Energy – A Grand Tour

Keeping the lights on

This document is intended to explain concepts, terms and issues in moving to a carbon-neutral energy supply. It was written in response to a request from Peoples Assembly and is published under a https://creativecommons.org/publicdomain/zero/1.0/ licence making it free to use in whole or part for any commercial or noncommercial purpose without attribution.

Basic concepts and units

There are basic laws of physics that say what's possible and what isn't. For example a **perpetual motion machine** that produces energy forever with no input such as fuel is known to be impossible. Calculations can show whether suggested ways of dealing with our energy problems are practical or not. We may not always want to choose the option producing the very best numbers but there's no point wasting time on ones that can quickly be shown to be unworkable or unaffordable.

> *A paragraph formatted like this one tells you something additional to the main text. The first time a term is used that's referred to later or that names an important concept in energy, it's shown in* ***bold****.*

For example, suppose someone says "They use hydro power in" Norway, Switzerland, Canada, Australia, wherever "and it's great. We should use it here." A simple calculation shown later demonstrates why we don't.

> *Doing these calculations requires some understanding of the laws and the units of matter, energy and power. Sorry if you don't like numbers. If you want, you can skip this section for now and come back to it if and when you need to.*

Energy can be neither created nor destroyed - *First Law of Thermodynamics*

> *This isn't exactly right ($E=mc^2$) but it's near enough true.*

Entropy is always increasing - *Second Law of Thermodynamics*

Entropy is a measure of disorder. There are two broad forms of energy: motion and heat. Motion is the lowest entropy form and is easily converted to higher entropy heat, e.g. in a car's brakes. High temperature (lower entropy) heat energy degrades to lower temperature (less concentrated - higher entropy) heat all by itself unless you slow it down, e.g. with insulation. Converting heat energy to motion is harder and the Second Law says it can never be 100% efficient. You can only convert a fraction of heat energy to low entropy motion with a **heat engine** (such as a petrol, diesel or steam engine or gas turbine) with the rest ending up as lower temperature heat so that overall entropy increases. Practical heat engines are 30-50% efficient. The Second Law is why unlike many materials, energy can’t be recycled.

Electricity is effectively the same as motion energy. You can convert one to the other either way with up to 100% efficiency. Practical conversion is never quite 100% of course.

Heat engines can be made that operate in reverse, taking in mechanical or electrical energy and lower temperature heat and putting out higher temperature heat energy. These are **heat pumps**. Their theoretical efficiency limit is the inverse of the heat engine efficiency limit and depends on the ratio of the two temperatures on an absolute scale such. as Kelvin. Practical heat engines and heat pumps are rarely anywhere near their theoretical efficiency limit.

> *An absolute temperature scale is one where zero is the lowest possible temperature where there is no heat at all. Absolute Zero is -273.15 Celsius.*

> *A refrigerator uses a heat pump driven by electrical energy to move heat from the lower temperature inside to the higher temperature room it’s in. Air conditioners are also heat pumps.*

In physics, **mechanical energy (work)** is usually measured in **joules**. Moving something 1 metre with a force of 1 newton expends or produces one joule. 1 **newton** is the force needed to accelerate a 1 kilogram mass at 1 metre per second per second. Earth's gravity accelerates falling objects at almost 10 metres per second per second so its force on 1 kilogram (its weight) is about 10 newtons and lifting 1 kilogram by one metre takes about 10 joules of energy.

Power is the rate of conversion or transmission of energy. Its unit is the watt (**W**) which is one joule per second. For example to lift that 1 kilogram mass 1 metre in 2 seconds takes about 5 W of power.

In dealing with larger scale energy, it's become customary to start with power and talk of kilowatt-hours (**kWh**) of energy. A kilowatt (**kW**) is 1000 watts and an hour is 3600 seconds so 1 kWh is 3600000 (3.6 million) joules. A 2000 watt heater uses 1 kWh in half an hour. A 10 watt LED light bulb takes 100 hours to use 1 kWh.

A megawatt (**MW**) is a million watts or a thousand kW. A gigawatt (**GW**) is a billion watts or a thousand MW. British peak electric power usage is around 50 GW.

Heat is more the domain of chemistry. A **Calorie (large C)** is the heat energy needed to warm 1 kilogram of water by 1 degree Celsius. One **BTU (British Thermal Unit)** is the heat energy needed to heat one pound of water by one degree Fahrenheit. As noted before, electrical or mechanical energy is easily degraded to heat with 100% efficiency. 1 kWh produces 860 Calories or 3412 BTUs of heat that way.

A **therm** is 100,000 BTU or 29.3 kWh of heat and is a common unit for measuring natural gas. In a typical modern gas power station (heat engine) with around 50% efficiency, it can generate around 15kWh of electricity. 1 therm is about 100 cubic feet or 2.83 cubic metres of natural gas (at atmospheric pressure). After recent price rises, a therm of gas is near £3 wholesale so generating 1 kWh of electricity from gas costs nearly 20p for the gas alone. Previously retail prices for electricity were around 15p per kWh, covering not only fuel but all the other costs and profits too.

Combined Cycle and **Combined Heat and Power (CHP)** are two ways of reducing the energy lost in power generation. They sound confusingly similar but are quite different and can be used together. Combined Cycle links gas and steam turbines in gas-fired power stations to increase the ratio of high to low temperatures and push efficiency up to 50%. CHP puts the low temperature heat from a generator that's otherwise wasted to use, e.g. to heat buildings, greenhouses or swimming pools.

Fossil hydrocarbon fuels

Hundreds of millions of years ago, long before the dinosaurs, the Earth was covered with lush vegetation. Plants absorbed energy in the form of sunlight and used it to split water and **carbon dioxide** (**CO_2**) from the air. Hydrogen from water and carbon from CO_2 were combined into carbohydrates in the plants. Some of the plants got buried in sediments before they could decay.

Over those millions of years pressure and heat underground changed the buried plants (including plankton in the ancient seas) into coal, oil and gas. Coal is mostly carbon. Gas is predominantly methane whose molecule consists of one carbon and four hydrogen atoms. The carbon content of oil is in between the two. When the fuels are burned, the energy originally captured from the sun is released as heat. The hydrogen content returns to water but there's huge amounts of water in the oceans and vapour in the atmosphere and the small additional amount is inconsequential. The carbon returns to CO_2 which is building up in the atmosphere as the main factor driving global warming. Eventually this CO_2 will be taken up by marine organisms and become incorporated into limestone but the process will take many thousands of years to mop up the excess.

Over the past few centuries, humans discovered that we could dig or drill holes in the ground and bring up huge amounts of these fossil hydrocarbons. The energy from burning them powered machines and allowed each of us to do work that would otherwise have taken dozens of people and pack animals. This drove the industrial revolution, allowed us to do previously impossible things such as flying and to enjoy a lifestyle that would have been unbelievably pampered to our ancestors.

It was always obvious that the coal, oil and gas would run out eventually and this is indeed starting to happen, resulting in periodic sharp price rises. But we've also realised that the CO_2 emissions are having dangerous effects on the climate and endangering food production so we can't even burn the fuel we know is still down there.

If we want to continue our pampered lives, we have to move away from reliance on fossil hydrocarbon energy. We always knew this and at one time expected to transition to nuclear energy "*too cheap to meter*" instead. But over recent decades, when dogma said the market should decide everything, there has been no long-term planning or preparation and we have left things very late.

Every cloud has a silver lining: see the section on nuclear energy later.

Mitigation is popular with fossil fuel companies who want to continue finding and selling their products. Here are some of their ideas:

Carbon capture and storage (CCS) means that CO_2 from burning fossil hydrocarbons is captured before it enters the atmosphere and stored, hopefully permanently, underground in empty oil and gas fields. It's certainly possible at large point sources such as power stations and blast furnaces but it's expensive and may use 20% or 30% of the energy obtained from the burning fuel. It's also only short term as the fuels are still running out.

Direct CO_2 extraction from the atmosphere would involve moving and filtering huge amounts of air using huge machines and vast amounts of energy. One cubic metre of air contains only about 0.18 grams of carbon. Even if it could all be filtered out, extracting a thousand tonnes of carbon in a year would mean processing a cube of air 1.8 kilometres on a side and weighing 7.3 million tonnes (185 cubic metres of air per second). Global carbon emissions from fossil fuels are around 9.5 billion tonnes a year and capturing that would need almost ten million of those huge energy-hungry machines.

Emissions can be expressed as amounts of carbon or as amounts of CO_2*. One tonne of carbon burned produces 3.67 tonnes of* CO_2 *because of the added oxygen.*

Offsetting often means planting trees to take up the CO_2. The carbon is locked away in the wood of the trees. The obvious problem is that the CO_2 gets released once the wood burns or decays. For this offsetting to work, the trees planted this year have to remain forever, being replaced when they die. Then an additional area of trees needs planting to mop up next year's emissions, again remaining there forever. Before long huge areas of land would be covered in trees that can never be removed and we might have nowhere to live or grow food. It's an even less practical proposition than biomass (see later).

Nuclear energy

There are two possible forms of nuclear energy: fusion and fission. **Fusion** or thermonuclear reactions combine the nucleii of light atoms such as isotopes of hydrogen to yield energy. It actually isn't hard to make fusion happen but for fundamental reasons relating to the incredible tininess of the nucleii we are trying to bash together, it's very hard to get out more energy than was put in to accelerating the nucleii to the required speed/temperature as they almost always miss one another. Except at extreme pressure in the massive core of a star such as the sun or in an exploding hydrogen bomb. People have been working on fusion for 60 years or more using ever bigger and more expensive machines but have yet to produce a net gain of energy. Some say 30 or 50 years but it's been like that all along and it seems unlikely that fusion will ever be a practical and affordable source of energy.

Fission exploits another form of fossil fuel. Very heavy elements such as uranium and thorium, formed and spread from the cores of exploding supernova stars before the solar system coalesced, can be mined. Energy is released if their heavy nucleii can be split into lighter isotopes such as those of caesium and strontium. Unfortunately the lighter isotopes that arise are mostly unstable. They continue changing into other isotopes at their own intrinsic rates for many years after they are removed or escape from the reactor and each time that happens ionising radiation is produced.

> *Ionising radiation is particles such as alpha and beta and electromagnetic radiation such as X-rays with enough particle/photon energy to break chemical bonds and damage DNA in living cells, risking mutations and cancers. Microwave radiation such as 5G uses lies at the opposite end of the electromagnetic spectrum (past visible light) and is definitely not ionising.*
>
> *An element such as uranium has chemical properties depending on the number of protons in its nucleus and the resulting electric charge. Its nucleus might contain a varying number of neutrons which have about the same mass as protons but don't carry an electric charge. They don't change the chemical properties but they affect the mass of the atom and its nuclear properties and stability. Different numbers of neutrons give different* **isotopes** *of the element.*

The easiest way to split the nucleii is in a chain reaction where each nucleus that splits releases some neutrons and those that strike other nucleii cause them to split too. But only a few heavy isotopes can sustain a chain reaction and the only naturally occurring one is Uranium 235 (92 protons and 235-92=143 neutrons in its nucleus). Less than 1% of the atoms in mined uranium are U_{235}. The rest is U_{238}. Depending on the design of the reactor, it may be necessary to increase the concentration of U_{235} by removing some of the U_{238} before making the reactor fuel. The removed U_{238} is known as **depleted uranium**.

In the reactor, some neutrons get absorbed into U_{238} nucleii which then turn into plutonium 239. This, like U_{235}, is fissile; it can sustain a chain reaction. Breeder reactors are designed to produce more Pu_{239} from U_{238} than the fissile materials they consume. Hence claims of producing more fuel than they consume, but the First Law isn't broken. They still need mined uranium to function, just much less of it.

Many countries had breeder reactor development programmes in the 60s and 70s but they have all been abandoned. One reason is the worry that some of that Pu_{239} would get diverted into making nuclear weapons, which it's rather well suited to. There are likely other reasons which turned everyone off the technology but we don't know what they are. Claims that we have enough nuclear waste to power the UK for 500 years are based on our piles of depleted uranium but the technology to use it has been abandoned for whatever reasons.

Thorium only occurs in nature as the 232 isotope which can’t sustain a chain reaction but it can be bred to U_{233} in a suitably designed reactor. That is fissile and rather similar in its nuclear properties to Pu_{239}. There are claims that you can’t make bombs with it but the reasons are unclear and human ingenuity is considerable. The breeding process seems to be easier than that for uranium but thorium isn’t a magic bullet and still has many of the same problems.

One of the biggest of those problems is what to do with the spent fuel. In current reactor designs the fuel is sealed in metallic tubes (fuel rods) which keep the nasty fission product isotopes contained. Most of those isotopes decay fairly quickly and would no longer be dangerous if the rods could be sealed away for one or two thousand years. But there are some longer lasting isotopes in there including Pu_{239} and it could take millions of years for those to decay to safe levels. The spent fuel rods also contain U_{238} and some unburned U_{235}: the rods have to be removed when there isn’t enough to sustain the chain reaction.

The fuel rods can be opened up and the contents chemically separated. This is **reprocessing**, as happens at Sellafield or Cap la Hague in France. The unburned fuel and the troublesome long-lasting isotopes can be returned to reactors in the hope that they will be burned up. You can also design reactors where the fuel is not sealed in rods and can be continuously reprocessed on site, such as some types of Molten Salt Reactor. But now all those highly radioactive fission products are swilling around the plant, contaminating it and inevitably leaking out to some extent.

In summary, nuclear is just nasty. It can work OK until something goes wrong but trying to head off all the ways that might happen is expensive and makes nuclear energy uncompetitive. It also takes a long time to build new nuclear stations – the prototype for the Hinkley C reactors is already over a decade late coming online. Claims of magical solutions such as thorium fall apart on closer examination because they still mean handling very dangerous materials in quantity.

Hydro, tidal and wave power

Hydro is one of the oldest and best ways of generating electricity, always used in preference to other sources where it’s available. It’s able to start and stop very quickly, can often store water to handle high short-term electrical demand and of course needs no fuel. It works by capturing the energy as a weight of water flows down through turbines. We can work this out from the principles in the first section. For example a cubic metre of water has a mass of 1000 kg and a weight of just under 10000 newtons. If it enters the station 100 metres (a bit over 300 feet) above where it leaves into a river or lake below, it can produce about 900,000 joules after allowing for losses in the turbine which are quite low (motion energy to electricity so no Second Law limit). But that’s only ¼ of a kWh. A cubic kilometre of water is a billion tonnes. It could supply 250 GWh, about 5 hours worth of our current maximum electric grid output. You can quickly see that the number of places where billions of tonnes of water falling hundreds of metres are to be found is rather limited. If the fall (head) is lower, even greater quantities of water are needed.

Hydro dams are often used for both flood control and power generation. They can of course cause ecological damage and submerge settlements and farmland.

Tidal lagoons can be set up to capture energy when water flows into and out of a closed lagoon as the tide flows in and out. The turbines need to cope with flows in both directions and varying, always rather low head so they are big and complex. Large amounts of water must be handled to generate significant energy and nothing is generated for two periods on each tide when the levels inside and outside the lagoon are equal. The economics of tidal lagoons aren't very attractive and few have been built.

Rather than using a lagoon, **tidal flow** uses units resembling wind turbines set underwater in places such as straits between islands where water flows as the tide rises and falls. Because water is much denser than air, the turbines can be smaller and more powerful. It's a new technique and it isn't clear how well it will work but it could be promising.

Wave power relies on any of a number of methods to capture energy from waves approaching the shore. The waves picked up the energy from wind blowing across the ocean. Wave power off the West of Scotland can be around 50 kilowatts per linear metre so the potential is large. One promising design was **Salter's Duck** but research on it was stopped by the UK Government in the 80s for unclear reasons. Maybe research could be restarted but the basic design couldn't be patented now as it's been known for decades.

Biomass

Plants are wonderful things. They grow instead of having to be manufactured. They capture solar energy and CO_2 and produce compounds of carbon and hydrogen that can be used as fuels in place of fossil hydrocarbons.

The problem is that solar energy is quite diffuse and plants don't capture it that efficiently. Vast areas would need to be planted to make much contribution to our energy use. These are already crowding out farmland needed to grow food as we add increasing amounts of **biofuels** to petrol and diesel.

The biggest biomass operation in the UK is **Drax**. Trees are harvested in Canada and elsewhere, made into wood chips and brought to the power station in Yorkshire where they are burned to generate up to 2 GW of power. The carbon emitted by the power station was previously captured by the trees so that bit is carbon-neutral and at least the land in Canada where the trees grow is unsuitable for farming although forests have their own value. But when greenhouse gases released from the cleared land before new trees can grow and the carbon emissions involved in cutting down the trees, bringing them to the mills, drying them, making the pellets and transporting them thousands of miles to Yorkshire are taken into account, emissions may not be less than if the power station burned coal.

There is of course some biomass available as a byproduct, including forestry and crop wastes, rubbish and sewage. This is already being put to use and will be exploited further. For example some diesel vehicles run on old cooking oil. But quantities of these byproducts are intrinsically limited and we need to make sure diverting them doesn't cause other problems. E.g. would soils be harmed if crop wastes are removed instead of being ploughed in.

Biomass will make sense as a way of making carbon-neutral fuels where there's no alternative, such as perhaps long-haul flights. But it's going to be very expensive.

Geothermal

The interior of the Earth is kept hot by natural radioactive decay of heavy elements such as uranium in its core, thousands of miles down. Where that heat reaches near the surface, especially in volcanic places such as Iceland, it can be tapped with wells and used to drive heat engines (steam turbines) generating electricity and for heating buildings. But in most parts of the world it doesn't come near enough the surface to be practical.

Solar and wind

These are the two biggest and most promising forms of renewable energy in most parts of the world, including the UK. As mass production of solar panels and wind turbines increases and is refined, costs keep falling and they are now about the cheapest sources of electricity.

Solar panels convert sunlight directly into electricity. They can produce about 170 watts per square metre in full sunlight but of course half the time over the year it is dark and much of the rest of the time the sun is low in the sky or it's cloudy. But they can still be a cost-effective source of energy, especially when installed in places which aren't useful for much else such as rooftops and unfertile land. One idea is to install vast solar farms in deserts such as the Sahara and transmit the energy to where it's needed. Some obvious issues are sandstorms and political instability.

The UK is well placed to use wind power and is ramping up its use quite rapidly. **Wind turbines** on land can coexist with other uses such as farming. **Offshore** turbines are mainly a minor inconvenience for shipping. The turbines themselves are now remarkably cheap: less than a dollar per nameplate watt. On the face of it that looks like an incredible bargain. Something like £800 for a kilowatt, 24 hours a day. Pay off the £800 over 10 years and it works out at under a penny a kilowatt hour. But of course it isn't that simple. The turbines have to be installed, connected to the grid and maintained. Even more, the wind doesn't blow all the time. Turbines offshore where winds tend to blow steadily produce around 50% of their nameplate output averaged over a year. Onshore it's only about 30% but onshore turbines cost less to buy, install and maintain and they are still competitive.

An equally important factor is that few of us actually want a kilowatt constantly throughout the year. So we've got renewable sources producing power only when the tide flows, the sun shines or the wind blows and we'd really like to use a load of energy to keep warm in the middle of winter. Which leads to:

Storage

Pumped storage is a form of hydro power which has been used in the UK since the 60s. Rather than relying on rain and snow to fill the upper reservoir, surplus electricity is used to pump water up from the lower reservoir. Then it flows down through the turbines when power is needed. But remember those cubic kilometres of water. The number of places where we can store them on top of mountains is very limited.

Batteries are starting to be used at large scale to try to match intermittent supply with demand. They can make sense especially in predictably sunny places without much seasonal change in power demand, such as Australia and Florida. But we can try a sum for them in the UK:

Suppose a typical house needs 5 kW constantly to keep it comfortable in winter and we need that for two weeks when it's cold and the wind doesn't blow. That's 14x24x5=1680 kWh of storage required. Lithium batteries currently cost about £100 per kWh so that's £168,000 of batteries for one house, having to be paid for whether they are individual for each house or centralised on the grid. It's still probably not enough, batteries don't last forever and is there enough lithium in the world? It might get a bit cheaper but it would have to be over 10 times cheaper to look at all attractive. We need something more like a fossil fuel that can be stored in whatever quantity we need:

Hydrogen

Hydrogen can be used as a fuel. It used to make up about 50% of coal or town gas before North Sea natural gas was introduced (much of the rest was carbon monoxide, making the gas poisonous). It's also used in many industrial processes, some mentioned later. There's no carbon in hydrogen gas and when it burns, all that's produced is water.

Hydrogen is produced in three main ways. "**Brown**" hydrogen is made with natural gas and the carbon from the gas is released into the air as CO_2. The First Law says that at least as much gas energy is needed as ends up in the hydrogen. Its only legitimate use in a green transition is to try things out, e.g. to see if existing gas boilers will run on hydrogen.

Blue hydrogen is Brown hydrogen with carbon capture and storage. Little CO_2 is released but even more gas is used. No wonder fossil fuel companies love blue hydrogen. **Green hydrogen** is the interesting one. It's made by splitting (electrolysing) water with electricity and if the electricity source is carbon-free (e.g. from wind), the hydrogen is too. A lot of work is being done now on the electrolysis process and it’s become over 80% efficient (8 units of hydrogen energy from 10 units of electrical energy) without needing rare and expensive catalysts such as platinum.

Without storage, there’s no point installing more renewable power sources than there is demand for electric power. For example if there’s a windy period in summer when demand is low and there’s more wind power capacity than that low demand, some of that capacity and investment is wasted. But if that surplus capacity can be turned to making hydrogen for storage until the winter, the situation changes. Then it makes sense to install renewable sources until their annual energy (not power) output matches annual energy usage, allowing us to decarbonise all energy if there’s enough places to put the renewables generators.

Hydrogen has its problems. With the smallest atoms of any, it leaks rather easily, even percolating through other substances. It can turn metals brittle. Its density is very low so storage means either huge volumes, very high pressures or storage as a liquid at very low temperatures. There are also ways to absorb it into solid materials. It’s rather explosive if it leaks although being so light it usually rises and dissipates quickly. But hydrogen is already handled widely in industry and stored in salt caverns and other places. None of it seems unsolvable especially compared to the nuclear waste problems and a lot of work is being done currently on distribution and use too. It seems to be possible to gradually convert the existing gas network to hydrogen.

If a better solution can’t be found, cryogenic liquid storage should be possible. If we just look at heating for 20 million houses at 15000 kWh a year each and use figures easily found with a search engine, it translates to a cube of liquid hydrogen 500 metres on a side. In practice less would be needed because energy would be generated in winter too but then there’s lots of energy needed for other things too.

In this situation bigger is better. Doubling every dimension of a thermally insulated store increases its capacity eight times (2^3) and its surface area four times (2^2). But the insulation is twice as thick so the heat leaking in is only doubled and the ratio to capacity is four times better. Obviously we can’t risk putting everything in a single store in case something happens to it. But there’s nothing here that looks unworkable and some of the energy used to cool and liquify the hydrogen could be recovered with a suitable heat engine as it returns to a gas.

Turning hydrogen back into electricity is a bit problematic. Fuel cells do this flexibly with no moving parts but use expensive and rare catalysts such as platinum. They could also be damaged by any impurities in the hydrogen. Existing gas-fired stations could be converted to burn hydrogen. Either way, the efficiency is around 50% and after allowing for losses in electrolysis as well, 2.5 units of renewable electricity would be needed for each unit of electricity generated this way. It’ll either have to be done or batteries employed to supply power for those things that need electricity but where possible it will be better to burn hydrogen directly.

Other carbon neutral fuels

Two fuels containing only hydrogen and nitrogen are ammonia and hydrazine. Nitrogen makes up over 70% of air and is easily extracted. Hydrazine is very dangerous. **Ammonia** isn’t the most pleasant thing either but it’s already made (with brown hydrogen which could be replaced with green) in large quantities as an ingredient for fertilisers and other industrial uses. It can be held as a liquid at moderate temperatures and pressures and is being proposed as a transport fuel, especially for ships and maybe aircraft.

We are accustomed to a wide range of convenient fuels containing carbon but the only ways to make these carbon neutral are to capture the carbon as they burn or to make them with carbon captured from the air. The first is impractical for mobile use and pointless for fixed use as we might as well burn hydrogen. The second is most practical via plants – the biofuels already mentioned.

Household energy

Heating is the biggest household use of energy. It’s even more of a problem because everyone wants that energy at the same time when the weather turns cold.

With new buildings, the easiest answer to the heating problem is to include lots of insulation. For example the **Passivhaus** standard specifies buildings that stay warm enough in cool weather just from the people in them and their activities such as cooking. Even when some extra heat is needed, it’s very little and can even be provided by inefficient means such as electric resistance (see below).

Existing buildings are far more of a problem. Once the easy improvements such as loft insulation are done, it mainly comes down to adding insulation to the inside or outside of the walls. Either is very disruptive, labour intensive and expensive. Insulation on the outside makes the building bigger and may not be possible in some cases. On the inside it makes the rooms smaller. If we’re using heat from renewables, it comes down to a choice between insulating or increasing the supply of renewable energy.

The simplest and cheapest form of heating to install is **electric resistance** but it’s about the most expensive to use. Not only is more fuel needed at the power station than with a 90% efficient modern boiler but the expensive power station and electric grid and their maintenance must be paid for. An electric current is forced through a resistance wire and the energy used turns into heat. There are various ways to distribute that heat including radiant heat and convection and it can be stored for a time in heavy bricks before it’s released (storage heaters). Some companies tout their overpriced electric resistance heating, e.g. on Facebook, as “100% efficient at the point of use” but that’s true of even the cheapest portable heater from a discount shop.

One way to reduce energy use is with heat pumps as described in the first section. There are two main types. **Air source** ones draw heat from the outside air but as the weather gets colder that gets harder. When it's cold and damp, the outside coil that captures the heat ices up and additional energy is needed to melt the ice and get it working again. The effectiveness of heat pumps is often quoted as a **Coefficient of Performance (COP)**. This is the ratio of the heat delivered inside to what would be delivered if the same amount of electricity was used for electric resistance heat. It's often quoted as 3 (or 300%) for an air source heat pump over the season but is considerably more in the mildest weather and as low as 1.5 in the coldest conditions. Just when the most heat is needed. In that specific case and if the electricity comes from gas, a boiler would use less gas and produce less emissions than the heat pump.

Ground source heat pumps draw heat from underground where the temperature is stable regardless of the weather. Either wells or long pipes buried under lawns and the like collect the heat. The efficiency is better with a COP of 4 generally quoted but they are much more expensive and disruptive to install and there are many places where they can't be used at all.

In both cases, it's essential to keep the output temperature of the heat pump as low as possible to achieve decent efficiency. Usually 50 C maximum. Radiators used with existing boilers are designed to operate at 70 C or more to keep the building warm in cold weather. They have to be replaced with much larger ones to do this at 50 C, meaning more expense and disruption and more valuable room space taken up.

A suggestion is to combine a small, inexpensive, air source heat pump with a hydrogen fuelled boiler and maybe electric resistance elements too. In mild weather, the heat pump can efficiently deliver enough heat even through existing radiators. In colder weather, the boiler kicks in using hydrogen supplied from national storage through existing gas pipes. When the boiler cycles off, it would be possible much of the time for the heat pump to keep the radiators warm enough to slow cooling of the building and reduce the hydrogen needed. When there's ample renewable power available and subject to the grid being able to distribute it (which might involve unjustified expense), electric resistance elements could supplement or replace the boiler heat, avoiding the 20% energy loss in electrolysis and heat lost through the boiler flue. A smart controller receiving weather forecasts and current and projected availability and costs of the two forms of energy would optimise operation of the system.

> *It's unfortunate that we get very little information about what plans there are for heating decarbonisation but one snippet is that there is apparently a plan to deliver a mixture of 20% hydrogen and 80% natural gas through the gas grid in a few years time and existing gas appliances are expected to work fine with that.*

Other uses of energy are less problematic. Water could be heated to 50 C by the heat pump, then boosted as needed with electric resistance. With hydrogen being explosive, cooking is likely to be all-electric. Only boil as much water as you need in the kettle. Lighting already is mostly with very efficient LEDs but anyone using older halogen or standard bulbs should look at replacing them. When it comes to other equipment, it should be noted that the electrical energy it uses almost all ends up as heat. If it doesn’t get warm, it isn’t using significant energy. Of course a physically large device like a TV can draw more power before becoming noticeably warm than something small like a phone charger on standby.

> *Heat pump dryers are now available and quite affordable. They recirculate air, cooling it to condense out water evaporated from the clothes before returning the heat to it and blowing it back into the drum. This is much more efficient than conventional electric resistance vented and condenser dryers.*

There can be a bit of a scam in the sale of electricity. Everyone gets their supply through the same wires with in truth the same mixture of renewable, nuclear and fossil-fuelled sources, changing from minute to minute. The suppliers quickly cottoned on to telling consumers who care about the environment that their electricity comes out of the renewable fraction and getting them to pay a bit more for it. But that just means that those who don’t ask are getting a higher nominal proportion from the other sources. Whether this paper exercise makes any difference to the mix of sources supplying the grid is debatable.

> *Nuclear supply to the grid is just about constant. Renewables vary according to sun and wind. It’s the fossil-fuelled bit that varies according to supply and demand. This means that every extra watt we individually use or avoid using varies that amount of fossil-fuelled power generated. If you turn on an electric heater to avoid burning gas in your boiler, you’re currently causing almost twice as much gas to burn in a power station. Even if you’re on a green tariff.*

Transport

Hydrogen fuelled cars can be bought now. They rely on fuel cells and hydrogen compressed to alarmingly high pressure and stored in cylinders but we are quite blasé already about driving around with gallons of highly flammable petrol behind us. The overall efficiency is not great but they are almost as quick to refuel as current cars if you can find a place to do it. Battery electric cars are widely available and becoming quite common. They can be charged in lots of places including at home but charging means long stops when travelling a distance. There are still major improvements to batteries in prospect so the cars are likely to get more attractive as time goes on. Overall energy efficiency would be similar to hydrogen cars when the charging electricity was coming from storage but a lot better at times when it could be taken directly from the renewable sources.

> *Cars don’t last forever. They can be replaced with electric or hydrogen versions as they wear out. Although it seems a simple idea to phase out private cars, getting families to go back to shepherding their children and lugging all their accoutrements onto public transport is a big ask.*

Trams are normally electric. Trolley buses supplied from overhead wires are out of fashion but could be brought back quite easily. Other buses can be fitted with batteries or fuelled with hydrogen or biofuels and this is starting to happen already. Ammonia might be another option.

Lorries follow flexible routes but maybe an overhead electrical supply could be provided on long routes such as motorways if practical issues can be worked out. Otherwise the options are similar to buses.

Electric trains are already common in many places. The chief snag to extending the network is the cost of raising bridges or the flooding risk of lowering the track to make room for overhead wires. It somehow gets overlooked that just about all of Southern Region trains operating out of London use third-rail supply. Those trains can't run as fast as ones supplied from overhead wires but that's irrelevant on lines such as Swansea to Cardiff that are never going to allow speeds over 100mph. Trains have already been built, e.g. for the Channel Tunnel, that can use either power source.

There already are battery electric ships in operation on short routes although getting sufficient power to the quayside to charge them in a reasonable time takes investment. Hydrogen or ammonia fuelled ships should be possible and the second of these are already being planned. Small on board nuclear reactors have been used occasionally but the risks are obvious, especially with flags of convenience standards in shipping. Sails may make a comeback as a supplement to mechanical propulsion. These will be advanced and automated without all the traditional crew and rigging.

Aircraft are problematic because weight matters so much. Battery powered planes are being designed now for short routes. Hydrogen or ammonia may be possible fuels for longer routes but are unlikely to support the longest flights. As noted previously, biofuels for those flights would be very expensive so maybe frequent refuelling stops will return to long distance aviation.

Industry

Across general industry, electricity is required for various processes as well as heat that could come from electricity or hydrogen combustion. This energy will inevitably be more expensive than in the fossil fuel era. Maybe this will encourage more efficiency and reuse and less waste of other resources. There are a few industries deserving a closer look:

As noted previously, ammonia is used for fertiliser production as well as for a potential fuel. It can be made with green hydrogen. Although it is of course possible to grow food without artificial fertilisers, it may not be practical to support current population levels that way and nobody sensible wants people to starve.

Plastics are carbon-based. The carbon currently coming from fossil hydrocarbon sources will need to come from plants instead. Plastics will become more expensive, encouraging reuse and recycling and reducing pollution.

Cement production, e.g. for concrete, is a huge source of CO_2 emissions, both from burning fuels to provide the necessary heat and from the chemical reaction that makes the cement itself. Cement production accounts for about 8% of global carbon emissions. Heat could be provided from renewable sources and capturing the carbon from the reaction itself may be a legitimate application for CCS. We ought to bear in mind the “**embedded carbon**” in building materials before we set out to tear down and replace buildings, even if the new buildings are going to be more energy efficient.

Iron is currently produced from ore (iron oxide) in blast furnaces. Carbon from coal provides heat as it burns and also acts chemically to strip oxygen from the ore, yielding metallic iron. A lot of iron and steel will be needed to build a green energy system. Electric arc furnaces can melt scrap metal for reuse but they cannot make iron from ore. Large amounts of new iron and steel are needed for new renewable energy infrastructure and this cannot all come from recycling.

Hydrogen can be used instead of carbon to strip the oxygen from ore and produce iron (and water vapour). This process is already being trialled at some scale and is expected to take over as the industry decarbonises. Things will be easier if hydrogen can be drawn from the gas grid as projected earlier.

Molten iron as it comes from a blast furnace contains about 4% dissolved carbon. When it solidifies it becomes cast iron which is given good and bad properties by the carbon. It’s dimensionally very stable and hard wearing and quite resistant to corrosion but it’s brittle and its tensile strength is poor. For example, the famous bridge at Ironbridge was built from cast iron before steel could be produced in quantity. You can easily see the weight and complexity compared to a modern bridge.

Steel making involves reducing the carbon content in the molten iron to various levels by passing air or oxygen through it (e.g. in a Bessemer Converter) to burn off carbon and adding small amounts of other metals for different uses including hard steels for making cutting and machining tools. Mild steel containing around 0.2% carbon is rolled to make girders and rails and sheet steel for car bodies and the like.

With hydrogen, this process will be reversed and carbon will have to be added to the metal from the furnace to make the various types of steel. When the steel eventually rusts away the carbon will be released so it ought to come from a source such as biomass.

Jobs and Security

There’s no doubt that energy is going to be more expensive than it was in the era of cheap fossil fuels. Why is this? It’s because making, installing and maintaining loads of generators such as wind turbines to capture diffuse renewable energy over wide areas takes more work than drilling a hole and having millions of years of captured sunlight in the form of hydrocarbons, trapped for us by nature, come gushing out.

But work means people doing jobs. Jobs largely in our own country. Instead of sending our money off to distant places where there’s still fossil fuels to be found and having much of it spent on glittering towers there, our money will go into the pockets of fellow citizens who will spend it and create even more jobs in our communities.

As fossil fuels remain to be extracted in fewer and fewer distant places, supply becomes less certain and prices, driven by the whims of global markets, surge higher unpredictably. Since the first part of this document was written, gas prices have spiked from an astronomical £3 per therm to a catastrophic £8. Not only would renewables be cheaper, their price would be far more predictable and their supply more certain.

Conclusions

People across the world are aware of the problems caused by our dependence on fossil fuels and a lot of work is being done right now on developing alternatives. None are as convenient or as inexpensive as fossil fuels used to be before they started running out but most are quite practical. We will become less profligate in our use of energy and resources because of the expense though one person’s expense is another’s job and there will be more of those overall. A few things, likely including long non-stop flights, will come to an end.

It’s unfortunate that with everything done primarily through the private sector, issues such as commercial considerations and confidentiality mean that we can’t always trust their or government motives and are told very little of what’s going on, ending up resorting to a form of Kremlinology. Many of us assume that nothing is happening and either look for inefficient small individual measures or imagine a bleak future of deprivation. We also waste a lot of time and breath discussing unworkable ideas instead of pushing for practical things to happen quickly. I hope this document saves us that and helps to reassure.

Steve Hayes, 21 March 2022