When that inevitable exhaustion has been accomplished, possibly around the end of *this* century, whatever electrical energy is consumed by our civilization must be derived from renewables or (possibly) nuclear. And that means we risk losing the convenient electricity-on-demand to which we have become accustomed — unless, of course, we have had the foresight to build massive electricity storage[1] sufficient to buffer the variations of supply and demand, accumulating energy during times of abundance and disbursing it during times of scarcity[2] [2]–[4]. This essay endeavors both to foresee the significant challenges that will be encountered in constructing such storage and to suggest realizable solutions to those challenges. It will proceed in easy stages.

First, in Section II, pertinent data will be presented to document (i) present electricity consumption in both developed and developing economies, (ii) historical per capita electricity use in the United States, and (iii) the correlation between Human Development Index (HDI) and per capita electricity consumption. From these data the global electricity demand in the year 2050 will be forecasted.

Second, in Section III, the estimated values of the planet's Ultimately Recoverable Resources of coal, natural gas, and petroleum will be documented. From these data, Fermi calculations will be made of the time remaining during which mankind can count on electricity generated by fossil fuels. This calculated time remaining will be rather less than a century.

Third, in Section IV, the concept of the Intermittency Challenge—the problem of buffering the interaction between primary electricity generation and instantaneous user demand—will be introduced. Due warning will be given of the danger posed by positing *deus ex machina* solutions.

Fourth, in Section V, and based upon a study of Steven Chu's celebrated Ragone diagram, the only four obvious solutions will be identified and critiqued.

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[1] The term 'massive electricity storage' is vague because 'massive' has no agreed upon definition. In the context of this paper, it will be defined as 'at least one gigawatt-day [GWd]'. This follows from the projection that, in 2050, the planet we be home to approximately 10^{10} persons, each seeking a lifestyle undergirded by approximately 1 kilowatt of reliable electricity. Therefore, a typical geographical enclave of a million persons should desire at least 1 GWd of backup electricity storage sited locally because (i) the modern world doesn't operate without electricity and (ii) backup a few hundred kilometers away is not very helpful if the grid fragments.

[2] The future being unknowable, the reality of this forecast risk can not be demonstrated rigorously. However, recent models of intermittent renewable generation seem uniformly to recognize a necessity for at least some form of electricity storage [2]–[4]. The type and quantity of such storage is open to debate.

Fifth, in Section VI, the possibility of actually deploying the requisite massive electricity storage will be examined in the light of historical experience.

Sixth, in Section VII, the more important forecasted outcomes will be summarized.

In contemplating electricity demand, one has no assured basis of foretelling the future as in Rational Mechanics but must be content with statements of likelihood as in Weather Forecasting.[3] We can not reliably predict the future: yet we can, based upon past events, anticipate likely future events, against which we would be well advised to hedge. It is as Apollonius of Tyana put it in the 1st century: "*…the Gods perceive future events, men what is happening now, but wise men approaching things…*" [5, Sec. VIII.7.27]. In this paper, the Author intends to document a variety of trends, which taken singly may seem innocuous; but, allowed to persist unmodified, they could concatenate into a perfect storm of electrical energy scarcity. And he requests of any who take strong objection to his dread of "approaching things": (i) please, if, as sovereign remedies for the Author's imagined dangers, you choose to cite future technical breakthroughs not yet realized, then pause and ask whether the underpinnings of your optimism are demonstrably sturdier than the underpinnings of the Author's alarm; or (ii) if you prefer to dismiss the Author's projections as hokum, hesitate, reconsider the factual underpinnings of your conclusion, and meditate upon Dator's Second Law of Futures that "*any useful idea about the future should appear to be ridiculous*" [6].

II. ELECTRICITY CONSUMPTION

A. INTRODUCTION[4,5]

Because the future is unknowable, making forecasts that transcend mere guesswork requires approximate estimation of a sort popularly termed Fermi Calculation, after the Nobel Laureate physicist Enrico Fermi who employed it with legendary deftness [7]. As used here it involves uncovering reliable-seeming data of acceptable provenance, carefully citing them, and then putting them to work in simple models to approximate quantities of interest. The answers thereby generated are not expected to be correct to a tenth of a percent, but merely to provide estimates off target by no more than 25%. If, for example, carefully reasoned predictions of electricity supply and demand a generation hence are found to differ by only a few percent, that probably is not worrisome; if they differ by a factor of 2, that is large enough to warrant immediate attention; if they differ by a factor of 10 or more, that probably is cause for intense alarm.

Massive electricity storage for ten billion people in the latter half of this century is a task so far outside the historical experience of humanity that even conservative estimates of how much of it will be desired, are daunting. Just thinking about how it might be provided should tempt one to concoct jaw-dropping mega-schemes involving joules and dollars and watts coupled with SI prefixes such as "giga" or "tera" or "peta" or even "exa", quantities beyond the effective comprehension of most citizens. A too frequent fate of such mega-schemes is unwitting avoidance by implicit denial. Often this can take the form of citing an *envisioned* technology, which (if successfully actualized) would make an immense difference[6] [8]. Decision makers, however, should avoid this trap and instead ask: If the Fermi calculations (based upon current trends) that provoked the mega-schemes were to be off by only a factor of only two,[7] would our global society still face trying times? If so, do not the decision makers have a clear and present duty to counter with their own independent calculations based on extant and proven technology. And, if these new calculations turn up numbers remotely close to those encouraging the avoidance, ought not the decision makers be obligated to respond proactively? Prudent avoidance of the challenge for a few election cycles while the future becomes clearer, could be misinterpreted as kicking the can down the road to where someone else has to deal with it!

TABLE 1. **Hard data for 2010 on population and electricity consumption. Closing the gap between the OECD countries and the rest will not be easy.**

Population Statistic	**Value**						
World Population	6.825×10^9						
World Electricity Consumption	19738 TWh $y^{-1} = 71.06\times10^{18}$ J y^{-1}						
OECD Population	1.232×10^9						
OECD Electricity Consumption	10246 TWh $y^{-1} = 36.89\times10^{18}$ J y^{-1}						
World *per capita* Power	3.156×10^9 J $y^{-1} \Rightarrow 330$ W						
Non-OECD *per capita* Power	6.109×10^9 J $y^{-1} \Rightarrow 194$ W						
OECD *per capita* Power	29.94×10^9 J $y^{-1} \Rightarrow 949$ W						
Calculated removal-of-inequity times							
Closure of gap requires [y]	10	20	30	40	50	75	100
If non-OECD steadily grows [% y^{-1}] faster than OECD	17.2	8.3	5.4	4.0	3.2	2.1	1.6

B. PRESENT WORLD ELECTRICITY CONSUMPTION

Tab. 1 presents 2010 electricity consumption data for the OECD and non- OECD worlds ([9, p. 48).[8] Total consumption in the two worlds is roughly the same, but the per capita annual consumption is roughly five-fold greater within

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[3] In fact, it may well be that futurologists do not agree on which aspects of the future are most deserving of attention. For example, the journal Futures published some 1387 articles during the period January 2000 through October 2014. A Web of Science search of these articles found only 90 had as a principal topic "energy". And only 2 of the 90 had as a secondary topic "energy storage", the chief focus of this article.

[4] Abbreviations (including units not commonly employed in SI): bbl, barrel (of oil, equivalent); d, day; kcf, 1000 standard cubic feet; p, person; scf, standard cubic foot (of natural gas, equivalent); scm, standard cubic meter (of natural gas, equivalent); st, short ton of 2000 pounds; toe, metric tonne of oil equivalent; URR, ultimately recoverable resource;

[5] Where appropriate, pointers will be given to page (p.), section (s.), chapter (ch.), equation (eq.), figure (fig.), table (tab.), appendix (app.), or experiment (expt.) of the of the pertinent reference.

[6] Thus the output-sluggish behavior of present nuclear generating plants can be envisioned away by small modular reactors. Unfortunately, the latter have been extant for over fifty years and have yet to fulfill their promise [8].

[7] The factor-of-two leeway is intended to shift attention away from the immense savings that can be realized by conservation and onto the enormous energy need that will still exist after the conservationists' best efforts.

[8] OECD is the acronym of the Organization for Economic Co-operation and Development, a consortium of what it considers to be "developed economies".

the OECD than outside it. If this gap is to be closed by 2050, the annual increase in per capita consumption of the Have-Nots of the World must exceed that of the Haves by about $4\,^3/_4\%$. Closing this gap is by no means impossible but seems improbable, given the rumors of political venality scattered about by the media. However, the economies of the developed countries currently are not growing as much as their electorates would wish, while whose of China and India have exceeded five percent over the past two decades [143]. Therefore, it will be assumed that, in 2050 and integrated over all humanity the average electric power draw attributable to a typical individual will be 1.00 kW. As shown in Tab. 1, it is already 330 W; and further electrification is greatly valued by developing economies. Additional justification of this last assertion will be provided in Section 2.D below.

C. HISTORICAL ELECTRICITY CONSUMPTION IN THE UNITED STATES

The historical growth of electricity consumption in the United States is shown in Fig. 1 as an illustration of the development of a well developed, well industrialized, and arguably emulated economy. It is seen that, for as long as records have been kept, the general was upwards and supralinear until the late 1970s, when it changed to increasing linearly until about 2000; thereafter, it was fairly steady for a few years and currently may be decreasing slowly. There is still room for significant increase in efficiency of use in both lighting and building climate control; and so it may decrease still further. On the other hand, increasing penetration of electrified personal transportation may reverse the trend.

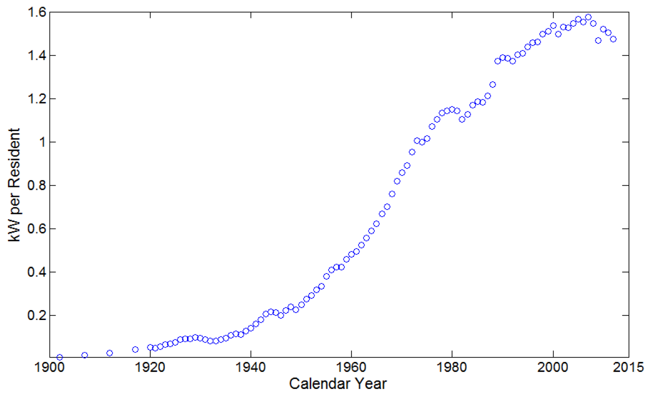

FIGURE 1. **Average steady-electric-power-consumption-per-resident in the United States as a function of year. Data on resident population were from the 1975 edition of the Historical Statistics of the United States ([10, Table Aa7]) for the period 1902-1970, and from the United States Census Bureau ([11]; [12]) for the period 1971-2012; data for electrical energy usage were from the United States Census Bureau ([13, Table S 120]) for the period 1902-1948, from the U.S. Energy Information Administration ([14, Table 8.2a]), and from the U.S. Energy Information Administration ([15, Table 7.2a]) for 2012.**

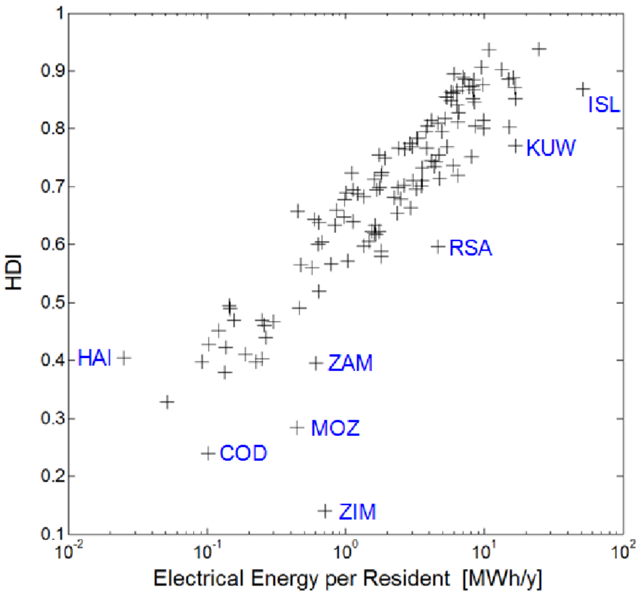

FIGURE 2. **Human Development Index (HDI) versus annual Electric Energy per Resident. Conspicuous outliers from the main logarithmically-varying pack are labelled with their three letter IOC country codes.**

D. ELECTRICITY AS AN ADJUVANT OF INCREASED QUALITY OF LIFE

Electrification has justifiably been labeled the "*greatest engineering achievement*" of the Twentieth Century [16]. And to anyone who has travelled in the developing world, it does seem as if both the quantity and the quality of the electrification do correlate with the apparent prosperity and quality of life of the community. This suspicion can be quantified. Fig. 2 displays a country-by-country plot of HDI [17] vs. per capita annual electricity consumption [18]. It would seem as if the Human Development Index increases linearly with the logarithm of the per capita annual electricity consumption: although this is not unexpected [19], why it should be so is unclear.[9]

1 MWh y^{-1} translates to 0.114 kW, which by Fig. 2 implies that a steady 1 kW *per capita* should deliver an HDI in the range of 0.88 ± 0.05. That is, the 1 kW- assumption of Section II.B should, other things being equal, suffice to sustain what most of humanity would deem an enviable quality of life. Certainly, a qualitative perception exists that a greater consumption of electricity in one's life associates with a better more contented life and should serve as a powerful driver of electricity demand throughout the developing world [20][10]: public desire for more electricity, whether or not it is met, can be expected to remain strong in the decades to come.

E. FORECAST WORLD POPULATION GROWTH IN THE TWENTY FIRST CENTURY

The current population of the world is reckoned to be around 7.2×10^9p. Of these some 78% have access to electricity

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[9] Obviously, this trend can not continue much farther in either direction along the consumption axis because HDI is, by its definition, constrained to the interval [0,1].

[10] For example, economists expect "near-universal saturation of air conditioning in all warm areas within just a few decades" [20]. This would include such populous nations with developing economies as India, Indonesia, and Nigeria; and it should result in a huge increase in electricity demand.

([21, Table 3.7]), while individuals numbering $\sim 1.6\times 10^9$ do not.

Nobody knows how many people will be on Earth in 2050; but the best estimate of the United Nations was 8.9×10^9, with an upper bound of 10.6×10^9 and a lower bound of 7.4×10^9 [22]; more recent studies have modestly increased these estimates [23]. Therefore, it will be assumed that, in 2050, the population of earth will be roughly 10×10^9 p.

F. FORECASTED WORLD ELECTRICITY CONSUMPTION IN 2050

Presumably, most people who exist in 2050 will yearn for ample supplies of electricity because electricity is commonly accounted an adjuvant of better living; and besides, there is negligible evidence of a high Human Development Index in the absence a high rate of electrification ([24, Table 12]).

Assuming optimistically (i) that power consumption within the OECD could, with determined conservation, asymptote at around 1000 W per person and (ii) that the non- OECD per capita consumption will also reach that level in 2050, implies that ten billion consumers could require an average generation of $\sim$10 TW : this is roughly ten-fold the current nameplate capacity of America's generators. To meet such a demand will require a global electricity production of $\sim$87600 TWh y^{-1} or $\sim 320\times 10^{18}$ J_e y^{-1}. If these electrical joules are to be derived from fossil fuel combustion in typical steam plants, then – due to Carnot inefficiencies – more thermal primary energy will be needed: $\sim 1000\times 10^{18}$ J_{th} y^{-1}, or $\sim 160\times 10^9$ barrels per year of petroleum ([25], s. 45K(d)(5)), or $\sim 34\times 10^9$ metric tonnes per year of coal [26], or $\sim 27\times 10^{12}$ standard cubic meters per year of natural gas [26]; alternatively, this amounts to $\sim 24\times 10^9$ toe (tonne of oil equivalent).[11] These figures are far in excess of the World's current annual production [9] of oil ($\sim 4.2\times 10^9$ toe), coal ($\sim 3.5\times 10^9$ toe), or natural gas ($\sim 2.7\times 10^9$ toe). And this is to provide in 2050 just the electricity for a world that is based on today's technology but has eliminated electricity poverty, a world in which the Haves and the Have-Nots can not be readily identified on the basis of per capita electricity consumption: energy generation for transportation or process heating, which today proceeds largely without electrical intermediate steps, is not considered [27].[12] As the fossil fuels bequeathed mankind are used up the demand for renewable energy and its associated storage solutions will markedly exceed that which arises from electricity use.

One final electrical supply issue should be mentioned. Could not countries with enviable supplies of fossil fuel impose stringent export controls on those supplies and, while everyone else regressed, live in isolated warmth and luxury for the centuries it took them to run through their happenstance endowments? For a number of practical reasons: definitely not! First, this is one world; and at least some of the energy have-nots will be well-informed, populous, and well-armed, even with nuclear weapons. One can not count upon *all* the leaders of *all* the energy-starved countries to accept supinely the lousy hand that Nature dealt them resource-wise. Such a situation could become extremely unstable. Second, the energy Haves would merely be postponing their own inevitable day of reckoning. Rationally, most nations should eventually conclude that massive cooperation increases for all the chance of a smooth transition from the Age of Fossil Fuels to an Age of Renewable Energy. Third, even though an acceptable transition might come to pass willy-nilly and even though there is insufficient historical precedent for dogmatically asserting that it will not come to pass, an every-man-for-himself response to the challenge is plainly unjust [28], [29].[13]

In addition to assuring an adequate supply of electrical energy, the world of 2050 must, if it is to be sustainable, also assure a sustainable supply of mineral resources. This task is predicted to be, with much much effort, tractable: but only if the sustainable energy hurdle has already been successfully jumped [30], [31].

G. INFLUENCE OF IMPROVED EFFICIENCIES

Many of the above comments may, in retrospect, have to be modified because of advances in (i) demand-side energy efficiency, (ii) demand response, and (iii) supply-side energy efficiency, none of which can be predicted with assurance. There is however, little obvious evidence that should cause the Reader to suspect that World per capita electricity demand will do other than increase monotonically from its present 330 W p^{-1} (cf. Tab. 1) to some higher value in 2050. It would therefore prove surprising if the demand of 1000 W p^{-1} predicted above for 2050 were to be off by more than a factor of two. Qualitatively, a factor of two error would have little effect on the urgent need for the massive electricity storage that is demonstrated below.

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[11] Often it is hard to translate joules into the non-metric units employed in practical energy calculations. The "barrel of oil equivalent" or "boe" is defined by the U.S. Internal Revenue Service as precisely 5.8 million Btu [25], which – employing thermochemical calories – yields the SI equivalence $\sim$6.115 GJ per boe; the Reader is cautioned that this value is nominal only and that the actual caloric content of a particular barrel may vary by a few percent from this defined equivalence [9]. The "tonne of coal equivalent" or "TCE" is defined nominally as 7E09 calories [26], here taken to be thermochemical calories; and thus, 1 TCE = 29.288 GJ, although considerable variation is to be expected from coal seam to coal seam ([9, p. 59]). The natural gas is traditionally measured in "standard cubic feet" for which a nominal caloric equivalent is 1000 Btu per cubic foot, which translates into $\sim$37.24 MJ per cubic meter; once again, there is considerable variation from gas field to gas field ([9, p. 60]). Alternatively, the energy content of any source of fossil fuel can be measured in terms of: 1 metric tonne of oil equivalent = 1 toe = 10E09 thermochemical calories =$\sim$ 41.84 GJ

[12] There are many kinds of energy in addition to electrical. And poverty in almost any of them can result in a sadly reduced quality of life [27].

[13] "Justice" is not commonly cited in the dispassionate realm of science. But this contribution is about engineering an electricity supply. And, within the United States, a B.S.E.E. engineering program that does not counsel its students on "an understanding of professional and ethical responsibility" is in danger of losing accreditation [28]. Moreover, Rawls' celebrated "Veil of Ignorance Test" would clearly mandate at least approximate equality of access to electricity [29]. And so would the Golden Rule (Matthew 7:12). The non-OECD five-sixths of humanity should not be uncharitably abandoned to fend for themselves.

III. WORLD RESOURCES OF FOSSIL FUEL

A. INTRODUCTION

Since the Pearl Street generating station came on line in 1882, developed economies have enjoyed the benefits of massive energy storage. This has always been visible as the coal pile behind the generating station, and almost no utility customers ever remarked upon this because they never connected the dots. Today that fossil fuel is rapidly being depleted and is forecasted to be nearly gone and rather costly within a few decades [1], [32], [33].[14]

B. ULTIMATELY RECOVERABLE RESOURCES

With respect to a particular nonrenewable substance, the ultimately recoverable resource is ''an estimate of the total amount of [that substance] that will ever be recovered and produced. It is a subjective estimate in the face of only partial information.'' [34]. Moreover, the estimated URR is subject to revision as the economic worth of the substance varies and as the technologies of extraction change. Nevertheless, there are two useful rules of thumb: (i) when resource depletion becomes so marked that the processes of extracting the substance costs more money than will be received when the substance is marketed, the substance ceases to be recoverable; and (ii), when the substance is a fossil fuel and a deposit becomes so lean that the energy stored in the substance is less than the energy expended extracting the substance, then the substance likewise ceases to be recoverable. Useful subsets of the URR are [34]: (i) proved reserves, the subset that is still recoverable with 90% probability; (ii) probable reserves, the subset that is still recoverable with 50% probability; and (iii)) possible reserves, the subset that is still recoverable with 20% probability.

Whenever a substance is nonrenewable and mankind is consuming it at a rate that will soon exhaust the URR, mankind is facing a crisis. Therefore, especially for fossil fuels, a more informative measure of the exhaustible substance is the Remaining Recoverable Resource (RRR): URR is an interesting historical datum, but what counts geopolitically is how much of the realistically recoverable stuff is left.

C. COAL IS RUNNING OUT

The October 2013 prediction from Professor David Rutledge of the California Institute of Technology is that 90% of the World's economically recoverable coal will have been recovered by 2067 [35]. Because his quantitative methodology has been so successful in modeling the exhaustion of already depleted coal fields, his date of 2067 should be taken seriously. Moreover, quantitatively similar predictions abound [1], [36]–[40].

The URR of coal has been estimated by several different authors. Mohr and Evans [36] predicted a URR of 700-1243 Gt. Höök et al. ([38, Table 4]) predicted ∼1000 Gt. Rutledge [41] predicted 653-749 Gt. These predictions average out at around 860 Gt.

D. PETROLEUM IS RUNNING OUT

First, recent studies predict that oil resources also are being depleted and will, by the end of this century, be sharply diminished [1], [32], [40], [42]–[44]. Second, ''From the beginning it was plain that only a finite amount of oil was in the ground and that no level of production, however low, could be maintained indefinitely. But as long as oil was being discovered faster than it was being produced, this limitation was a matter of only vague concern.'' ([45, p.648]). Petroleum discovery, though complex, does seem to follow certain simple rules: (i) most of the petroleum in a region is contained in a few large fields [45]; (ii) when a region is explored, its large fields are discovered early [45]; (iii) giant oil fields (URR above 0.5 Gbbl) are responsible for ∼60% of world production [46]; (iv) in recent decades the discovery of giant fields has fallen precipitously [46]; and (v) for the past thirty or so years the consumption of oil has exceeded the discovery of new reserves ([47, Fig. 5.10]).

The data analyses of Brecha [44] suggest an estimate range of 2-3 Tbbl for ultimate planetary petroleum production. Therefore, for Fermi calculations, a reasonable URR value for Fermi calculations could be 2.5 Tbbl.

E. NATURAL GAS IS RUNNING OUT

Natural gas, oil, and tar sands are different end points achieved by the same basic geological processes ([32, Ch. 4): just as oil is a finite resource that is running out, the same is to be expected of natural gas - although its timeline may be modestly different ([1, Fig. 5]).

F. THE SIZE OF THE PLANET'S DOWRY OF FOSSIL FUEL

Fermi estimates of the planet's RRR of fossil fuels are provided in Table 2. It seems clear that, if the World's developing economies are to achieve Human Development Indices characteristic of present OECD economies, fresh energy supplies must be developed. Even if the projections of Table 2 are off by a factor of as much as three, the situation is still dire. For remember that Table 2 considers only the energy needs of traditional electricity generation: the demands of process heating in industry and the demands of transportation were not included.

The seriousness with which one should take such gloomy projections may seem questionable given the Reserves/Production (R/P) numbers presented by BP's 2015 *Statistical Review of World Energy* [48]. Nevertheless, the Reader should not be lulled by these well-intentioned statistics: R/P numbers above fifty mean only that production sufficient to meet the current rate of consumption may be sustainable for fifty years or so, whereas the looming anticipated shortages arise from the vastly increased consumption predicted to arise within the five-sixths of the World's citizens who live in developing economies. And who would dare suggest that their Human Development Indices should not

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[14] Do not be lulled into potentially unwarranted complacency by projections that stop at 2035 or 2040. It's the latter half of the century when painful scarcity is projected to become unmistakable.

TABLE 2. **Nominal fossil fuel equivalents of 1000×10^{18} J_{th} y^{-1} in terms of bbl y^{-1} of petroleum, t y^{-1} of coal, and m^3 y^{-1} of gas. Plus 2012 production. Plus an optimistic estimate of Remaining Recoverable world Resources (RRR). Plus the number of years that each of the three RRRs could, unaided, supply 1000×10^{18} J_{th} y^{-1}. For those who are curious, the abbreviation 'bbl' is the recognized abbreviation for 'barrel' ([49], s. 9.58); this abbreviation antedates both the American oil industry and its standard 42 gallon barrel [50].**

Fuel	Equivalent of 1 ZJ_{th}	Production 2014[a]	RRR, URR, etc. 2014	Lifetime at 1 ZJ/y[d]
Petroleum	160×10^9 bbl	32×10^9 bbl	~2.5×10^{12} bbl [b]	< 16 y
Coal	34×10^9 t	~5.6×10^9 t	~890×10^9 t [c]	< 26 y
Natural Gas	27×10^{12} m^3	3.5×10^{12} m^3	~350×10^{12} m^3 [b]	< 13 y

[a] BP Statistical Review 2015 [48]. The energy content of a tonne of coal varies with the deposit, but is cited nominally as 29.3 GJ t^{-1} [26].

[b] Proved reserves [48] plus undiscovered resources [42].

[c] Proved reserve [48]. At least one expert would consider this proved reserve to be larger than a realistic estimation of the URR [41].

[d] Column 4 divided by Column 2.

be allowed to catch up with those of citizens within the developed economies?

A World Economy based upon energy from exhaustible fossil fuels therefore faces a triple whammy: (i) World population is growing; (ii) within developing economies, expectations and consumption are growing; and (iii), as a result of production and consumption, the resource bases themselves are shrinking rapidly. These trends combine to expand global demand for the benefits of fossil fuels while simultaneously diminishing mankind's dowry of those fuels: what appears today to be an ample reserve can become depleted with startling rapidity.

But suppose, for example, that vastly increasing fossil fuel usage could continue unabated until the end of this century. Should this make anyone feel markedly better? Certainly not, because it would merely postpone by a few decades the date at which the fossil fuel did indeed run out, and that at the cost of significantly increasing the atmospheric CO_2 burden.

IV. RENEWABLE ENERGY AND ITS CHALLENGES

A. INTRODUCTION

On no timescale relevant to human evolution is renewal of our rapidly depleting fossil fuels resource a rational possibility: when what we now have is used up, it is gone forever [32].

Fissile nuclei are, *sensu stricto*, a finite resource, even though their supply can (in principle) be extended by neutron irradiation of rather more common fertile but non-fissile nuclei. The ultimately recoverable resource (URR)[15] of naturally occurring fissile nuclei is a matter of debate, as is the case with the better studied fossil fuels [40]. The supply of fertile nuclei (e.g., ^{232}Th and ^{238}U) is very large so that (in principle) "breeding" of fissile nuclei by irradiating fertile nuclei with neutrons could supply many thousands of years of fissile material. A significant impediment to a nuclear fission solution is that safe and profitable breeding has yet to be well-demonstrated, despite decades of off-again on-again research activity. A major downside to fission power is the generation of large quantities of radioactive waste that must be somehow be permanently and safely disposed of; and nigh seventy years into the "atomic era" this problem has not demonstrably and unequivocally been solved [51]. Nuclei for use in fusion reactors are much more abundant, but profitable fusion reactors have neither (i) been built nor (ii) been operated safely and for extended periods; moreover, they too should generate long-lived radioactive waste. In summary, there is widespread doubt that anthropogenically generated nuclear-based power can meet the World's electricity needs [8], [52]–[56].

If a nuclear reactor of some sort is not a realistic source of sustainable power, then one must fall back upon the renewables. Two eminently readable treatises on renewable/sustainable energy are those of Armaroli and Balzani [57] and of MacKay [58]; the latter is notable for its dedication (p. vii) "*to those who will not have the benefit of two billion years' accumulated energy reserves*". For readers in a hurry, the review article by Abbott ([59, pp. 48–52]) provides a compact no-nonsense summary of the relevant numbers: solar radiation and wind, both conspicuously intermittent generators of electricity, are the obvious hegemonic sources; and the others are anticipated to be niche players only.

B. MATCHING SUPPLY AND DEMAND: THE ACHILLES' HEEL IS MASSIVE ELECTRICITY STORAGE

Early in the Twentieth Century, the celebrated radio pioneer Reginald Fessenden pithily described the challenge of electricity storage [60]:

> "*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.*"

This Intermittency Challenge is with us still, so much so that the World's questionable technological preparedness has been memorialized by calling massive electricity storage "the Achilles' heel of renewable energy" [61].

If electricity storage of requisite quality and quantity does not become available in timely fashion, then both

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[15] In the definition of "recoverable", there is a caveat (often unspoken) that the energy return on the energy invested (EROI) shall be large enough to enable the entire energy system to operate at an energy profit [31].

''developed'' and ''developing'' economies will most probably stagnate and, in some cases, may regress egregiously. Worse yet, nations with grossly underdeveloped economies can be expected to remain mired in poverty. The Industrial Revolution, which drove mankind's three centuries of remarkable ascent from poverty and grinding manual labor, was itself powered by fossil fuel: and fossil fuel is finite.

As it would be most unwise to bungle the transition from the Age of Fossil Fuels to an Age of Renewable Energy, we should presumably develop storage facilities for massive amounts of electrical energy. The quantity of such storage is readily estimated by noting that, the world around, the populations detest interruption of their electricity supply. Absolute safety of supply is not achievable, but a hundred hours of backup would be enough to ride out most catastrophes. The quantity the World would need works out to be on the order of 1000 $\mathrm{TW_eh}$.[16]

C. STEADY-OUTPUT GENERATORS OF ELECTRIC POWER ALSO PROFIT FROM ELECTRICITY STORAGE

A practical device for ''storing'' massive quantities of electricity *as electricity* seems not at present exist [62]. However, as suggested by Fessenden [60], the energy can be converted into a form that can be stored; and the stored form can, at will, then be back-converted into electricity. Thus, for practical purposes, an electrical storage device can be thought of as a sort of ''granary'' for electricity, storing when electrical energy is in surplus and disbursing when it is in deficit: in concept it should work equally well, either with solar photovoltaic generation on a day of scudding clouds or with nuclear plant generation, which is output-sluggish and hard to match to diurnally shifting consumer demand.

D. UNTESTED SOLUTIONS TO THE INTERMITTENCY CHALLENGE SHOULD BE DISCOUNTED

In theological terms, ''*faith is the assurance of things hoped for, the conviction of things not seen*'' (Hebrews 11:1). But faith-based decisions in practical energy policy are better replaced with the epigram ''hope makes an excellent travelling companion but a poor guide.'' For, while many papers are written in which the merits of massive electricity storage are modeled, the evidence for the existence of such storage is sparse [63]–[66]. To be specific, if one defines ''massive'' as ''at least one gigawatt-hour'' and consults the U. S. Department of Energy's ''Global Energy Storage Database'' [67], one discovers that the database does not sort entries by energy capacity! If instead one tries 'at least 250,000 kW rated output' plus 'at least 4 h operation at rated output', one comes up with 37 projects that have a record of successful operation: all are pumped hydro and only 10 exceed 9.9 GWh, the largest being 39.1 GWh. This last figure is minuscule compared to the electricity storage that will be desirable in an era of renewable energy: it misses the impending need by perhaps four orders of magnitude!

Some Readers may stand firm in their belief that modern science and technology will, when the need becomes urgent, triumphantly surmount the technological challenges facing mankind. They are requested to study the cautionary tales presented *in extenso* in the Appendix: the history of technology abounds with compelling ideas that just did not work out as expected. *Deus ex machina* solutions may have been a useful devices in classical drama, but they have no place in guiding the course of nations.

V. THE RAGONE DIAGRAM AND ITS CONSEQUENCES

A. INTRODUCTION: THE STORAGE ''SMORGASBORD''

A storage facility for electrical energy is conceptually decomposable into three parts: (1) an input energy conversion module, which accepts electrical energy from (for example) a grid and converts it to a storable form; (2) an energy storage module, which actually warehouses that storable form; and (3) an output conversion module, which back-converts the stored form into electrical energy to be transported over the grid. Such a storage facility will typically be described by a Ragone diagram[17] that displays two of the three variables: (i) the maximum rate (W) of energy conversion to/from the stored form; (ii) or the time (s) that this maximum rate can be sustained; or (iii) the rated capacity (J) of the storage module. A typical Ragone diagram is shown in Figure 3. The many colored areas indicate roughly (very roughly) the current operating ranges for single units within the ''smorgasbord'' of available storage technologies [67]; but all these technologies can in principle be stretched by building bigger or by combining storage units in series or parallel.[18] What are vital to massive electricity storage are those technologies that appear in the upper right of the diagram, because (i) that corner is where *extant* massive storage technologies are located and

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[16] A Fermi estimation of how much storage will be needed could proceed like this. The public tends to be understanding of outages due to rare acts of God (e.g., a typhoon) but impatient of outages due to infrastructural inadequacy. Because solar and wind generation are so notably intermittent, fours days backup storage should not be viewed as excessive. Therefore each cohort of a million people would probably like $(10^6\ \mathrm{p})\times(1000\ \mathrm{W_e/p})\times(100\ \mathrm{h}) = 100\ \mathrm{GW_eh}$. In 2050, we may need to service 10,000 such cohorts.

[17] Attributed to David V. Ragone, then of Carnegie Mellon University, who introduced it during a meeting presentation in 1968 (Review of Battery Systems for Electrically Powered Vehicles. SAE Technical Paper 680453. doi:10.4271/680453).

[18] The Reader's attention is called to the ancient Scots adage, ''Many a pickle makes a mickle.'' It is indeed true that massive quantities of electrical energy could surely be stored in enormous arrays of small batteries, perhaps widely distributed. That would, however, tend to spread the care of the batteries over large numbers of individuals, each of whom would have to be trained and vetted. Moreover, the largest operational battery array listed in the DOE Global Energy Storage Data Base [67] is the Rokkasho Village Wind Farm array of sodium-sulfur batteries, rated at only 0.24 GWh. This is minuscule compared to the storage needed to back up electricity for ten billion users.

There is no intent on the Author's part to rule out enormous arrays of small batteries as a valuable contributor to the massive electricity storage that will ultimately be needed; nor should such arrays be dismissed without extensive testing. Neither should the four ''massive'' technologies, to be briefly examined above, be accepted before being stringently vetted.

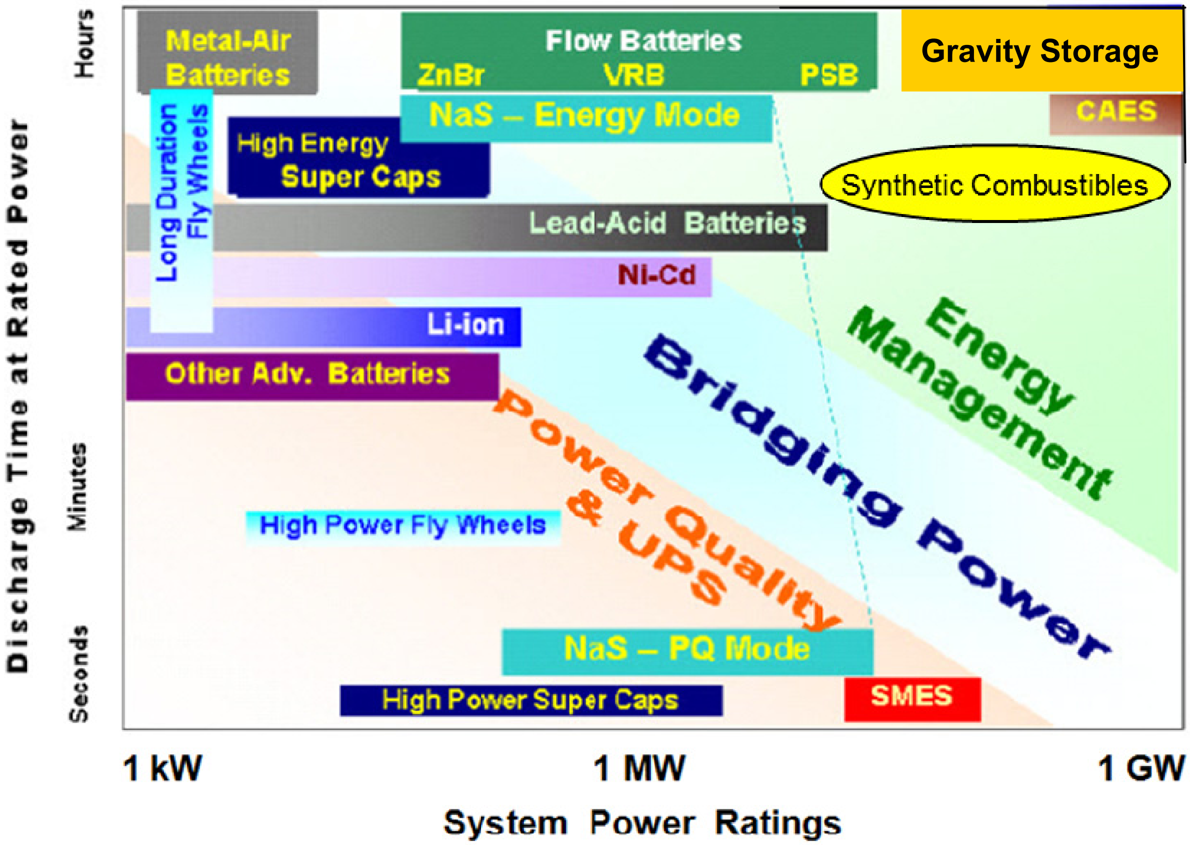

FIGURE 3. Ragone diagram of the discharge time at rated power (a factor in energy storage) vs. system power rating for a number of different electricity storage technologies; it is similar to many others that can be found on the Web. This one, ascribed to Nobelist Steven Chu and available at http://energy.wesrch.com/wiki-511-energy-storage-is-critical-to-grid-operations, has been augmented to include: (i) gravity storage; and (ii) stable synthetic chemicals (e.g., hydrogen gas, methane, or ammonia) that can be manipulated to produce mechanical energy. The maximum rates of charging and discharging of a storage module need not necessarily be the same.

(ii) all devices located there can (easily, in principle) be scaled up enormously. It is they that will be focussed upon below: synthetic combustibles, electrochemical storage in flow batteries, and storage as mechanical energy via either compressed air or elevated mass.

The discussions of electricity storage given below are intended, not to be encyclopedic, but rather to provide brief overviews of those technologies that cluster toward the upper right-hand corner of the Ragone chart of Fig. 3. A detailed discussion of the complex question of massive electricity storage based upon arrays of small-capacity storage devices is beyond the scope of this paper. For more extensive discussions of electricity storage, there are numerous recent reviews that may be consulted [64], [66], [68]–[72].

B. CANDIDATE MASSIVE TECHNOLOGIES

1) SYNTHETIC COMBUSTIBLES

Coal, oil, and natural gas - the backbone of the Age of Fossil Fuels [32], [73]–[75][19] - are natural products, the end result of photosynthesis coupled with eons of ordinary geological processes. What rendered them so historically important were: first, their ease of harvesting, with the useful energy returned by the harvest greatly exceeding the energy expended during the harvest; and, second, their high energy density, making their transport, storage, and use relatively convenient. As exhaustion of fossil fuels forces a switch to renewable energy, that convenience is in danger of being lost. Without jet fuel, the convenience of modern air travel vanishes. Without high energy liquid fuel, ground transport as we know it likewise vanishes. Consequently, many researchers have suggested that surplus renewably-generated electricity could be stored by using it to drive the synthesis of suitable combustible chemicals, which might then be used in roughly traditional ways: this certainly seems better than letting the surplus energy go to waste.

Hydrogen (H_2), for example, could be extracted from water by electrolysis at efficiencies of 70% or better [76], stored until needed, and then used as a transportation fuel [77]. However, the comparative energy costs of its compression, storage, and transportation have not yet been proven in extensive commercial practice, whilst being predicted to be poor [78]. Also, hydrogen filling stations are distinctly

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[19] Technically, peat should probably have been included in this list since historically it was of great importance in the industrialization of the Netherlands and also in the development of its landscape [73]. At present, however, it seems to find its most widespread use as a soil adjuvant in horticulture [74], although it still is extensively employed as a fuel in parts of Scandinavia [75].

uncommon.[20] On the other hand, there is considerable optimism that hydrogen can be developed into a major fuel source [79], [80], work continues enthusiastically, and there is no knowing what ultimately can be accomplished unless the prospect is pursued. Moreover, BMW's Hydrogen 7, the first production IC automobile to run on hydrogen, and the Toyota Mirai, powered by hydrogen fuel cells, are now on the road in minuscule quantities.

Given energy and hydrogen, it seems readily possible to synthesize ammonia (NH_3) [81]. Ammonia is easily liquefied, stored, and transported. However, the idea of using it as a fuel has yet to be proven in extensive commercial practice. Moreover, liquid ammonia is inconveniently volatile; although its peculiarly sharp odor enables its easy detection, thus permitting appropriate avoidance behavior. It is toxic, although not particularly so; and some 25% of the ammonia produced is applied directly to the soil as pure ammonia [82].

Because various common alkanes and alcohols are of proven convenience, modest volatility, great volumetric energy density, and ease of transportation, it would seem eminently worthwhile to consider using surplus renewably-generated electricity to synthesize them from water and recycled carbon dioxide; and such proposals abound [80], [81], [83]–[89]. It has been suggested, for example, that synthetic methanol might be produced for less than $2 per gallon [85] and synthetic gasoline for around $3 per gallon [84]. More tellingly, however, it has been recognized that "it is impossible to predict the cost of an undeveloped technology" [90], and the following call to action issued [90]: "There is abundant R&D to be undertaken with regard to the possible materials, components, and workings of air capture technology. Given the enormity of the global climate challenge, we think this R&D needs to be scaled up urgently." It is hard to fault the imperative tone of this remark because until, by dint of industrial-sized experiments, "prospectively" becomes "realistically" there will be no compelling evidence that mankind can count on this technology to meet its forthcoming need for massive energy storage.

2) STORAGE IN BATTERIES

In Fig. 3, the only batteries that appear anywhere near the upper right-hand corner are flow batteries. Flow batteries are exceptional among batteries in that the current-limiting surface areas of the anode, ion-selective membrane, and cathode are effectively independent of the volumes of anolyte and catholyte that determine the quantity of energy stored [91]. However, despite much research and many specialist meetings over the past several years, there is not yet very much of such storage extant. For example, among the operational flow-battery facilities listed by the DOE Global Energy Storage Database [67], the largest appears to be only 10 MWh. A recent DOE publication states that "…due to lack of MW-scale field history, flow batteries have not gained substantial commercial traction in the US, with various flow-battery technologies still in the demonstration phase, and the largest single operational system at 0.6 MW … " ([92, p. 18]). Moreover, even if one were tempted to fall back upon the tried and true non-flow lead-acid battery, this prospective energy storage device has been considered by two different groups and judged non-viable at the terawatt-day quantities needed [93], [94]. Finally, the modularity of batteries should make them seem extremely attractive, but only if (i) the chosen module uses no scarce mineral elements and (ii) the problem of weak links in the storage array can be resolved.

With flow batteries, as with all batteries, questions of round-trip energy efficiency, wastage during long term storage, supply sustainability of rare ingredients, and end-of-life recycling (or waste management) loom large. However, recent advances in flow batteries with carbon-based electrodes and quinone-based electrolytes [95] do hold out hope for better technologies that sidestep many of the above limitations.

3) STORAGE AS MECHANICAL ENERGY

a: A SHORT COMMENTARY ON EXERGY

Ideally, electrical energy and mechanical energy can be converted from one to the other with efficiency approaching 100%. Similarly, it is well known that either electrical or mechanical energy can be converted into heat energy with efficiency approaching 100%, whereas it is impractical to back-convert heat energy into either electrical or mechanical energy with anything like the same efficiency. This asymmetry of behavior is commonly described by considering a system not in equilibrium with its surroundings and defining any portion of its total system energy (heat, kinetic, potential, chemical, electrical, etc.) that is capable of doing useful mechanical work to be exergy [96]. In massive electricity storage, the goal is always to store the energy in ways that do not grossly diminish its exergy content. Energy conversions that generate heat always destroy exergy and, preferably, should be avoided.

b: COMPRESSED AIR ENERGY STORAGE (CAES)

Whenever massive energy/electricity storage is mentioned, CAES is always high among the list of "usual suspects". And, over the past decade or so, it has generated a great deal of (academic?) interest [97]–[105]. It may therefore surprise the Reader to learn that that the DOE Global Energy Storage Database [67] lists only two operational sites of power exceeding 10 MW: (i) the in-ground natural gas combustion facility at McIntosh, AL, USA (max. output 110 MW/ energy capacity 2.86 GW h); and (ii) the in-ground natural gas combustion facility at Huntorf, Germany (max. output 321 MW/

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[20] For example, as of May 2015, the state of Missouri (population ~6.0 million) seemed to have only one. http://www.netinform.net/H2/H2Stations/H2Stations.aspx?Continent=NA&StationID=-1. Accessed 22 May 2015.

energy capacity 0.64 GW h).[21] It can not yet be confidently asserted that CAES is ready to play a major role in the massive storage of electricity, especially in a sustainable post-carbon society.

c: GRAVITY STORAGE

By contrast, hydroelectric pumped storage is mature and widespread, with the United States alone reporting approximately 156 completed projects with an aggregate rated power capacity just under 21 GW [106]. Pumped hydro could realistically be termed hegemonic. However, it has a shortcoming: ''environmental concerns over water and land use severely limited the ability to build additional pumped hydro capacity'' ([91, p. 33]); and no additions to U.S.A. capacity are anticipated during the next few years [107]. Moreover, it is also true that: (i) convenience dictates having the energy storage near the intended energy sink; (ii) storing water at a high head is desirable, whereas flat-topped mountains over 500 m high and suitable for an upper reservoir are scarce near metropolitan areas; and (iii) the public is justifiably concerned about dam failures that could launch millions of cubic meters of water rolling downhill. In fact, this siting problem is not as difficult as it might seem because a pumped storage hydro scheme merely needs an upper and a lower reservoir between which the stored water is moved. If the upper reservoir is a lake at and below ground level and the lower reservoir is an excavated cavern 500 m underground, where's the danger to surrounding residences[22]? This fix was devised over a century ago [108]: but it has never yet been tested in practice and so can not yet be said to solve the problem, even though an instantiation of it is under consideration in the Netherlands [109]. Underground pumped hydro remains therefore just another of many candidate solutions waiting to be given a chance.

Another under-development variant of gravity mediated massive electricity storage is a heavily loaded rail car with individual axle-drive motors [110]. It propels itself uphill when grid electricity is in oversupply; and, in times of electricity oversupply, it returns the energy to the grid by coasting downhill.

4) THE SMORGASBORD IS LESS NOURISHING THAN, AT FIRST GLANCE, IT APPEARED

None of the candidate technologies for massive-scale renewable/sustainable generation of ''green'' electricity deliver it in a form suitable for high-efficiency storage. None of the prospectively-massive storage modes for transformed-electricity is at present well enough developed to be designated a sovereign remedy for Intermittency.

Challenge: This is not a desirable state of affairs!

VI. DEPLOYMENT OF MASSIVE ELECTRICITY STORAGE EXAMINED IN THE LIGHT OF HISTORICAL EXPERIENCE

A. IS THERE AN IMMEDIATE NEED FOR DECISIVE ACTION?

If one consults the various quantitative predictions for when fossil fuels will become scarce and/or pricey [1], [33], [35], [37]–[39], [40], [43], [44], it will be seen that they scatter, although most lie within a band of 60 ± 30 years from now. The historical evidence is very clear that previous transitions between principal energy sources have taken fifty or more years to approach completion [111]–[115]. Moreover, the switch is expected to be demanding [56].

The time left to make a shift to renewables seems limited, the favored strategies for storing electricity are immature, and pathways to a successful outcome remain obscure. Given that this situation was foreseen at least a century ago [116], the prospects for its speedy resolution seem discouraging.

B. WHERE DOES THE MONEY TO CREATE ENERGY STORAGE COME FROM?

This question is prescient!

To answer it for the United States requires first an estimate of how much of America's domestic product is at present attributable to the cost of primary energy; and a Fermi-type estimate for that is readily calculated as follows.[23] The US consumption of liquid fuels is currently about 19 Mbbl d^{-1} @ ∼60 \$ bbl^{-1} for an approximate annual cost of ∼420 G\$ y^{-1} [117]. The US consumption of coal is currently about 1.0 Gst y^{-1}, where 'st' stands for 'short ton of 2000 pounds'. The pricing of coal is rather more complicated than that of petroleum; but @ ∼ 45 \$ st^{-1} its approximate annual cost is ∼45 G\$ y^{-1} [118]. The US consumption of natural gas is currently about 25 Gkcf y^{-1} @ ∼5 \$ kcf^{-1}, where 'kcf' stands for '1000 cubic feet'; and thus its approximate annual cost is ∼125 G\$ y^{-1} [119]. In total, America's volatile annual bill for Primary Energy is on the order of ∼600 G\$ y^{-1}, or roughly 3.5 % of its Gross Domestic Product, currently ∼17.5 T\$ y^{-1} [120]. Although primary fossil fuel is less than 5% of the country's economic activity, without this expenditure America would grind to a halt. If the price of the primary energy were to double, America would have little choice but to pay up for most of it.

So what is America's government doing proactively to safeguard its supply of energies and its balance of payments? Precious little. In fact, America has a recent record of **dis**investment in energy research, development, and demonstration [121], [122].

The fiscal 2015 Federal budget of the United States is proposed to be ∼3900 G\$ (∼22% of GDP) of which maybe 648 G\$ (∼16% of Federal budget) is classified as Defense [123]. By comparison, Energy and Environment at ∼44G\$ is ''buried in the noise'' (∼1 % of Federal budget). If Federal spending were boosted by increasing

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[21] Because both sites require natural gas for their operation, neither is sustainable in a post-carbon setting.

[22] The Author admits that surface subsidence in the wake of subsurface excavation is a possibility but holds that good geotechnical design should suffice to eliminate this danger.

[23] The volatility of future fuel prices makes impossible an accurate estimation of energy costs in the future. These figures ought to be interpreted as Fermi calculations that should inform one of the boundaries of the ballpark within which the correct answer lies.

Energy and Environment to 435 G\$ y^{-1} (a modest $2^1/_2$% of GDP, only 11% of the Federal budget, and much less than Federal expenditures for defense), a massive improvement of America's energy position could be achieved between now and mid-century. Think of it as an adjuvant of national security: 650 G\$ y^{-1} of direct defense expenditure plus 435 G\$ y^{-1} of indirect defense expenditure (assuring the national energy supply). Such an expenditure would bring defense, broadly construed, to around 25% of the augmented Federal budget.

Of course, according such priority to defense, whether direct or indirect, might bring unwarranted predictions of economic dislocation – the term "unwarranted" being entirely justified because the First Czechoslovak Republic did, without visible ill effect, a closely similar experiment in the 1930s. Following the crash of the American economy in 1929, the economies of Central Europe first contracted by lesser amounts than America's and then slowly commenced to recover ([124, Table 6]); this was especially notable in Germany after the National Socialist takeover in 1933. By 1937 the Czech economy was again close to 1929 levels. However, the bellicose maneuverings of Germany under Hitler provoked the Czechs into a major increase in defense expenditures and border fortification[24] [125]: specifically, defense was 27% of the national budget in 1935, 55% in 1936, 47% in 1937, and 63% in 1938. Nevertheless, until France and the United Kingdom executed the Munich betrayal of late 1938, things in Czechoslovakia were definitely looking up economically ([126, Ch. 6]).

Therefore, one could reasonably expect that money could be found to switch the World from fossil fuels to renewables, but only if the will to switch were to be found first, and only while there is still enough fossil fuel remaining to tide us over while the switch is being made [127].[25]

VII. CONCLUSIONS AND POLICY IMPLICATIONS[26]

Data have been presented in the body of this paper to support the five theses propounded below. In each case, it is claimed: (i) that the data are of sufficient weight to constitute *prima facie* evidence for the thesis and (ii) that the consequences of the thesis being correct are so grave as to merit immediate policy responses of: either (a) prompt and definitive falsification of the thesis; or (b) prompt, intense, and abundantly-funded further study of the thesis; or (c) prompt, ongoing, and putatively-adequate remediation of the alleged threats to our society.

I. Rapidly rising electricity demand could well exhaust, this century, mankind's dowry of fossil fuels (s. II.B-II.F, III.A-III.F, VI.A). Presuming this conclusion to be credible and considering the likely public outcry against a colossal buildup of nuclear power generation, an obvious suite of policy responses might include: (i) discouraging fossil fuel use by putting a price on CO_2 emission; (ii) encouraging fuel efficiency by a slowly rising "tax at the tipple" on the caloric content of newly recovered fossil fuel; and (iii) providing R&D support and slowly falling subsidies for underdeveloped technologies such as solar thermal generation.

II. The principal, alternative, non-fossil energy sources are either intermittent (e.g., wind or solar) or output-sluggish (e.g., traditional nuclear) (s. IV.A-IV.E) and seem distinctly less dispatchable than fossil sources. Even so, a great deal of load balancing seems achievable by policies and rate schedules that encourage: (i) integration of energy sources from huge geographic areas; (ii) a broad mix of generation technologies; (iii) a massive transmission backbone that facilitates low-loss transmission of terajoule quantities of energy; and (iv) voluntary load shifting and shedding at appropriate times.

III. Massive electricity/energy storage is alleged to be able to compensate for intermittency or slow response of a grid's sources (s. IV.A-IV.E). Yes it could; and, witness the efficacy of coal piles behind so many generating plants, it has for over a century. But the approaching end of the Age of Fossil Fuels means that different storage strategies must be adopted; and major technological switches of primary energy source can easily take half a century to complete. Because we can not foretell today precisely when in the next hundred years it will become critical to have completed the switch, prudence suggests policies, such as "tax at the tipple" fees on fossil fuel, which should encourage the public to switch away from it sooner. There is little reason to believe that unaided market forces will elicit correct and timely responses to unprecedented challenges. On the other hand, it has been claimed that "[a]dvanced electricity storage [is] a necessary first step in creating an international market for energy" ([128, p. 61]) and that such a market is essential for our global society to thrive ([128, p. 54]).

IV. None of the principal electricity storage contenders have been adequately tested and proven in practice (s. V.A-V.E). An obvious policy would be for key governments (e.g., China, Germany, Saudi Arabia) to launch crash programs in which (i) each government funded several different National Storage Demonstration Facilities and (ii) each such facility met the specifications of: Rated Steady Output, 2 GW_e; Rated Available Capacity, 50 GWh_e; Rated Lifetime, >20 y. Typical candidates would presumably include carbon-based flow-batteries, advanced adiabatic compressed air energy storage, and underground pumped hydro. The cost of each such demonstration project would be several billion

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[24] The Author happened upon this information when a tour he was taking visited a military historic site outside Dobrošov in eastern Bohemia, and he noted the phenomenal expenditures cited on the site's explanatory signage.

[25] The failure to switch to sustainable energy sources in advance of exhausting the fossil ones is predicted to risk a painful economic belt-tightening known as "The Energy Trap" [127].

[26] The Author wishes to be meticulous in his use of the term 'implications'. In the strict sense of Aristotelean logic, the data presented above imply no policy actions. Instead, if correct, they imply probable unwelcome outcomes. These predicted outcomes, if believed, should inspire public policies designed to avoid those unwelcome outcomes. The "policy implications" to be listed represent only the Author's favorite ideas for prudently avoiding the probable outcomes of ignoring the coming end of the Age of Fossil Fuels. Because learning to live without fossil fuel will take mankind into *terra incognita*, many different strategies could be should be tried as optimal solutions are sought.

euros, but that cost could be met by ''tax at the tipple'' impositions. And the example of the First Czechoslovak Republic in the Thirties serves as an example of how economies can courageously adapt when there is a will.

V. Virtually none of the necessary electricity storage capacity exists today (s. V.A-V.E, VI.A-VI.B). Nor is it apt to exist until something akin to Step *IV* has existed long enough to validate the technological foundations for it. The policies that will provide the needed electricity/energy storage are those that elicit public will: first, to embark upon the quest for such storage and, second, to persevere until that quest succeeds.

When a societally disruptive future event is forecast, he Power Brokers of this world should never pursue a policy of neglect: either they should definitively falsify the claim with a weight of evidence that overwhelms the evidence for it; or else they should institute prudent precautionary activity sufficient to neutralize the danger. Throughout history, human endeavors have been graded, not upon hopeful reassurance and not upon effort and input (however laudable), but upon effective output. Thus, seventy years of study and debate have served only to permit the growth of mankind's burden of nuclear waste, but not to find safe and permanent repositories for that waste. Mankind deserves better where massive electricity storage is concerned!

APPENDIX

DANGERS OF ENGINEERING INTO THE UNKNOWN

A. CONVENTIONAL WISDOM ON ELECTRICITY STORAGE

There are many sources from which to seek the conventional wisdom of electricity storage: from simple elementary texts [129], to undergraduate level monographs on energy [57], [58], to advanced review articles on energy storage, loosely categorized as general [62], [68]–[70], [130], [131], chemical [86]–[88], or electrochemical [71], [132]. For Readers who desire a quick overview, there is no ''royal road''! The Author suggests beginning with the nontechnical guide by Richard Baxter [129], continuing with the SBC Energy Institute's ''FactBook'' [133], and ending with a reality-checking browse through the U. S. Department of Energy's ''Global Energy Storage Database'' [67]. With all of the above, as with references yet to come, the Reader is advised to take care, because (i) some of the prospects could prove highly alluring whilst (ii) being, at the same time, not realistically achievable under the constraints of the moment. After all, virtually anything can be accomplished in a Gedankenexperiment: whereas what counts are those activities that can legally be carried out in a real setting, with real personnel, on a real budget, in a real period of time.

B. THE PRICE & DELIVERY TEST

Come the end of the Age of Fossil Fuels, massive electricity/energy storage will be neither a boutique luxury nor a niche-market specialty item: it will be a major and indispensible part of the World's energy future. Such items, however proud of them one may be, will nonetheless be only bulk commodities. A technocrat must therefore document with care the Properties needed and then go forth seeking accurate Price and Delivery data from the available purveyors of massive storage. Equivocation is not an acceptable answer. Inability to provide reasoned quantitative responses (or at least data on comparables) is a warning flag. And, because the technocrat is an active customer today, rather than a dreamer envisioning a bright tomorrow, references to ''technologies currently under development'' are largely irrelevant: the successful technocrat will insist upon tightly-specified reliable product delivered on his schedule, not the supplier's. If neither reasonable answers nor data on comparables are forthcoming from the sales associate consulted, the technocrat would be well advised to seek a different supplier[27] [134].

C. FAMOUS PROJECTS IN WHICH PUTATIVELY REASONABLE A PRIORI HOPES PROVED FAULTY

In the history of mega-schemes, the construction of mega-dams is probably the best documented [135]. For the years 1934-2007 (inclusive) it proved possible to find data on 245 mega-dams: the mean cost overrun was 100%; while the mean schedule slippage was 50%. Yet dam building is a relatively mature technology. These statistics show that, even so, it is difficult to obtain accurate *a priori* estimates of price and delivery; they are a danger warning to all technocrats endeavoring to launch megaprojects in renewable energy, where the depth of experience seems rather shallower. The three case histories and a comment, which follow immediately below, do not pretend to reveal gems of scientific information – they are intended instead to drive home the banal *engineering* truth that infrastructure buildout beyond the limits of past experience oftentimes encounters a shockingly difficult unexpected.

THE EDISON CONJECTURE: In 1891 Henry Ford joined the Detroit Edison Illuminating Company and rose quickly through its ranks, while moonlighting on the development of a gasoline-powered automobile. In 1896 he was counseled by Thomas Edison to ''Keep at it. Electric cars must keep near to power stations. The storage battery is too heavy.'' [136]. Subsequently, by 1898, Edison had become disenchanted with the lead-acid battery, especially because of its short life, and embarked upon building a lead-free alkaline battery [137]. After roughly a decade of effort and an expenditure of a bit less than two million dollars of his own money, he finally perfected an alkaline iron-nickel battery which (compared to the lead-acid of the era) was of extreme longevity, higher energy density, notable electrical and mechanical durability, ease of maintenance, and (sadly) several times the initial price. In short, Edison did not come up with a suitable battery, and the internal combustion engine triumphed. Now, a century later, the American public is still not flocking to buy

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[27] Modelling exercises that incorporate the effects of energy storage on a large-scale system are numerous [2]–[4], [135]. In some, however, the application of the Price & Delivery Test has been rather less vigorous than might be desired.

purely electric automobiles [138].[28] And, come to think of it, many would wish their cell phone and laptop batteries were rather less finicky.

Energy storage for individual transportation devices scarcely qualifies as massive energy storage. However, if one considers the aggregate energy storable in the 10^8 40-L vehicle fuel tanks of major geographic region, that amounts to 4×10^6 m^3 at perhaps 32 GJ m^{-3}, or 128 PJ $=\sim$36,000 GW h. That certainly qualifies as massive energy storage. But since such quantities are not today stored in a form from which they can readily be converted into electricity, they lie outside the scope of the enquiry.

AMERICA'S MISSILE DEFENSE PROGRAM: The length of time that this program has been underway could be subject to argument [139], but ''fifty-some years'' is a figure that no one is apt to contest seriously. Over that period it has absorbed tens of billions of dollars [140], has had both successful tests and unsuccessful tests, and has convinced almost no one that it could withstand an all-out attack, especially by intercontinental ballistic missiles dispersing multiple warheads and decoys [140]–[143]. In short, despite confidence, high hopes, much sophisticated engineering, and vast expenditures, it has not deployed robust and dependable hardware.

F-35 JOINT STRIKE FIGHTER: The F-35 is bruited to be the most expensive weapons system in America's history, and its lifetime cost is estimated to total ∼1.5 T$ [144]. As of September 2013, supersonic flight, night flight, flying within 25 miles of lightning, and firing its guns were severely restricted. It is well behind schedule and well over budget. More recent reports have revealed still more difficulties with the project [145], [146].

D. A PRIORI PRICING

THE BLACK & VEATCH EXPERIMENT: In October 2012, Black & Veatch, a major global engineering firm, published a report in which they endeavored to develop an accurate estimation tool for predicting transmission line and substation construction costs in the Western Interconnection region of the United States [147]. This effort was carried forward under the supervision of a peer review workgroup composed of transmission experts familiar with the area. The tool they developed was then tested by comparison with four recently completed projects and found to deliver estimates ranging from ∼10% too low to ∼60% too high. Moreover, massive electricity storage was not considered in this report.

DOE/EPRI COST TABLES: The United States Department of Energy in collaboration with the Electric Power Research Institute publishes from time to time an *Electricity Storage Handbook* that contains a wealth of information on the sorts of storage useful for ancillary services and infrastructure services applications [91]. But it provides rather less information on massive electricity storage.

COMMENTARY: The ''Gold Standard'' for judging a particular instantiation of electricity storage is experimental verification of the project's operating characteristics, that and the Auditors' financial statements: *show me*! This is why meticulous design must precede construction. And this is why the technocrat's most basic demand must be ''Properties, Price, and Delivery!''. On the other hand, we realize from the Black & Veatch experiment that we may never, in advance, know the cost exactly—not even if one is dealing with familiar technology and familiar terrain. And, as for operating characteristics when the envelope is pushed, things sometimes do not work out: that is the nature of engineering development [148].

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[28] However, modern pure-electric-drive vehicles have now been available in the United States for only three years, and sales figures suggest that converts are being made: in 2011, 17735 were sold; in 2012, 52835; in 2013, 96702; and in 2014, 118773 [138].

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