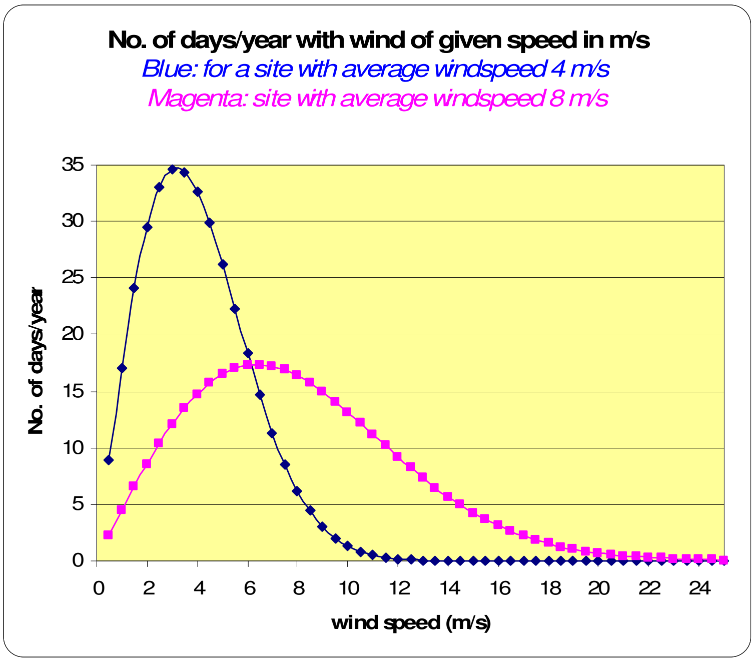
On Renewables

John S. Reid

Wind turbines

Sometimes it's calm, at other times one can scarcely stand up in the wind. The wind is a variable feast and the distribution of wind speeds is important because the output of a wind generator depends on wind-speed. The distribution of wind speeds is quite well represented by a formula named after Lord Rayleigh, one of the great mathematical and experimental physicists who was active in the last quarter of the 19th century and the first part of the 20th century. He was one of the first recipients of a Nobel Prize, though not for this formula. The probability that the wind will have a speed of v is given by $P(v) = \frac{1}{a^2} e^{-0.5(v/a)^2}$, where the average speed $v_m = a\times\sqrt{(\pi/2)} = 1.253\,a$. The single constant a characterises a location and is proportional to the average wind speed at the site. In a calm site where the average wind-speed is 4 m s^{-1}, the formula tells us that for at least 2500 hours a year a wind turbine will produce nothing; in a windy site of average speed 8.5 m s^{-1} (and some sites are more windy than this), the turbine won't turn for about 700 hours a year. The wind increases with height above ground, as the frictional effect of the ground decreases. A turbine 20 m above ground will generate more power than one with the same size of blades lower down. Other influences are the local topography and the presence of nearby obstacles. Both of these factors depend on the direction of the wind so all these influences mean that there is no formula that will enable you to predict within a few percent what power any one individual installation will produce.



Wind turbines need some basic wind-speed before they start to produce any significant power. 2.5 m s^{-1} is a starting figure, some would say it's often a bit more. The power in the wind increases as the cube of the wind speed, v, but wind turbines are less efficient at extracting this power at higher wind-speeds so don't be surprised if the power available increases more nearly in proportion to the wind speed up until some maximum wind-speed where the turbine is rotating as fast as it safely can and no further power is available. 16 m s^{-1} is a reasonable estimate for this speed. Many turbines are shut down when the wind exceeds 25 m s^{-1}. To estimate the total power one might expect from a wind turbine over a year you need Rayleigh's formula (or an alternative) and the output power for different wind-speeds for your chosen generator. Wind turbines are rated by the maximum power they can produce but fortunately for daily life the wind doesn't blow strongly enough for them to produce this power all the time. Using the numbers above, you'll find that for our calm site the wind isn't likely to blow at 16 m s^{-1} even for a day in the year and the generator will on average produce about 10% of its maximum rating. For the windy site, the figure is about 40%. There will be additional 'losses' as far as customers are concerned due to inevitable downtime and transmission inefficiencies. It's no argument against wind turbines to say that they don't produce their rated power all the time. Wind turbine developers are well aware that there are plenty of days in a year with light winds and even calm. The figures above, though, show that there is a comparatively high return at windy sites but it's scarcely worth the effort in sheltered sites. The situation is a bit like the one that faces the owner of a performance sports car. Driven in a congested city, its average speed may be only 10% of the maximum it is capable of but on the country roads it will achieve an average of much more, but still a lot less than its maximum. Just because it can't be driven at maximum speed all the time doesn't mean to say it's useless. Turbines in power stations aren't run at their maximum power all the time either.

Another aspect of turbines is that they can't extract all the kinetic energy of the wind, for that would mean bringing the air to a standstill where it would just try to pileup, and that can't happen. Anyone wishing to look further into this should look up 'the Betz limit'. The Betz limit says that the maximum power one can extract from the air is about 60% of the power that is in the air's motion. After passing through the turbine, the air expands out and generates a large area of turbulence and altered flow behind. One effect of this is that wind turbines placed too close together reduce the performance of each other. The typical area that needs to be provided around a wind turbine to give it free air is about 40 times the square of the diameter of its blade. The power produced by a turbine also depends on the square of the diameter of the blade (i.e. the area swept out by the blade) so if you double the blade diameter you get 4 times the power. However, you need 4 times the area of ground (twice the distance to the side and twice the distance to the next one behind) so the net result is that an area of ground (like 1 km^2) can produce a certain amount of wind power that is the same if it is populated with a small number of large turbines or a large number of small turbines. The '*a*' factor above characterises the area (windy or otherwise). For a reasonably windy area the wind power available is about 2 W m^{-2}, equivalent to 20 kW ha^{-1}. This is not the maximum power but an average power, some 40% of the maximum. More than this average energy can be extracted from a given area but the efficiency falls. For example if the density of turbines were doubled, the output from all the turbines would be significantly less than twice the previous output. The figure of 2 W m^{-2} has no relevance to a single isolated wind turbine, whose footprint on the ground is quite small.

Now for the important question. How much wind energy can we hope to get by putting wind turbines on UK soil? There are at least 2 strategies that could be used. The first is blanket coverage of wind turbines in suburbia, housing estates, retail parks and so on. A 1 kW maximum power generator has a blade of about 2 m diameter, which on a windy site might give an average of 400 W, less so on a sheltered site. Most people nowadays would say that a wind generator on every house will make the countryside look ridiculous. Maybe so, but if it were a choice between a wind generator and no electricity then we'd all get used to the sight of one on every house. However, my main point is that a few hundred watts per household (and the average will be less) will not provide anything like the electricity required for daily life. It might just manage to supply the lighting, with the high efficiency lights we expect will be the norm in 20 year's time.

The second option is wind-farms. There are already small ones in quite a few places in the countryside. Sitting with the wind shaking the windows in a dark autumn evening it's easy to think that a vast amount of wind power is available, almost all of which is going to waste at the moment. Time for some figures. Our local gas and oil fired power station (Peterhead) has a capacity of over 2 GW (1 gigawatt = 10^9 W). It occupies a 10 hectare site (10^5 m^2) and can generate power day and night, come wind, come rain or days of calm weather. If that same site were part of a wind-farm, at 2 W m^{-2} it would produce about 0.2 MW. Putting it the other way around, a wind farm to generate 2 GW would need an area of 1000 km^2 of reasonably windy countryside, probably a bit more since some turbines are always out of action on a sizeable wind farm. That's a huge area of land just to replace one existing power station. In future if we run electric cars, use electric trains more than road-freight and heat our houses and factories mainly by electricity then we'll need much more capacity than existing power stations. Without doing any more sums on national needs it should be clear that wind farms will make a contribution to future electricity needs but are a long way from the total solution.

Obtaining 1000 km^2 of space in the North Sea is in principle easy, even 10 times this, and the North Sea is comparatively shallow and has only a modest density of marine traffic. However, as oil companies know full well, the North Sea is a physically destructive and chemically corrosive place. Building extensive off-shore wind-farms is marginally economic at present, but the situation is changing by the year. There is an equal amount of territorial water off the west of the UK but that has to cope with the Atlantic. Various practical and important details concerning the strength of a structure needed to resist the buffeting of wind and waves, the depth of 'dead space' below the water level, the impact on other users of the sea and much else come into the decision as to whether to use a large number of smaller turbines or a small number of large ones in a given area. Current thinking favours a smaller number of large turbines. In future, offshore structures may be able to extract combined wind, tidal and wave power, making them more attractive, and I'd be surprised if the North Sea and other UK waters weren't awash with power generators by the end of the century but that's a long time in the future. Meanwhile, a lot of wind power is going to waste in the UK and as a matter of some urgency we need to be harnessing several GW as a contribution towards the national energy budget.

I wrote the above about a year before reading about the Smart Wind Consortium's project to build a wind farm well off the Yorkshire coast. The design figures reported in *The Times* are that it will generate a maximum of 4 GW of electricity using about 1000 wind turbines covering an area of 4735 sq km (4.7×10^9 m^2). These figures are pretty much in agreement with those above, though rating the achieved output at only 1.2 W m^{-2}. The project is more than just a drawing-board exercise, for the National Grid has agreed to take 1 GW by 2014 and the full 4 GW by 2020. As I'm reviewing this note in 2013, plans have been submitted to install 339 turbines over 20 km off the Caithness coast. This is a much larger scheme than the Aberdeen offshore windfarm that has attracted a lot of local comment. In fact as of 2013, a reliable source informed me that the UK has more offshore installed wind power capacity than there is in the rest of the world. Wind power has the potential to provide a few tens of percent of UK electricity. Current UK consumption averages at about 43 GW, with peak consumption about double. In future when electricity will have to supply a bigger fraction of total power requirements (e.g. for heating and transport) demand will certainly increase beyond these figures.

Since I first drafted this piece, numerous wind turbines have appeared on the Scottish landscape, mainly in upland areas. They spell 'independence' from imported oil, from the diminishing North Sea reserves, from imported gas and from fracking developments. They or their successors will be there long after the pipelines have corroded into industrial archaeology. If you're not a fan of wind turbines in the landscape, think of them as pumping virtual oil – no fracking, no contamination spillage, no flammable liquid, no pipelines, no refineries, no price at the whim of an international cartel, no tankers on road or rail, no CO_2 production when the energy is used; that's a lot to be said in their favour. In a way I'd be surprised if many more don't appear. If I owned a farm of say 100 Ha, the average size in Scotland, I would want to put in one or more wind turbines. At 20 kW/Ha they could generate 2 MW. I could easily double this if I was prepared to spill ‘dirty’ air over my neighbour’s land but let’s not be greedy. The turbines wouldn’t stop my sheep and cattle grazing or my cereal growing so they would bring in extra income. At 20 p per kW hour feed-in tariff the income would be £200 per hour per MW. Let’s conservatively say that my farm generated an average of 1 MW over the 8766 hours in a year, since it is not in the most favourable location. My additional income will be £1.75 million per year. This is more than just a ‘nice little earner’, exceeding the income from all my farming activities. So why doesn’t every Scottish farm have a 2 MW wind turbine on it, or the equivalent for smaller and larger farms? Maybe they will some day. There are some 6 million Ha of agricultural land in Scotland. Wind turbines don’t care if the land is fertile or covered with rocks, gorse and bracken. 6 million Ha at an average of only 10 kW per hectare would produce 60 GW of electricity. At the current average UK energy consumption rate that would support more than twice the population of Scotland even in future when everything runs off electricity including all transport and heating.

So will the country be covered with wind turbines in 40 years’ time? Don’t bet against it. When people see the wind not as something that blows leaves and litter past but pound notes and euros, then expect change. When it becomes more common for the lights to go out without warning, the TV to die in front of you, your heating and cooking to turn off with barely an audible ‘click’ as yet another power outage strikes, then the value of being able to generate electricity from our own resources will be glaringly obvious. Putting turbines on land is much cheaper than putting them in the sea. Less capital needs to be raised and the payback is quicker since the sale price of electricity is the same wherever it’s generated. Electricity is the staff of today’s civilisation and the twin horses of necessity and profit may well drive the wind turbine lobby to a great many farms in the country.

Solar power

Solar power comes mainly in two forms, light and heat. There is also some UV (7% in the incident solar spectrum) but most of that is absorbed by the atmosphere. The light and residual UV can be used to generate electricity directly by photovoltaic action. Heat can’t activate photovoltaic cells made of silicon or another semi-conductor. Each silicon cell produces about half a volt. The ‘efficiency’ of photovoltaic cells is often given relative to the energy of the whole spectrum of sunlight they receive but this isn’t as useful an idea as it seems because the solar spectrum at ground level itself depends on how much of the atmosphere the sunlight traverses and what is in the atmosphere. Also the solar spectrum contains some 50% of heat that is never going to activate a photovoltaic solar cell. I’ll assume an achievable efficiency of a solar cell measured against the energy of white light falling on it as 20%. Heat, the wasted energy as far as photovoltaics are concerned, can be used by other means to raise steam that can drive a turbine connected to a generator. This is one technology that allows solar heat to generate electricity with similar efficiencies to a power station. The method is suitable for a solar energy ‘farm’, not for individual houses.

The most effective use of solar heat that falls on individual houses is to use it for direct heating, allowing energy in through windows and utilising what falls on roofs and walls. Windows let in only the light from the Sun, not the heat, thus excluding some 50% of the radiant energy but that’s better than walls. Roofs and walls are not only opaque but need to be highly insulated in countries like the UK to prevent heat energy escaping from within to the cooler environment outside. To utilise incoming solar radiation, buildings therefore need active heat-transfer technology incorporated within their design that can transfer heat in when the sun is beating down outside and prevent heat escaping when it is not. Almost the only attempt at this currently in production is the provision of roof mounted energy converters for domestic water heating. Much more sophisticated building design could be used.

Although more than 1.2 kW m^{-2} of solar energy arrives at the outer atmosphere of the Earth, some of it is absorbed by the atmosphere and at times the remainder is diffused so much over the whole sky by clouds that one can't tell where the Sun is by looking up. What penetrates directly to the ground always reaches the UK at a glancing angle, an angle that depends on the altitude of the Sun in the sky. At our latitude (57º) there is a factor of 5 difference in the spreading effect of the angled Sun at mid-day between mid-summer and mid-winter. The length of the day between sunrise and sunset varies from eighteen hours at mid-summer to six and a half hours at mid-winter. Of course there's the daily variation in altitude of the Sun everywhere in the world too. The result of all this is that there is both predictable and unpredictable variability in available solar energy. I ran the Physics Department calibrated solar radiation station for many years that contributed to the National Radiation Network. A ball-park figure for the total (direct and indirect) June/July radiation was 200 W m^{-2} averaged over a 17.5 hour day, reducing to 50 W m^{-2} averaged over a 7 hour day in December/January. Interpreted as 24 hour averages, the figures change to 150 W m^{-2} in summer and 15 W m^{-2} in winter.

You might think that solar power would be useless at our latitude of 57º in winter but daily temperatures rise several degrees Celsius with the rising Sun so there is some energy there and moreover available wind-farm energy is only 2 W m^{-2}. Taking half the solar energy to be suitable for photovoltaic generation with a solar panel of efficiency 20% gives a winter target of 1.5 W m^{-2} and a summer target of 15 W m^{-2}. Given the expense of solar panels, it's not much. On these figures, a 1 m^2 photovoltaic panel will take about 3 days to charge an empty 80 Ah (amp-hour) car battery in summer and the best part of a month in winter.

The figures above quote the radiation received on the ground but in our latitude the Sun is mainly at an altitude of less than 45º, which means that vertical walls facing the Sun receive more radiation than the ground. However, a south facing vertical wall will miss out on early morning and late evening sun in the summer. In another article, calculating how much sunlight falls on a given surface (http://www.abdn.ac.uk/~nph120/meteo/Sunlight.pdf), I have put some figures on the sunlight received over a year by differently oriented surfaces and broadly speaking a south facing wall is a sensible place for a photovoltaic panel, leaving the roof for solar heaters. Photovoltaics will be a useful local resource in this part of the world when panels of 10 m^2 become widely available at a price that is affordable by many. Large-scale solar electrical generation facilities clearly have to be located in largely cloud-free desert locations a lot nearer the equator where the change in irradiation with seasons is much less conspicuous.

Photovoltaics don't require focusing technology and can therefore use much of the area available. Solar energy farms with concentrating technology of mirrors or Fresnel lenses have significant overheads of space requirements for servicing and for the electrical generation technology itself. They are lucky to achieve 15 W m^{-2} in optimum high-sun desert areas. The fact of the matter is that even when we (mankind) try, we can harness less than 2% of the incident energy of the Sun to produce electricity at ground-based facilities. This sounds bad but the upside is that in generating solar electricity we aren't going to upset the natural processes of the Sun heating the Earth and driving the weather system. The other message is that solar energy, like other renewable energy sources, is spatially diffuse and to harness it intensely requires lots of land area that is not much use for anything else. The global 'bottom line' is that to produce the electricity from solar energy that is now being produced by coal, oil and gas will take around a million square km of well-located solar energy farms. The more local 'bottom line' for the UK and even Europe as a whole is that we haven't the sunny, unused and unpopulated land to do our share of it in. To make extensive use of solar power we will need to import it from sunny desert regions. This has economic and political consequences well beyond the science involved.

[I'm tempted to add here one of my digressions to the effect that the sentiment above is not new 21st century thinking. These are the words of Sir William Grove in his address as President of the British Association for the Advancement of Science in 1866 (not a mistype), reflecting on what mankind might do when coal runs out: *As the sun's force, spent in times long past, is now returned to us from the coal which was formed from that light and heat, so the sun's rays, which are daily wasted, as far as we are concerned, on the sandy deserts of Africa, may hereafter, by chemical or mechanical means, be made to light and warm the habitations of the denizens of colder regions. The tidal wave is, again, a large reservoir of force hitherto almost unused.* He did acknowledge that *the prospective exhaustion of our coal fields* was *somewhat premature perhaps* but his message at the time was that we need to foster the science of the conversion of energy (he used the word 'force') from one form to another to solve problems that will affect everyone.]

Looking out of the window between typing this I can survey a sweep of the North Sea bathed in sunshine from an almost cloudless sky. An estimate of the area visible to my horizon is 400 km^2. If the sunlight over half of this area were to be converted into electricity, allowing lanes for shipping and fishing, though not a single vessel is in sight, at 15 $W\ m^{-2}$ the off-shore solar energy farm would be generating 3 GW, more than the capacity of our local power station. In principle the UK doesn't need to import solar power if the sunlight over UK waters could be harnessed but as far as I know no-one has any idea how this could be done economically in the watery, stormy, salt-sprayed environment that is usually the North Sea. Natural resources constrain what can be done in the future but, in addition, the basis of viable plans for mid-century, 40 years away at the moment, has to be technologies that one can see can be made to work, not science-fiction ideas one can happily draw on a computer screen that won't survive a reality check.

Fluctuating supplies

Wind, wave and solar power all suffer from major power fluctuations that could take generating capacity in one location right down to almost zero for days on end. Our ancestors thousands of years ago realised that rainfall was also a variable gift of nature and in many places irrigation was developed to sustain farming. For renewable energy generation today, storage technology is needed. So is large-scale electrical transmission capability that will enable working capacity in one place to be shared when generators are down elsewhere due to lack of wind, waves or usable sunlight. Electrical energy comes in the form of the energy of electric and magnetic fields. There is no technology that can store industrial amounts of electrical energy directly so energy storage must be in some other form. Batteries use chemical energy. A decent sized lead-acid car battery is rated at 80 Ah and 12 volts, implying a storage capacity that will generate 1 KW h of electricity. To store enough energy this way to supply 10 GW for 1 day (~20% of average UK electricity consumption for 1 day) would need 240 million car batteries fully charged, or the equivalent in large batteries. Lithium batteries are several times better but on a national level batteries will be small players.

Flywheels can store mechanical energy, a technique that is now used in formula-1 racing cars and was used in a few prototype buses before that. Unwanted kinetic energy that would be dissipated in the brakes as the vehicle slows is used instead to spin up a flywheel. The energy stored in the flywheel can be recovered later to provide more acceleration. A system that stores 1 KW h of energy using 20 kg of fast rotating mass would be doing very well. As with batteries, the task of storing 10 GW days is beyond practicality, requiring a few million 1 tonne flywheels spinning close to the limits of their strength. It's not really a feasible storage mechanism at the national level but could be useful in local circumstances.

Photovoltaic generation has no intrinsic storage capability. The best one can do with unwanted photovoltaic electricity is to feed it into the grid for use elsewhere. A solar powered thermal generating electricity system using high pressure steam can include steam storage that allows some electrical generation at night. This technique has already been tried.

Some techniques that can be used on a local scale will certainly be used as electricity generation morphs from centralised gigawatt facilities to local provision driven by wind, solar, or other 'renewable' energy sources. Another local technique is to store energy in pressurised air, for example contained in a depleted salt mine. A variant with much wider applicability, already shown to be successful at pilot plant level, is to store energy as liquefied gas, such as air. The liquid air is allowed to boil, pass through a turbine and drive an electrical generator. Liquefaction technology is well tried and tested and emissions from the plant are simply dry air.

Probably the most useful storage technology is one already in use on a substantial scale, namely pumped water storage. Readily available electricity is used to pump water uphill to a reservoir supplying a hydro-electric station. One could store 240 GW h worth of energy by pumping a few hundred million cubic metres of water up a head of a few hundred metres. There are few opportunities to do this on a very large scale with massive pumps and gigawatt transmission lines both for the incoming electricity and the outgoing hydro-power but on a smaller scale Scotland is very well supplied with existing hydro schemes and re-cycling water is technically possible with most of them. The environmental impact of installing pipes and pumps in areas of natural beauty is an issue but almost all of it could be done underground, as has already happened in many places with existing hydroelectric stations.

The point of this section is to raise the issue that smoothing the supply side needs to be part of the solution and can be done, but it will involve its own large-scale technological challenges. There are also gains to be made in smoothing the demand side. For example if electricity is priced cheaper on windy nights, then hundreds of thousands of people may opt to run their washing machines and tumble driers at night, top up-electrical storage heaters at night, etc. Given adequate incentives the demands for stored electricity can be reduced.

General considerations

The energy consumption in the UK averages about 5 KW per person. This includes the energy used by all the cars, lorries and vans on the motorways and other roads, the energy to run factories and services, the energy to heat and run all our houses, etc. Taking a population of 60 million, that's 300 GW. You can see the problem if most if this energy is to come from electrical generation. Our local (unsustainable) power station with a capacity of 2 GW is a large power station. The 4 biggest potential contributors to future power sources are solar, nuclear, "clean coal or gas", namely with post generation carbon-capture, and fusion power. Fusion power, if it does become a commercial possibility, is unlikely to be a major player before the last quarter of this century. (See the brief appendix). A feasible plan needs to use at least two of the remaining three options. Oil and natural gas will run out much sooner than coal. If you ditch nuclear power then it's hard to provide enough capacity without a substantial input of imported 'desert' solar energy, leaving the country a hostage to other people's fortune. The risk is greater than being a hostage to the price of a world-wide commodity such as coal or uranium. If you want wind power to contribute say 20% of the total then that's 60 GW of wind power at 2 MW km^{-2}, namely 30,000 km^2 of wind farms, one-and-a-half times the area of Wales. In spite of the earlier calculation of the power available if the whole of Scotland were covered with wind turbines, realistically the more likely development is that much of it would need to be off-shore.

There are a raft of other 'alternative' technologies as well as wind power, including tidal power, wave power, hydroelectricity, bio-fuels, burning rubbish, using gas from land-fill sites and geothermal power. They will all be needed but none on its own is likely to challenge the big three. To get parochial, Scotland has 1.5 GW of installed conventional hydroelectric power and in addition 700 MW of pumped storage hydroelectricity at two power stations (Cruachan and Foyers). This is an impressive base of renewable energy but even in comparatively wet Scotland, they don't work at capacity all the time. There's probably not much more to come from this source. There is much more energy potentially available offshore in tidal power (extracted from both changes in height of the tide and tidal flow) and wave power but decades of exploratory work have not yet come up with a viable and cost-effective means of tapping this. The potential is there but I'd be surprised if 2GW will be available at a commercial rate from this source in less than 2 decades time. However, it's clear that from now on the UK waters will be far more valuable as a source of energy than as a source of fish.

What every country needs is a flexible plan that spells out the target contributions to the total energy budget from various sources (most of which are hardly used at present), given the natural resources that the country has. This needs to be accompanied by a research, development, fabrication and investment programme on a suitable scale. Along with this there are big infra-structure implications associated with the electrification of transport, such as more railway traffic, an electrical charging and battery exchange infra-structure for transport, a hydrogen refill infra-structure (hydrogen power essentially being part of the electric economy, since hydrogen is produced by the electrolysis of water). There needs to be a big collateral investment in energy efficient buildings, a big re-think in the balance of public/private transport and, I would say, nothing short of a re-think in how our towns are planned and laid out in future.

It seems to me that at the moment that such a national energy plan as we have is weak. It is driven not by a long term view of what the country needs but by keeping face with international agreements that are themselves compromises. The easiest target for satisfying renewable energy obligations of this decade is to install renewable electrical energy supply. This is worthy but it seems to be happening at the expense of ignoring the need to include heating and transport in the integrated long-term solution. Electricity alone will not do it. Providing renewably sourced heating and transport is a task that will take longer to implement and require bigger changes to the status quo, particularly transport. Looking over the whole renewable energy scene there is comparatively little investment in new technology and what there is is patchy; there is comparatively little production capacity, poor public awareness of the issues and inadequate strategic initiatives of the kind that will be needed. Political and media discussions are seldom numerate.

People are very good at producing arguments, or at least rhetoric, for not making significant changes, not putting up wind farms, not building nuclear power stations or investing in carbon capture, postponing putting in place trans-national electric transmission lines capable of moving tens of GW, and so on. In Aberdeen we are very conscious of the decommissioning associated with dried up oil fields. In other parts of the country, grassed over slag heaps litter the landscape as relics of dried up coal mines. Big business doesn't seem to have fully grasped yet that if they are licensed to produce renewable power, then the source of the energy (wind, waves, tide, sunshine, etc.) isn't going to run out, unlike the case for licences to extract oil or coal. Billions will be needed to start up the new enterprises with little to show for it at first but the pay-back time stretches out indefinitely into the future. Politicians set renewable 'targets' but know full well that they personally aren't likely to be in power when the deadlines are looming. Without the necessary action, the targets are hollow. The political fall-back when the likes of emissions targets aren't met will be to force the population to use less energy by cutting supply. It is us, the public, who will pay the price of inaction so if you want something worth lobbying for then it's time to argue for an energy plan that makes sense and includes the investment necessary to make it happen.

Reference

If you would like to follow up the science of any of my topics above and look in more depth at similar numbers and see where they come from, do consult David J. C. MacKay "Sustainable Energy – without hot air" UIT Cambridge, 2008 ISBN 978-0-9544529-3-3. It is available free at http://www.withouthotair.com. I don't agree with absolutely all his conclusions but the book is an excellent repository of relevant science and good numbers.

Appendix on fusion power

Fusion power is hardly mentioned these days in future scenarios yet it could be a game-changing option in the long-term. The Sun generates its energy from fusion power. The energy mainly comes from fusing hydrogen and deuterium nuclei together to form helium. The energy generated by this process is substantial and how it happens is well understood. It needs very high temperatures (hundreds of millions of degrees), very high pressures and a method of containing the reaction. Gravity does the business in the Sun. It provides the weight that compresses the Sun's core to the temperature and pressure needed to create a plasma of hydrogen and deuterium and gravity provides a means of containing the reaction. There is also a path for the energy created to escape via diffusion, convection and radiation so the whole process is self-continuing at a fairly constant rate. It's all rather neat. So why can't we do this on Earth? The problem is that the gravity needed requires a mass comparable to that of the Sun. Jupiter is over 300 times more massive than the Earth, it is composed largely of hydrogen and deuterium and yet has no nuclear fusion at its centre. It hasn't got enough mass. The Sun is over 300 thousand times more massive than the Earth. Fusion works in the Sun. Between the mass of Jupiter and that of the Sun there is a start-up point where nuclear fusion using the Sun's mechanism begins to work. That point is certainly more than 10 times the mass of Jupiter but it's all academic really, as far as making a fusion reactor on Earth.

Maybe we can sustain and contain fusion power in a completely different way? Mankind has begun to get quite a good track record of doing things differently. To take a couple of examples, we can make machines that do arithmetic millions of times faster than any of nature's brains; we can generate useful electrical power far better than in any way we find done in our surroundings. There is a vast reservoir of deuterium in the sea. It is as good as a renewable resource. Can we generate energy by fusion in a different but yet controllable way? Once the principles were understood, it didn't take mankind long to generate fusion power. The hydrogen bomb of mid-20th century was the result, fortunately never used in anger because it was thousands of times more powerful than the atomic bombs that were dropped at the end of WWII. Containment is the key issue with fusion power. One of the first to ponder how this could be done was our former Nobel Prize winning Professor of Natural Philosophy (i.e. Physics), G P Thomson, though he had left Aberdeen by this time, the mid 1940s. The UK built one of the first machines designed to explore the containment issue. It was called 'Zeta' and began operation in 1957. Zeta continued through much of the 1960s in parallel with developments in several other countries. I saw it working on a visit to its home in the Culham Laboratory. It was an impressive sight. As a vast bank of capacitors was discharged to create a huge momentary current through the thick coils whose magnetic field would confine the hydrogen isotope plasma, the conductors pulsed outward before snapping back onto the torus within which the plasma had been created. The plasma, though, was always unstable. It became apparent to everyone that the technical problems in achieving controlled fusion were going to be very difficult to overcome.

Zeta morphed into JET (the Joint European Torus) which, after various developments, is still providing a platform for plasma confinement science. The evolution of this work is ITER (which began as the International Thermonuclear Experimental Reactor) a world-wide collaboration with hardware in the South of France at Cadarache. Mankind is investing tens of billions in this project. It is attempting the controlled fusion of tritium (a radioactive isotope of hydrogen) and deuterium, which is an energetically easier problem to solve than using ordinary hydrogen. ITER may produce more power than it consumes in a decade's time, a decade from the time of writing this, though its function is to develop the technology for fusion, not a fusion reactor. The demonstration fusion reactor that will hopefully come from ITER is known as DEMO and is already under development.

If ITER and its developments are eventually successful, and that's by no means a given, it seems clear to me that it will have taken mankind about a century from first starting out in this endeavour to come up with a workable fusion reactor design. It won't be small and it won't be simple. It's true that there are other possible routes to fusion than ITER. Some half a dozen other plasma confinement machines are in operation, smaller than ITER and working in significantly different ways but none of them seem likely to deliver any sooner. Mankind is trying to achieve in a building less than 100 m in size what nature can only achieve in a star at least 500 thousand km in diameter – the fusion of hydrogen isotopes into helium. It's a very tall order. Whatever the result of the various efforts to achieve controlled fusion power generation, the fuel may be plentiful and cheap but the technology will be hugely expensive. In short, the cheapest fusion power available in our lifetimes will be solar power. That said, we need to invest in fusion reactor technology, for it is the sole option for large power stations in the long-term future. Uranium and plutonium are scarce and dangerous elements, both toxic and radioactive; deuterium is plentiful and safe.

Appendix on unsustainable 'eco-friendly' power

The big environmental problem with burning coal, oil or natural gas is the carbon dioxide waste product that is vented into the atmosphere. What if burning could be done without producing carbon dioxide (or even worse, carbon monoxide)? Coal is a lost cause but both oil and natural gas contain lots of hydrogen. If the hydrogen only were to be combined with atmospheric oxygen, for example in a fuel cell or by burning, then the resulting waste product would be water. The additional water created would be trivial compared with the amount of naturally occurring water on Earth – I'm tempted to say 'a drop in the ocean'. There would be lots of 'waste' carbon but carbon has a good many uses and more uses could be found if a mountain of waste soot began to build up. What might be involved?

Making this line of thought work is largely a problem for the industrial chemists. Natural gas is the most promising raw material. It is mainly methane (CH_4). What is needed is the reaction $CH_4 \rightarrow C + 2H_2$. The 'C' is the soot and the 'H_2' the hydrogen gas. Methane molecules don't disintegrate of their own accord and some energy is required to decompose ('crack' is the word used in this context) the methane (76 kJ/mole). The hydrogen is then combined with atmospheric oxygen (O_2) in the reaction $2H_2 + O_2 = 2H_2O$ + energy out. You'll notice that an oxygen molecule needs to be split apart so that its separate halves go into different water molecules but that does not take much energy. The net result is that a considerable amount of energy is available from hydrogen, the exact amount depending on such things as whether the water is created as a liquid or as a vapour. If as a liquid then 286 kJ/mole is available from this reaction and since cracking one mole of methane creates two moles of hydrogen then the energetic expense of cracking methane to make hydrogen is very well worth it.

Writing down chemical symbols suggests what might be possible but doesn't give much of a clue as to how to do it in practice. If other chemicals are also involved in cracking methane then other reactions will occur that may use more energy or need extra raw materials or may create corrosive by products, and so on. What is needed is a 'catalyst' that is not used up in the process and not contaminated by the soot produced. This is such a big ask that at the time of writing (2016) large-scale cracking of methane has not been developed. People are trying, though.

I must admit that when I wrote the paragraphs above I was thinking in basic industrial chemical terms. Looking out of the window at a tree, though, makes me think again. The leaves of a tree take in CO_2 (from the atmosphere), H_2O (from the ground) and sunlight. The end process is wood and O_2. Wood is immensely useful to mankind and oxygen is life-giving. Maybe the answer to cracking methane will be biochemical: vast enclosed lakes of bacteria through which CH_4 bubbles in and H_2 bubbles out. The carbon appears not as soot but as a useful carbon-based compound. Some energy is required, as we have seen, that may be provided by sunlight or created from a fraction of the hydrogen produced. Well, anyone can write words but making such an idea feasible could take many decades.

Oil, being liquid, is made of larger molecules than methane. Petrol, for example, is high in octane, C_8H_{18}. Crude oil is not entirely hydrocarbons either but some of the longer molecules are routinely cracked into shorter ones so the concept of cracking both natural gas and oil to obtain hydrogen and carbon is theoretically possible. Doing it industrially is another matter. If the problems can be solved, then the Earth's still huge reserves of natural gas and crude oil could be used as fuel without producing any CO_2. That would be a major gain for society at large. Enough could be done to make a difference but unfortunately the sheer scale of operation needed to convert all natural gas and fuel oil is likely to make it just a dream. It's not a 'renewable energy' option either but if the dream materialises it could provide decades of breathing space while the world converted to renewables in the coming century, which it will have to do as oil and natural gas reserves run out. Watch out for this development.

JSR