Energy, the global challenge, and materials

After some definitions to establish common ground and illustrate the issues in terms of orders of magnitude, we note that meeting the Energy challenge will require suitable materials. Luckily, we can count on the availability of natural resources for most materials. We briefly illustrate the connection between materials and energy and review the past and the present situations, to focus on the future. We wrap up by arguing that more than bare economics is required to use the fruits of science and technology towards a world order, built on sustainable energy (and materials) resources.

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Background and perspective

What is often called the "energy crisis" or "energy problem"[1,2] is basically an environmental problem (one of pollution, sustainability, climate change), which presents a challenge, the "Energy Challenge". This challenge is to find a mix[3] of energy resources (cf. Fig. 1) that will allow the types of life styles that people desire, for a global population that may reach 10 billion. History shows that, *grosso modo,* the higher the standard of living the slower the population growth (which can even become negative; cf. Japan today). Therefore, the sooner people reach a higher standard of living, which requires an increase in power available to and affordable for them, i.e., their energy consumption, the sooner the world population will stabilize and the smaller the challenge. Thus, we have here a double challenge, the faster we face the challenge and meet it, the smaller it is!

The present need for power for an average US lifestyle is ~11 kW/person, while Western Europe manages with ~3.5 -5.5 kW/person, India and China with much less than and about 1 kW/person and the world average is nowadays ~2 kW/person. A good guess appears to be that we should strive towards a world *average* that is no less than 4 kW/person, i.e., not less than 40 TW for a 10 billion people world with a somewhat stable energy (and wealth) status. Compared to today's ~14 TW of total world power this calculations explains the phrase "the terawatt challenge".

To provide 10 TW of power will require building a 1 GW power station (coal, nuclear or wind [today's largest wind farm: 0.735 GW in FL, USA]) a day for the next 27.5 years. If, instead, we want to rely only on photovoltaics, PV (and, naturally, this will require also storage), and we use the 14 MW installed PV power plant at the US air force's Nellis base in Nevada as example, we will need to build one every hour for the next 81 years. It is clear that in all cases enormous amounts

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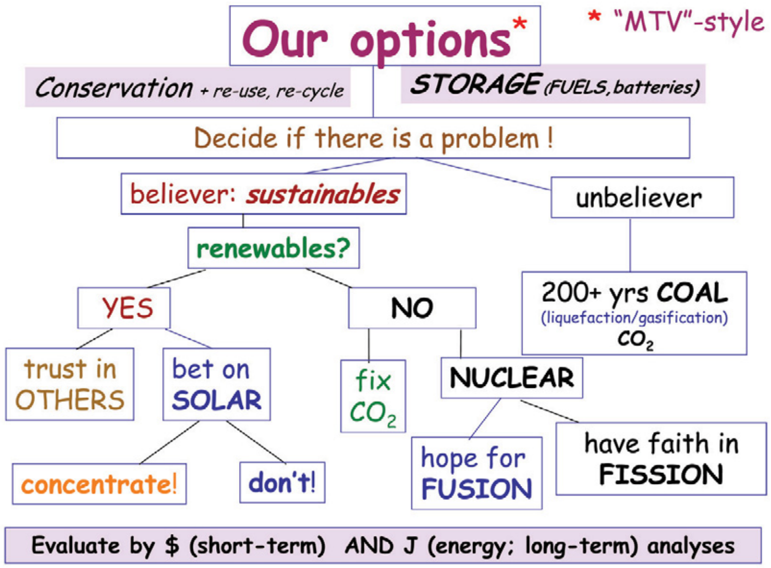

Fig. 1 Schematic overview of possible options to face the Energy Challenge, depending on one's views, starting with the basics, i.e., if there is at all a problem, and down to what appear to outsiders esoteric arguments, such as that about the benefits of concentration for solar energy utilization. Following ref. [3], the scheme can also be viewed as a way to show that there are many solutions, many ways to face the challenge and it is unlikely that any one of them alone will be the panacea.

of materials will be required. The question then arises, if we have such amounts available?

Options

Already during the first energy crisis, several analyses of materials' availability were made and published and the reader is referred to the literature[4,5] for details. From these analyses it is clear that apart from C (including reduced C) and P, the raw materials resources to meet the TW challenge exist, but being able to use them will depend on the price in non-renewable energy that has to be paid.

The real challenges

What then are our options? This is a very dangerous question to answer and would require the magical crystal ball, to avoid making mistakes. The best we can do at present is shown in Figure 1 in schematic form, where we take into account different opinions about the global energy and environment situation.

In the following we will assume that the energy cost of materials will define the technology(ies) that we can use. This implies that the Energy Challenge is to a large extent a challenge to find energy-affordable, stable and, preferably, mostly re-useable materials[†].

Such conclusion, though, begs the question: "What makes a material energy-affordable?" To answer that we need to take into account the energy price of materials and their durability, i.e., we need to perform what are known as "total (or net) energy analyses". Those analyses are well-known (and still controversial) for biofuels, esp. ethanol from corn and sugar cane[7], but also can be (and have been) done for many other processes and materials. A well-known (also somewhat controversial) example concerns photovoltaic modules[8].

[†] *A very useful secondary reference volume on Materials for Energy was recently published[6], and the reader is referred to it for primary literature sources.*

Energy costs of materials

Without going into details, we note that we can rank materials in terms of decreasing energy cost, e.g., Titanium, Aluminium, Plastics (on the average), Iron and Cement (cf. Table 1). Naturally, this is not the whole story, because one also needs to consider the capacity, how much material is needed/fabricated, and at which rate? From that point of view, cement is the world leader. Some idea of the amount of concrete, which is the combination of cement and sand/ rocks that we use for building, is used, can be gotten by considering the world concrete production per capita, one ton of concrete/person. This is understandable if we realize that concrete makes up half to 2/3 of the world's building infrastructure. But, the upstart is that the global manufacturing and use of cement requires ~7% of all industrial energy use, which, itself, constitutes ~1/3 of all global energy consumption. Energy is also a major element (1/4 to 1/3) in the dollar cost of cement.

Table1 Energy costs of materials

Material	Energy cost to manufacture / process the material [M J/ metric ton]
Concrete	600-800
Cut wood (plywood)	~500 (~4000)
Glass	16,000
Steel	21,000
Steel From scrap	11,000
Aluminium (recycled)	164,000 (18,000)
Plastics, high-density polyethylene	81,000

For Aluminium, the combination of its production process and its energy requirements lead to the situation that Al is produced close to cheap electrical energy sources, i.e., hydroelectric plants that produce electricity well in excess of the local electrical energy needs (e.g. Iceland, to which all the ore has to be shipped from afar).

Plastics constitute a special case because their present raw material is oil. This fact should make oil-producing countries highly interested parties in cutting down the use of oil as fuel, because oil's added (money) value as raw material for plastics is many times higher than its value as fuel that is just burned.

How to meet the challenges

Past

For a bird's eye view of history and pre-history we can define human development not only by materials, as is often done (stone, bronze, iron, plastics-silicon), but also by energy type, such as human, animal, water, wind, peat, coal, oil-gas (cf. Fig. 2).

In fact the development of Materials and Energy technologies are intimately connected, geared towards fulfilling human needs. What is meant by this sentence is that their developments allow us to achieve certain standards of living and life styles that were unattainable (or attainable only for a miniscule fractions of the population), with earlier technologies.

If we follow the development of energy sources through the ages (Fig. 2) we find that very often new (or rediscovered, as in the case of cement) materials become widely available with the advent of new energy sources, or reduced cost of existing ones. At the same time, being able to move from one type of energy source to the other has often depended on the affordable availability of new materials on an industrial scale.

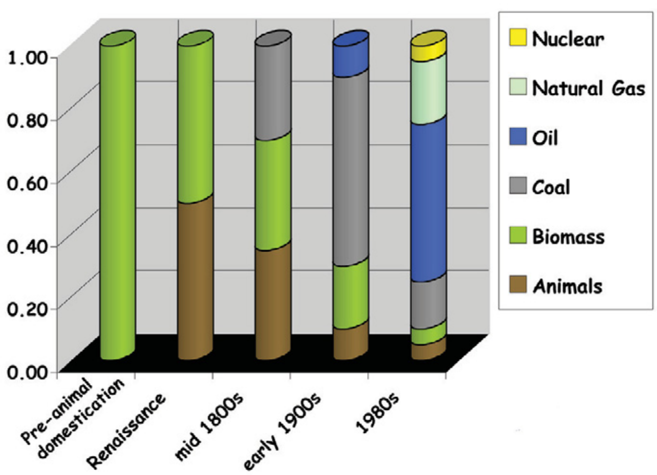

Fig. 2 Global energy sources through the ages - A pictorial view of how things have changed with time, in terms of the way mankind satisfied its power needs, in the "Western World". Wind and hydropower (both solar energy resources), which were sources of energy for long-haul transporta-tion (wind for sailing) and for industrial power (wind for grain milling and water pumping; hydropower for iron production) till the advent of the steam engine, are not included. Of these, today only hydropower is significant, accounting for a few percent of the power on a global scale, even though wind power has become one of the fastest growing sources for power in the West. Note that in China hydropower was an impor-tant energy source, together with coal, for iron-casting, already in the 5th century A.D.; cf. text). Adapted from various sources, esp. from http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/evolenergy.html and http://www.fi.edu/learn/case-files/energy.html .

Roughly speaking, every new form of energy replaced an earlier one that was less dense, in terms of volume (cf. Fig. 2). Thus, one gallon of gasoline contains about 36 kWh, which is equivalent to 500 man-hours of (agricultural) work (some 7 weeks), 50 hrs of 1 horse-power (one week), or 1 full day (equivalent to 6 hrs full sunshine here in Israel in the summer) on a 60 m^2 10% efficient solar panel. Thus, it looks unlikely that we can meet the Energy Challenge that we face today in the ways that were done before because, except for nuclear energy, all alternatives are less energy dense than oil. Therefore, the challenge is not "just" technical, but one for our way of thinking about energy.

Present

We started our story with a short description of the present role of materials in our society, in terms of their connection to the global demand for energy today. Today we have plenty of coal (not always very clean, unfortunately) and the short term (till, say 2020) solutions appear to be heavily dependent on *evolutions in technology*. A few examples are improved conservation, re-use and recycle materials, i.e., limit the throw-away society[9] and reduce use wherever possible. Also included are improving the efficiency of power stations and better use of their waste heat, expanding the use of solar space (esp. water) heating, make coal burning (in power stations) cleaner, improve existing means for energy storage and optimize existing renewable energy technologies (e.g., wind, geothermal).

Future

From a scientific point of view the future, the time where the science that we do now can be expected to make an impact, is likely beyond ~2040. Probable impact will be largest via *revolutions in science* and *changes in paradigms*, including the kind of revolutions that are brought about by new instrumentation (e.g., how scanning probe microscopy influenced the advent of nanoscience). In the interim period *evolutions in science* may well lead to significant improvements in various areas.

Cleaner coal

Cleaner coal technologies will be a must and should include ways for temporary CO_2 storage. CO_2 reservoirs will be valuable for use when we will have found energy-positive, industrially practical and environmentally sustainable ways for artificial photosynthesis (cf. *Mimicking the essential features of photosynthesis b*y Harriman and Benniston, HB, in this issue). Additional areas can be advanced geothermal energy utilization, with an estimated theoretical potential of ~12 TW) which will require, among other things, new materials to drill for tapping hitherto inaccessible reservoirs.

Nuclear fusion

Nuclear fusion, as discussed in the article by Ward and Dudarev (WD) on *Economically competitive fusion power generation*, encompasses our long-term hope for clean, inexhaustible power. The materials preparation and processing challenges for nuclear fusion (cf. WD) were vividly illustrated by the recent cancellation of the Princeton Plasma Physics Lab's stellarator project[10†]. Our "faith in fission" may well be strengthened if we can develop cleaner near–breeders, such as an accelerator-driven, partly Th^{232} – based reactor scheme[11‡], bypassing, rather than solving the storage problem.

Solar energy

Solar energy (cf. *The solar solution* by Sanden, in this issue), which includes also wind and use of natural photosynthesis, is likely to play an increasing role. Materials play a key role for solar cells, solar thermal conversion (also for the optics) and for wind turbines. Indeed, here the advent of new materials can rather drastically change the relative importance of each of these options in the energy mix.

In the long range one would hope that also efficient and affordable artificial photosynthesis (cf. HB) can enter the picture. Here materials design and synthesis of suitable non-noble metal catalysts will require efforts from a wide spectrum of exact and life sciences. This is also an area where we can hope to profit from efforts in nanoscience and technology. To be able to use the potential of 50 TW of wind power that is theoretically available to mankind will require major developments in, for example, building materials, to be able to catch winds at higher altitudes and/or above the oceans.

While the $ price of coal and oil is not something that can be predicted, it is likely that we have left permanently the age of cheap (*2008*US$ 20-30/barrel) oil. This rise in the actual cost of raw energy, at least in the foreseeable future, will require a re-evaluation of the types of materials we will want to use for which purposes and how we make them. It is likely also to affect our lifestyles, but without the spectre of returning to the dark ages

Likely, some materials will fall out of favor, such as some uses of plastics as throw-away, one-time use materials[9] and, possibly, of certain energy-intensive metals.

Thus, we can predict that the search for new materials that combine affordable energy price with durability will be an important part of the future. Such a search is intricately connected with that for affordable and sustainable energy sources... Use of existing and new materials will be measured in terms of energy payback time and, for fuels (see below), their energy density. While, because of existing infra-structures, it is unlikely that sudden changes will occur, only gradual changes are likely.

† *The large budget over-runs of this project can be ascribed (in part) to lack of a relatively affordable method to construct extremely convoluted metallic parts.*

‡ *It gives a popular account of how a sub-critical nuclear reaction can be the basis for a nuclear reactor that has minimal possibility of uncontrolled melt-down, produces nuclear waste with much shorter average half life than current reactors, and, maybe most importantly, does not use or produce material suitable for making a bomb.*

Before we forget...

Storage (cf. Table 2)

Even if we assume that an adequate energy source is found, this does not alleviate the current or a near future energy crisis. Consumption of energy by the end user is a result of a complex chain of energy generation, transportation and, often, conversion. For the case of electricity consumption, the system is amazingly efficient, if we ignore the primary source of the generated energy, which currently is mostly fossil fuel.

However, storage is clearly a very central issue as is also clear from the scheme in Fig. 1. If more than 5-10% of the total electrical power generating capacity comes from a variable source, such as direct solar radiation and wind,[‡‡] conversion to electrical energy will require storage.[‡‡‡] This central role is also clear from the fact that two of the articles in this issue of *Materials Today* deal with storage, i.e. *Materials for hydrogen storage* by Chen and the earlier mentioned HB article. Here we will try only to separate the hopes from the hypes[12] and carry out some reality checks.

Possible fuels

To this end we can consider what are possible fuels for a planet like ours. Because of our oxygen-rich, oxidizing atmosphere, this has to be a reduced material. For land, air and sea transportation, our use of oil has a very logical explanation. Oil and oil products are easy to transport, relatively easy to convert (refine) into useable liquid fuel and have large energy density/volume and weight. Since, it is highly improbable that the entire infrastructure built for gasoline will be suddenly abandoned, one can foresee that whatever the alternative(=synthetic) fuel will

‡‡ *Waves and tides are mostly too small a source to create a problem*

‡‡‡ *A way around this would be a grid with minimal loss that spans more than 12 time zones at least (Buckminster Fuller; cf. e.g., http://www.geni.org/)*

Table 2 Energy density of various materials

Fuel	Energy Density	
	by weight [kJ/gm]*	by volume [kJ/liter]*
Coal (average)	25.0	34,000
Wood (varies with type)	6.0 - 17.0	1,800 - 3,200
Gasoline = petrol (average)	44.0	31,000
Diesel	43.0	30,000
Natural Gas	50.0	32 (25,000 as liquid)
Methanol	19.5	15,600
Hydrogen	120.0	10 (10,000 as liquid)

* without container

be, it must satisfy three major requirements: a) easy to generate from the primary energy source; b) easy to store and transport and c) have high energy density, both per volume and per weight (Table 2). Though simple, these requirements impose significant limitations, on the possible choice of alterative fuels. Alcohols, like ethanol and methanol, easily satisfy all the above-mentioned requirements for an acceptable fuel, and they are far less toxic and more environmentally friendly than oil products. The same logic almost immediately disqualifies all solids from being alternative fuels and among gases only those that are non-corrosive and can be easily condensed into a liquid can be considered.

The question, though, is if apart from reduced C, other reduced materials are potential fuels. For instance, hydrogen (unfortunately often portrayed incorrectly in the popular press as a primary energy source) can be easily generated by water electrolysis (and in sufficient quantities, provided you have enough Pt). However, H_2 is difficult to store, is highly corrosive with respect to the many commonly used materials, such as ferrous alloys and, naturally, is only C-neutral if it can be generated in a C-neutral fashion. Because stored hydrogen has relatively low energy content per volume and even as liquid H_2 is not as good a transportation fuel as gasoline(cf. Table 2), it would seem that using it as an intermediate on the spot is the most attractive approach.

Using considerations of generation (can we mine it....), ease and safety of use, material compatibility, toxicity and energy density, to a variety of proposed synthetic fuels, (H, reduced N, B, Be, Al or Zn), one finds that reduced C, especially alcohols and synthetic gasoline, is an extremely attractive fuel[†].

Energy history, a scientist's economic view

Despite the surge in oil prices, both recently and in the mid 70s and early 80s of the 20th century, the fraction of natural resources in one dollar of product steadily declines, i.e., we learn to produce more and more from the same amount of the natural resources. Changes in the price of various natural resources actually work as a stimulus to develop alternatives. One of the best examples is the replacement of (whale) blabber, which was the primary source of domestic lighting oil in 1860s, and was replaced completely by kerosene in 1890s, when over-hunting of whales made blabber too expensive and cheap kerosene became available. However, economic leverage by itself may be insufficient to balance the consumption of the natural resources and it is here that we reach the limits of the market economy (and of science and technology) and governments really should get involved. The major reason is that the economic leverages may be too slow to act and society may start losing its complexity (level of development) and, with it, its ability to cope with the shortage of vital resources, before new materials and technologies become available. The history of mankind abounds with the examples of both, very successful and utterly unsuccessful transitions from one energy (and any natural[13]) source to another as a result of a shortage of vital resources.

In the second half of the 19th century, wood shortage for steam locomotives led to requests to curtail railroad expansion in the USA. Luckily for railroads, coal became a major fuel for locomotives towards the end of that century. In the same period, in places where wood and coal were scarce, everything that could burn was burnt[13], including occasionally highly exotic fuels, such as Egyptian mummies that were dug out and burnt by the 1000s. This example illustrates how energy shortages can lead to actions that, in hindsight, appear ludicrous.

An example of a successful government-stimulated change of energy source is the transition from wood to coal in China in the 4th-6th centuries A.D., after invention of a high temperature blasting oven for iron casting resulted in an alarming rate of deforestation. Clearly, the government-dictated measure was unpopular with people, whose livelihood depended on supplying the wood, but ... the emperor did not face re-election.

Materials and their development will be crucial to help us to meet the "Energy Challenge" in ways that prevent such situations and worse. mt

[†]*Industrial processes exist for producing gasoline-equivalent liquid fuel from coal. If we can reduce CO_2 (even just to CO), the chemical industry today knows to make useful liquid fuel from such partially reduced C. Unfortunately, the existing processes are not environmentally friendly ("green"), although, to be fair, relatively little effort was made in that direction.*

Acknowledgements

It is hard to impossible to claim originality in a topic such as this and, therefore, there is little doubt that many colleagues will find somewhere some of their ideas in the above. We thank all of them, as well as the many people that bothered to ask questions at our lectures and made us think harder. Special thanks are due to the participants of the Sept. 2007 Bat Sheva seminar on Alternative Sustainable Energy Options[14].

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