Materials for Low-Carbon Power—A White Paper

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Clockwise from top left: land-based wind turbines in Brittany, a solar array (image courtesy of Voodo Solar, CA.), Pelamis wave machine in Portugal, Icelandic Geothermal plant (photo by Asegeir Eggertsson).

Contents

1. Introduction and synopsis

If you want to make and use materials the first prerequisite is *energy.* The global consumption of primary energy today is approaching 500 exajoules (EJ)[1], derived principally from the burning of gas, oil and coal. This reliance on fossil fuels will have to diminish in coming years to meet three emerging pressures:

- To adjust to diminishing reserves of oil and gas.
- To reduce the flow of carbon dioxide and other greenhouse gases into the atmosphere.
- To reduce dependence on imports of fossil fuels (where this is large) and the tensions this dependence creates.

The world-wide demand for energy is expected to treble by 2050. Most of this energy will be electrical. How will it be generated in ways that relieve these pressures? And how much time will the transition take? The options are listed in Table 1.

We have history as a guide for the time it takes to replace one source of power by another. Figure 1 shows the way in which power sources have changed in the last 150 years. Past transitions have taken about 40 years for 50% replacement. Speed, of course, depends on urgency and ability to manage change, and both, in the coming years, may be greater than in the past. But the message of the figure is clear: a major shift in a vital underpinning technology such as power generation takes decades.

Table 1. Alternatives for power generation with current (2008) installed capacity and cost.

Power system	Current installed capacity (GW)	Growth rate (% per year)	Delivered cost ($/kW.hr)	Lifetime (years)
Conventional (gas)	960	1.5	0.01 – 0.03	30 – 40
Conventional (coal)	2800	1.5	0.015 – 0.04	30 – 40
Fuel Cell	0.1	50	0.08 – 0.1	10 – 15
Nuclear – fission	400	2.2	0.02 – 0.04	30 – 40
Wind	204	20-35	0.02 – 0.05	25 – 30
Solar Thermal	1.3	50	0.013 – 0.016	25 – 35
Solar PV	154	40	0.04 – 0.07	20 – 30
Hydro	675	4.5	0.003 – 0.014	75 – 100
Wave	0.004	50	0.03 – 0.07	20 – 30
Tide (current)	0.03	10	0.015 – 0.04	20 – 30
Tide (barrage)	0.26	10	0.009 – 0.015	75 – 100
Geothermal	8.9	20	0.01 – 0.02	30 – 40
Biomass	35	16	0.007 – 0.02	30 – 40

[1] 1 MJ = 0.28 kW.hr = 948 Btu. 1 quadrillion (10^{15}) Btu is called a “Quad”, symbol Q. Thus 1 EJ $\approx$ 1 Q.

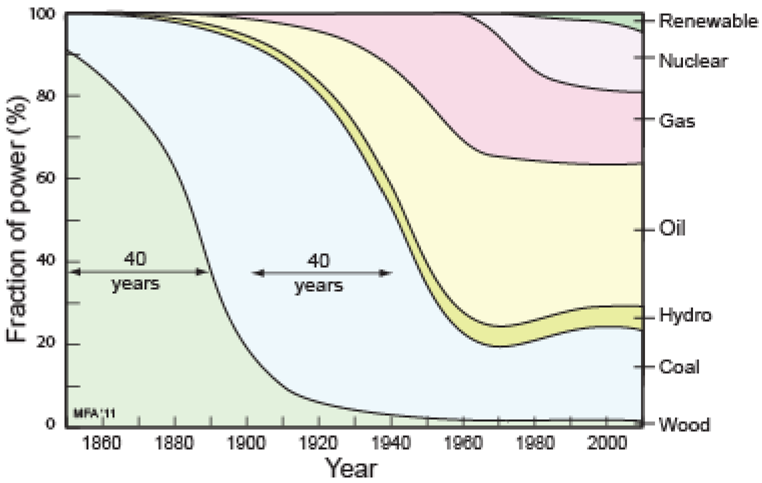

Figure 1. The replacement of one source of power by another over the last 150 years. Transition times are of the order 40 years. (Data from IEA, 2010)

Renewable power systems draw their energy from natural sources: the sun, through solar, wind, and wave power, the moon, through tidal power, and the earth's interior, through geothermal heat. But it is a mistake to think that they are in any sense "free". Their construction incurs a capital cost, which can be large. They occupy land area. Materials and energy are consumed to construct and maintain them, and both construction and operation have an associated carbon footprint.

The best way to compare these alternative power systems is to examine their *resource intensities*[2]. By this we mean the quantity of capital, land area, energy, and carbon-release per kW of generating capacity. Equally important, each system has a *material intensity*, meaning the quantities of materials, in kg per rated kW of generating capacity, required to construct it. If a chosen power system were adopted on a scale that would make a major contribution to global power needs, its demand for materials could distort the materials supply chain. We explore this by comparing the demand of each power system for critical materials (material deemed by governments to be vital for their economy) with the current global production of these materials, highlighting where supply shortages might arise.

The main findings are introduced in Section 2. Subsequent sections develop the background and examine the implications. A warning before we start. The resource intensities of a given power system depend on many things—on the type and scale of the system, on its location, and on the way it is managed. The intensities are tabulated and plotted as representative ranges, but there is no guarantee that they enclose all members of a given system. There are also distinctions between energy and power, between the rated power of a system and the power it actually produces, between its efficiency and its capacity factor, and between energy and carbon of construction and those of operation. Appendix 1 defines all these terms fully.

[2] Similar metrics are used by IAEA (1994) and San Martin (1989), reviewed by Rashad and Hammad (2000).

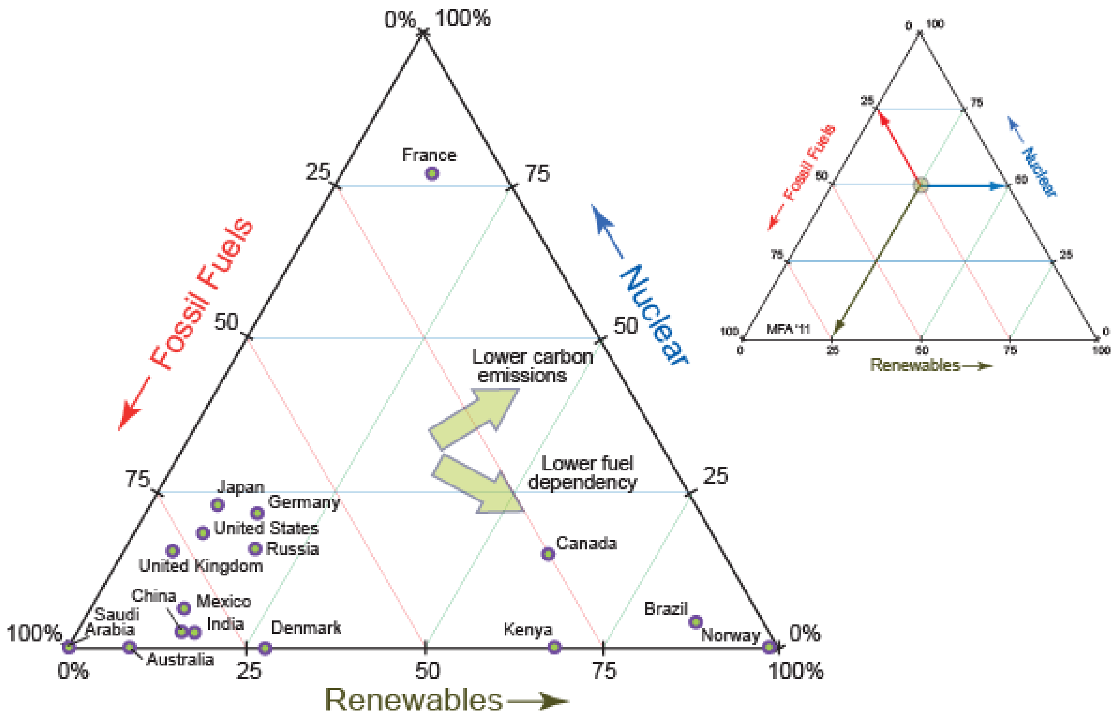

Figure 2. A map of the distribution of electric power generation from fossil fuel, nuclear, and renewable sources. The map is read in the way shown in the smaller triangle: the energy mix is found from a vector at 3 o'clock for nuclear, one at 7.00 for renewables and one at 11.00 for fossil fuels.

2. The resource intensity of power sources—the big picture

The current world electric power-generating capacity is 2,200 GW. At present about 66% of this derives from fossil fuels, about 16% from hydro-power, 15% from nuclear, and 3% from other renewable sources (IEA 2008). Electric power appears to be the future for almost everything except sea, air, and space transport. Before examining individual systems for generating it, we should look at the electric energy-mix to which individual nations have committed themselves. The fossil / nuclear / renewable power triangle of Figure 2 shows that this is diverse. The green arrows indicate the way changes of the mix reduce carbon emission or reduce dependence on non-renewable fossil or nuclear fuels. The smaller triangle and the caption explain how to read the diagram.

In one way this is a reassuring picture. We are not all stuck in one corner. Nations that are endowed with natural energy sources (Norway, Brazil, Canada, Iceland) have developed cost-efficient ways of using them. The high commitment to nuclear power in France demonstrates that it is a viable option.

The flows of energy through the industrial system are complex. Energy is drawn from the sources listed in Table 1. Some is converted from one form to another—gas to electricity, for instance—before its final use to provide domestic, commercial, industrial, and transport services. The flows can be visualized in what is called a Sankey diagram[3], of which Figure 3, based on an original assembled by the Laurence Livermore National Laboratory, is an example.

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[3] Riall Sankey, an Irish engineer, devised the diagram in 1898 to display losses in steam engines.

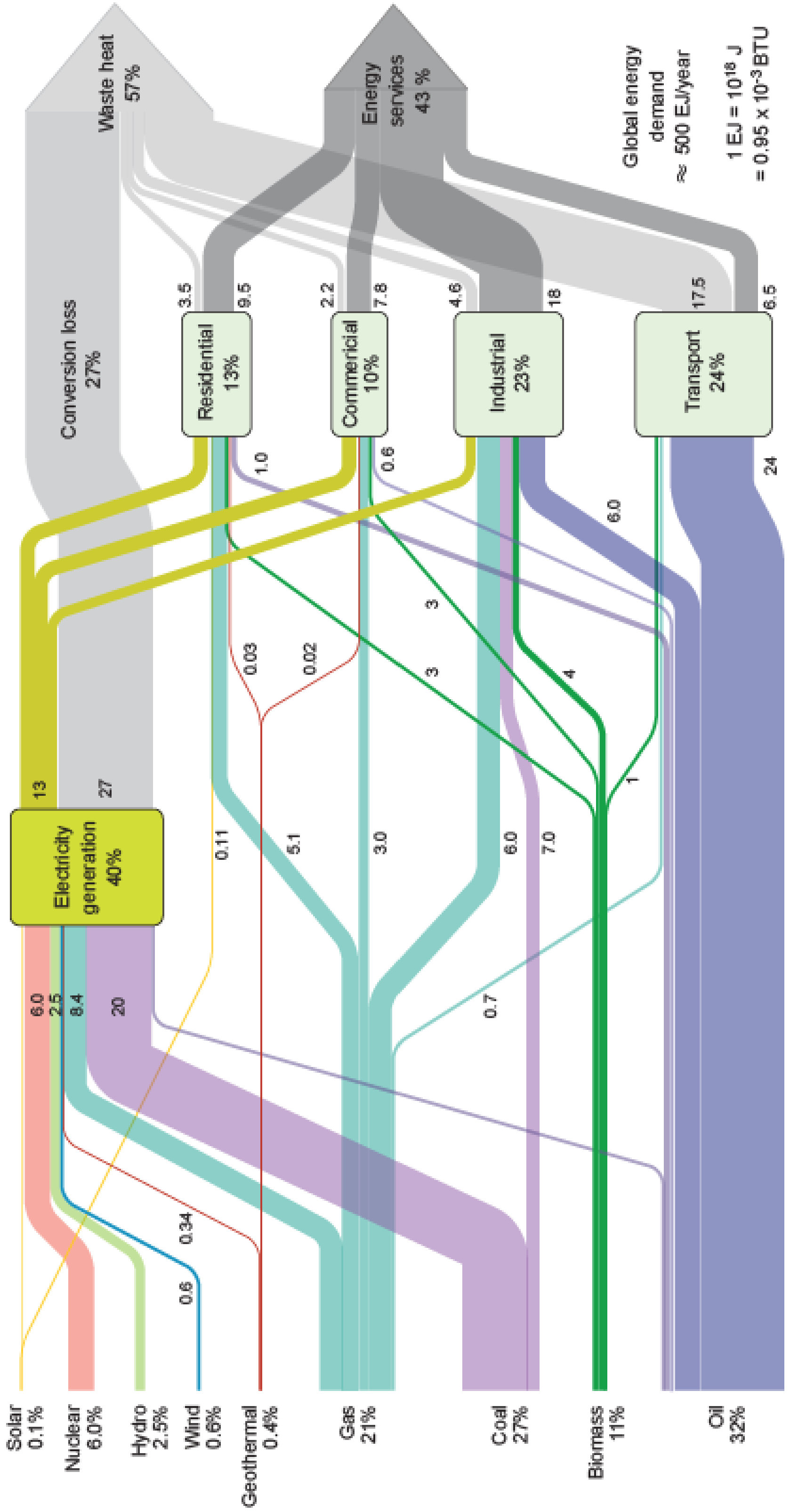

Figure 3. The approximate flows of energy in the global system in 2009. The numbers show the % of the incoming energy in each path. (Compiled from multiple sources.)

Table 2. Average approximate global resource intensities for power generating systems.

Power system	Capital intensity ($k\$/kW_{nom}$)	Area intensity (m^2/kW_{nom})	Material intensity (kg/kW_{nom})	Construction energy intensity (MJ/kW_{nom})	Construction carbon intensity (kg/kW_{nom})	Capacity factor (%)
Conventional, gas	0.6 – 1.5	1 – 4	605 – 1080	1,730 – 2,710	100 – 200	75 – 85
Conventional, coal	2.5 – 4.5	1.5 – 3.5	700 – 1600	3,580 – 9,570	100 – 700	75 – 85
Phosphoric acid fuel cell	3 – 4.5	0.1 – 0.5	80 – 120	5,000 – 10,000	600 – 1000	>95
Solid oxide fuel cell	7 – 8	0.3 – 1	50 – 100	2,000 – 6,000	200 – 400	>95
Nuclear – fission	3.5 – 6.4	1 – 3	170 – 625	2,000 – 4,300	105 – 330	75 – 95
Wind, land-based	1.0 – 2.4	150 – 400	500 – 2,000	3,500 – 6,000	240 – 600	17 – 25
Wind, off-shore	1.6 – 3	100 – 300	300 – 900	5,000 – 10,000	480 – 1,000	30 – 40
Solar PV, single crystal	4 – 12	30 – 70	800 – 1,700	30,000 – 60,000	2,000 – 4,000	8 – 12*
Solar PV, poly-silicon	3 – 6*	50 – 80*	1,000 – 2,000	20,000 – 40,000	1,500 – 3,000	8 – 12*
Solar PV, thin-film	2 – 5	50 – 100	1,500 – 3,000	10,000 – 20,000	550 – 1,000	8 – 12*
Solar thermal	*3.9 – 8*	*20 – 100*	*650 – 3,500*	*19,000 – 40,000*	*1,500 – 3,500*	*20 – 35*[x]
Hydro-earth dam	1 – 5	200 – 600	15,000 – 100,000	7260 – 15,000	630 – 1,200	45 – 65
Hydro- steel reinforced	1 – 5	120 – 500	8,000 – 40,000	30,000 – 66,000	1,000 – 4,000	50 – 70
Wave	1.2 – 4.4	42 – 100	1,000 – 2,000	22,950 – 31,540	1670 – 2070	25 – 40
Tidal-current	10 – 15	150 – 200	350 – 650	12,000 – 18,000	800 – 1130	35 – 50
Tidal-barrage	1.6 – 2.5	200 – 300	5,000 – 50,000	30,000 – 45,000	2,400 – 3,520	20 – 30
Geothermal-shallow	1.15 – 2	1 – 3	61 – 500	7,000 – 13,500	160 – 250	75 – 95
Geothermal- deep	2 – 3.9	1 – 3	400 – 1200	20,000 – 40,700	1,700 – 3,900	75 – 95
Biomass-dedicated	2.3 – 3.6	10,000 – 33,000	500 – 922	5,000 – 19,800	600 – 1800	75 – 95

*Estimated capacity factor for PV in the UK and equivalent latitudes in Europe. The capacity factor in central Australian, Sahara or Mojave deserts could be four times greater.

[x] Typical capacity factor for solar thermal built in a suitable location, such as Spain, North Africa, Australia, or Southern USA.

It shows the flows of energy in the global industrial system, which is broadly typical of an industrialized nation.

The raw sources of energy enter on the left. Threads run from the left, through intermediate energy conversion steps, delivering energy to the sector listed in the boxes on the right. The width of a thread is proportional to the quantity of energy it carries per year. Colored threads represent the flow of useful energy. Light gray threads represent energy lost as low-grade waste heat. Dark gray threads represent energy used to provide useful services, which generally degrade it to the level of waste heat. Values for the flows are listed in exajoules (10^{18} joules).

The major mid-path conversion is that of coal, gas, oil, and nuclear energy to electricity at an overall efficiency of 33%, resulting in a "loss" of two-thirds of the incoming energy as low-grade heat. The electricity passes to the sectors on the right within which it is again converted to provide services: heat, light, manufacturing, transport, etc. Primary energy also enters these sectors in the form of gas, oil, coal, and biomass. They too provide services with varying efficiencies, all of which contribute to the light grey waste-heat threads exiting the sector-boxes. The energy that provides final services is shown as the dark grey threads leaving the boxes.

The most striking feature of the diagram is that barely 40% of the incoming primary energy survives to provide useful service. The other 60% is lost on the way.

Table 2 summarizes the resource intensities and typical capacity factors of alternative power systems. The data from which they are derived appear in subsequent sections of this paper. We define "resource intensity" as the quantity of each resource per kW of nominal power generating capacity, "nominal" meaning the rated power of the system ("a 5 kW solar array; a 600 MW power station"). The actual averaged power output of the system over one year is less than the nominal rating because the *capacity factor*—the fraction of time that the system operates at full power—is less than 1. Thus for nuclear power the capacity factor is typically above 75%. That for hydro power is about 55%, for off-shore wind about 35%, for land-based wind about 22%, and for photo-voltaic solar power in Europe, about 10%. The table lists typical ranges of capacity factor.

Some of the data in Table 2 are easy to find but others are not. Some have been estimated from diagrams or schematics of the system, some deduced by analogy with other

Example: *energy conversion efficiencies.*

Which two energy-conversion processes are the least efficient in the energy flows of the global industrial system? Use the Sankey diagram Figure 3 to find out.

Answer.

The two energy conversion processes with the lowest efficiencies are:

- Electricity generation from coal, gas, oil, and nuclear sources, overall efficiency 33%; and
- Provision of transport (conversion of energy as oil to kinetic energy as motion), overall efficiency about 25%.

systems with similar structural requirements, some inferred from the physics on which the system depends. The material intensities vary greatly with the design—alternative choices exist for magnetic materials for generators and for the semiconductor panels for solar cells, for example—allowing wide variation. That means that the precision of this data is low. But the differences between the resource intensities of competing systems is sufficiently great that it is still possible to draw meaningful conclusions.

Example: *system efficiency and capacity factor.*

What is meant by the *system efficiency* and by the *capacity factor* of a power system? How do they differ?

Answer.

The system efficiency (%) is the efficiency of conversion of the primary energy source (coal, solar radiation, wind, wave, or tidal energy) into electrical power under ideal working conditions. Taking photo-voltaic power as an example, up to 20% of the energy of the incident radiation is converted to electricity provided the incident intensity of the radiation is within the working range of the solar panel.

The capacity factor (%) is the fraction of time that a power system operates at its rated or nominal power. It is reduced by down-time for maintenance or fuel replacement and by the unavailability of the primary energy source. Photo-voltaic power, for example, has a capacity factor as low as 10% because the sun does not shine at night, because of cloud cover, and because of the inclination of the panel to incoming radiation.

Example: *resource intensities.*

What is meant by the resource intensities of a power system?

Answer.

Construction and commissioning of a power system requires resources: capital, materials, energy, and space, meaning land or sea area. A resource intensity is the amount of the resource required to create one unit of power generating capacity. Power systems have a rated nominal power, kW_{nom}, but none operate at full capacity all the time so it is necessary to define also the average delivered power, kW_{actual}. Because of this we need two intensities for each resource. The first is the intensity of the resource per unit of rated nominal capacity (per kW_{nom})—a well defined quantity since the rated power is a fixed characteristic of the system (e.g., a 1kW solar panel). The second is the intensity of the resource per unit of delivered power when averaged over a representative period such as a year. It is equal to the nominal value divided by the capacity factor C expressed as a fraction (e.g., C = 20% = 0.2). The resource intensity per kW_{actual} is always larger, sometimes much larger, than the intensity per kW_{nom}, and it is less well defined because it depends on how the system is operated, and, in the case of renewable systems, on the influence of the weather on sunshine, wind, wave, and tide.

The remainder of this section examines what can be learnt from the data in Table 2.

Charts of resource intensities. The data of Table 2 are displayed in the next five figures. The first (Figure 4) shows the material and area intensities. For a meaningful comparison the nominal power will not do; instead we need the intensities associated with the actual power output averaged over a year, kW_{actual}. To calculate these we divide each nominal intensity in Table 2 by the capacity factor expressed as a fraction. The most striking thing about the figure is the enormous differences between the area intensities of different systems. Gas and coal-fired power stations, nuclear, and geothermal have small footprints of around 3 m^2/kW_{actual}. All others require an area 50 to 500 times greater. This space-hungry characteristic may not be a problem for offshore wind and wave power, but for land-based systems the occupancy of land that could be used for other purposes presents difficulties. Conventional, nuclear, and geothermal systems also have lower material intensities than many of the others, but to understand the material implications of alternative power systems we must examine their bills of materials in more depth: some systems, like hydro-power, use materials that are cheap and readily available; others, like fuel cells, use materials that are scarce and expensive. This we do in subsequent sections of this white paper.

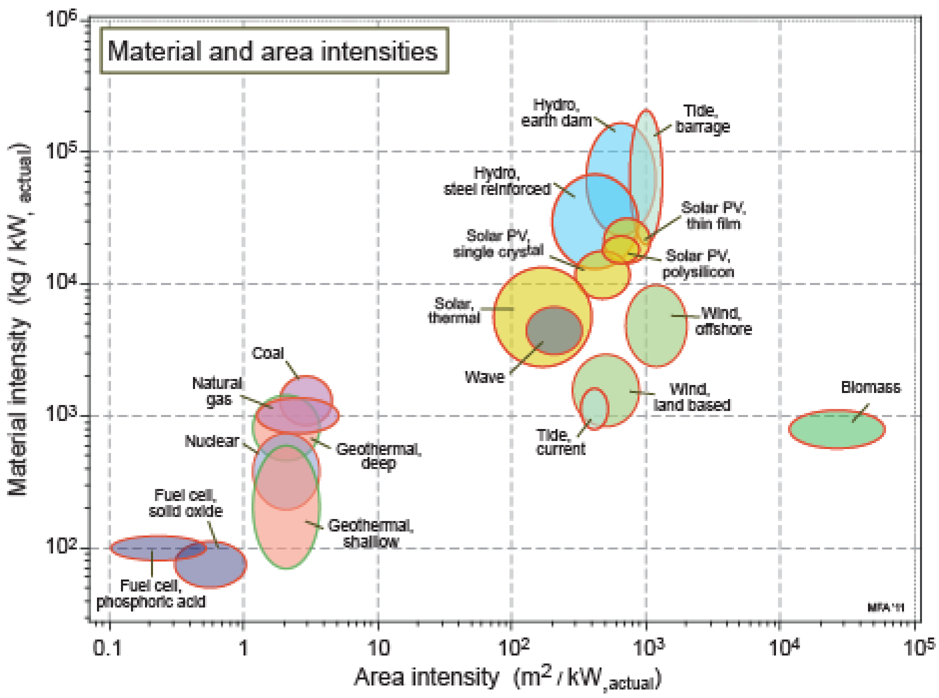

Figure 4. The area and material intensities of power systems, based on actual power output during life.

Example:
the demand for space.

Use mean values of the area intensities of Table 2 to compare the land area required to build a *nominal* 0.5 GW of new generating power using (a) nuclear, (b) single crystal solar PV power, and (c) land-based wind sources. How do these areas change if 0.5 GW of *actual*, not nominal, power is to be built?

Answer.

For 0.5 GW of nominal power, the areas are (a) nuclear, 1 km^2, (b) single-crystal PV power 50 km^2, and (c) land-based wind, 138 km^2.

For 0.5 GW for actual power, these values must be divided by the capacity factor, C. Using mean values from Table 2, the areas become (a) nuclear, 1/0.8 = 1.2 km^2, (b) single-crystal PV power 50/0.1 = 500 km^2, and (c) land-based wind, 138/0.21 = 657 km^2.

Example:
material intensities.

The material intensity for the construction of offshore wind turbines averages about 825 kg per rated (nominal) kW of generating capacity. If the capacity factor for offshore wind is 0.35, what is the material intensity per kW_{actual} of delivered power?

Answer.

An offshore turbine rated at 1 kW actually delivers an average of 0.35 kW, a capacity factor of 35%. To deliver an average of 1 kW_{actual} thus requires 1/0.35 = 2.5 kW of nominal generating capacity, making the material intensity 2063 kg/kW_{actual}.

The capital and energy intensities for the construction of power systems, plotted in Figure 5, are calculated in the same way as those for material and area by dividing the nominal intensities by the capacity factor expressed as a fraction. The two actual intensities are approximately proportional. This arises partly because systems that are energy-intensive to construct are generally more expensive than those that are not, and partly because a low capacity factor (like that of solar photovoltaics) inflates both intensities.

Figure 6 shows the balance between the energy to construct the power system and the energy it generates per year in MJ of electrical energy, per nominal kW of generating capacity[4]. It should be remembered that the construction energy is expressed in oil equivalent, whereas the delivered energy is electrical. Contours show the energy pay-back time, equal to the time in years before the delivered energy exceeds that invested in construction of the plant. The data suggest an energy pay-back time of 1 – 2 years for wind and hydro, rising to 3 – 10 years for solar and tidal barrier.

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[4] 31,530 x Capacity factor MJ_{elec}/kW_{nom}, (31,530 is the number of hours in the year multiplied by 3.6 to convert kW.hr to MJ).

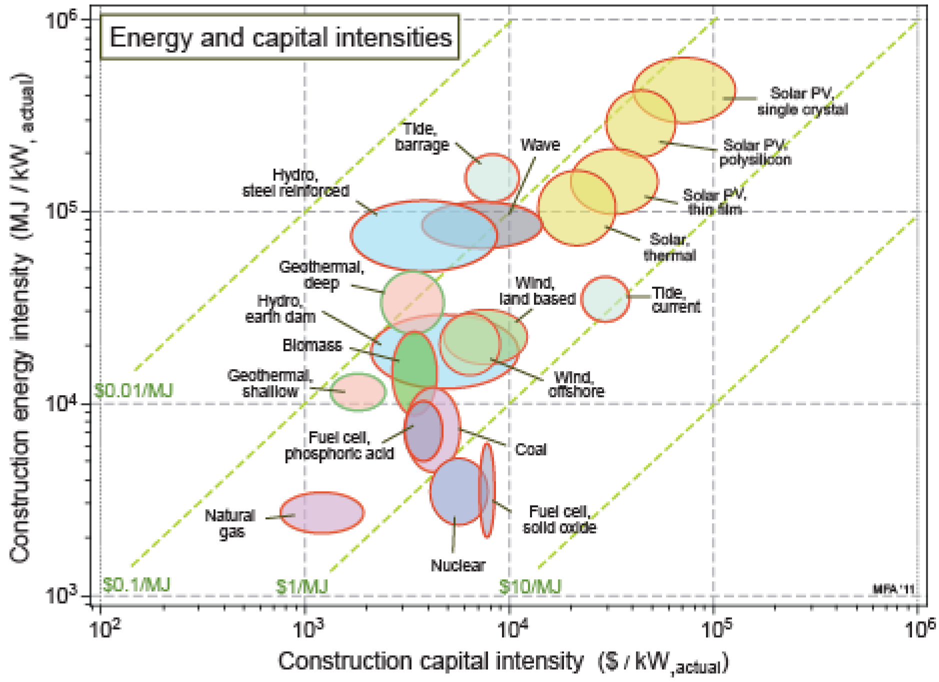

Figure 5. The capital and energy intensities of construction of power systems, base on actual power output during life. The low capacity factor of solar PV systems in temperate climates makes them expensive in both capital and energy.

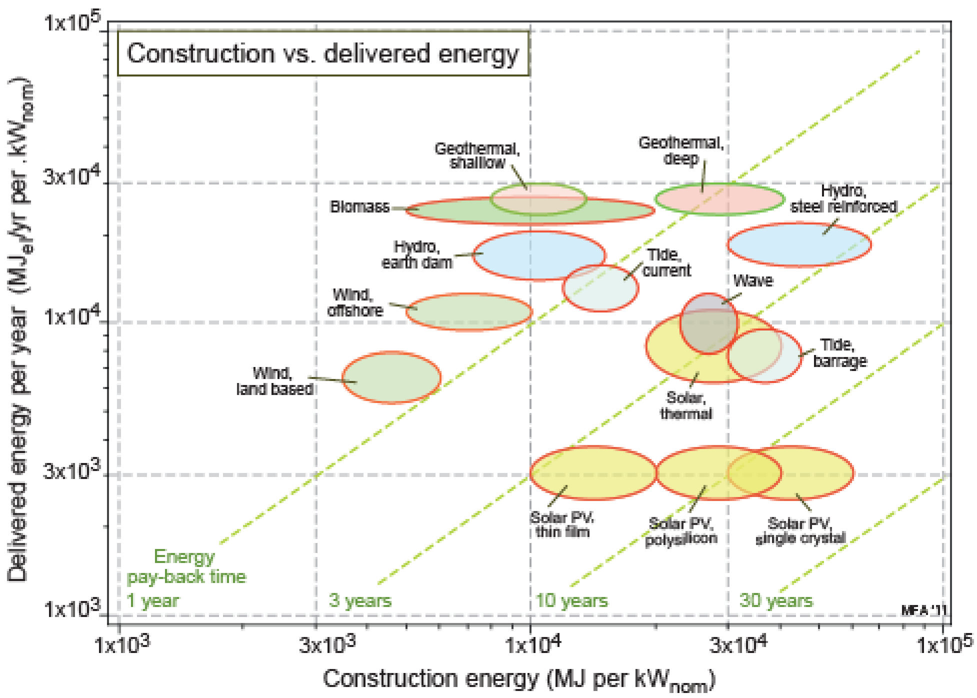

Figure 6. Energy pay-back—the balance between construction and delivered energy.

Figure 7 brings out the large differences in carbon emissions of power systems, measured in kg of CO_2 per kW.hr of delivered energy. Each bar describes the sum of three terms:

- the construction carbon intensity (kg/kW_{nom}) pro-rated by the energy delivered over the system life in $kW.hr/kW_{nom}$, using the system lives listed in Table 1[5]
- the carbon release associated with plant operation, estimated at 0.03 kg/kW.hr for coal and 0.02 kg/kW.hr for the others (estimates by White and Kulcinski, 2000), and
- the release of CO_2 from hydrocarbon fuels, where they are used, per kW.hr of delivered electrical power.[6] (Fuel cells are assumed to burn methanol.)

The figure demonstrates that no power system is completely carbon free because of the contributions from construction and maintenance, but renewable systems produce up to 30 times less carbon than those burning fossil-fuels. The capacity factor for solar PV systems used in the calculation is that for Northern Europe. Solar panels in sunnier climates will have larger C and lower CO_2 emissions per kW.hr.

In subsequent sections we examine power systems in turn, focusing on the underlying physics of their operation and the implications for material supply if they are deployed on a large scale. One concern that emerges is the demands made on materials deemed to be critical because, for example: the global supply is limited; the main ore-bodies are localized in such a way that a free market does not operate; or they play a vital economic role for which no ready substitute exists (like copper for electrical conduction and manganese as an alloying element in steels). Figure 8 provides background for discussing this. It shows the 2008 world production of twenty nine elements that are considered to be critical[7]. Later sections compare the demand of each power system for these elements with the world production, highlighting where material constraints are likely. To do this we examine a hypothetical scenario: that 2,000 GW, roughly equal to the current world generating capacity or one third of that projected for 2050, were to be replaced by a given alternative power system over a period of 10 years. From this we calculate the fraction of current world production of each critical material that would be required to make the replacement, revealing where material supply might be a problem.

[5] Equal to (Construction carbon intensity / 8544 L C) where C is the capacity factor, L the system lifetime in years, and 8544 is the number of hours in a year.

[6] For coal this is equal to 0.088 kg/MJ x 3.6 $MJ/kW.hr_e$ / 0.33 (conversion efficiency from coal to electric power) = 0.96 kg/kW.hr. For gas it is equal to 0.055 kg/MJ x 3.6 $MJ/kW.hr_e$ / 0.38 (conversion efficiency of gas to electric power). For nuclear fuel it is approximately 0.022 $kg/kW.hr_e$.

[7] Many publications, such as that of the British Geological Survey (2011), list critical materials, though not all agree.

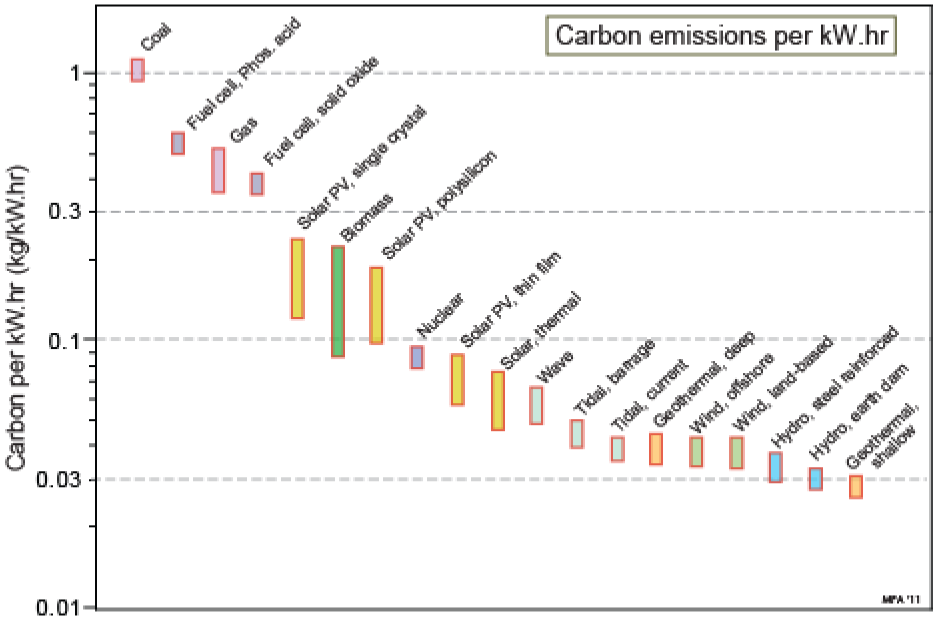

Figure 7. The approximate release of carbon to the atmosphere from the building and operation of alternative power systems, assuming a 20 year life. None are carbon free, but all emit less than coal.

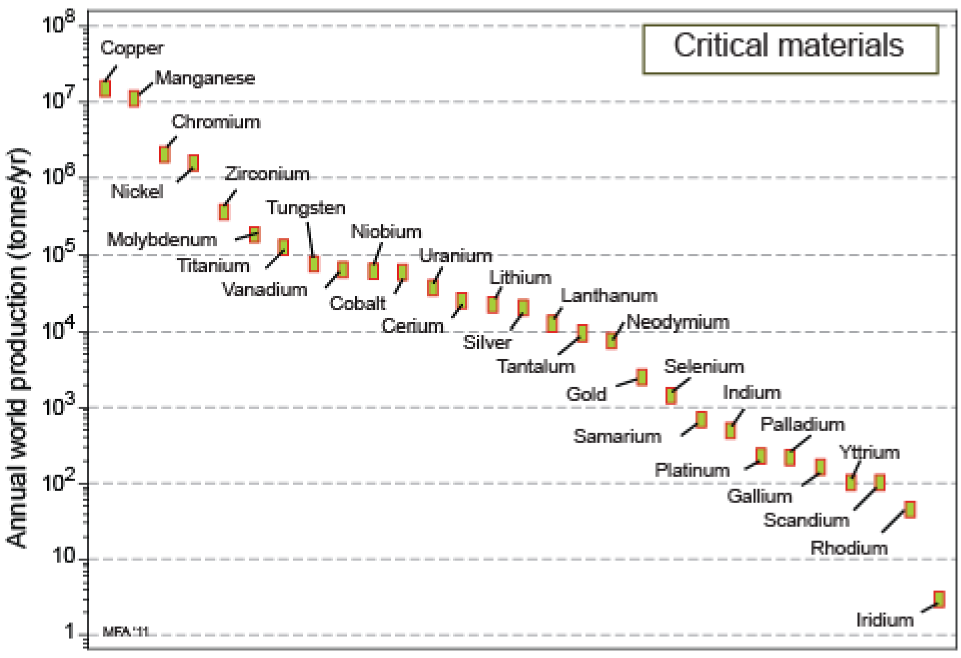

Figure 8. Current annual world production of twenty nine critical elements. Many of them are used in power generation. A major shift from one power system to another can put pressure on their supply.

Example: ***why are graphite, gallium and lithium listed as critical?***

Answer.

Graphite. Over 95% of the world's supply of graphite comes from a single country (China). This makes graphite vulnerable to export tariffs or restrictions.

Gallium. Gallium is recovered from bauxite during aluminum refining; it cannot be economically mined on its own. Increase in supply is only possible if demand for aluminum increases or the efficiency of gallium recovery from bauxite is improved.

Lithium. Production of lithium is dominated by South American countries, not all of which are politically stable. Stable supply is essential to meet the anticipated surge in demand for lithium batteries, for which no viable substitute is currently known. This unique functionality is the reason lithium is classed as critical, despite its relative abundance.

3. Conventional fossil-fuel power: gas and coal

Fossil fuel power generation is the bench-mark against which alternatives must be judged. The use of fossil fuels as a source of energy started in the 1700s and has grow in scale ever since. The high energy-density of fossil fuels makes them easy to transport and allows a large amount of power to be generated in compact plants taking up little land area. Today, fossil fuels are our principal source of power but they are also a source of political and social tensions as the limits to their supply become more apparent. And there is the concern about the emissions that attend their use.

Natural gas. It is said that natural gas, leaking from the ground and burning, so awed the people of Delphi that the place became both a shrine and an appropriately mysterious seat for an oracle. Be that as it may, natural gas is the star among fossil fuels. The low capital cost and the short lead times for building natural gas plants makes them the first choice for new capacity. Natural gas is primarily methane. It is the cleanest-burning and least polluting hydrocarbon fuel. Gas was at one time made from coal but today is drawn from gas, oil and shale reservoirs where it is found along with heavier hydrocarbons. Many gas reserves are now depleted, and while others remain to be exploited, most are deep and lie beneath water or ice.

For electricity generation, gas is either burnt to produce steam or combusted in a gas turbine. In combined cycle units, a gas turbine produces electricity and the waste heat generates steam to drive secondary steam turbine, giving conversions efficiencies above 50%. Natural gas fuel-cells, which we meet in section 6, allow small-scale electricity generation. In addition to its use as a fuel, natural gas is also crucial for the manufacture of plastics, fabrics, and other chemicals and materials. It is, however, a finite resource, the production of which is expected to peak before 2050. The number of high-tech industries that rely on natural gas as a feedstock highlights the importance of conserving it for the future. This conservation imperative

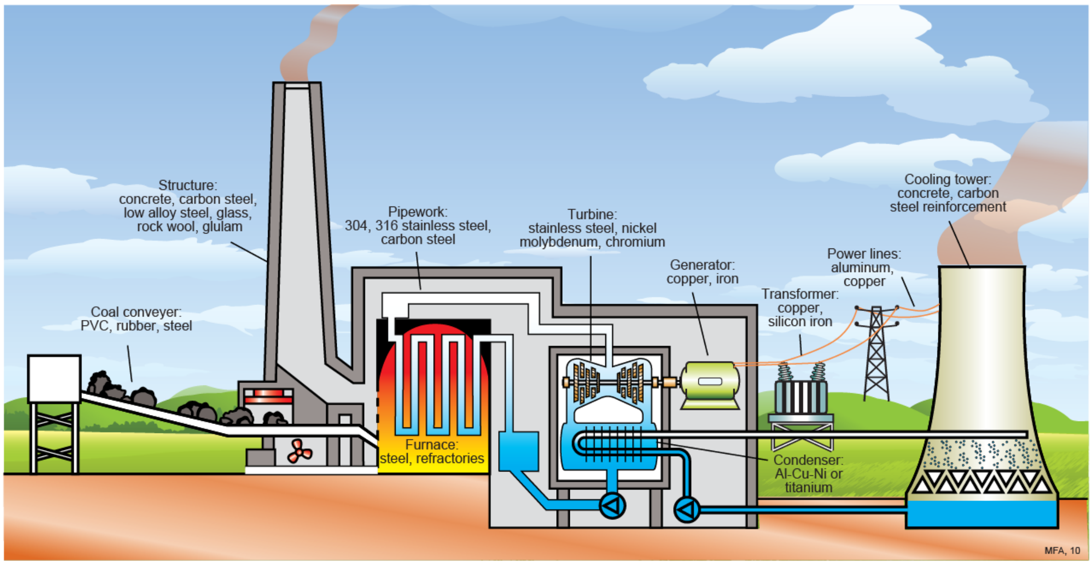

Figure 9. Coal fired power station (Based on an original by Bill C, Wikipedia).

and the emissions associated with burning gas for energy motivate the efforts to find alternative sources of power.

Coal. Coal is the sun's energy in solid fossil form. There are four basic types, classed by their carbon content and calorific (heat) value. *Anthracite,* with 86-98% carbon, is the cleanest-burning of the four. *Bituminous coal*, the most common type, contains 46 – 86% carbon. The final two classes, *sub-bituminous* and *lignite,* both with a carbon content of 46 – 60%, are soft and burn with a smoky flame. All forms of coal are used to generate electricity in large plants (at a typical conversion efficiency of 38%), but they also have important secondary uses: many plastics and organic chemicals rely on the distillation of coal for feedstock.

The global reserves of coal far exceed those of oil or gas. If we are to generate power from fossil fuels then we will be driven to build coal-fired stations. Coal contains hydrogen, nitrogen, sulfur, and many other elements besides carbon. Combustion releases not only green-house gases such as carbon dioxide but also the oxides of sulfur and nitrogen that cause acid rain. These environmental concerns have prompted the development of clean-up technologies. *Washing* reduces the nitrogen content of coal. *Scrubbing*, spraying a lime-water mix into the smoke, removes acidic oxides of sulfur by neutralizing them. *Carbon capture and storage (CCS)*, an emerging technology, captures the carbon dioxide, compresses it and stores it in spent oil and gas reservoirs. This last possibility would allow coal-derived power to be included in the list of low-carbon power sources, although the material implications of CCS are not yet known.

Figure 9 shows the layout of a coal-fired power station and identifies the materials used in the largest quantities. An approximate bill of materials is given in Appendix 2 of this chapter, expressed as mass of material in kg per nominal kW of generating capacity, kg/kW_{nom}. As already explained, the actual output of any power source, averaged over life, is less than the nominal or rated value because the capacity factor C is less than 1, making the actual material intensities, kg/kW$_{actual}$, larger than the nominal ones by the factor $1/C$.

If a sufficient number of new coal stations were built over the next 10 years to provide 2,000 GW of additional capacity, would the drain on material supply be significant? As an indicator we divide the annual material demand that this implies by the current annual global production of that material, expressing the resulting demand ratio in %. Thus a demand ratio of 1% means the construction would require a mere 1% of annual global production; a demand ratio of 100% means a quantity equal to the current global production would be needed. The results, for critical materials, are plotted in Figure 10. Only chromium might give cause for concern.

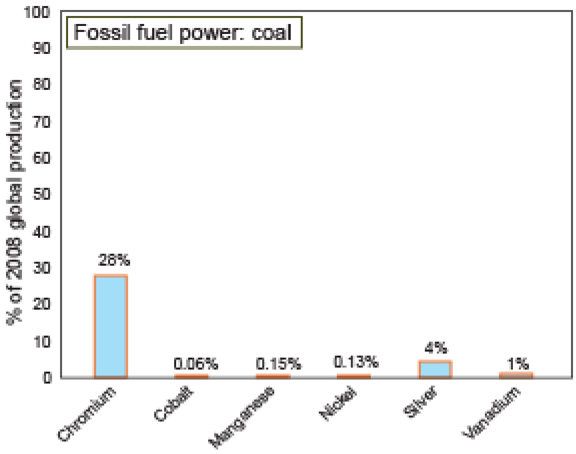

Figure 10. Resource demands for strategic materials used in conventional power systems.

4. Nuclear power

Nuclear power is seen by some as a viable means of generating the electrical power needed to meet future needs. Others perceive it to be only an interim solution and one with inherent risk of accident and nuclear proliferation. Today, many governments take the view that, despite the risks, nuclear power offers the fastest, cheapest way to reduce dependence on imported hydrocarbons, cut carbon emissions, and assure energy supply to 2050.

Nuclear power derives from the energy release on the fission of a nuclear fuel—typically Uranium-235—when it captures neutrons. The briefly formed Uranium-236 is unstable and breaks into lighter nuclei, releasing more neutrons in a chain reaction. The energetic neutrons are slowed by a moderator, usually water, converting their kinetic energy to heat. Fuel consumption is roughly 1 mg of uranium per kW.hr of electrical energy. Fuel is replaced every 1 or 2 years, during which time the plant is shut down.

Currently there are 436 nuclear power stations world-wide, of which 60% are pressurized water reactors (PWRs) and 21% are boiling water reactors (BWRs). The remaining 19% include older CANDU and gas-cooled reactors and new, more advanced reactor designs. The most controversial issue surrounding the large scale use of nuclear power is that of dealing with radioactive waste, which requires secure storage for up to 1000 years.

The core of a pressurized water reactor (Figure 11) has some 200 tube assemblies containing ceramic pellets of enriched uranium dioxide (UO_2) or of a mixture of both uranium and plutonium oxides known as MOX (mixed oxide fuel). These are encased in a cladding of a zirconium alloy, Zircaloy 4. Either B_4C-Al_2O_3 pellets or borosilicate glass rods are used as burnable poisons to limit the neutron

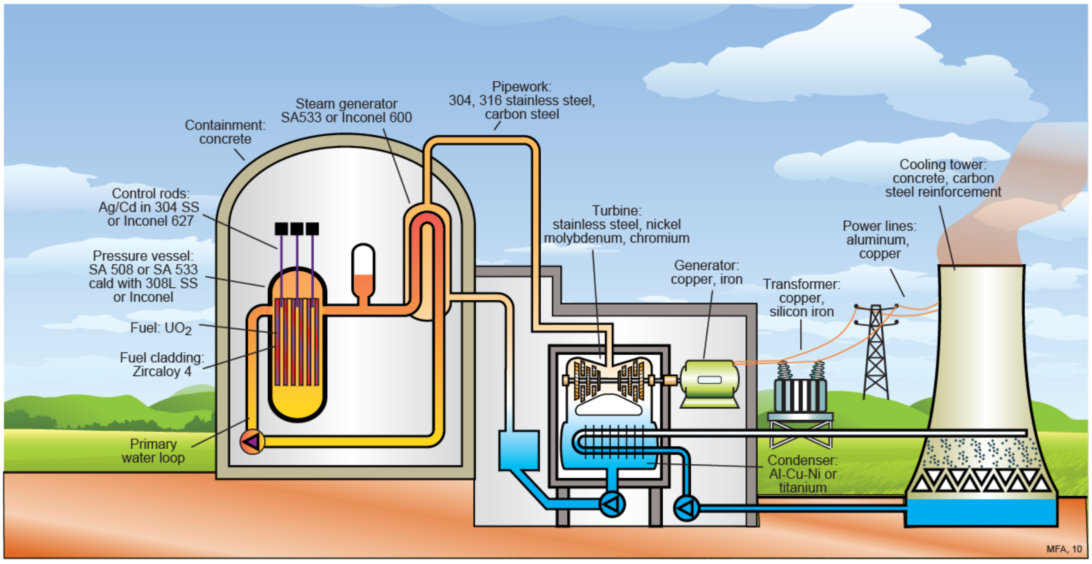

Figure 11. The pressurized water reactor.

flux when the fuel is new. Water, pumped through the core at a pressure sufficient to prevent boiling, acts as both a coolant and a moderator, slowing down high energy neutrons. The power is controlled by control rods inserted from the top of the core and by dissolving boric acid into the reactor water. The boron carbide (B_4C) or Ag-In-Cd alloy control rods are clad in Inconel 627 or Type 304 stainless steel tubes. The primary pressurized water loop carries heat from the reactor core to a steam generator under a pressure of about 15 MPa, which is sufficient to allow the water in it to be heated to near 600 K without boiling. The heat is transferred to a secondary loop generating steam at 560 K and about 7 MPa that drives the turbine. An approximate bill of materials appears in Appendix 2.

Example: *resource demands of nuclear power (1).*

The energy density of uranium is 470,000 MJ/kg. If this energy is converted to electrical power at a conversion efficiency of 38%, how much uranium is required per year to provide a steady 1GW of electrical power?

Answer.

1 kg of uranium delivers 470,000 x 0.38/3.6 = 49,600 kW.hr electrical. (The factor 3.6 converts MJ to kW.hr.) There are 24 x 365 =8760 hours in a year, so a steady power of 1 GW over one year equates to an energy of 8760 x 106 kW.hr. This requires 8760 x 106/49,600 = 1.77 x 105 kg = 177 tonnes of uranium per year.

Example: ***resource demands of nuclear power (2).***

The annual global production of uranium (in 2008) was 40,000 tonnes per year. How many GW of power will that support? How does this compare with the anticipated demand in 2050?

Answer.

The previous example showed that 177 tonnes of uranium is needed to provide a steady 1 GW of power for one year. The current annual global production of 40,000 tonnes of uranium could provide 40,000/177 = 226 GW continuously for one year, sufficient to provide 15% of today's consumption, or 5% of the expected demand in 2050.

Installing 2,000 GW of additional nuclear capacity over the next ten years carries the implications for critical materials plotted in Figure 12 The annual demand for indium for control rods and of uranium for fuel greatly exceeds the current annual production of these two materials.

5. Solar energy: thermal, thermo-electric and photo-voltaics

If you think of the earth as a flat disc facing the sun, then the energy that the sun beams onto the disc is a prodigious 1 kW/m^2. Multiplying this by the disc area (roughly 10^{14} m^2) gives 100,000 TW (10^{17} W), more than a million times more power than we at present use. Not all of it is accessible: some is reflected, some absorbed in the atmosphere, and much falls where it can't be reached. Nor is it evenly distributed: the length of day and the angle that the surface presents to the sun differ between the poles and the tropics. When cloud cover and length of day are allowed for, the sun's energy per unit area in countries with a temperate climate averages 100 W/m^2; that in the tropics can be three times larger.

Simple thermal systems. If a black panel is placed so that photons fall onto it, their energy is absorbed as phonons—lattice vibrations—raising its temperature. The energy can be harvested by passing water or air through the panel, providing low-grade heat for water or space heating.

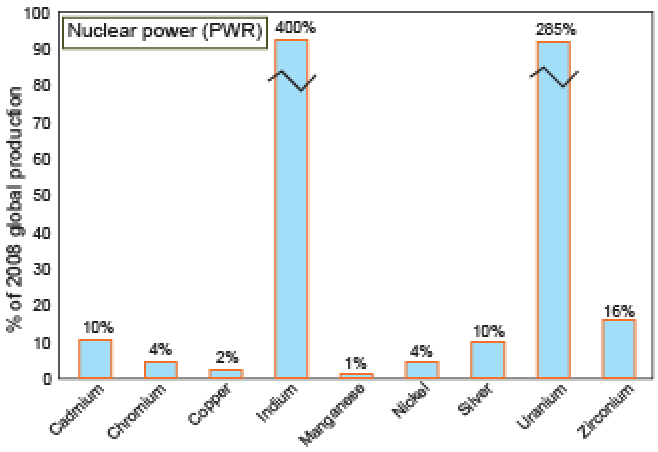

Figure 12. Demand ratios for strategic materials used in nuclear power systems.

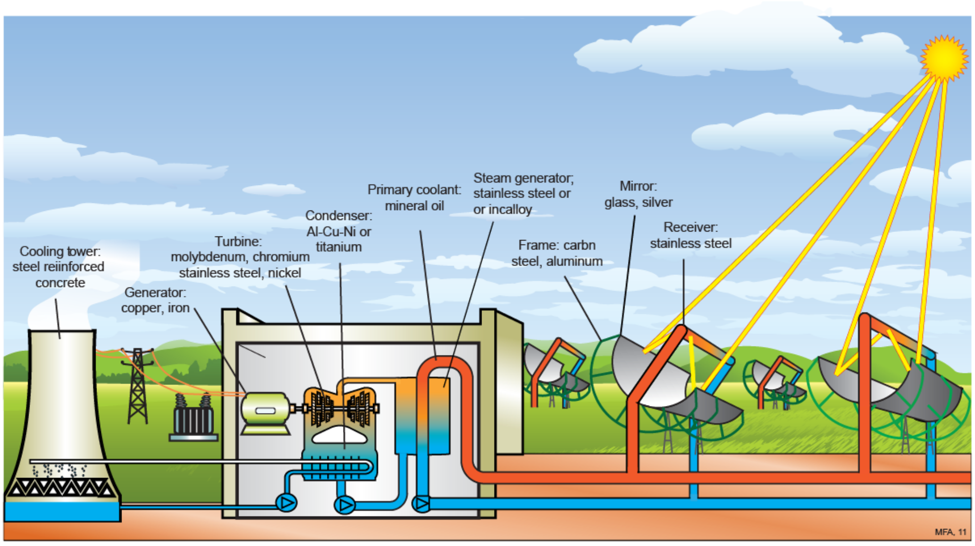

Figure 13. A solar concentrating thermal system using parabolic reflectors, which can be replaced by Fresnel mirrors.

The main materials issues here are those of durability and cost. The materials of the panel must survive for the design life (30 years or more) without maintenance, and they must be sufficiently cheap that the cost of the panel is quickly offset by the value of the energy that is captured.

Concentrating thermal systems. Archimedes, it is said, incinerated enemy ships at the Siege of Syracuse by using polished shields to focus the sun's rays into lethal beams. Concentrating Solar Thermal (CST) plants use the same idea to generate high temperature steam to power turbines, using one of three schemes.

1. Helio-static mirrors track to follow the sun (Figure 13) focus radiation on a tower receiver where it heats molten salt or pressurized water to above 400°C. The heated fluid is used to generate steam for a conventional turbine.

2. Parabolic mirrors or linear Fresnel reflectors track the sun in one dimension, focusing radiation on a tube running down their length which contains the heat-transfer fluid. The fluid, typically mineral oil, passes to a heat exchanger where it is used to produce steam to drive the turbine.

3. Parabolic dish reflectors resembling a satellite dish have a central receiver mounted in front of the mirror. The receiver is a Stirling engine coupled to a small generator which, combined with three-axis tracking of the sun, gives this design the highest efficiency. Expense limits their deployment.

Some of the incoming energy is lost by reflection, and some is lost by parasitic conduction or convection giving overall conversion efficiencies of 30 – 50 %. If this heat is then used to generate electricity there is a further conversion loss, reducing the efficiency to 8 – 15%

The parabolic trough is the cheapest and the most robust scheme for harvesting solar energy. Both it and the solar tower, which can reach higher temperatures, are compatible with thermal energy storage using molten nitrate salt as the storage medium. This energy is recovered when there is less sunlight but still high demand.

A bill of materials for a typical parabolic trough or solar tower plant appears in Appendix 2. Figure 14 shows the demand ratios. It is clear that supply constraints on the use of silver for the reflectors would be a concern for widespread use of CST. Low cost polymer based mirrors with aluminum reflective coatings are under trial. Molten salts used for storage are not critical materials and are already produced in large quantities for agriculture.

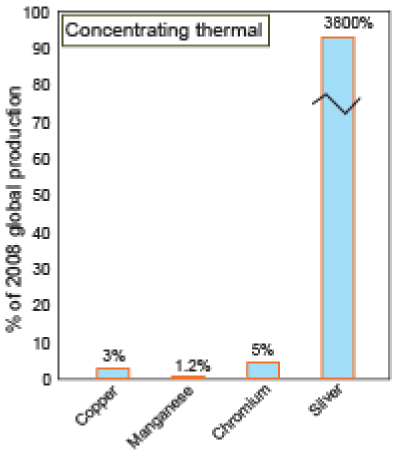

Figure 14. Demand ratios for strategic materials used in solar concentrating systems.

Thermo-electric systems. Two dissimilar metal wires, joined at one end, develop an emf (a voltage difference) $\Delta V = S\Delta T$ between the two un-joined ends when the joined end is heated, where S is the Seebeck constant with units of volts/K, a characteristic of the materials of the couple. Thermo-electric capture can be used in combination with photo-voltaics to generate useful power from otherwise wasted heat.

The efficiency of a thermoelectric system depends on the materials that form the junction and the temperature difference between the junction and the free ends of the wires. It is measured by a figure of merit, Z:

$$Z = \frac{S^2 \kappa_e}{\lambda} \qquad (1)$$

where κ_e is the electrical conductivity, and λ the thermal conductivity. This is more commonly expressed as the *dimensionless figure of merit ZT* by multiplying Z by the average temperature $T = (T_1 + T_2)/2$ of the extremes of the wires. Larger values of ZT indicate greater thermodynamic efficiency. Values of *ZT* = 1 are considered high, but values in the 3–4 range are needed for thermoelectrics to compete with conventional power generation. Compounds of bismuth (Bi), selenium (Se), tellurium (Te), ytterbium (Yb) and antimony (Sb) have the highest values of ZT but none as high as 4. These are materials with small reserves and localized sources, making large scale deployment of thermo-electric generation problematic.

Photo-voltaic (PV) systems. Although photo-voltaic power is expensive, world capacity is growing rapidly, spurred on by government subsidies to expand renewable electricity generation. In remote locations where transmission costs are high, solar power can compete with power from fossil fuels. But as Figure 5 showed, constructing PV systems is both capital and energy intensive.

The semiconductor that forms the active element of a PV collector has an energy gap (the gap between the conduction band and the valence band) comparable with the energy of

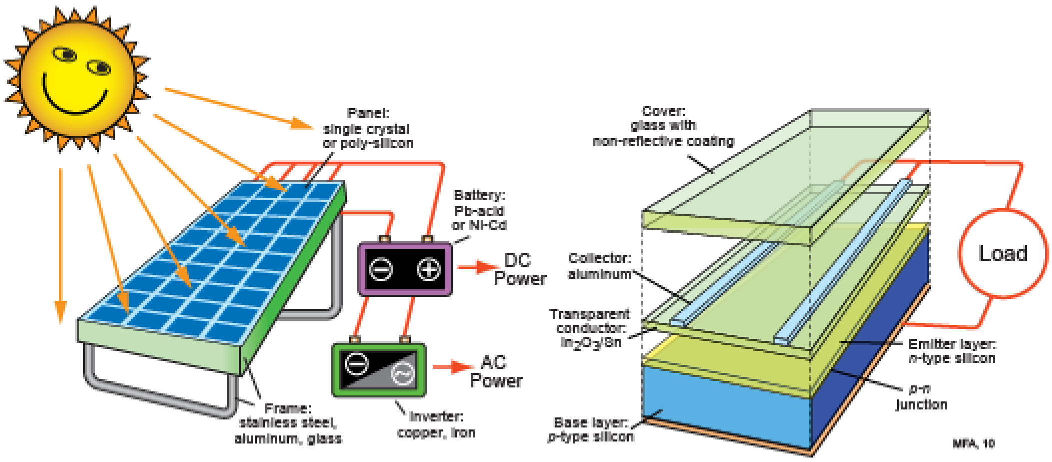

Figure 15. A silicon-based photovoltaic panel.

the sun's photons. Solar radiation arrives as photons with wavelengths λ between 0.3 and 3 microns, the intensity peaking at 0.5 microns. The corresponding photon energy is hc/λ (here h is Planck's constant, 6.6 x 10^{-34} J/sec and c is the velocity of light, 3 x 10^{8} m/sec). If an electron with a charge e absorbs a photon it acquires a higher electric potential

$$\Delta V = hc/\lambda e \qquad (2)$$

For solar photons, ΔV is between 0.5 and 2.5 volts. If the energized electron now flows through an electric circuit across this potential difference it can deliver electrical energy to an external load.

Most photovoltaic cells today use silicon as the semiconductor (Figure 15). A *base* layer of *p*-type silicon is joined to a thin *emitter layer* of *n*-type silicon that is exposed to the sun's rays, which are absorbed in a layer near the *p-n* junction. The *n*-layer is doped with electron donors (5-valent elements such as phosphorous or arsenic) that readily give up an electron. The *p*-layer is doped with electron receptors (3-valent elements such as boron or gallium) that readily accept an electron, creating an electron "hole". The mobile electrons in the *n*-layer and mobile holes in the *p*-layer provide charge carriers that allow an electric current to flow through the cell. At the *p-n* junction a potential difference exists because of the excess electrons on one side and holes on the other. When solar photons with an energy greater than the band gap penetrate this junction they create electron-hole pairs. The electrons move to the negative electrode and the holes to the positive one to provide the current in the external circuit.

Only a fraction of the incoming solar energy is captured because long-wavelength photons have too little energy to create electron-hole pairs and are simply absorbed as heat; short wavelength photons have more than is needed and the difference, again, is absorbed as heat. The result is that the efficiency of conversion is low and it is reduced further if the panel does not face the sun but lies at an angle to it. Static thin-film devices made of amorphous silicon are the cheapest and give an efficiency of 8-9%. Poly-silicon crystals have efficiencies of 12-14%. Single crystal silicon cells (the most expensive) provide an efficiency of 15-17%, though they are more energy-intensive to make. The average output is increased further by tracking the panels so that they face the sun continuously, allowing up to 20% conversion efficiency. Concentrators in the form of lenses or mirrors can improve the efficiency further. Newer systems use cadmium telluride (CdTe) or copper selenide Cu(In, Ga)Se_2 semiconductors.

Once installed, solar PV power is effectively carbon-free, and although conversion efficiency declines over time, it requires little maintenance and has a long life. The difficulty with solar power in temperate climates is the low capacity factor, about 10%. This is because the rating of a panel (1 kW for example) is the power it produces when the incoming solar power density is 1000 W/m^2, a value only reached at midday on a completely clear day. The average incoming power density, allowing for hours of darkness, cloud cover and other factors, is about 100 W/m^2. This low capacity factor drives up the capital and material intensities and stretches the energy pay-back time to between 3 and 10 years (Figures 5 and 6). When installed in a dry, tropical location the capacity factor increases by 3 or more times, with a proportional drop in these intensities and times.

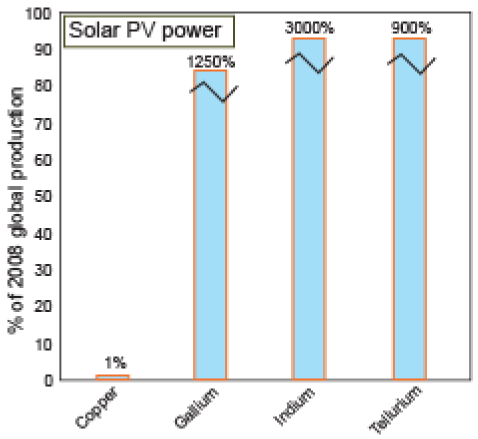

Figure 16. Demand ratios for strategic materials used in photo-voltaic power systems.

A bill of materials for a typical PV system is given in Appendix 2; details vary with panel type and manufacturer. Many of these materials, such as indium, gallium, and tellurium, are critical (Figure 16). A major expansion in photovoltaic power generation would put their supply under pressure. It is for this reason that current research focuses on cheaper, more plentiful alternatives such as copper or iron sulfides.

6. Fuel cells

Electrical conduction in solids can be electronic (a flow of electrons) or ionic (a flow of ions). Many ionic conductors are electronic insulators, a characteristic exploited in fuel cells. A fuel cell consists of an anode and a cathode separated by an electronically-insulating electrolyte. Oxidation takes place at the anode releasing electrons, while reduction at the cathode absorbs them:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (3,a)$$

(typical anode reaction)

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (3,b)$$

(typical cathode reaction)

To allow the reaction, protons (H^+) diffuse through the electrolyte from the anode to the cathode. Anode and cathode are connected by an external electron-conducting circuit that includes the load. The reactions have to be catalyzed by platinum, a critical material.

Fuel can be fed to the cell as hydrogen gas, but hydrogen supply is at present limited. Most fuel cells create hydrogen by reforming methane with steam:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad (4,a)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad (4,b)$$

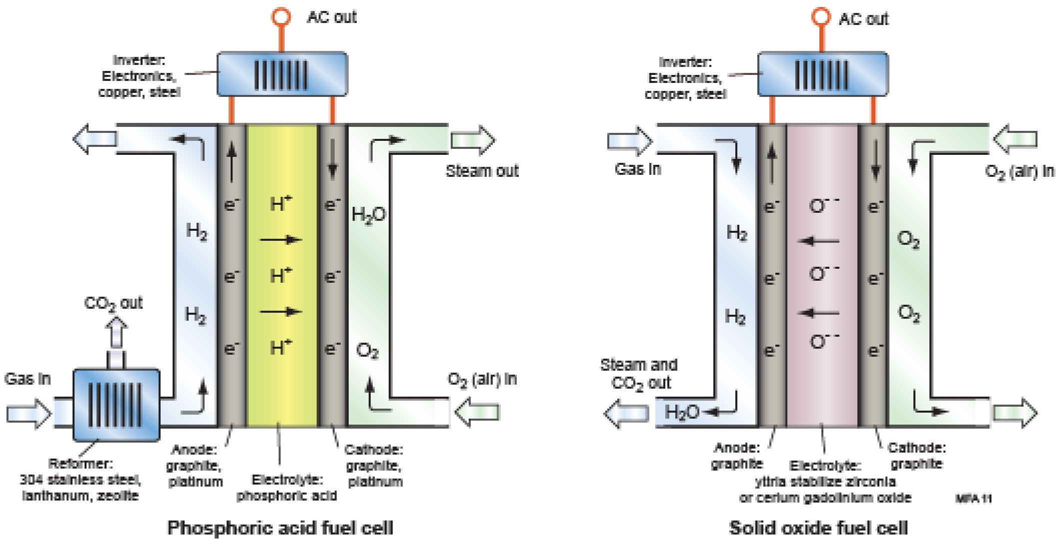

Figure 17. Phosphoric acid and solid oxide fuel cells.

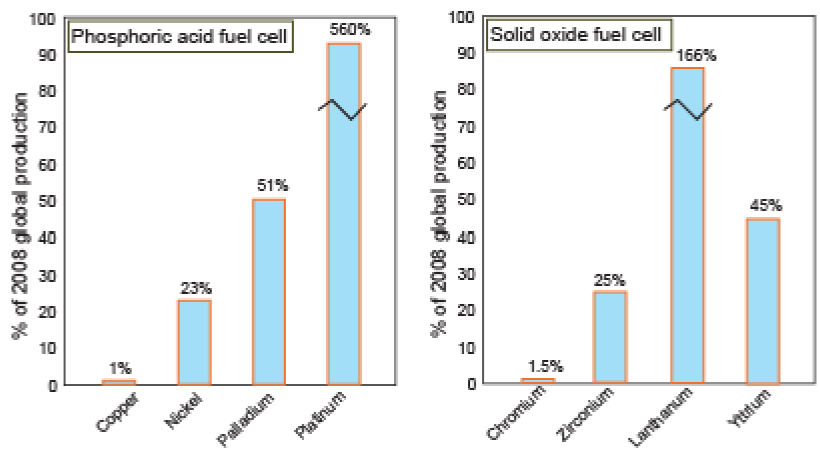

Figure 18. Demand ratios for strategic materials used in fuel cells.

These reactions must be catalyzed with nickel and require high temperatures. Low temperature fuel cells use external reformers. High temperature fuel cells can reform the methane at the electrolyte. Both emit CO_2, generated by the reforming process.

There are many types of fuel cell, which are generally classified by their electrolyte.

Phosphoric acid fuel cell (PAFC). The PAFC is the cheapest fuel cell and the one with the largest installed base (over 75MW) and the longest useful life (10 years). It uses a liquid phosphoric acid electrolyte at relatively low temperatures of 150-200°C. Protons from the oxidation of hydrogen at the anode are transported through the phosphoric acid to the cathode where they react with oxygen from the air to form water, as in Figure 17. The reaction requires a platinum catalyst. The low temperatures limit efficiency to around 40%, which is not competitive with the most efficient gas power plants. Appendix 2 contains a bill of materials for a PAFC. Platinum is the only critical material that might constrain widespread deployment (Figure 18).

Solid oxide fuel cell (SOFC). The electrolyte of a SOFC, typically, is yttria-stabilised zirconia (YSZ). The high temperatures required for sufficient ionic mobility, typically 600-1000°C, remove the need for expensive catalysts, like platinum, at the electrodes. Oxygen ions diffuse though the electrolyte, and react with hydrogen at the anode to give water:

$$O_2 + 4e^- \rightarrow 2O^{2-} \quad \text{(cathode reaction)} \qquad (5,b)$$

$$2O^{2-} + 2H_2 \rightarrow H_2O + 4e^- \quad \text{(anode reaction)} \qquad (5,a)$$

SOFC systems can run on natural gas, LPG or biogas. The hydrocarbon fuel is steam reformed to hydrogen and carbon monoxide within the cell. The high temperatures give an efficiency of 50-60% but, because many components of a SOFC are ceramics, the start-up has to be slow to prevent thermal shock. Replacing the YSZ electrolyte by cerium gadolinium oxide reduces operating temperatures to 500-600°C, allowing the replacement of many structural ceramic components with stainless steel, improving thermal shock resistance and reducing startup time.

The bill of materials for a YSZ electrolyte SOFC in Appendix 2 suggests that the only critical materials used in significant quantities are yttrium, zirconium, and lanthanum, a component of the oxide electrolyte.

7. Wind power

Wind has been used as a source of power for centuries. Today wind turbines are the fastest-growing sector of the renewable power business driven, like solar PV power, by government subsidies (Figure 19). The problem with wind power, like that of most other renewable energy sources, is the low *power density,* that is, power per unit area. On land, it averages 2 W/m^2; off-shore it is larger, about 3 W/m^2. The average land area per person in country with a population density like that of the UK is about 3500 m^2. That means that if the *entire country* where were packed with the maximum possible number of wind turbines, it would generate just 7 kW per person (MacKay, 2009), approximately what we use today. Placing them off-shore helps solve the overcrowding problem, but maintenance costs are higher.

Example:
living on wind power alone.

The land area of The Netherlands (Holland) is 41,526 km^2. Its population is 16.5 million and the average power consumption per capita there is 6.7 kW. Could Holland's power needs be met by land-based wind turbines operating at a (high) capacity factor of 0.3? Use mean values of the data in Table 2 to find out.

Answer.

The land area occupied by wind turbines required to meet The Netherlands' needs is

$$A = \text{Population x Power per person x Area per unit power / Capacity factor}$$

From Table 2, the mean area-intensity for land-based wind turbines is 275 m^2/kW$_{nom}$. The capacity factor is 0.21, giving

$$A = 1.01 \text{ x } 1011 \text{ m2} = 101{,}000 \text{ km}^2$$

This is 2.4 times the area of the Netherlands. There is no way land-based wind power alone can supply all the country's needs.

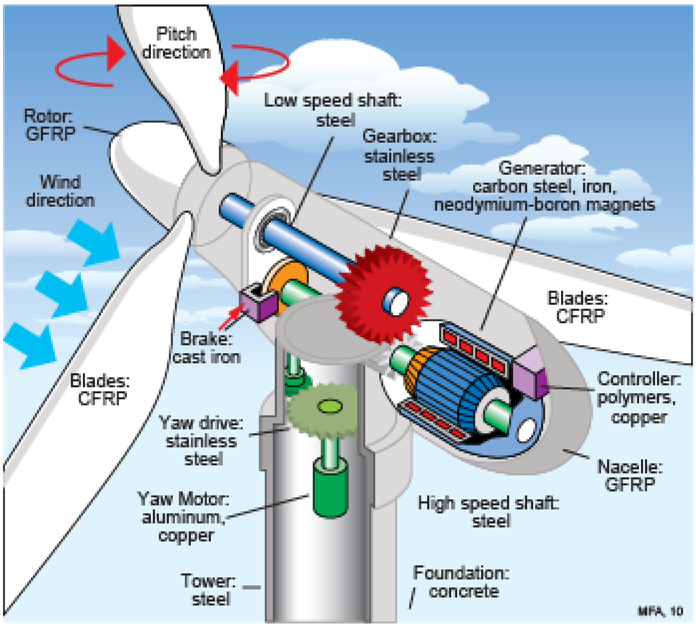

Figure 19. A wind turbine (Figure developed from a diagram from the US Department of Energy, www1.eere.energy.gov/windandhydro).

When wind comes into contact with the rotor of a wind turbine, some of its kinetic energy is imparted to the blades, driving their rotation. This rotation is transmitted through a gearbox to a generator, creating electric power. Wind speed v increases with height h above ground level:

$$v(h) \approx v_{10}\left(\frac{h}{10}\right)^{0.14} \qquad (6)$$

where v_{10} is the wind speed at a height $h = 10\,m$. We show in a moment that power depends on wind speed cubed, so increasing the height of a wind turbine by a factor of 2 increases power by 30%, as we show in a moment. Wind turbines have a cut-in and cut-out wind speed (typically 3 m/s^2 cut-in and 20 m/ s^2 cut-out). They stop altogether when the wind speed is outside this range.

The maximum power generated by a turbine is limited to 58% of the kinetic energy of the wind stream passing though it (the Betz limit, symbol C_B). It is calculated by considering mass and energy conservation across the turbine, shown in Figure 20. Here the approaching wind velocity is v_1, the exit velocity is v_2, the swept area is S and the mean velocity in the plane of the turbine is $\bar{v} = 1/2(v_1 + v_2)$. The energy flux per second (= power) of an uninterrupted air flow of velocity v_1 across an area S is

$$P_{in} = \frac{1}{2}\dot{m}\,v_1^2 = \frac{1}{2}(S\rho\, v_1)v_1^2 = \frac{1}{2}S\rho\, v_1^3 \qquad (7)$$

where ρ is the density of air, assumed constant and $\dot{m}$ is the mass per second passing through S.

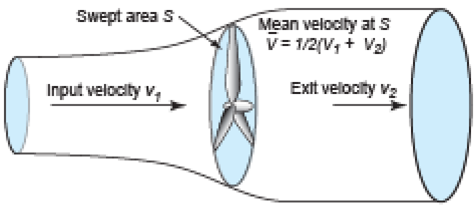

Figure 20. Control volume across a wind turbine.

Flow in an ideal (non-viscous) incompressible fluid is governed by Bernouilli's equation:

$$p + \frac{1}{2}\rho v^2 + \rho g h = constant \qquad (8)$$

where p is the pressure, v the flow velocity, g the gravitational constant and h the height. Thus the pressure difference Δp across the turbine caused by the drop in flow velocity from v_1 to v_2 at constant h is

$$\Delta p = \frac{1}{2}\rho(v_1^2 - v_2^2) \qquad (9)$$

The air velocity in the plane of the turbine is $\bar{v}$ so the work done by Δp per second, and thus the power P delivered to the turbine, is

$$P = \Delta p\, S\bar{v} = \frac{1}{4}S\rho(v_1 + v_2)(v_1^2 - v_2^2)$$

The power coefficient is found by dividing this by the kinetic energy per second of the uninterrupted air flow passing across an area S giving

$$\frac{P}{P_{in}} = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \left(\frac{v_2}{v_1}\right)^2\right)$$

Differentiating and equating to zero to find the maximum gives the value of the Betz limit: $(P/P_{in})_{\max} = C_B = 0.58$. The power P is then

$$P = C_B P_{in} = \frac{1}{2}C_B\rho S v_1^3 \approx 0.3\,\rho S v_1^3 \qquad (10)$$

Thus the peak (rated) power of a turbine varies as the swept area S times the cube of the incoming wind speed v_1.

The power rating of a wind turbine (e.g., 2 MW) is its peak power. The actual power output depends on its capacity factor and this depends on turbine design and location. Off-shore turbines have a capacity factor of about 35% but they are expensive to build and maintain. The average capacity factor for land-based turbines is closer to 21% but they are cheaper to build and easier to service[8].

Wind energy is free, but harvesting it is not. There is an energy investment associated with the construction of a wind turbine. Figure 6 showed that the energy pay-back time is typically between 1 and 2 years. The problem with wind power is not energy pay-back time but the small power output per unit. Even with an greatly over-optimistic capacity factor of 50%, about 1000 2 MW wind turbines are needed to replace the power output of just one conventional coal-fuelled power station, so the capital intensity, and that of land and materials is high (Figures 4 and 5).

The blades are the most vulnerable parts of a wind turbine. The drive for ever longer blades (to increase S) places constraints on the choice of materials. The self-weight of the blade creates alternating bending loads at the blade root as the turbine rotates. Superimposed on these is an axial load cause by centrifugal force and a bending load caused by wind pressure. The most efficient configuration for a light, strong structure is a shell made from a material with the smallest value of the index ρ/σ_y, where σ_y is the yield strength and ρ the density: laminated wood, GFRP and, above all, CFRP, the material of choice for the blades of large wind turbines. The generator, too, is a critical component. Wind

[8] The averaged capacity factor for all British wind turbines, land-based and off shore, for the 12 months to April 2011 was a mere 21.7% because of unusually calm weather conditions (the Times, April 1, 2011).

turbines typically rotate at 10-20 rpm. Some use induction generators (which do not use permanent magnets) that are efficient only at around 750 rpm, requiring a gearbox that needs regular maintenance. Permanent magnet generators operate efficiently at the low speeds at which the blades turn, allowing direct-drive. Neodymium-iron-boron magnets (Nd-Fe-B) give the highest performance generators, with only the significantly more expensive samarium-cobalt (Sm-Co) coming close.

Appendix 2 has an approximate bill of materials for a wind turbine. The resource-demand ratios for critical materials, assuming CFRP blades and Nd-Fe-B magnets, appear in Figure 21. Both that for CFRP, the blade material, and for neodymium, a component of the permanent magnets of the generator, far exceed current production capability. It may be necessary to greatly increase production or find substitutes for both.

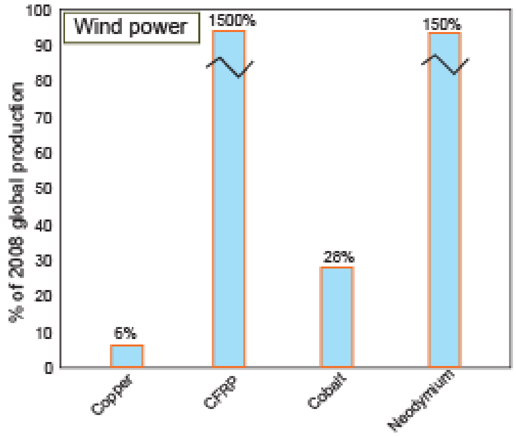

Figure 21. Demand ratios for strategic materials used in wind power systems.

8. Hydro power

More energy is generated from hydropower (Figure 22) than from any other renewable energy source. It supplies most of the electricity for thirteen countries, among them, Norway and Brazil. The technology is simple, the power is always available (provided it rains), and dams built without hydroelectric capacity can be retro-fitted with turbines and generators. Hydro plants are particularly flexible because they both store energy and generate power, either continuously or intermittently to deal with spikes in demand.

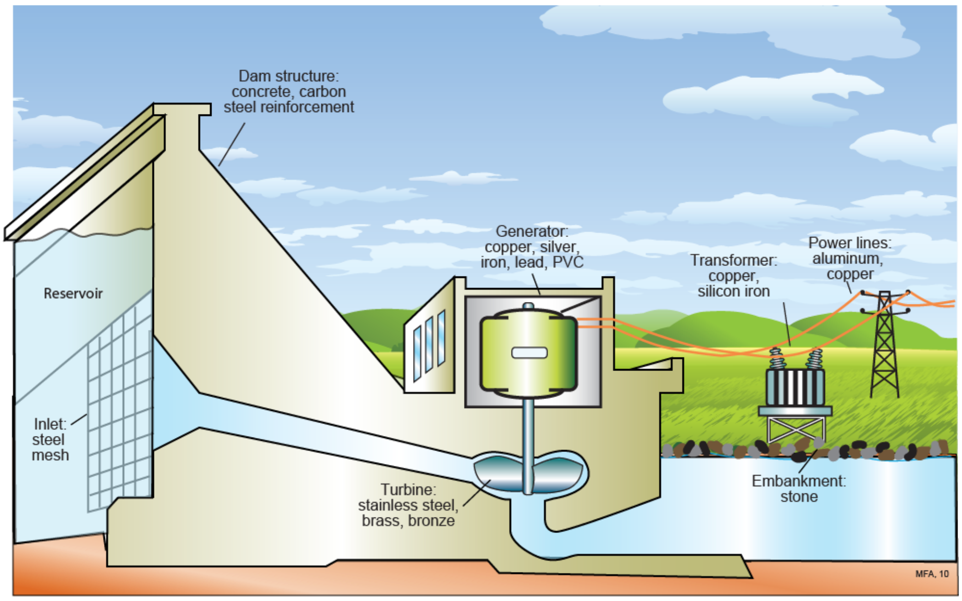

Figure 22. Schematic of a hydro-electric plant.

The energy to fill reservoirs comes from the sun, but it is gravity that drives the water through the turbine. The flow of water through a water turbine, like that of air through a wind turbine, is governed by Bernoulli's equation. When the water flow is from an essentially stationary reservoir to an essentially stationary out-flow pool, the pressure difference between the inlet and the outlet is $\Delta p = \rho g \Delta h$, where Δh is the difference in surface height between the reservoir and the out-flow pool. The power captured by the turbine is then

$$P = \eta g \dot{Q} \Delta h \qquad (11)$$

where $\dot{Q}$ the volumetric flow rate in m^3/s and η the efficiency of the system (over 90% for large hydro falling to 50% for small). The capital cost of a hydro plant can be high, and its construction may damage natural and human habitat. But its lifetime is long, it requires little maintenance, it creates no emissions, and its fuel is free. Hydro-power is a long-term investment.

The most material-intensive part of a hydro-plant is the dam. Small dams can be made of earth. Larger ones are made of concrete, some requiring 5 tonnes of concrete for 1 kW_{nom} of generating capacity. The demands on other materials are modest (Figure 23).

9. Wave Power

Energy can be captured from waves by placing something in their path—a fixed barrier with a turbine driven by the water whooshing in and out, for instance. Waves carry an energy per unit length rather than an energy per unit area, and it is large—as much as 40 kW per meter—as you will know if you've been hit by one. Capturing it, however, is not easy; it is unlikely that any wave machine would trap more than a quarter of this. Not many countries have long coast-lines (some have none), but for those that do, wave power is an option. Once again the scale of the operation has to be vast to make a real contribution: to provide 1 kW per person to a country of 50 million inhabitants needs something like 4,000 km of barrier. And any wave-driven device takes a battering, making maintenance a problem.

There are three schemes for harvesting wave power are known as *buoyancy devices*, *overtopping devices*, and *oscillating water-column devices*. Buoyancy devices use the motion of waves to pump a working fluid through a turbine. Overtopping devices uses a vertical axis turbine with a floating ramp; waves ride up the ramp and spill into the turbine below. Oscillating water-column devices trap water and air within the structure, and as the waves pass under it, the air is alternately compressed and allowed to expand through a turbine.

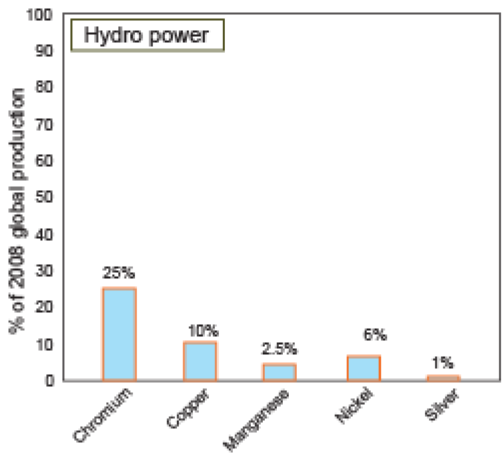

Figure 23. Demand ratios for strategic materials used in hydro power systems.

The Pelamis is an example of a buoyancy wave energy converter (Figure 24). It floats on the ocean surface with cables securing it to the seafloor. Links in the body allow it to flex with the motion of the waves, driving pistons that pump oil through a turbine inside the unit. To survive the harsh environment the device requires a great deal of steel, making it material and energy intensive to construct.

The total world installed capacity of wave power is currently a mere 4 MW but more devices are under development. The demand for critical materials for harvesting wave power is relatively low with the exception of copper. The small power per unit and the long cables connecting them to shore means that building sufficient capacity to generate 2,000 GW over the next ten years could consume up to 20% of current global copper production.

10. Tidal Power

The moon orbits the earth and the earth orbits the sun. As they do so, gravitational and centrifugal forces act on seawater, pulling it into tidal bulges. As the Earth rotates on its own axis, these bulges sweep across the planet's surface creating two tides each day. When sun, Earth and moon are aligned the forces pull together, creating high and low "spring" tides. When the moon is at right angles to the sun with respect to the Earth, the gravitational fields work against each other, giving smaller "neap" tides.

The highest tidal ranges in the world are in the Bay of Fundy in Nova Scotia and in the Severn Estuary in Britain where tidal water funnels into a narrowing channel. Tidal power where tides are high can deliver 3 W/m^2 by making both the incoming and the outgoing tidal flow drive turbines. This is about the same as wind power, but few countries have the coastline to

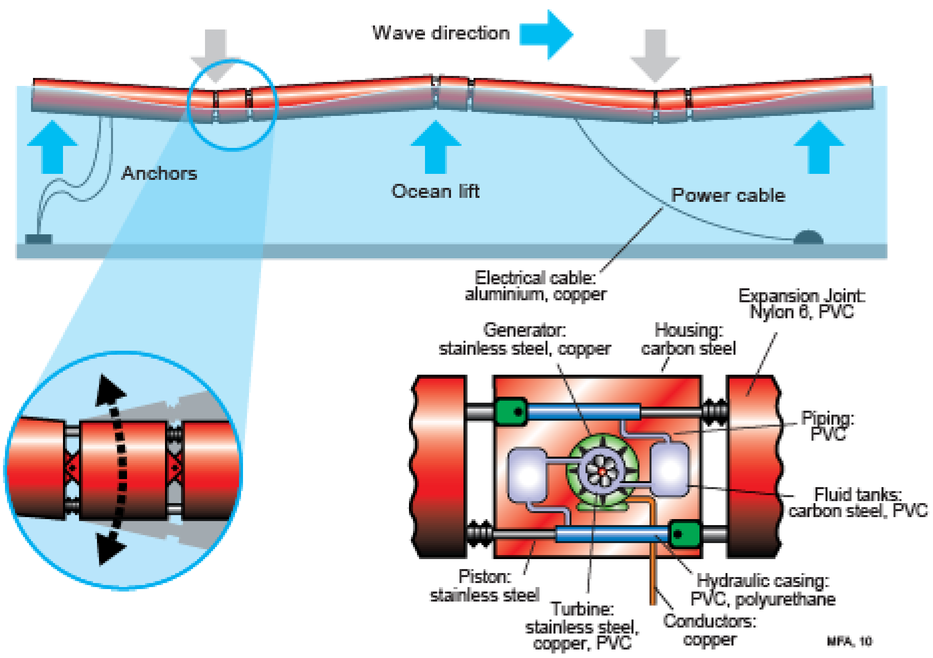

Figure 24. Schematic of Pelamis wave-power device.

capture much of it. To those with tidal estuaries or those that lie at the mouths of land-locked seas (like the Mediterranean) harnessing tidal power is an option. There are two schemes for harvesting it: *tidal-stream* and *tidal-barrage* systems.

The Seagen tidal-stream power generator is an underwater wind turbine driven by the flow of the incoming and receding tides (Figure 25). One is in service. It has a power of 1.2 MW, a claimed capacity factor of 48%, and a design life of 20 years. A tidal barrage is a hydro-electric plant driven by a reservoir filled by tides rather than by rain. The largest tidal barrage is the 240 MW unit on the river La Rance in France, where the tidal range is 8 m. Tidal barrages have longer lifetimes than tidal stream generators because the machinery is simpler. The attraction of tidal power is that it is completely predictable. The drawback, as Figures 4, 5, and 6 showed, is that the systems are material, energy, and capital intensive.

Tidal power puts little pressure on critical materials. Using the same demand scenario as before the consumption of copper might reach 5 % of current production.

11. Geothermal power

The core of the Earth remains at a temperature above 5000ºC, heated by the slow radioactive decay of elements at its centre. Heat is carried to the Earth's surface by conduction and by convection of the magma in the mantle, the layer between the core and the crust. This heat leaks out at the surface but little of it is in a useful

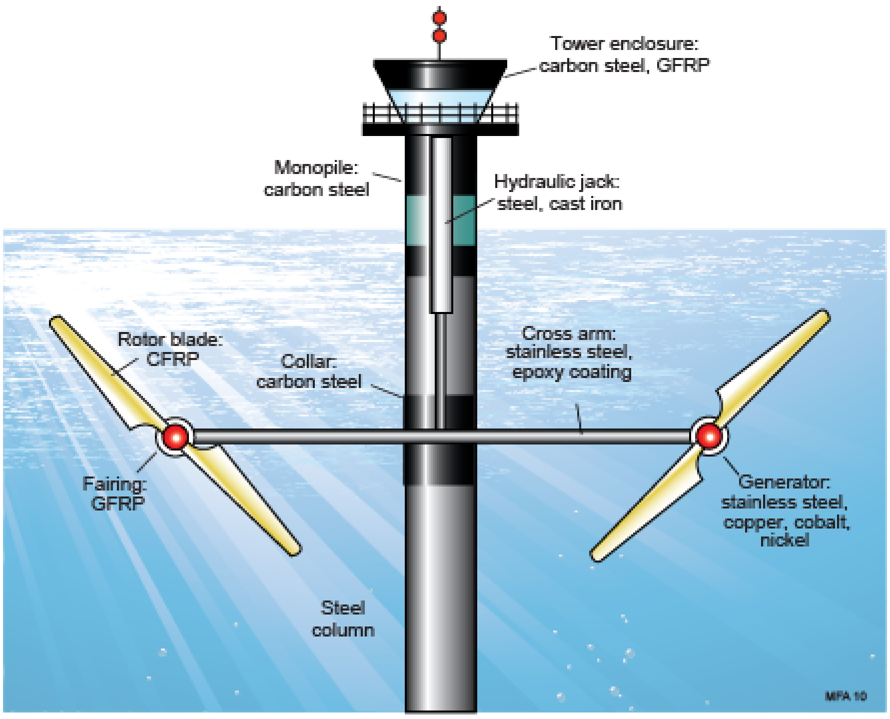

Figure 25. Diagram of a Seagen tidal power generator.

form. On average the near-surface temperature gradient is 20°C/km, delivering 50 mW/m^2 at the surface. To generate electricity it is necessary to heat water to at least 200°C, and for most of the earth's crust that means drilling down to about 10 km, making it expensive to harvest. Where magma wells up close to the surface the gradient rises above 40°C/km. In such places (Iceland, parts of the US, New Zealand, and Italy) extracting geothermal heat is a practical proposition.

To do so, water is injected into the hot rock from which it is recovered as hot water or steam (Figure 26). High-temperature plants feed steam directly to a turbine then pump the condensate back into the rock. Low temperature plants pass the hot water to a heat exchanger where it vaporizes a low-boiling point working fluid—isopentane or isobutene—that drives the turbine. Typical power outputs are 0.1 to 2 GW.

Geothermal power may have the largest potential of all renewable energy sources; a USGS study in 2008 estimated that the US electrical power potential from geothermal heat exceeded 500 GW. It is at present just potential, requiring advances in deep drilling to make it a reality. Most of the cost of a geothermal power plant is that of drilling, but aside from small maintenance costs, the electricity it generates is free. As with wave and tidal power, the only critical material used in large quantities is copper. Using the same demand structure as before, the deployment of 200 GW per year of geothermal power (could it be found) would require about 2% of current copper production.

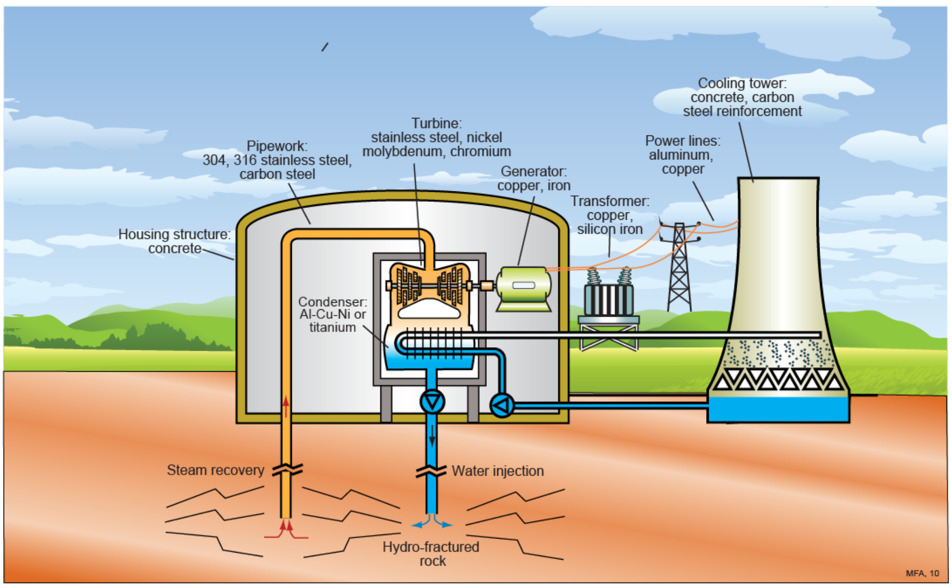

Figure 26. Geothermal power plant.

Figure 27. A bio-crop.

12. Biomass

Green plants capture the sun's energy and use it to photosynthesize carbohydrates, oils, and proteins from atmospheric CO_2 (Figure 27). The carbohydrates can be dried and burned to release the energy, or they can be fermented to give olefins (methane, ethane) and alcohols (methanol, ethanol) that can be used as fuels. Seed oil (soybean, sunflower, palm oil) can be burnt or processed into bio-diesel. Plant growth requires little fossil fuel energy, is relatively clean, and—until it is burnt—it sequesters carbon. But the efficiency of energy-capture by plants is low, typically 0.5%. The average annual flux of solar radiation in a temperate climate is about 100 W/m^2, so the area-intensity of biomass, before it has been converted to a useful fuel, is about 2000 m^2/kW, already greater than that of any other source of power. To make it useful it must be dried for combustion or fermented to make bio-diesel, both with imperfect efficiency, driving the area intensity up to 5,000 – 10,000 m^2/kW$_{nom}$. Biomass is said to be a carbon-neutral fuel because the carbon dioxide it emits when burnt was drawn from the atmosphere during its growth, but this is not quite true because farming and transport generates some CO_2 that cannot be credited to biomass.

The use of biomass for liquid fuels is already generating competition for land to grow fuel, food, and materials. By 2007, almost a quarter of US coarse grain production and one half of EU vegetable oil was used for bio-fuels, yet together they provided only 0.36% of global energy supply. According to Pimm (2001) the global production of natural and cultivated biomass is about 140 Gt/year and the global consumption of biomass as food, fodder for livestock, conversion of forest to pasture, firewood, construction, and fiber is currently 58 Gt/year, about 40% of the total. If we already use this fraction of biomass production, further consumption cannot grow much, even allowing for increased yields. It appears, then, that there is a limit to the supply of biomass. Only about 2% of the total, dominated by woods and natural fibers, is at present used to make engineering structures, so there is some scope for increasing this, but it will ultimately be at the expense of other uses of biomass.

13. Summary & conclusions

If the world is to have the electrical power that extrapolation suggests it will need by 2050, it will mean building an additional generating capacity of up to 6,000 GW. The global fluxes of solar radiation and of energy in the form of wind, wave, and tides all comfortably exceed this value, and the accessible coal and nuclear fuel reserves, too, could provide it. But each has its difficulties, and even a balanced combination of all of them presents problems.

Renewable power systems carry a carbon footprint that is 10 to 30 times less that the gas and oil based systems on which we now largely depend. But almost all require greater surface area, more capital, more energy, and more materials to build them than to construct fossil fuel power stations with the same nominal generating capacity. Worse, most renewable power systems have lower capacity factors than fossil fuel plants, further increasing the differences.

A high material intensity is manageable if the materials in question are those with large reserves, low embodied energy, and low carbon footprint. Some materials meet this ideal—iron and carbon steel, concrete, wood, and commodity polymers are examples. But the sheer scale of construction if just one third of the anticipated demand in 2050 is to be met over a 10 year time span puts pressure on the supply of some critical materials and greatly exceeds the current production capacity of others.

The conclusions: no single renewable source can begin to supply energy on the scale we now use it. A combination of all them might. But think of the difficulties. There is the low power density, meaning that a large fraction of the area of the country must be dedicated to capturing it. If you cover half the country with solar cells you cannot also plant crops for biofuel on it, nor can you use it as we now do for agriculture and livestock for food. There is the cost of establishing the network needed to connect-up such a dispersed system and—in the case of off-shore wave and wind farms—there is the cost of maintenance (even on land some 2% of wind turbines are disabled each year by lightning). And there is the opposition, much of it from environmentalists, that paving the country and framing the coast with machinery would create. MacKay's (2009) book examines all this in greater depth. For now we must accept that the dream of copious cheap, pollution-free, and renewable energy from sun, wind, and wave is not realistic.

14. Appendix 1. Definitions of properties

Keeping track of units and the meanings of the various resource intensities can be confusing. These definitions will help keep them clear.

Energy and power

Energy **MJ or kW.hr**
(1 kW.hr = 3.6 MJ)

Energy appears in more than one form in this white paper. It is important to choose one of these as the basis for comparison of conventional and renewable systems. By convention, the basic unit is MJ_{oe}, meaning megajoules, oil equivalent. Oil (like coal and gas) has a calorific value or heat content, 38 MJ_{oe}/litre or 44 MJ_{oe}/kg. The conversion efficiency when oil is used to generate electricity is about 36% (it depends on the age and type of generator), so one MJ of electrical energy (MJ_{elec}) requires the consumption of 1/0.36 = 2.8 MJ_{oe}. Thus 1 kW.hr of electrical energy is equivalent to 3.6 x 2.8 = 10MJ_{oe}.

Power **kW, MW, or GW**

Power is energy per unit time, meaning J/sec (= Watt, W) or, in the context of power systems, kW, MW, GW or even TW (Terawatt = 10^{12} J/sec)

Rated or nominal power output
kW_{nom}, etc.

The rated power output of a power system is the power it delivers under optimal conditions. Oil and coal fired power stations operate optimally for much of the time, but renewable power systems do not because they depend on a certain minimum level of solar radiation, wind velocity, wave height or tidal flow, and for much of the time this minimum is not met.

Actual or real average power output
kW_{actual}, etc.

The optimal conditions required for a power system to provide its rated power occur for only a fraction of the time, so the actual power output of the system, averaged over (say) a year, is much less than the rated value. The ratio of the real, averaged power output to the rated power output is called the capacity factor, expressed as a %. Some systems have capacity factors as low as 10%, meaning that to generate an average of 1 kW of actual power it is necessary to install a system with a nominal capacity of 10 kW.

Resource intensities

Construction and commissioning of a power system requires resources: capital, materials, energy, and space, meaning land or sea area. A resource intensity is the amount of the resource required to create one unit of power generating capacity. Power systems have a rated power (kW_{nom}, see above), but none operate at full capacity all the time so it is convenient to define also the average delivered power (kW_{actual}). Because of this we need two intensities for each resource. The first is the intensity of the resource per unit of rated capacity—a well defined quantity since the rated power is a fixed characteristic of the system (e.g., a 1kW solar panel). The second is the intensity of the resource per unit of delivered power when averaged over a representative period such as a year. It is always larger, sometimes much larger, than the intensity per unit of rated capacity, and it is less well defined because it depends on how the system is operated, and, in the case of renewable systems, on the influence of the weather on sun, wind, wave, and tide.

Capital intensity, construction (rated power) GBP/kW$_{nom}$

The quantity of capital (money) used to construct the power system per unit rated power (per kW$_{nom}$, for example) of the system. If you want the cost per kW of actual delivered power, as in Figure 4, you have to divide the capital intensity by the capacity factor (expressed as a fraction).

Capital intensity (fuel) GBP/kW

The cost of the fuel used in the system per kW of power generated. This is based on input/output figures from plants and scaled to be a nominal value.

Area intensity m^2/kW$_{nom}$

The land area used by the power system per unit rated power (kW) of the system. If you want the area per kW of actual delivered power capacity, as in Figure 3, you have to divide the area intensity by the capacity factor (expressed as a fraction).

Material intensities kg/kW$_{nom}$

The quantities of materials required to build a given power system per unit nominal power. If you want the material per kW of actual delivered power, as in Figure 2.4, you have to divide the material intensity by the capacity factor (expressed as a fraction).

Energy intensity (construction) MJ/kW$_{nom}$

The energy is used to construct the power system, per unit rated power (kW) of the system. To get the build-energy per kW of actual delivered power, you have to divide the energy intensity by the capacity factor (expressed as a fraction). This is not done in Figure 5 because the other axis, delivered energy per year, is also nominal. The point of Figure 5 is to illustrate the pay-back time.

Energy intensity (fuel) MJ/kW.hr

The energy is consumed as fuel by the power system to generate each kW.hr of delivered energy.

CO_2 intensity (construction) kg/kW$_{nom}$

The quantity of carbon dioxide, in kg, released to atmosphere during the construction of a given power system per unit of nominal power (kW$_{nom}$) of the system.

CO_2 intensity (fuel) kg/kW.hr

The quantity of carbon dioxide, in kg, released to atmosphere because of the burning of hydrocarbons by the power system per kW.hr of delivered energy.

Operational parameters

Capacity factor %

The fraction of time, expressed as a percentage, that a power system operates at its rated power. This takes into account time when a system would be unavailable or generating less power than it potentially could due to maintenance or because the natural resource it uses is unavailable.

System efficiency %

The efficiency with which the fuel or resource is converted into electricity.

Lifetime yrs

The expected time that the power system will remain fully operational in years.

Status

Current installed capacity GW

The total global rated capacity of a given power system.

Growth rate %/year

The rate at which installed capacity currently grows each year expressed as a percentage.

Delivered cost **GBP/kWh**

The cost of generating one kilowatt-hour of electrical energy for a given power system.

15. Appendix 2. Approximate material intensities for power systems

The bills of materials for the power systems assembled here are expressed as material intensities, I_m, meaning the mass (kg) of each material per unit of nominal generating capacity (kW_{nom}). As far as we know, no previous assembly of such data exists, so it has to be patched together from diverse sources. These differ in detail and scope. Some, for instance, are limited to the system alone, others include the iron, copper and other materials needed to connect the system to the grid, and this is large for distributed systems like wind, wave and solar power. Others give indirect information from which missing material content can be inferred. So be prepared for inconsistencies.

Despite these reservations there is enough information here to draw broad conclusions about the demand that large-scale deployment of any given low-carbon power system could put on material supply. The resource-demand plots in the text use data from these tables. They are based on an imagined scenario: that the global electric power demand will triple by 2050 and that, to meet it, the capacity of a chosen system is expanded by 200 GW (2 x 10^8 kW) per year. The metric for resource pressure, R_s, is the mass of each material required for the expansion of the system per year, $2 x 10^8 I_m$, expressed in kg/year divided by the current (2009—the most recent available) global production per year, P_a, also expressed in kg/year.

$$R_s = \frac{2 x 10^8 \, x \, I_m}{P_a}$$

The resource-demand plots in the main text show this, expressed as the per-cent demand of current production.

The resource demand is not interesting when it is trivial. The plots show the demand on the materials that are deemed to be "critical", as explained in Section 2. They are starred (*) in the tables below.

Table 2 included the capital, energy and carbon intensity of fuels. They are used to construct Figure 7. Some burn fuel for power. The others use much smaller quantities in operation and maintenance. The data used in the construction of Figure 7 are summarized below.

Fuel	**Cost / kW.hr ($/kW.hr)**	**Energy/kW.hr (MJ/kW.hr)**	**CO_2 / kW.hr (kg/kW.hr)**
Coal	0.02 – 0.04	9.7 – 12	0.9 – 1.1
Gas	0.025 – 0.055	6 – 8	0.33 – 0.5
Fuel cell (Phosphoric acid)	0.025 – 0.055	9 – 10	0.49 – 0.55
Fuel cell (Solid oxide)	0.025 – 0.055	6 – 7.2	0.33 – 0.39
Nuclear	0.005 – 0.006	9.6 – 12	0.06 – 0.07
All other power systems	0.05 – 0.09	0.05 – 0.1	0.005 – 0.01

Coal-fired station

Material	Intensity (kg/kW$_{nom}$)
Aluminum	2.58 – 4.5
Bitumen	0.33 – 0.37
Brass	0.24 – 0.27
Carbon steel	30 – 614
Ceramic tiles	0.39 – 0.44
Chromium*	2.33 – 3.2
Concrete	460 – 1200
Copper	1.47 – 5.17
Epoxy	0.21 – 0.23
GFRP	0.55 – 0.605
Glass	0.026 – 0.029
Glulam	0.004 – 0.005
HDPE	0.16 – 0.17
High alloyed steel	0.5
Iron	50.2 – 809
Lead	0.04 – 0.23
Low alloy steel	13.6 – 15.1
Manganese *	0.084
Molybdenum*	0.032
Nickel	0.01
PP	0.08 – 0.09
PVC	1.82 – 2.02
Rock wool	3.9 – 4.3
Rubber	0.12 – 0.13
SAN	0.026 – 0.031
Silver*	0.001 – 0.007
Stainless steel	37 – 41
Vanadium*	0.003
Zinc	0.06 – 0.08
Total mass, all materials	**520 – 1800**

Materials and quantities from White and Kulcinski (2007).

Pressurized water reactor

Material	Intensity (kg/kW$_{nom}$)
Aluminum	0.02 – 0.24
Boron	0.01
Brass/bronze	0.04
Cadmium	0.01
Carbon steel	10.0 – 65
Chromium*	0.15 – 0.55
Concrete	180 – 560
Copper*	0.69 – 2
Galvanized iron	1.26
Inconel	0.1 – 0.12
Indium*	0.01
Insulation	0.7 – 0.92
Lead	0.03 – 0.05
Manganese*	0.33 – 0.7
Nickel*	0.1 – 0.5
PVC	0.8 – 1.27
Silver*	0.01
Stainless steel	1.56 – 2.1
Uranium*	0.4 – 0.62
Wood	4.7 – 5.6
Zirconium*	0.2 – 0.4
Total mass, all materials	**170 – 625**

Materials and quantities from White and Kulcinski (2007).

Silicon based PV

Material	kg/kW
Acids + Hydroxides	7.0-9
Aluminum	15-20
Ammonia	0.05-0.1
Argon	3.0-5.0
Carbon allotropes	10.0-20.0
Copper	0.2-0.3
Glass	60-70
Gold	0.05-0.1
Indium	0.02 – 0.08
Plastics	20-60
Silicon	25-40
Silicon Carbide	6.0-10.0
Tin	0.1-0.2
Wood	10.0-20.0
Total mass, all materials	**150-250**

Materials and quantities from Phylipsen & Alsema (1995), Keoleion et al (1997) and Tritt et al (2008).

CdTe thin film PV

Material	kg/kW
Aluminum	20
Cadnium	0.1 – 0.3
Tellurium	0.1 – 0.3
Copper	1
Glass	60
Indium	0.005 – 0.025
Lead	0.05
Plastics	30
Stainless Steel	20
Tin	0.2
Total mass, all materials	**130**

Materials and quantities from Fthenakis and Ki, (2005) and Pacca, Sivaraman, and Keoleian (2006).

Balance of plant for solar PV

Material	kg/kW
Aluminum	20-30
Concrete	500-550
Copper	1-2
Steel	1000-1200
Total mass, all materials	**1500 – 1800**

Materials and quantities from Pacca & Hovarth (2002) and Tahara *et al.* (1997)

Solar: Concentrating thermal power

Material	Intensity (kg/kW_{nom})
Aggregates	50-500
Aluminium	0.1-0.3
Borosilicate Glass	3
Chromium (Stainless Steel)	2-10
Concrete	200-2000
Copper	0.5-5
Glass	90-220
Magnesium	0.3-0.9
Manganese	0.008-0.2
Nickel	0.001
Paint	1-3
Silver	2.5-6.5
Steel and Iron	300-800
Total mass, all materials	**650-3500**

Materials and quantities from Viebahn, et al (2004)

Phosphoric acid fuel cell

Material	Intensity (kg/kW_{nom})
Aluminum	0.9-1.1
Carbon Allotropes	5-9
Ceramics	1-5
Chromium	3-7
Concrete	10-20
Copper	3-8
Iron and Steel	60-90
Molybdenum	0.02
Nickel	1.7
Palladium	0.0005
Phosphoric Acid	0.5-2.5
Plastics	1.5-5
Platinum	0.005
Zinc	2.3
Total mass, all materials	**89 – 150**

Solid oxide fuel cell

Material	Intensity (kg/kW_{nom})
Aluminum	0.5-2
Concrete	10-20
Chromium	0.5-3
Iron and Steel	60-80
Lanthanum	0.01-3
Manganese	0.01-1
Nickel	1-6
Yttrium	0.1-0.4
Zirconium	0.1-3
Zinc	0.01-1
Total mass, all materials	**70-110**

Materials and quantities from Karakoussis et al 2001 and Thijssen 2010

Onshore Wind

Material	kg/kW
Aluminum	0.8-3
CFRP	5.0-10
Concrete	380-600
Copper	1.0-2
GFRP	5.0-10
Steel	85-150
Neodymium	0.04
Plastics	0.2-10
Total mass, all materials	**500-750**

Materials and quantitites from Ardente *et al.* (2006), Crawford (2009) and ***Vindmølleindustrien (2007),*** Vestas (2008) and Martinez et al (2007).

Offshore Wind

Material	kg/kW
Aluminium	0.5-3
Chromium (stainless steel)	4.5
Concrete and Aggregates	400-600
Copper	10.0-20
GFRP	5.0-12
Steel	250-350
Neodymium	0.04
Plastics	1.0-10
Total mass, all materials	**650-1000**

Materials and quantities from Ardente *et al.* (2006), Crawford (2009), Vindmølleindustrien (2007), and Weinzettel (2009).

Wind power, off shore

Material	Intensity (kg/kW_{nom})
Aluminum	0.85 – 15
Carbon steel/cast iron	380 – 532
CFRP*	10.5 – 54
Cobalt* (alternative magnets)	1
Concrete	1200 – 1600
Copper*	10 – 22
GFRP	14 – 20
Neodymium* (magnets)	0.9
Polymers	0.7 – 9
Stainless steel	36 – 50
Total mass, all materials	**1100 – 2000**

Materials and quantities from Vestas (2008) and Martinez et al (2007).

Wave power (Pelamis)

Material	Intensity (kg/kW_{nom})
Aluminum	25 – 30
Copper*	10 – 20
Nylon 6	8 – 12
Polyurethane	12 – 18
PVC	25 – 31
Sand (ballast)	640
Stainless steel	50 – 60
Steel	410
Total mass, all materials	**1145 – 2000**

Materials and quantities from Anderson (2003).

Tidal current power: Seagen

Material	Intensity (kg/kW_{nom})
CFRP (blades)	3.25
Copper*	3.88
Epoxy	0.25
GFRP (enclosure)	4.5
Iron	28.3
Neodymium or cobalt	0.9
Stainless steel	2.33
Steel	344
Total mass, all materials	**387**

Materials and quantities from Douglas et al (2008).

Tidal barrage power

Material	Intensity (kg/kW_{nom})
ABS 30% glass fiber	0.019
Cement	1728
Copper*	0.004
Gravel	996
Pre-stressed concrete	3416
Rock	28686
Sand	20488
Stainless steel	0.026
Steel	33
Total mass, all materials	**55,350**

Materials and quantities from Roberts (1982) and Miller et al (2010)

Geothermal power

Material	Intensity (kg/kW_{nom})
Bentonite	20.9 – 45
Calcium carbonate	37.9
Carbon steel	10.8
Cement	3.3 – 41
Chalk	31
Concrete	21.9
Copper*	1.2 – 2.2
EVA	1
High alloy steel	342.4
LDPE	20.4
Low alloy steel	2 – 476
Portland limestone cement	133
PVC	0.1
silica sand	39.6
Total mass, all materials	**61 – 1200**

Materials and quantities from Saner et al (2010)

Biomass

Material	Intensity (kg/kW_{nom})
Aluminum	1.1 – 6.7
Bitumen	0.5
Brass*	0.37
Cast iron	1.47
Ceramic tiles	0.59 – 9.3
Chromium*	0.0024
Cobalt*	0.0018
Concrete	36 – 790
Copper*	1.04 – 3.5
Epoxy resin	0.31
GFRP	0.82
Glass	0.04
Glulam	0.006
HDPE	0.23
LDPE	3.25
Lead	0.104
Low alloy steel	20
Low carbon steel	33 – 112
Nickel*	0.02
PP	0.12
PVC	0.45 – 2.74
Rock wool	1.65 – 6
SAN	0.04
Stainless steel	4.5 – 5.5
Steel (electric)	0.82
Synthetic rubber	0.18
Titanium dioxide*	0.4
Zinc	0.16
Total mass, all materials	**69 – 922**

Materials and quantities from Bauer (2008) and Mann & Spath (1997)

16. Further reading

The starting point—sources that help with the big picture.

Andrews, J. and Jelley, N. (2007) "Energy science: principles, technologies and impacts", Oxford University Press, Oxford, UK. ISBN 978-0-19-928112-1. *(An introduction to the science behind energy sources and energy storage systems.)*

Boyle G. (editor) (2004) "Renewable energy", DE.158

British Geological Survey (2011) "Risk list 2011" www.bgs.ac.uk/mineralsuk/statistics/riskList.html *(A supply risk index for critical elements or element groups which are of economic value.)*

Cullen, J.M. (2010) "Engineering fundamentals of energy efficiency", PhD thesis, Engineering Department, University of Cambridge UK. *(A revealing analysis of energy use and efficiency of energy conversion in modern society).*

Fay, J.A. and Golomb, D.S. (2002) "Energy and the environment", Oxford University Press, Oxford, UK. ISBN 0-19-515092-9. *(The environmental background to energy production, with an exploration of the potential for replacing fossil fuels by lower carbon alternatives.)*

Harvey, L.D.D. (2010) "Energy and the new reality 1: energy efficiency and the demand for energy services", Earthscan Publishing, London, UK. ISBN978-1-84971-072-5. *(An analysis of energy use in buildings, transport, industry, agriculture and services, backed up by comprehensive data.)*

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Hunt, W. h. (2010) "Linking transformational materials and processing for an energy efficient and low-carbon economy", The Minerals, Metals and Materials Society (TMS) www.energy.tms.org *(A pair of reports assessing the materials challenges raised by a low-carbon economy.)*

IAEA (1997) "Sustainable development and nuclear power", International Atomic Energy Agency, Vienna, Austria.

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