# "Fast food" energy

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New R&D is needed to provide the nonlegacy world with the "fast food" equivalent of solar energy—light-weight and highly manufacturable solar capture and storage systems



The energy appetite of our global society is enormous.[1,2] In 2007, worldwide primary energy consumption was 458 × $10^{18}$ joules, which is an average energy consumption rate of 16.2 terrawatts (TW, one TW equals $10^{12}$ watts, or $10^{12}$ joules per second).[3] Even in light of unprecedented conservation, global energy need will roughly double by mid-century and triple by 2100.[2,4] Much of this demand is driven by a growing world population, which is projected to increase from 6.1 billion in 2001 to approximately 9.4 billion by 2050.[5] In addition to these 3 billion new inhabitants of the planet, 3 billion people in the non-legacy world seek a rising standard of living. Geopolitical, environmental, and economic security will likely only be realized by meeting the energy demand of these 6 billion additional energy users by supplying a sustainable and carbon-neutral energy source, and within the next 10–20 years. To do so will require invention, development, and deployment of carbon-neutral energy on a scale commensurate with, or larger than, the entire present-day energy supply from all sources combined.

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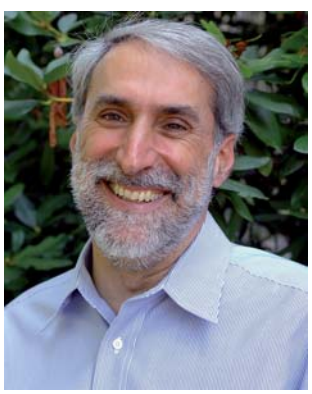
The success in meeting the energy challenge in the non-legacy world will largely depend on the design and development of new technologies that are at odds with the energy systems of the legacy world. In the legacy world, energy systems of the past and present operate at a large scale, they are centralized, and energy is distributed to the masses. In 2007 in the US, the total value of generation, transmission and distribution infrastructure for regulated electric utilities was $440 billion and capital expenditures exceeded $70 billion.[6] Such an infrastructure is not compatible in the near term future of the non-legacy world where it is cost prohibitive to build centralized energy and distribution systems. Rather, a cost-effective strategy that is better adapted to making energy available to the 6 billion new energy users is highly distributed energy systems for the individual. This will require personalized energy (PE) systems that can be produced by high throughput manufacturing and place a premium on low cost.[7,8]

Low cost in a manufacturing environment is most profoundly affected by materials goods of the system (most generalized by the weight of the system) and the production volume.[9,10] This manufacturing issue is illustrated in Fig. 1, which emphasizes consumer goods that are neither high-tech (*i.e.* pharmaceuticals, computer chips) nor commodity. The figure is striking because manufactured goods that are very different in their sophistication and utility in our society, be it a fast food hamburger or airplane, fall on the same curve. One sees, to a first approximation, that the systems cost will be low if the manufactured item is light in weight and is able to be produced at a high volume. These criteria are precisely the antithesis of the design and production of most energy systems of the legacy world. Current energy technologies find their origins away from the asymptotic limit of the figure. They emphasize labor-intensive manufacturing of large materials systems that necessarily must be very efficient for reasonable recovery of capital expenditures. Hence, the aforementioned large capital expenditures are incumbent to the legacy world owing to the sheer largess of the systems. Moreover, efficient energy comes with significant balance-of-system (BOS) costs. Down-scaling such technology does not scale economically because the BOS costs do not scale commensurately. Thus off-the-shelf technology and "existing" technologies will be difficult to adapt to low cost energy systems. Rather, the disruptive energy technologies of the future will be those that conform to the message of Fig. 1—light-weight and highly manufacturable energy systems that are at the same time robust and of low maintenance. Simply put, new R&D is needed to provide our society with the "fast food" equivalent of energy systems.

Solar energy is particularly well adapted for "fast food" energy. Low cost and



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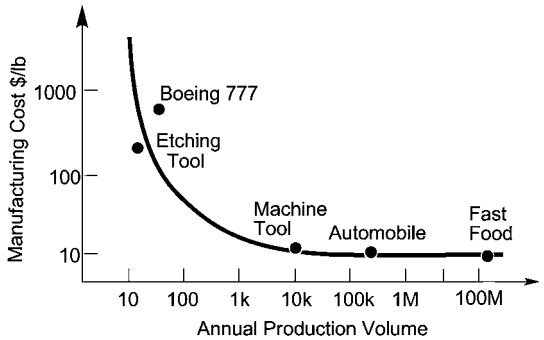


**Fig. 1** Manufacturing costs of consumer (non-hi-tech) goods as a function of weight and production volume. Data provided by Professors Martin A. Schmidt and Alexander H. Slocum (MIT).

large-scale manufacturing are already an emerging trend in the capture and conversion of solar energy. Thin film, ribbon and "plastic" (*i.e.* polymer) photovoltaics each have the promise of low cost because they can be adapted to high throughput manufacturing. Indeed, in the case of thin film CdTe photovoltaics, low manufacturing cost owing to high volume production of cells possessing a minimal amount of semiconducting material has resulted in a multibillion dollar market. However, the development of photovoltaics is not enough for the non-legacy world. Solar energy needs to be stored because it is diurnal and also subject to intermittency arising from variable atmospheric conditions as shown in Fig. 2. An analysis of the power frequency ($f$) bears this out; the power spectrum of the solar output is $f^{-1/3}$.[11] Accordingly, a 24/7 plentiful and large scale energy supply will only be possible if an inexpensive storage mechanism is also developed.

In light of the message of Fig. 1, the energy density of the storage medium is an extremely important parameter for the deployment of solar energy in the non-legacy world. Most current methods of solar storage are characterized by low energy densities and consequently they present formidable challenges for large scale solar implementation. This is also true of batteries, which are often discussed as an effective energy storage medium for solar PE. Though considerable efforts are currently being devoted to battery development, most advances have to do with power density (*i.e.* the rate at which charge can flow in and out of the battery) and lifetime. Energy densities of batteries are low (~0.1–0.5 MJ kg$^{-1}$) with little room for improvement because the electron is stored typically at a metal center of an inorganic network juxtaposed to an electrolyte. The volume in which the electron and attendant cation reside and transfer is thus limited by the physical density of materials. Some of the lightest elements in the periodic table, and hence lowest physical densities, are already used as battery materials and consequently energy densities of batteries have approached a ceiling. Continuing along this line of reasoning, the smallest volume element in which electrons may be stored is in the chemical bond. It is for this reason that the energy density of liquid fuels (~50 MJ kg$^{-1}$) is 100 times larger than the best of the foregoing storage methods; hydrogen possesses an even greater energy density. Indeed, society has intuitively understood this disparity in energy density as all large scale energy storage in our society is in the form of fuels. For this reason, it is likely that solar-derived fuels will prevail, especially as an energy storage medium for solar PE in the non-legacy world.

Water splitting is a particularly attractive storage mechanism for highly distributed solar energy,

$$\text{solar storage: } 2H_2O + \text{solar} = 2H_2 + O_2$$

$$\text{solar release: } 2H_2 + O_2 = 2H_2O + \text{electricity}$$

In this reaction, solar light rearranges the low energy content bonds of water to the high energy content bonds of oxygen and hydrogen. Solar light is thus stored in the re-arranged bonds of water. At a later

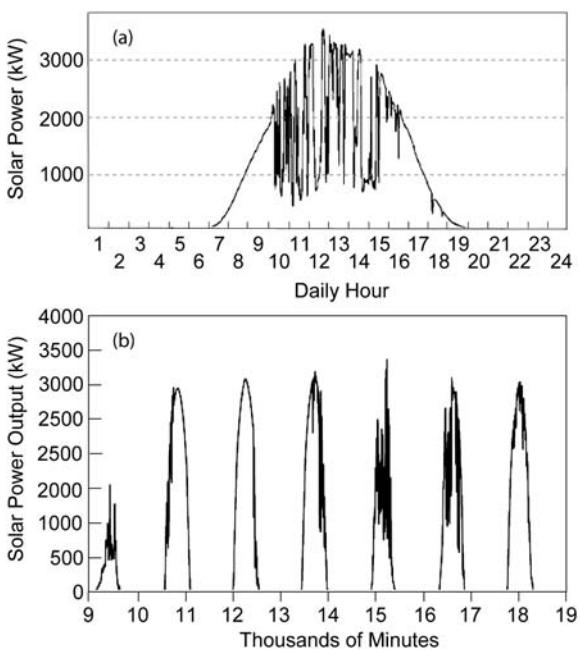


**Fig. 2** (a) Power output (kW) sampled with one minute resolution for a 4.6 MW solar PV array over the daylight period of one day. (b) Real power output (kW) sampled with one minute resolution for the same 4.6 MW solar PV array for one week. Data taken from ref. 11. The PV array is operated by Tuscon Electric Power in northeastern Arizona.

 

time, when the sun no longer shines, the stored solar energy in hydrogen and oxygen can be released in the form of an electrical current upon their recombination in a fuel cell. The recombination reaction gives back water; thus the overall cycle is: sunlight in → water to hydrogen and oxygen → hydrogen and oxygen to water → electricity out. Water is cycled and not used up in the overall energy conversion cycle. To understand the storage capacity of water splitting, consider the average American home, which uses ~31.2 kW h of electricity per day. The storage of 31.2 kW h can be achieved by splitting only 8 L of water (or 2.1 gallons) per day. For the non-legacy world, lives can be dramatically changed with a drinking bottle of water. Of course, compression efficiencies for hydrogen and the efficiency of the fuel cell must also be factored into the system, thus increasing the amount of water that needs to be split (but not more than by a factor of two). The point here is that energy storage needed for solar PE is currently within reach with the design of systems with low BOS and material costs that effectively promote water splitting in the forward (solar storage) and reverse (solar release) directions.[12,13]

Solar PE is transformative in its scope to provide economic equity to people of the non-legacy world and, in doing so, to stem the flow of non-anthropogenic sources of $CO_2$ into our environment. However, down-scaling current solar capture/conversion and storage technologies to the personal level will not be economically feasible. Most energy systems are incommensurate with the very nature of solar PE because they have been designed to operate at a large scale and high efficiency, and thus significant costs are associated with the BOS on a small scale. Hence, the solution to solar PE will be one that begins with a blank sheet on which the discovery of PE for the non-legacy world will be written. If the cost of solar PE through discovery can be decreased, then the development of the non-legacy world can occur within an energy infrastructure that is of the future and not of the past. Considering that it is the 6 billion non-legacy users of the present and future that are driving the enormous increase in energy demand in this century, a research target of solar PE provides global society with its most direct path to providing a solution for a sustainable and carbon-neutral energy future.

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