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Transporting the terajoules: Efficient energy distribution in a post-carbon world

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HIGHLIGHTS

- Abundant renewable-electricity will often be captured far from load nodes.
- It must, at once, be used, shipped, or converted with loss and stored.
- Efficiency dictates (a) immediate use or (b) shipment to load node for storage.

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ABSTRACT

In a post-carbon energy economy, just as during the Age of Fossil Fuel, the locations where men take control of energy resources (e.g., the coal-pit, the mill wheel, the terminals of a concentrating solar power generator) will often be far removed from the locations where they wish to expend those resources. Therefore, the captured energy resource, once isolated, must somehow be translated from its point of origin to its point of use; and in doing so, its owner must expend energy. In this paper it is argued that, in a sustainably fueled future: (i) renewable energy in its initially transportable form will be overwhelmingly electrical; (ii) energy frugality will dictate long-distance transport of energy as electricity; (iii) intermediate-term (less than a fortnight) storage of energy will be via compressed air energy storage or pumped hydro- or electrochemical batteries, which can not be comparatively evaluated without extensive expensive development and demonstration; and (iv) massive conversion of electrical energy into synthetic fuels will be restricted to selected transportation applications.

1. Introduction

In the calendar year 2010, the United States consumed 98.00 quads of primary[1] energy (EIA, 2011, tab. 1.1)[2]; this is also

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[1] Just what is meant by 'primary energy' is subtle. The U.S. Energy Information Agency offers the following definition (EIA, 2010, p. 402): "**Primary Energy Consumption**: Consumption of **primary energy**. (Energy sources that are produced from other energy sources—e.g., **coal coke** from **coal**—are included in primary energy consumption only if their energy content has not already been included as part of the original energy source. Thus, U.S. primary energy consumption does include net imports of coal coke, but not the coal coke produced from domestic coal.) The U.S. Energy Information Administration includes the following in U.S. primary energy consumption: coal consumption; coal coke net imports; **petroleum consumption** (**petroleum products supplied**, including **natural gas plant liquids** and **crude oil** burned as fuel); **dry natural gas**—excluding **supplemental gaseous fuels**—consumption; **nuclear electricity net generation** (converted to **Btu** using the nuclear **heat rates**); **conventional hydroelectricity** net generation (converted to Btu using the fossil-fuels heat rates); **geothermal** electricity net generation (converted to Btu using the fossil-fuels heat rates), and geothermal heat pump energy and geothermal direct use energy; **solar thermal** and **photovoltaic** electricity net generation (converted to Btu using the fossil-fuels heat rates), and solar thermal direct use energy; **wind** electricity net generation (converted to Btu using the fossil-fuels heat rates); **wood and wood-derived fuels** consumption; **biomass waste** consumption; **fuel ethanol** and **biodiesel** consumption; losses and co-products from the production of fuel ethanol and biodiesel; and electricity net imports (converted to Btu using the electricity heat content of 3412 Btu per kilowatthour)." To be useful as a component of primary energy consumption, 'nuclear electricity net generation' must be interpreted as 'total heat generated by the fission process'. Whereas, the useful electricity leaving a nuclear plant is secondary energy. The intent above seems to be that 'primary' should refer to that energy deposited within an energy carrier by natural (i.e., non-human) processes that can be released by human intervention and become in part subject to human control and transformation. A possible difficulty with the official definition of the preceding paragraph is that nuclear electricity generation arises from nuclear processes that first give rise to thermal offsets, which human intervention directs to a steam boiler; secondarily steam from the boiler is caused to spin a turbine, whose shaft drives the rotor of a generator, thereby generating electrical energy. The primary energy seemingly is the gross fission energy released by the nuclear processes; and back conversion from electrical joules to thermal Btu seemingly neglects those nuclear joules which are primary but are lost to entropy during expansion of the steam. This nicety is not expected to influence the qualitative arguments made in this contribution. But it does point up the difficulty of exact quantitative reasoning about energy. Within ecological economics, the distinction is made as "A primary energy source is an energy source that exists in nature and can be used to generate energy carriers (e.g., solar radiation, fossil fuels, or waterfalls). An energy carrier is a vector derived from a primary energy source (e.g., electricity, gasoline, or steam)." (Murphy and Hall, 2011).

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Nomenclature

Latin

$\mathcal{M}$	molar specific weight of substance (kg mol^{-1})
N	moles of gas of a nominal molecular weight in a volume V (dimensionless)
$\mathcal{NPW}$	net present worth of a proposed or actual investment ($).
p	pressure (Pa)
$\mathcal{R}$	gas constant. $\mathcal{R}=8.314$ (J K^{-1} mol^{-1})
T	absolute temperature (K)
V	volume of a mass of gas (m^3)

Greek

η	fractional energy efficiency of a conversion or transport event. $1-\eta$ Is called the "energy intensity" of the event.
ρ	mass density (kg m^{-3}).

equal to 103.4 EJ or 28.72×10^{12} kW h. Because the official U.S. population in 2010 was 308.7×10^{6} (U.S. Census Bureau, 2010), the per capita energy consumption for the year was 93.04×10^{3} kW h; and since there are 8.766×10^{3} h in a year, it follows that the average per capita power draw was 10.61 kW. This is conveniently rounded to a steady U.S. power draw of 10 kW person^{-1}. If this figure seems surprisingly large, it should be borne in mind that only a fraction, perhaps one-quarter to one-third, of that power is actually available for doing useful work, the rest being lost as low temperature heat. Nevertheless, if even 3 kW are available as exergy (high-utility electrical or mechanical energy), that is still many times the 24-h-average daily output of 0.05 kW which might reasonably be expected of a young, healthy human athlete (cf. Pickard, 2012a). Stated differently, if those 10 kW were not available, life would be much harder for the average citizen; for example, as recently as 1800, 40% of the United Kingdom's primary energy consumption for power was in the form of food for human laborers (Fouquet, 2010, fig. 2).

To comprehend better the magnitude of 98.00 quads, reflect that one barrel-of-oil-equivalent is defined as 1 boe≡5.8×10^{6} Btu$=6.119\times10^{9}$ J$=$1700 kWh (IRS, 2012, s. 2).[2] Hence, 98.00 quads$=16.89\times10^{9}$ boe⇒46.24×10^{6} boe d^{-1}. By comparison, the Trans Alaska Pipeline running at capacity could deliver a bit over 2.0×10^{6} boe d^{-1} (AOPL, 2007); and thus, only twenty three Trans Alaska Pipelines could carry all the primary energy the United States needs.[3]

Building pipelines is not an impossible task and indeed is normally straight forward, as is building railroads, as is building interstate highways, as is building electrical transmission lines. Technically, America should be able to transfer the terajoules it needs without undue difficulty, but not necessarily at an *energy cost* that will please its citizens.[4] Because, *in the long run*, obtaining terajoules in conveniently transportable form may be much more energy intensive than drilling a simple well into a large Siberian gas reservoir, *in the short run*, precautions should probably be taken to assure that the transportation of energy is as energy frugal as *reasonably* is possible.

A sensible initial activity in determining the energy frugality of energy transportation is simply listing the aspects of the problem. To begin with, attention will here be focussed upon *massive* quantities of a terajoule or more: 1 GW for one hour is 3.6 TJ; and a large tanker truck filled with hydrocarbon liquids holds between 5500 and 9000 gallons (131–214 barrels or ~1 TJ). Table 1 lays out (i) the principal varieties of energy to be shipped, (ii) the forms in which it might exist during shipment, and (iii) the currently hegemonic modes of transport. Barring quite unforeseen technological developments: (a) significant quantities of thermal and mechanical energy are never going to be shipped long distances; (b) the energy cost of transporting nuclear fuel will remain an inconsequential fraction of the fission energy released; and (c) one need consider, therefore, only the comparative costs of source-to-sink transportation of captured energy in a chemical form versus those of transporting it in an electrical form.[5] Before one can comparatively evaluate the forms of transportation, it is also necessary to consider how the chemical and the electrical forms came into being; and this will be done in Section 3.

2. How to make economically sensible decisions in a sustainable society

Que sera sera may be a reasonable attitude towards life's happenstance events over which one has no significant degree of control. However, it degenerates into feckless maladaptation when prudent effort seems likely to effect markedly better outcomes. Although the future can not reliably be foretold, philosophers have, since earliest times, preached that it can be anticipated: such anticipation is, in fact, the motivation for saving and an underpinning of investing.

Traditionally, an investment can be viewed as separable into three phases (cf. Grant and Ireson, 1970):

(1) *Construction*. An investment is made and a business entity successfully launched. In this zeroth time period the cash flow is $C_0<0$, a net expenditure.
(2) *Operation*. In each succeeding time period $0<n\leq N$, the entity experiences a net cash flow C_n of unknown sign, which is (i) a sum of operating expenses, income from operations, etc., and

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

[3] The term "primary energy" may, in fact, deserve more explanation than was provided in Footnote 1. All the energy of the universe presumably can be traced back to the Big Bang, the primal event of creation. The energy passed around within the solar system derives primarily from processes of solar nuclear fusion (manifested in sunlight), natural terrestrial radioactivity (manifested in heating of Earth's core), and gravitational interactions (manifested by tides). Any or all of these could legitimately be termed "primary". However, when discussing energy resources, "primary energy" is *by convention* taken by most people to mean energy that has by natural processes been deposited within an energy carrier, from which it can be abstracted and controlled by human intervention (e.g., a lump of coal, or a reservoir of natural gas, or the wind). Secondary energy is then a manmade store or a controllable flux of energy (e.g., an automobile battery, or heat moving from a hot water bottle into cold feet, or electricity moving along a wire).

[4] The term "cost" is ambiguous. Is this direct cost to the purchaser or total cost to the broader societal system? Does "broader societal system" include both current citizens and also future citizens? When the several components of a total cost are measured by different scales, how are they to be rendered commensurable? To facilitate comparison, should they be monetized, or rank ordered by their energy efficiency, or…? These conundrums will be considered in Section 2.

[5] This conclusion is reinforced by the observation that, in the renewable and sustainable energy futures presently envisaged (e.g., MacKay, 2009; Abbott, 2010; Armaroli and Balzani, 2011a; Jacobson and Delucchi, 2011), the energy to be transported to end users is usually presented in an electrical or a chemical form, no matter how it was extracted from the environment.