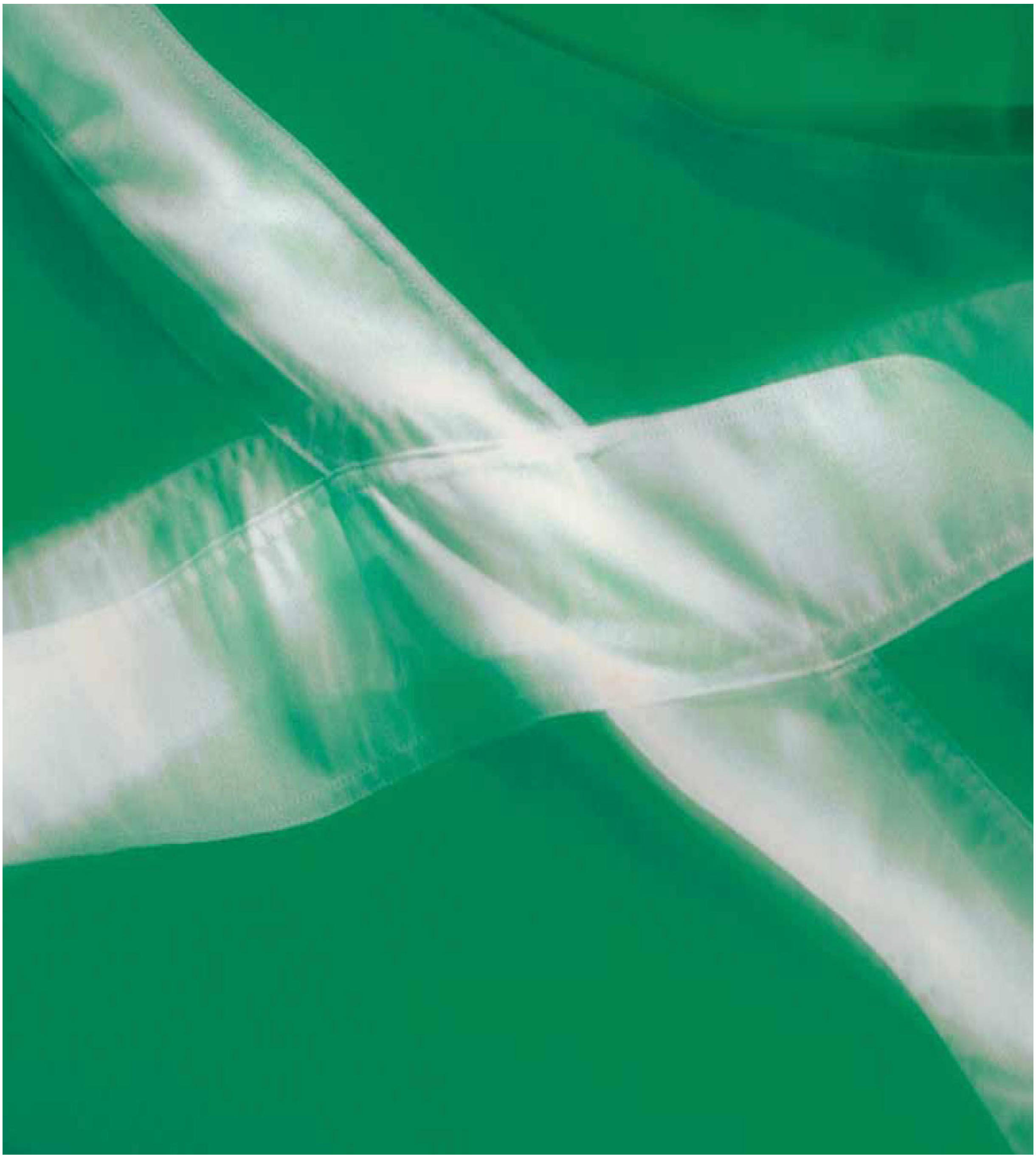
Scottish Energy Review



Scotland’s opportunity – Scotland’s challenge

Stephen Salter, Kerr MacGregor, Clifford Jones

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Foreword

I would like to thank Professor Stephen Salter and his team for the excellent work they have undertaken to produce this Scottish Energy Review. It is a comprehensive and encouraging study of Scotland's current and future energy needs and generation potential. Clearly, we have what it takes to retain our current energy independence, and perhaps more importantly, to remain a major energy exporter. With the right approach the lights certainly won't be going out!

This report, therefore, is about more than the generation and distribution of energy in Scotland. It is about the creation of low cost, clean and reliable energy sources; it is about high-quality jobs that will come from a growing expertise in renewable technologies; and it is about the export opportunities if Scotland does become a world leader in green and low carbon technology.

The review team has identified Scotland's energy opportunity, and also Scotland's energy challenge. Do we have the political will to turn opportunity into reality? Today Scotland has the energy potential, but we lack the political power – much of energy policy remains with a UK government that seems determined to press ahead with new nuclear power stations, and new nuclear dumps. It views our oil and gas reserves as a cash cow for today rather than as a catalyst for the development of new offshore technologies tomorrow; and has disadvantaged Scottish based electricity generation through unfair and economically illiterate transmission charges.

The UK government will soon be publishing its own energy review. It will be interesting to compare the findings in relation to nuclear power generation. Professor Salter and his colleagues highlight some of the hidden costs of nuclear power, including the substantial greenhouse gas emissions, now and in the future. If we had no other option, then we would be forced into taking the risk with nuclear, but clearly we have an abundance of opportunity and a range of workable technologies more deserving of investment. Scotland has no need to step back into the nuclear age. I hope this report will be read and absorbed by ministers in London and Edinburgh. The challenge it presents is as much to them as it is to the people of Scotland. They and we have a big choice to make.

Next year I intend leading a Scottish government. As First Minister, I will prioritise energy policy. I will block the building of new nuclear power stations in Scotland, I will make sure Scotland does not become Britain's nuclear dustbin and I will remove the obstacles to Scotland fulfilling its potential as the European powerhouse of low carbon energy production.

In the first 100 days of an SNP government, the inaugural £5 million Saltire Prize – a Scottish Nobel Prize to reward innovation and invention – will be launched with a focus on developments in offshore wind, wave and tidal generation. I want Scotland to be at the forefront of these new technologies and able to offer world-beating solutions. That is why an SNP government will, as a focus for our relations with EU partners, also press for Scotland to become the headquarters for a Europe-wide green energy research centre, building on the expertise that exists in our current offshore energy sector and the huge renewable energy potential around our shores.

Among the most convincing arguments presented in the review is the need to focus more on localised, community and small-scale renewable projects. The SNP is now looking at specific policy proposals in this area and these will be included in our manifesto for the Scottish elections in May 2007. Similarly, we need to address the many infrastructure and transmission issues, including proposals for greater use of undersea and underground cabling. Meeting this particular challenge will be an early focus for ministers. This report does not in itself become SNP policy, however many of its findings will be taken into the heart of an SNP led government. We will seize the opportunity presented, and in doing so begin to build the better future our nation deserves.

Alex Salmond MP
Leader of the Scottish National Party

EXECUTIVE SUMMARY

The Starting Point

Scotland is at present a major EXPORTER of energy and could be one into the infinite future when less fortunate other countries may be shivering in the dark.

We export more than ten times the oil that we use. We export about six times more gas than we use. We produce almost twice as much coal as we use. We export almost 24% more electricity than we need to meet Scottish demand.

We are therefore not in the same position as the rest of the UK. Scotland does face looming problems because of delays in renewing conventional plant and researching renewable replacements. However, it is not being totally paranoid to ask where these delays arose.

The reporting team agreed to focus on five questions:

- How long will Scotland's coal, oil and gas last?
- What can supplement oil and gas in the short term and replace them in the longer term?
- How can variable renewables be matched to the pattern of demand?
- How can we reduce the visual impact of on-shore wind and power lines?
- Should we build new nuclear power stations?

Where possible we have included links to websites so anyone can return to our sources.

Scottish Energy Use

For the latest available year the primary energy input to Scotland was 240TWh of which 164TWh ended up doing useful things for consumers. We can expect that these figures will rise at about 1% a year.

The 67.14TWh of energy wasted by thermal generators is greater than the 56.05TWh used for domestic purposes, which is itself greater than any other category.

The 2004 figure for electricity generation in Scotland was 50.9 TWh while the consumption was only 35.8TWh. Use by the generators themselves was 4TWh, Transmission losses were 2.5 TWh and export 8.6TWh. Nuclear output was 15.86 TWh which is 31.2% of total Scottish electricity and 6.6% of all Scottish energy.

Coal, Oil and Gas

There are vast proven reserves of coal remaining. A renaissance of the coal industry is possible if there is a move to coal-derived liquid fuels, to manufactured gas or to solid coal coupled with carbon sequestration. The sequestration of CO_2 in depleted oil fields is already done in Algeria and Norway. Advice from independent geologists is that it is promising for Scotland.

It is possible now to carry out underground gasification of coal using steam to produce a mixture of hydrogen and carbon monoxide like old town gas. Coal seams below the Firth of Forth would be suitable. It might also be possible to use electrolytic hydrogen supplied directly from offshore wind turbines to produce methane, which could go directly to all present gas customers and retain the value of the gas distribution network and all our central heating systems.

Scotland has plenty of oil and gas for its own requirements for many years to come. There may be lots more gas in the form of methane hydrates if we can find ways of releasing it safely from the seabed.

Hydro

Large-scale hydro was one of the best energy investments Scotland has ever made. Not only is it the cheapest electricity, it provides a unique flexibility and storage in the operation of the grid. The annual output of the existing hydro plant is about 2.9TWh.

There is opportunity for more hydro-power. Conventional new large hydro rated at 780MW can deliver a further 3.5TWh. New small hydro rated at 280MW can deliver 1.2TWh.

There is 700MW of pumped storage with a possible 1200MW more available and much more if single basin sites can be accepted, using sea-water.

Biomass

Biomass can be used to provide heat and generate electricity, but conversion to liquid fuels such as methanol would be particularly valuable for vehicles. At least 20% of our transport fuels, bio-diesel and bio-ethanol, could come from Scottish-grown bio-sources and farm wastes. This would be an annual 4.6TWh.

There is a potential to have at least 450MW electrical capacity in combined heat-and-power plants. Assuming an annual plant capacity factor of 80%, that gives an annual output of 4TWh of electricity and 8TWh of heat. It would be reasonable to assume that there is at least another 8TWh of heat from heat-only biomass plants, from domestic-scale stoves and boilers to industrial scale boilers.

Wind

Without new types of energy storage in turbines there is an upper limit of about 20% to the amount of wind that can be accepted in an electrical network without causing instability. This suggests the need for a cap on onshore wind projects in favour of offshore ones. Problems of variability would be reduced if some of the output were used for the electrolytic production of hydrogen for use in synthetic liquid fuels.

Onshore wind installations in Scotland have increased rapidly but are now being slowed by opposition to some locations and a shortage of connections. We have been told by Scottish Power that no further grid connections can be accepted before 2015. We believe there should be a greater community focus to onshore wind developments, with small, local schemes providing a clear community benefit.

Onshore wind is choking the development of younger renewables and much of the subsidy is going overseas. This is unfortunate because variable renewables need diversity as a substitute for absolute firmness. There should be different flavours of renewable energy certificate to help the fledgling technologies and significant support made available for offshore wind projects, such as the Beatrice project in the Moray Firth.

Waves

Close-packed, deep-water, wave-energy devices with good exposure to the Atlantic will have maximum power ratings of 50 to 100 kilowatts per metre, and so the 400 kilometres of the Scottish Atlantic sea front could contribute 20 to 40 GW peak with winter capacity factors of 40%.

Edinburgh-based company Ocean Power Delivery has built up a brilliant team of engineers and has secured its first export orders to Portugal. We need ways to make Scotland as financially attractive as Portugal for this new enterprise.

Marine currents

Previous assessments of the energy potential of the Pentland Firth may have underestimated the generation capacity by ignoring bottom friction and restricting depth. If turbines can work in the full depth it is our estimate that tidal energy in the Pentland Firth might be converted to 10 to 20 GW of synchronous electricity. This would be more than twice the peak Scottish electrical demand. If we were ever to use all of it there would be a need for an energy-hungry chemical process such as the manufacture of a synthetic liquid fuel, or very much larger cables south. A sea-bed cable from the Pentland Firth to Peterhead, perhaps carrying direct current, would be a useful start.

Solar

Scotland is a cold country and a high proportion, about 50%, of our energy demand is for heat for which solar is particularly suitable. Research concludes that Scotland has one of the BEST climates in Europe for using solar heat in buildings. A total annual figure of 10TWh of solar heat is possible.

Energy efficiency

We estimate that energy demand in Scottish buildings could be reduced by at least 30%. That is effectively an annual energy contribution of 5TWh of electricity and 8TWh of heat. A combination of techniques should lead to a reduction in heat and electricity demand in industry in Scotland of at least 25%. This is equivalent to an annual electricity contribution of 4TWh and a heat contribution of 7TWh. We also believe there is a strong case for the inclusion of micro-renewables as a requirement in all new building schemes.

There is also potential to reduce Scotland's transport energy requirement by at least 25% over the next 30 years. With present annual transport energy needs of 32TWh, that reduction comes to 8TWh.

Matching renewables with demand

A 6 GW mix of wind, wave and tidal could ***on average*** meet at least 40% of the 2020 Scottish demand. It would exceed the target for 45% of the time. The 6 GW mix is very much less than the total installation possible if all viable sites were used.

Visual impact

Many places in Scotland are so beautiful that we must pay for underground cabling.

Nuclear

The case for new nuclear generation capacity in Scotland has not been made. If there is to be an extension of the life of current nuclear stations this can only be an option of last resort, and only for so long as is required to deliver alternative capacity.

There would be a 4.07 pence per kilowatt hour clean up cost for existing nuclear power if all accounts were squared up today. Accumulated research costs might add a further 3 pence per kilowatt hour.

The CO2 produced with present ore grades is about 80 grams per kilowatt hour ignoring dismantling and 140 gm per kilowatt hour if that is included. At ore grades below about 300 parts per million, the energy for fuel production shoots up and at 100 parts per million (or 0.01%) the CO2 from the whole nuclear process is equal to the amount from gas turbine generators producing the same energy.

If uranium use continues at its present level the CO2 equality point is about 50 years away but if there is a dash for nuclear reactors it will be much sooner, within the lifetime of plant planned now.

Nuclear technology releases other greenhouse gases including chlorine, fluorine, organic compounds containing them and compounds they can form when released into the atmosphere. These can be ten thousand times more powerful as greenhouses gases than CO2.

Chairman's Personal Statement

Anyone can have a go at writing an Energy Review. Since the beginning of this century it seems that nearly everybody has. The number of people writing reviews, scoping studies, briefings, reports, policy advice, presentations, position statements, predictions and projections about energy and climate change far exceeds the number of people in laboratories and workshops who are actually designing and making things to solve our energy problems.

I was reluctant to interrupt my design work to accept an invitation from the Scottish National Party to write yet another review. But the study of previous ones revealed a fascinating conflict of data, with some diametrically opposed conclusions.

There was widespread regurgitation of previous reports coupled with a reluctance of some authors to include references. Often one could predict the conclusions by identifying the source of the funding or names of the review panel. One beautifully produced report carried the statement:

'Energy is vital to a modern economy. We need energy to heat and light our homes.'

While this is indisputable it is also as uninformative as the statement made by a football commentator that 'the team that scores the most goals wins the game.'

Many aspects of the energy problem had been covered and re-covered so many times that it was going to be difficult to think of anything original to say. However, few of the documents had a specifically Scottish dimension and few of the authors had been at the sharp end of energy research. I hope that we have been able provide decision makers with some new insights.

Useful evidence was received from many people and organizations. I wish to record my thanks to all of them. The contributions can be seen at

http://www.snp.org/policy/energyreview

The evidence showed a general consensus on the need to accelerate developments in energy-efficiency and renewable sources, with some concern about excessive on-shore wind and power lines in sensitive areas. A few replies stressed the need for new nuclear plant, mainly on the grounds of reliable power and low emissions of carbon dioxide, but the clear majority expressed concern about it. Accordingly the carbon-from-nuclear question has been given special attention.

Some readers may find appendix A helpful to understand technical terms.

Stephen Salter

1. Visual summary

While the Department of Trade and Industry publish excellent and comprehensive statistics on UK energy supply and consumption, splitting data into many categories and identifying releases of CO2, [1] it is much harder to find separate numbers for Scotland.

However, this daunting task has been attempted by the Scottish Executive [2]. The work was done for them by AEA technology who claimed that 40% of Scottish electricity was nuclear generated with 0.00 kg of carbon per kWh, both of which can be disputed.

Close reading shows some fascinating results. For example, although road use in Scotland has been rising, it seemed that the use of transport fuel was falling faster than improvements in fuel economy could explain. It turned out that petrol sales in Scottish supermarkets were reported as coming from the head office of the supermarket chains in England. How do you count fuel used by tourists or the transmission losses of different renewable sources sent to different consumers? What fraction of the nuclear output is exported? What happens if some people use part of their own output?

By far the best way to see what is going on is by the use of a Sankey diagram, such as the excellent one below from the Scottish Executive study [2].

Raw inputs from many sources come in on the left, get converted with some losses and are used for different functions (which may have blurred boundaries) on the right of the diagram. For example, Scottish oil refineries need quite a lot of electricity (10.6TWh) to produce oil, some of which is used to make electricity. The widths of bands are drawn to scale.

Things to note are that the 67.14TWh of energy wasted by thermal generators is greater than the 56.05TWh used for domestic purposes, which is itself greater than any of the other categories. Domestic coal is tiny compared with domestic gas, which will soon run short.

The diagram does not show 1090TWh of oil and 400TWh of gas from the Scottish sector of the North Sea which went straight through Scotland and which would have been much wider than the entire diagram. A month-by-month video made from morphing these diagrams would be compulsive viewing.

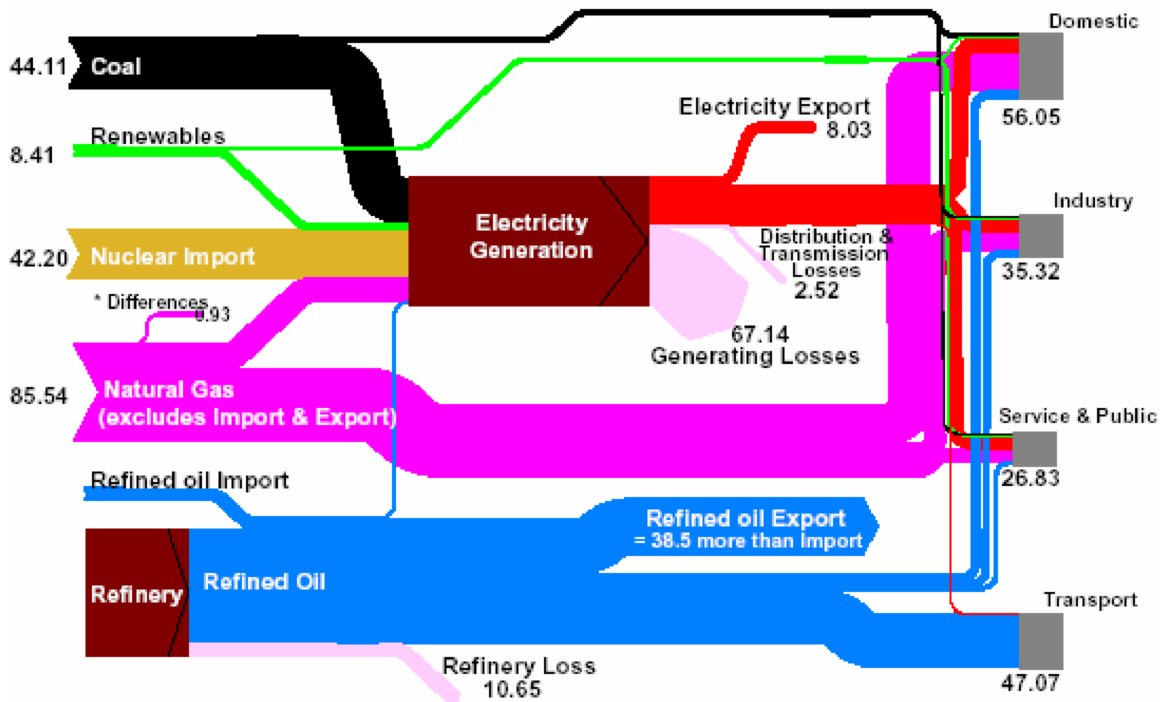

Figure 1. A Sankey diagram for Scottish Energy flows, courtesy of the Scottish Executive [2].

Even though one very brave MEP, Gordon Adams, tried to make it illegal to burn gas for generating base-load electricity in Europe, the biggest recent change has been the large swing from coal to gas. This allowed politicians to claim wonderful carbon reductions in addition to those caused by exporting all our heavy industry to Korea and China. Sadly these are once-only tricks, and the next carbon reductions will be more painful.

Many people find it hard to understand numbers from different places using different units covering different periods. Rather than plagiarise this vast amount of information, the review committee rationed itself to the minimum critical numbers of what is happening now and what could happen in the future. We skipped all data based on weight of coal and barrels of oil. Despite a preference for Petajoules or watts and load factors, we converted everything to more widely used Terawatt hours per year, which keeps figures below the imaginable 1000.

For the latest available year of 2002, the primary input to Scotland was 240TWh of which 164TWh ended up doing useful things for consumers. We can expect that these figures will rise at about 1% a year. The 2004 figure for electricity generation was 50.9TWh while the Scottish electricity consumption was only 35.8TWh, the difference being exports, 8.6TWh transmission losses 2.5TWh and in house use by the generators themselves.

Our ‘old’ hydro produces about 4TWh depending on levels of rainfall. Biomass could deliver about 25TWh which would be increased in value if used with hydrogen for carbon-neutral liquid fuels The rate of installation of onshore wind is now so fast that last year’s numbers for generation are unhelpful. By the start of 2006 there was 560MW completed and as much again being built. With a capacity factor of 30% one GW would produce about 2.6TWh a year. About 5.5GW are being planned but this will be close to the onshore limit and some might have to be in less favourable sites.

If we can get 6 GW to produce at 25% capacity factor we will have 13TWh out of the total requirement of 164TWh a year.

A later section of this report suggests that estimates for the output of tidal plant in the Pentland Firth are too low because the effects of bottom friction and the use of turbines in the full channel depth have not been considered. If it is safe to extrapolate friction measurements from the Menai Strait and find a way to live with shipping, we may be able to get about **40TWh from Scottish marine currents, bringing the total renewable electrical energy to more than electrical consumption.**

If we can make them and their cable connections reliable, advanced designs of close-packed wave energy plant using the entire Scottish Hebridean coastline could produce about 80TWh. Not all energy uses can be satisfied by electricity and these numbers highlight the importance of developing commercially feasible ways to convert electrical energy to liquid fuels. The diagram below shows an estimate in annual TWh of what we use now and what we may be able to get.

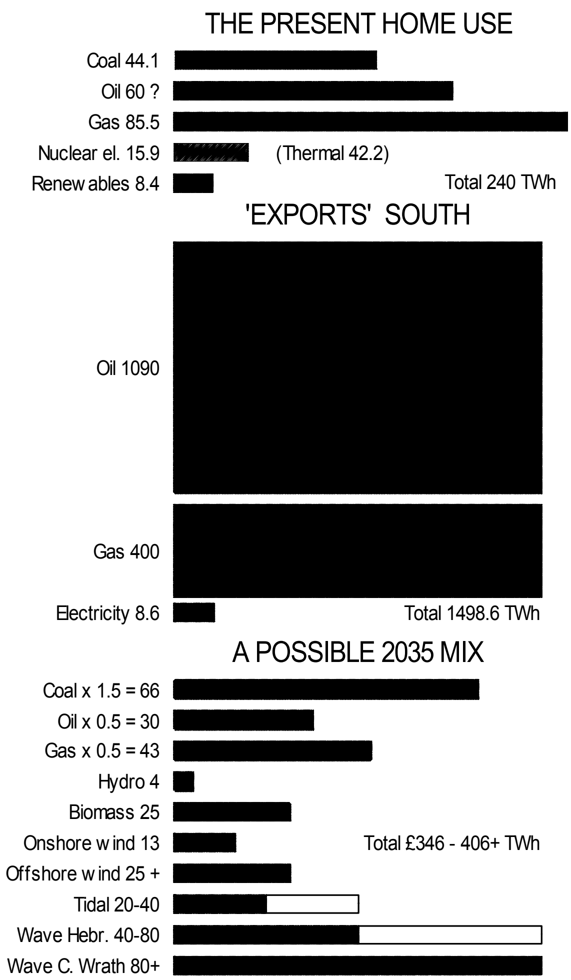

Figure 2. Data from reference [2] and the future.

2. Oil, gas and coal – how long will it last?

There is no straightforward answer. Inevitably much will depend on how thriftily Scotland can control existing reserves and on how effectively we develop new means of energy production. But how big are these reserves now?

Coal

The UK had an annual production of 300 million tonnes of hard coal eighty years ago. This was three-quarters of the US production at that time. Serious decline began in the 1960s and by 1999 the output was a mere 37 million tonnes per year. There is now limited activity in deep mining and in open-cast mining. Abandoned pits have been allowed to flood, destroying a great deal of capital equipment such as hydraulic pumps and roof props.

People with the skill and courage needed to work underground have been badly treated. Even so, there are vast proven reserves of coal remaining. A renaissance of the coal industry is not impossible if there is a move to coal-derived liquid fuels, to manufactured gas, or to solid coal coupled with carbon sequestration.

So for coal, whether this will happen and if so *when* it will happen is the key question, not how long the reserves will last.

The sequestration of CO2 is already done in Algeria and Norway. Advice from independent geologists is that it is promising for Scotland. This would make coal burning acceptable and also allow the extraction of more oil. A Scottish based company, Mitsui Babcock, are world leaders in CO2 sequestration and a carbon capture scheme is under consideration at Peterhead.

It is possible now to carry out underground gasification of coal using steam to produce a mixture of hydrogen and carbon monoxide like old town gas. This would not need people below ground. Coal seams below the Firth of Forth would be suitable. It might also be possible to use electrolytic hydrogen supplied directly from offshore wind turbines placed in a line past the grid connection at Cockenzie. Underwater gasification would avoid the subsidence problems of underground mining.

Carbon Capture - Peterhead

On June 30 2005, BP and their partners and Scottish and Southern announced that they were to build in Peterhead the world's first industrial scale project to generate carbon-free electricity from hydrogen.

The project will convert natural gas to hydrogen and carbon dioxide, then use hydrogen gas as fuel for a 500 MW power station and export the CO2 to a North Sea oil reservoir for increased oil recovery and ultimate storage.

The feasibility of the scheme will be determined by late 2006 and should be up and running by 2009 at a cost of £600m.

Oil

The widely used terms 'oil depletion' and 'peak oil' are not really clear. The maximum point of a bell-shaped plot of the production of an oil field against time is frequently taken to signify that the field is 'becoming depleted'. This is not necessarily so.

The decreased output from the wells might be due simply to a drop in the pressure of gas within the field. This was recognised in the US in the 1920s when production was from onshore fields only. A well producing at a higher gas-to-oil ratio than that prescribed as a maximum by State Law would be deemed a threat to the entire field by reason of its potential to lower the internal pressure, and would be compulsorily closed down.

In the longer term it became common for pressure drop at an onshore field to be compensated for by the use of beam pumps known as 'nodding donkeys'. At offshore fields pressure drop can be compensated for by injection of sea water, re-injection of associated gas or, increasingly frequently, injection of carbon dioxide as part of a sequestration process.

The Forties field in the North Sea, as an example, produced half a million barrels per day in 1978. This had dropped to 43,000 barrels per day by 2003, the year in which it was sold by BP to the Houston-based Apache company. A plot of the productivity of the field up to the change of ownership looks dismal: the negative slope following the BP maximum is very steep indeed. But by early 2006, production from the Forties field had risen from the BP low to about 81,000 barrels per day.

This improvement has been achieved partly through sea water injection. Under-balanced drilling (reducing pressure round the drill to stop clogging the wall of the bore) and extended-reach drilling (going out sideways) have also been applied, notably at the Clair field and the Alba field respectively, to obtain previously inaccessible oil.

The Beatrice field in the Moray Firth was believed to be no longer economically workable in 1996. But the new technique of biological oil stimulation was applied, with the result that the field is still producing ten years later. The relevance of the 'depletion' issue is that a plot of production against time is strongly dependent on production conditions and quite possibly has no fundamental meaning. Moreover, if the performance of an oil field is plotted with *revenue* earned from the oil instead of quantity of oil as the vertical co-ordinate the maximum might well move. This is the case with the Forties field: it is peaking ***now*** in revenue terms having peaked in quantity of oil terms twenty or more years ago. The tragedy is that so much oil was produced when prices were low and that so much of the revenue went to pay unemployment benefits to people thrown out of useful jobs because oil raised the value of the pound. Scotland cannot insulate itself from world market prices except by developing competitive rival technologies. Both industry and government may wish to examine current exploitation rates with a view to increasing long-term revenue.

In discussions of 'peak oil' the 'Hubbert Peak' hypothesis [3] from fifty years ago is frequently invoked. According to this, for any finite resource such as crude oil, the point of maximum production corresponds to 50% depletion. If this is so, it follows that 50% of the entire crude oil reserves that the world has been used up only about a century after significant crude oil use began. There are however counter views on the question of the depletion of oil reserves. The US Geological Survey expects that in that country the 'peak' will not come before the mid 2030s. [4]

Gas

Much of the natural gas produced worldwide is 'associated gas', meaning that it is produced along with oil. This is typically 30 to 300 cubic metres of gas for each tonne of oil. The world's largest oil field is the Ghawar field in Saudi Arabia, producing 5 million barrels of crude oil per day. The associated gas from this field accounts for a third of the entire natural gas reserves of Saudi Arabia. Large amounts of associated gas accompany the oil obtained from the fields off the Scottish coast. At the start of the exploitation of the North Sea it was regarded as a nuisance and simply flared off, but this was made illegal in 1976 [5]. Flaring is still being done by Shell in Nigeria and contributes more greenhouse gas than all other sources in sub-Saharan Africa [6] [7].

The conventional natural gas reserves of the world are, however, known to be greatly exceeded by the quantities of methane obtainable from natural gas hydrate. Reserves are well distributed round the world, with large volumes locked into permafrost. This is a mixture of water and methane which forms a solid heavier than sea water, known as a clathrate. It is produced when conditions of temperature and pressure fall on the low-temperature / high-pressure side of a line on a graph. Methane is formed by the decomposition of biological matter in the absence of oxygen and sulphur [8] and can by synthesised [9]. The methane can be released from the hydrate form by raising temperature or reducing pressure. The energy needed to do this is about 10% of the energy which could be later released from the methane. It would be essential to prevent methane leaks to the atmosphere, which would be 23 times worse than CO2 as a greenhouse gas.

Summary

- Scotland has plenty of coal. We need to find ways of burning it cleanly.
- Scotland has plenty of oil and gas for its own requirements for many years to come.
- There may be lots more gas in the form of methane hydrates if we can find ways of releasing it safely from the sea bed.

3. Future energy options

What can supplement oil and gas in the short term and replace them in the longer term?

Large Hydro

At present Scotland has approximately 1300MW of conventional hydro installed capacity, mostly in the Highlands. Much of it was built in the 1950s by the nationalised North of Scotland Hydro-board and was aimed not only at generating electricity but at improving the economic prospects of the Highlands.

The Hydro-board had a unique 'social clause' in its constitution. The programme was driven by the then secretary of State for Scotland Tom Johnston, helped by Winston Churchill, and it stopped at Churchill's death. Most of the plant was based on large dams, with storage, and was to be operated at a relatively low plant capacity-factor in conjunction with coal-fired plants. (The capacity factor of a generator is the amount of energy it produces over some long period divided by the amount it would have produced if it ran at full power all that time). The two big pumped storage schemes (Foyers and Cruachan) were built to work in conjunction with nuclear power. As with present wind farm proposals, there was much opposition from land-owners and environmental organisations. However, in retrospect hydro was one of the best energy investments Scotland has ever made. Not only is it the cheapest electricity, it provides a unique flexibility and storage in the operation of the grid. The annual output of existing hydro is approximately 2.9TWh, a capacity-factor of 28%.

It is often claimed that there is practically no more big hydro capacity left to exploit in Scotland. However, a paper published in 1979 by DG Birkett [10] claimed that there is additional large-scale hydro potential of 780MW installed capacity, with an annual output of 3.5TWh. His paper listed the possible sites. He was a professional engineer employed by the Hydro-board. We believe he is credible. It is noteworthy that Scottish and Southern, the privatised successors to the Hydro-board, are now building a new 100MW hydro scheme at Glen Doe near Loch Ness.

We may also have to consider more pumped storage to work alongside our wind resources. Scotland already has 300MW of pumped storage at Foyers, 440MW at Cruachan and the possibility of a larger one, 1200MW, at Craigroyston proposed by NSHEB for Loch Lomond almost 20 years ago. It was abandoned due to opposition from environmental organisations but the physical capacity still exists.

The storage time of present facilities fits well with the four daily deliveries of tidal current energy but sadly not with the weekly period of neap and spring tides. There are losses which give a round-trip efficiency of about 75%, depending on transmission distances. All the present sites use the movement of fresh water between two basins. Other sites for even larger pumped storage schemes could be made available with single basins working to the sea if we can accept a risk of salt water seepage.

Small Hydro

The best source for estimating this is a UK government paper [11]. It concluded that Scotland has almost 90% of the UK's potential for small hydro power defined as between 25kW and 5MW, with a Scottish installed capacity of 286MW and an annual output of 1.2TWh.

Summary

- Conventional new large hydro rated at 780MW can deliver 3.5TWh
- New small hydro rated at 280MW can deliver 1.2TWh
- There is 700MW of pumped storage, a possible 1200MW more and very much more if some sea water leakage from single basins can be accepted.

Biomass

Biomass includes all energy derived from biological matter such as trees, bushes and crops. It can be produced as solid wood, liquid oil from rape seeds or gas such as methane from the digestion of animal waste. It can be used to provide heat and generate electricity, but conversion to liquid fuels such as methanol [9] would be particularly valuable for vehicles. The calorific value is low so we should avoid moving it long distances.

Methanol is less toxic than petrol and can be used in spark-ignition engines with minor changes to seals in the fuel supply lines. It is widely used for drag-strip racing and is compulsory for the Indianapolis 500. It can be used as a feedstock for the plastics industry and be converted to dimethyl-ether, which can replace natural gas or run a Diesel engine with modified fuel injectors. At present methanol is made from natural gas.

In Scotland, the biggest present source of biomass is probably timber for producing logs, pellets or chips to burn for heat, electricity or both in the form of combined heat and power. The low calorific value means that it is best to use it in small units close to where it grew rather than hauling it long distances to large central plants. We have much forestry in Scotland and the annual crop is increasing. At present, much of it goes to waste. Even worse, the decay of unused material can produce methane with much more greenhouse damage than if it burned - so burning can be much better than merely being carbon neutral.

Other countries such as Austria or Finland have developed significant industries based on wood. Under the stimulus of German occupation which blocked coal imports, Norway developed extremely efficient and conveniently operated wood-burning stoves. Buccleuch BioEnergy is pushing commercial developments in Scotland.

The best source for assessing biomass potential in Scotland is the recently published paper from the Scottish Executive [12] by the Forum for Renewable Energy Development in Scotland.

The authors considered only electricity generation from wood and concluded that there is a potential to have at least 450MW electrical capacity in combined heat-and-power plants. At 70% efficiency, that would yield an additional 900MW of heat. Assuming an annual plant capacity factor of 80%, that gives an annual output of 4TWh of electricity and 8TWh of heat.

The report did not consider heat-only biomass plants, but it would be reasonable to assume that there is at least another 8TWh of heat from that technology, from domestic-scale stoves and boilers to industrial-scale boilers.

We have not been able to trace any credible estimates of liquid or gaseous fuels from bio-mass in Scotland. However, it would seem reasonable to assume that at least 20% of our transport fuels, bio-diesel and bio-ethanol, could come from Scottish-grown bio-sources and farm wastes, better in the long term than using edible sources such as maize and sugar which may be more economical now. This would be an annual 4.6TWh. The production of larger quantities of liquid fuel can be done with surplus electrical energy from variable renewables and any carbon source including coal and household rubbish. Germany recycles a much larger fraction of waste than Scotland. It would take little extra effort to separate discarded plastics, a possible feed stock for future synthetic liquid fuel, from all other domestic rubbish and leave our descendants neatly sorted rather than homogenised piles of landfill.

Summary

Our best estimates for contribution from bio fuels to Scotland's energy needs are:

- Electricity generation of 450MW delivering 4TWh
- Heat rated at 286MW delivering16TWh
- Transport fuels rated at 1000MW delivering 4.6TWh and very much more if used with electrolytic hydrogen.

Wind

Exploitation of wind predates coal by hundreds of years. It was used for draining much of the Netherlands and the fens in East Anglia. There were six million wind turbines pumping water in the United States in 1900. Despite this long record it was dismissed with contempt at the start of the 1973 energy 'crisis' on grounds of low power density - typically about 500 watts per square metre of swept area of disk. This figure was compared with very much higher values at the core of the fast-breeder reactor, as if high densities were desirable. In fact they were an almost insoluble problem in heat transfer and killed fast reactors. If power density figures are calculated with reference to the area of the tower-base of a wind turbine and the area inside the security perimeter fence of a nuclear power station, the comparison changes. From the viewpoint of many land users, these would be more useful reference dimensions.

The science of aerodynamics benefited from enormous leaps forward in two world wars with abundant data on aerofoils pouring out of hundreds of wind tunnels. There was also the big advantage, not shared by wave energy, that because of low connection costs very small turbines were useful and there was a continuous range of scales starting with something an amateur could build in the garage. Large aircraft manufacturers thought it would be easy to jump straight into large wind turbine construction and found it was much harder than it looked. The reliability of the first machines installed in America was appalling, giving capacity factors below 5%, partly because of some strange tax rules which allowed profits to be made even from machines which could not rotate. The leader of the American programme said that wind turbines were fatigue-testing machines with a by-product of electricity.

By contrast the support given by the Danish Governments to their home market resulted in a steady series of size increases. Typical reliability has risen to over 98%. This cost several billion dollars and took 20 years. The key engineering solutions involved understanding the fatigue stresses and producing components with fewer stress concentration points. Turbine costs have steadily decreased. Denmark has also managed to plan the sites of a large number of turbines with very little antagonism. Most of the remaining technical problems concern gear boxes and power electronics. The simplest, cheapest and most rugged generator for a wind turbine is an induction machine driven slightly faster than its synchronous speed. To some extent this is parasitic on the rest of the network because of the phase relationship of voltage and current needed for magnetic excitation. This means that with induction generators there is an upper limit of about 20% to the amount of wind that can be accepted in an electrical network without causing instability. **There may be a need for a cap on onshore wind projects, with the focus of industrial scale wind farms being moved offshore.**

With more complex electronics and double-wound induction machines the limit can be raised. With hydraulics and some fast-response energy storage to ride out network transients, the stability limit can be removed entirely and synchronous machines can be driven by rotors at the best tip-speed ratio. Wind turbine makers would all like to be the *second* company to take this step!

Problems of variability of any renewable source would be reduced if some adjustable fraction of the output was used for the electrolytic production of hydrogen, now produced from natural gas or coal. The Norsk Hydro alkaline process achieves an efficiency of 80% and is better at low power densities [13]. Moreover the shape of the converter cells is strongly reminiscent of a wind turbine tower.

Onshore wind installations in Scotland have increased rapidly but are now being slowed by opposition to some locations and a shortage of connections. We have been told by Scottish Power that no further grid connections can be accepted before 2015. **We also suggest a greater community focus to onshore wind developments, so that schemes provide a clear community benefit.**

There should be less opposition to offshore wind. This has higher wind velocities and lower turbulence but suffers from much more expensive initial assembly and later access for maintenance. A desirable goal would be to reduce the weight of machinery at the tower top to the point where complete turbines could be built and tested on land and then moved offshore.

This is not yet possible, and the UK offshore installation has been very small with only two demonstration units planned in Scotland. This may be because sites with the right water depths close to grid connections and consumers are more plentiful in England.

Wind is taking a very large fraction of the subsidies for renewable energy and wind developers vehemently resist any reduction in the value. Developers of other technologies feel that they are being frozen out. This is unfortunate because variable renewables need diversity as a substitute for absolute firmness. There should be different flavours of renewable energy certificate to help the fledgling technologies and significant support made available for offshore wind projects. Projects similar to Talisman's Beatrice project in the Moray Firth must be encouraged and supported.

Offshore Wind – the Beatrice Project

Hunterston nuclear power station is rated at 1190MW but on completion, the Beatrice offshore wind farm will be only just less than that at 1000MW.

According to Talisman UK, the developers of the field, they will consider the construction of a full-scale offshore wind farm including building up to 200 turbines linked to the Beatrice platform. Two demonstrator turbines are currently under construction.

At full output a commercial venture could generate about 20% of Scotland's current electricity demand (enough energy to power a million average UK homes) while extending the life of our Beatrice oil.

The project has the potential to be the largest renewable energy development in Scotland and could become the world's largest wind farm.

Waves

Close-packed, deep-water, wave energy plant with good exposure to the Atlantic will have maximum power ratings of 50 to 100 kilowatts per metre, and so the 400 kilometres of the Scottish Atlantic sea front could contribute 20 to 40 GW with winter capacity factors of 40%.

When this line has been built we can do a deal with the Irish, who will never need to exploit all their vast resource. Later, we can extend north-west from Cape Wrath towards Iceland and get very much more. One bit of open sea behaves very like another so there is less bespoke design needed than for tidal current sites. Areas with special importance for other uses such as fishing can be avoided or wave plant can be used, after proper consultation with the industry, to preserve fish breeding grounds. Perhaps we would need only one go at planning permission!

Because of Archimedes' Principle about the displacement of water, wave power devices tend to be heavier than wind ones just as ships are heavier than aircraft. This gives wave energy a disadvantage if cost predictions are based only on weight. However the chunky shapes of many wave devices are usually suitable for taking heavy loads through short distances and do not need the precision or elegance of wind turbine blades. Many will be made from concrete rather than carbon fibre.

Wave inputs are delayed in phase from wind, and we will be able to make accurate forecasts several days ahead because tomorrow's waves are already in the sea. Plant can run steadily for days, even weeks at a time. But because energy comes in pulses at twice the wave frequency, and wave amplitudes follow the Gaussian distribution, there are large power peaks - ten or more times the mean values. This would be unacceptable for weak networks. To absorb them would involve high electrical plant ratings, used for only a small fraction of the time, and high part-load losses. Ways have to be found to provide front-end storage for about 100 seconds of output.

The stresses that a rigid structure must withstand in the extreme waves are about ten times higher than those that would occur at the economic power limit. Designers must therefore either pay ten times more for structure than they need to or find ways to dodge waves with unusably large amounts of energy.

Many different solutions have been proposed with efficiencies from 2% to nearly 100%. As so often in engineering the probability of survival will depend on the effort put into predicting design loads and component strength but the cost effectiveness will depend on how close to the danger line we can get without crossing it. Not all designers agree that the best way to do this is by the inclusion of moving parts which can yield to escape unusable extremes.

Wave energy research in the UK was officially supported for about six years from 1976, which were then followed by a long period in the wilderness. Project teams in the first UK wave programme were given the terrifyingly large task of designing 2GW installations - much bigger than any nuclear plant so far - from a standing start with nothing like the aerodynamic knowledge which helped early wind. The resulting designs were terrifyingly large even though the power per square metre of projected area was well above that of conventional, land-based generation plant.

The initial costs were very high but fell fast to the point at which the programme manager predicted a final cost for fully developed plant of 3.3 pence per kilowatt hour.

The early pioneers have learned that good onshore wave sites are bad research laboratories and worse construction sites, that sea water is bad for electronic circuitry, that many parts optimised for use on dry land are unsatisfactory in salt water and that the failure of the simplest, cheapest components can be very expensive and waste a lot of time. These initial obstacles are not surprising. Humanity sank many boats, crashed many aircraft and burst many boilers before the engineering problems were properly understood. To grow confidence we need demonstrations that wave devices can survive the worst winter weather and perform as the designers have forecast. We need much cheaper methods for installation and a platform to test large numbers of components and sub-assemblies in parallel to get reliability.

But the deep-water resource is very large and the sea is very empty so that there is little competition for space and few complaints from neighbours. The Edinburgh-based company Ocean Power Delivery has built up a brilliant team of young engineers and has secured its first export orders to Portugal. We need ways to make Scotland as financially attractive as Portugal for this new enterprise.

Marine Currents

The big barrage systems like the one working at La Rance in Brittany and considered for the Severn would give rather expensive electricity for 25 years and then nearly free electricity for more than one hundred. The environmental impact would be large, especially for the feeding grounds of wading birds, who have many influential friends. However, the main snag is that investors get anxious about large, long-term projects that must be fully complete before there is any return.

Getting energy from sea areas where there is a high velocity rather than a large rise and fall can use smaller incremental investments with a quicker start to the repayments and a gradual increase to larger installations. Scotland has a superb tidal current site in the Pentland Firth and several smaller places to start.

A first prototype in the Bristol Channel by Marine Current Turbines has been working well since May 2003 and a second grid-connected one will be installed in Northern Ireland soon.

These machines look very like underwater horizontal-axis wind-turbines and borrow several aspects of wind technology. Other designs are possible and there are important differences between wind and water. There are two pieces of research that will be essential for safe, economical outcomes but both are too expensive for individual developers.

The first is understanding the interactions of waves and currents and how plant will behave in response to the most dangerous combinations of them. It is known that waves can get very steep when they meet currents head on. We could start in the few current sites with low exposure to waves but this is a severe limitation to the size of the resource and would rule out the Pentland Firth.

We now know that currents are more complicated than a first glance at the Admiralty publications might suggest. There are short-term random variations in both velocity and direction. There are even some places with a circular flow and no slack water. We must fully understand how these variations, combined with waves from any direction, will affect structural strength and power-conversion mechanisms.

It is much better to discover one's design mistakes at a small scale in private in a model tank because extreme events that might occur only once in fifty years at sea can be arranged at twenty seconds notice and repeated thousands of times. Launching and recovering small models takes minutes not months and is free and safe rather than costing tens of thousands of pounds and being liable to endless delays for weather and safety.

If Scotland truly wants reliable marine current energy with generators which are strong enough, but only just strong enough to survive, we must build a model test tank with complete control of both waves and currents.

The second problem is that we do not know enough about what electrical engineers would call the impedance of the flow channels. This is something that we can think of as the 'determination' of the water to overcome obstacles placed in its path. In this respect turbines in water channels can be very different from those in air.

Water cannot flow through the sea bed or over plant which breaks the surface. It cannot easily flow around machines in a close-packed array. A long shallow channel with a rough sea bed will already be dissipating lots of energy by bottom friction. Installing – one – or even several, banks of close-packed turbines will slow the flow much less than in a short, smooth channel and estimates of the resource which are made for a single row of widely-spaced units will be too low (see the box below).

Any mechanism that extracts energy from the flow will reduce the flow velocity and so reduce bed losses releasing some for us. If we are too greedy and try to extract too much, the flow velocity will be too low and the capital cost of the turbines will rise.

But because of the velocity-cubed term in the power equation the reduction is initially quite small. If we remove 30% of bottom friction power the resulting velocity will still be 88.8% of the starting value or 3.1 metres per second, a good value for turbine designers.

> A useful mathematical ratio for quick mental calculations is [*channel-length times bottom friction-coefficient*] divided by [*water depth times turbine performance-coefficient*]. If this ratio is unity then there is already as much energy being wasted at the bed as would be generated by a bank of machines filling the entire flow-window. The Pentland Firth is about 23 kilometres long and about 70 metres deep. For a shear friction coefficient of 0.015 (which would be a Manning coefficient of 0.056 $s/m^{1/3}$) and a performance coefficient of 0.4, the ratio of bed friction losses to one-bank close-packed turbine power would be over 12. The width is about 10 kilometres and so at a current velocity of 3.5 metres per second there will at present be 75 GW of power dissipation on the seabed. There will of course be more kinetic energy radiated out to sea but, for this suggested friction coefficient, it is far less than the bed losses.

About 75% of what we remove from bottom friction can be converted to a peak of 18 GW of synchronous electricity. This would be more than twice the peak Scottish electrical demand in 2020 and so if we were ever to use all of it there would be a need for an energy-hungry chemical process such as the manufacture of a synthetic liquid fuel, or very much larger cables south. A seabed cable from the Pentland Firth to Peterhead, perhaps carrying direct current, would be a useful start.

This estimate is far above ones made by the Carbon Trust [14] and the Scottish Executive [15]. This is because their consultants used widely separated turbines in only shallow water, took no account of energy released from bottom friction losses and used a very cautious assumption (the threshold of detectability of the best instruments) about the environmental impact of reduced current velocities. As there are many places in the world which survive happily with much lower current velocities than the Pentland Firth and show no ill effects, it is not clear why a reduction from 3.5 to 3.1 metres per second will cause problems. The real limit is set by the increase of tidal range at each end of the channel after turbines are installed.

All these, however, are mere estimates. The necessary research to confirm the true values of friction coefficients and power lost in bottom friction would be measurements of deviations from mean sea level and local current velocity through the whole water column along the full length of the flow channel through a tidal cycle. These can be combined to give a numerical value of the channel impedance and friction coefficient. We then need designs of turbines that can be installed in 70 metres water depth and operated as a close-packed array filling a large fraction of the channel depth.

It would be best if the lines of turbines could be placed towards the easterly end of the channel so as to avoid the largest Atlantic waves. A line from Duncansby Head to Muckle Skerry, a distance of 6.54 kilometres, looks a good place to start. Admiralty chart 2162 shows that the maximum flow to the east is 9 knots (4.63 metres per second), slightly faster than the 8 knot (4.1 metres per second) return flow to the west. There will be conflicts with shipping such as tankers going in to Flotta.

There are already proposals to stop large oil tankers taking short cuts past sensitive coastlines and there may not be oil to carry in them for much longer. While there is, it would be possible to direct all shipping to the passage north of Muckle Skerry. If the lines of turbines were placed in an interdigital plan like two mated letter Es, there would still be a passage, albeit a longer one, and places for turbines across nearly the full width of the firth. A small fraction of the revenue would compensate owners of trans-Atlantic shipping for longer sea distances round North Ronaldsay. Cross firth traffic should not be affected

If we look at the Admiralty charts through the eyes of a fluid dynamicist it is clear that the placement of the islands of Stroma and Swoma is sub-optimal. The width of Stroma perpendicular to the flow is about 3500 metres. It has been uninhabited since 1962 [16].

If we can apply the usual drag equations with a coefficient of unity for bluff bodies the result is a power loss of 5.4 GW. A further 3 GW can be calculated for Swoma.

Both islands are the cause of many dreadful shipwrecks and the supplies of concrete aggregates from UK sources are becoming critical.

Using rock from these islands would quell anxieties about super-quarries on Harris and Dartmoor. Removing circular bores from the core of the island down to some calculated distance below the 70 metres depth of the main channel will leave an outer shell formed as a series of thin walls with circular interiors, rather like a honeycomb built by very different sizes of bee.

This structure will be strong while it remains as group of continuous shells, but will collapse if the web continuity is destroyed. If this is done by blasting selected internal walls at slack low water, a large fraction of the debris will fall into the bottoms of the bore holes to leave a 'level' surface. The output of aggregate would be more than from the Harris super-quarry.

Scotland is not short of lonely islands and such a step could lead to considerable benefits. There should of course be appropriate financial compensation payments to the community.

Solar Thermal. In Scotland?

Yes. Scotland is a cold country and a high proportion, about 50%, of our energy demand is for heat for which solar is particularly suitable. Research concludes that Scotland has one of the BEST climates in Europe for using solar heat in buildings. That is because our cool maritime climate allows a much better use of solar heat than in more southerly and sunnier countries, and that this more than compensates for slightly lower solar radiation levels. We sometimes still feel cold in 'summer'.

The best estimate we can get for the solar heat potential is from 'Scotland's Solar Energy Potential' [17]. Results were based on the following assumptions:

That heat is collected from domestic roofs only; that 70% of all domestic roofs (1.75 million) roofs are available; that each roof has 10m2 of collector area; that the annual solar irradiation is 1000kWh/m2; that the collection efficiency is 40%.

These assumptions give an annual heat yield of 400kWh per roof and an annual total solar heat contribution of 7TWh.

This is a conservative figure because it ignores more possible contributions from industrial rooftops and also large ground-based collectors. If these are also included, a final total annual figure of 10TWh of solar heat is possible.

At this point the Review Chairman, with approval from SNP Headquarters, asserts his editorial power to point out that one of the cheapest and easiest ways to retrofit solar heating to the Scottish housing stock has been developed by a co-author of this review who is too honourable to exploit his position. It involves gently sucking air through the gaps between roof slates, which are admirable, free solar collectors.

The pumping power can all be obtained from a solar photovoltaic cell. The system will deliver warm dry air to the basement of the house. It will even reduce turbulence in the boundary layer of the air stream over the roof to reduce the heat transfer coefficient, and so works even in winter.

Solar Electricity

Photovoltaic solar cells are normally mounted on rooftops, though they can also be ground based. The estimate of possible solar electric contribution in Scotland is based on the same source as for solar heat generation. It is based on the same assumptions but with a collection efficiency of 10% although the latest technology gives over 15%. This gives Scotland an annual solar electric input of 1.75TWh.

If we also include possible contributions from industrial and commercial roof tops and also ground based arrays, the likely possible solar electric contribution rises to at least 2TWh.

Though we have lower solar radiation levels than in more southerly countries, this is balanced by the fact that we also have lower air temperatures which lead to higher operating efficiencies in photovoltaic cells.

It should also be noted that though Scotland presently has a winter peaking demand for electricity, increasing global temperatures and the increased numbers of bigger buildings are pushing up the demand for electricity to drive air-conditioning plant.

Capital costs for cells are still high but have fallen dramatically. The lowest figure for April 2006 is £2.1 per watt down from £3.2 in April 2002 with a goal of £0.8 per watt in 10 years [18]. The semiconductor industry has a record of seemingly endless cost reductions all of which would have been thought impossible by the leading engineers of previous generations.

4. Energy efficiency

Energy efficiency is about getting more useful benefits from the same amount of energy or using less energy to provide the same benefits. It is the neglected technology even though it can be regarded as a new source of energy. If you use less energy to do a job, the energy you are not using is now available for somebody else, just as if another energy source had been used.

The possibilities for energy efficiency are many and significant. They will be briefly considered under three headings: buildings, industry and transport.

Buildings

The main demand for energy in Scottish buildings is for heating. Heat demand can be reduced by basic techniques such as insulation, draught exclusion and double glazing. A new house built to the latest Scottish building standards will need only half the heat used by a building built to the heat retention standards of 1960. With the latest available techniques developed in Scandinavian countries (all small and independent), it would be possible to halve again the modern consumption.

These techniques include:

- Latest glazing (low-emission glass and inert gas infill of double glazed units).
- Heat recovery from ventilation air (reduces heat loss by 60%).
- Passive solar heat design (reduces heat loads by 70% at no extra cost).
- Breathing wall (insulation with moisture absorption ability).
- Low energy domestic appliances.
- Reduction of stand-by consumption of electric appliances such as televisions
- Low-energy light bulbs.
- Condensing boilers.
- Micro heat-and-power units based on fuel cells or Stirling engines.
- Micro wind turbines and solar heating systems.
- More sophisticated controls for heating systems.
- Ground source heat pumps instead of direct electric heating systems. These give up to 4 times more heat for the same electricity.

It is relatively easy to incorporate these into new buildings. This can be done by tightening up building standards in Scotland, still well behind those of our Scandinavian neighbours, and making it mandatory for new buildings to incorporate micro renewables, for example as a planning condition.

A bigger challenge is to do something similar for existing buildings. The turnover of the Scottish housing stock is slow and solid stone walls are more difficult to insulate. However, several passive solar techniques work well on older buildings and there are already some notable examples in Glasgow at Easthall and in Berwickshire at Duns.

Overall, the committee estimates that energy demand in Scottish buildings could be reduced by at least 30%. That is effectively an annual energy contribution of 5TWh of electricity and 8TWh of heat.

Industry

The main uses of energy in industry are for process heating and electricity for driving pumps and fans. For heating, the options for savings include:

- Better insulation of pipes and vessels
- Heat recovery
- Process integration with heat being cascaded down through temperature ranges
- Better control of heating plants
- Lower embodied energy processes and materials
- Flow control of pumps and fans with variable-speed motors rather than throttling.

A combination of these techniques should lead to a reduction in heat and electricity demand in industry in Scotland of at least 25%. This is equivalent to an annual electricity contribution of 4TWh and a heat contribution of 7TWh.

Energy for transport

At present almost all the energy used for transport in Scotland comes from oil. This use is still growing, especially for road and air transport. Possibilities are:

- More efficient engines
- Hybrid systems combining fuel-using engines and electric battery/motors or hydraulics for regenerative braking.
- Better aerodynamics
- Lighter vehicles
- Stricter policing of speed limits
- Lower speed limits
- Better traffic management with fewer people driving around looking for parking
- Move to public transport
- Higher fuel prices
- Higher road tax for gas-guzzlers
- Any form of tax on air transport
- Vehicles using renewable electricity
- More cycling and walking
- Reducing the need for travel by making people happy where they already are!

Many of these policies would be contentious. However, a determined government could take steps to reduce transport energy over a fairly long time scale.

The above techniques could reduce Scotland's transport energy requirement by at least 25% over the next 30 years. With present annual transport energy needs of 32TWh, that reduction comes to 8TWh.

5. Matching renewables with demand

There is a regular stream of letters to the Scottish press from a small but persistent group of writers who dismiss present wind and future wave energy on the grounds that they are intermittent and that the introduction of wind turbines means that the writers cannot have coffee when the wind is not blowing. None of the people working on these variable sources has ever claimed that they were firm.

The intermittency critics also imply that backup generation is consuming fuel and emitting CO2 at the full rate when on standby. This is by no means the case. Hydro-electric plant can come on stream in much less than one minute and gas turbines in little more. Even big coal generators can keep steam pressure up with moderate thermal losses. This HAS to be done now to follow the variable patterns of demand. At the half-time interval, a few seconds after David Beckham scored a goal against Argentina, the UK grid suffered a 1.5 GW surge in demand [19].

This had the same effect as a simultaneous change from maximum rated wind speed to zero wind speed in every turbine of an installation three times the size of the present Scottish one. What matters to grid operators is step size, rate of change and the length of advance warning. Nobody can tell when goals will be scored but we do have good weather forecasts. We should also recall that NONE of the present electricity technologies is truly firm.

Miners can strike. Oil and gas supplies can be blocked for political reasons. Nuclear plant can suffer long, unplanned outages at very short notice. Transmission lines can be struck by lightning. There is nothing as unfirm as a depletable source once it has been depleted.

While any gas is being burnt for the generation of electricity, every kilowatt hour generated by a renewable source, no matter how variable, will leave 0.2 cubic metres of gas in the ground.

Fortunately there are now hard numbers to quantify the problem. The Scottish Executive is to be congratulated for commissioning a report entitled Matching Renewable Electricity Generation with Demand [20]. Continuous historical data for onshore wind (10 years, hourly) offshore wind and wave (4 years each, three-hourly) were obtained from the Meteorological Office. Data on tidal currents were more easily available from tide tables. The most recent years, 2001 – 2003, for which demand data were available or could be directly inferred, were then used for time series analysis. Scotland and adjacent sea areas were mapped as a 500 by 750 kilometre array of one kilometre cells, a total of 375,000. From these were removed cells thought to be unsuitable for installation of renewable sources, such as those with unfavourable geography, proximity to airfields, navigation obstruction, wrong water depth or ones thought to be sensitive by Scottish Natural Heritage.

The costs of producing electricity were then calculated for each feasible cell in the form of lifetime production costs in pence per kWh, taking into account expected annual electricity production, fixed capital costs and variable annual costs over a project lifetime of 20 years. Connection costs to the next suitable grid supply point were included. In the case of the islands (Shetland, Orkney, Western Isles) projects had to share the costs of the undersea cable connection. Some allowance was made for future technological developments, but overall the cost estimations are believed to be conservative.

Cells were ranked by cost with generally reducing capacity factor for the less attractive sites. The most economic cells were then used in a number of scenarios for which key figures were derived. This process also took downtime, electrical and park losses into account. Contribution from the much less variable existing hydro and future biomass plant were excluded from the analysis - again conservative because, in practice, they would contribute a useful and well-controlled substitute input.

The output was compared with the actual pattern of electrical demand for the same period, increased at a rate of 1% a year up to 2020, for various amounts of installation in rank order of cost for each of ten regions. This allowed the calculation of the amount by which the output of any chosen installation would produce less than any chosen target (such as the 40% by 2020) and also the number of hours for which the demand would NOT have been met from any mix of renewable sources under study. This work gives kilometre-by-kilometre and hour-by-hour information for the whole country and provides an enormously powerful tool for planners to test any pattern of plant installations, now and in future.

The immediate conclusion was that a 6 GW mix of wind, wave and tidal could ***on average*** meet at least 40% of the 2020 Scottish demand. It would exceed the target for 45% of the time. The 6 GW mix would sometimes leave a shortfall of up to one quarter of the 40% target. This would leave 10.4% of the total Scottish electrical demand to be filled from the several other options.

The analysis is conservative, and correctly so. The dispatchable hydro and biomass plant are excluded from the analysis but could fill in some of the gaps. The 6 GW mix is very much less than the total installation possible if all viable sites were used. Any of these would increase the fraction of time for which the renewable output exceeded the 2020 target. Even with the 6 GW installation there will be times when the renewable inputs exceed the total demand leaving the problem of exporting, storing, dumping or finding alternative uses for the excess.

The capacity of a heat store rises with the cube of scale while the losses from its surface rise only with the square. This means that large heat stores are more cost effective. It is easy to put electrical energy into a store as heat but much harder to get it out as electricity or work.

However, stores filled by electrically driven heat pumps might be cost effective for district heating if the heat transfer from the storage medium to water pipes can be arranged. This ought to be attractive for Scotland because of the long heating season and its coincidence with possible over-supply of variable renewables.

It is also possible to measure the frequency and local voltage of the mains supply and use this information locally to bring on or defer non-critical electrical loads such as water heaters, the battery charging of electric cars, fridges, freezers and driers so as to give a large and highly responsive, virtual electricity store with a response time of tens of milliseconds and storage times of a few hours. A fast response with a low phase lag is desirable to prevent grid oscillations. The capital cost of such virtual storage is only a few pounds per kilowatt compared with £500 per kilowatt for the cheapest gas turbine generator. The 'round trip' energy losses are very small – a few watts per house. The main problem is the commercial one of how to pay people to use the technique. We need accountants to show as much ingenuity as the electronic chip designers.

Electrical generators like to rotate at high velocities and most renewable sources involve velocities which are awkwardly low. Gears become increasingly unattractive at high torques especially as an infinitely-variable ratio is what is really needed to link a violently alternating input to a synchronous electricity network. One possible solution is the use of hydraulic pumps and motors. Some special designs with digital displacement control, which makes them easy to link to computers and gives high part-load efficiency, have been designed for renewable energy applications.

They allow easy, bidirectional connection to gas accumulators which can give minutes of energy storage linked to true synchronous electrical machines rather than induction generators. Even a few seconds can help ride through network transients which can lead to successive trips. [21] All this can be built in to the power train of new wave, wind and tidal plant and would make them most welcome contributors to network stability.

The same technology could be used to give regenerative braking in vehicle transmissions and allow better acceleration from smaller engines, lower pollution and very much lower urban fuel consumption.

Grid problems will rise as the fraction of variable inputs increases but the rise will go with only the square root of the increase. While there can be arguments either way about the relative benefits of large and small generators, there is no question about the attractions of a large grid to smooth both variable inputs and variable consumption which are almost identical in the problems they cause network dispatchers. Whatever the politicians decide, it is important that Scotland's connection to the UK grid is improved and extended perhaps one day to Iceland, Norway and mainland Europe.

Some people may see it as deeply symbolic that the present inter-connector between Scotland and England can deliver 2000MW going south but return only 600MW coming back north [22] [23]. Others may be surprised that the return can be as high as 600MW. See the box below.

Every reader with a higher degree in power systems analysis will see at once that although the I^2R thermal rating of a line has to be identical for power flows in either direction, the effective ratio of the imaginary complex Fourier convolution phasor components on the superposition capability of the two reactive harmonic impedance vectors at the 440 kV bus will distort the relative hyperbolic Liapanov stability spiral so as to cause the observed asymmetry.

Maybe aye and maybe hooch aye.

What matters is that randomly-variable generators are merely negative versions of randomly-variable consumers and network dispatchers know how to handle them.

6. Visual Impact

How can we reduce the visual impact of on-shore wind turbines and power lines?

Some of the people who are concerned about the intermittency of variable renewables are also concerned about the effects of visual intrusion of onshore wind turbines.

The US horror DVD entitled 'Life Under a Turbine' is being distributed to every Highland politician as a warning. Sleep deprivation, strobe effects, noise and vibration, infra-sound and an 80% drop in property values are cited as reasons for objection.

Complaints from other objectors include interference with television reception and airport radar systems, risks of bird strike and impacts with low-flying aircraft.

At the dawn of the railway age the canal companies felt threatened. They mounted a campaign which is strikingly similar to that being waged by opponents of wind. It was claimed that cinders from the firebox would burn all the crops, that livestock would stampede to death, that rail passengers would be unable to breathe at speeds above 15 mph and even that the morals of boys at Eton would be corrupted by the possibility of cheap travel of prostitutes from the east end of London [24].

During a recent visit to Denmark the review chairman had the chance to fly in a small aircraft over a wide stretch of the country. There were turbines to be seen in many places but they seemed intrusive in only one. Crops were being grown and sheep could safely graze right up to the concrete turbine bases. Cows could scratch themselves on the towers. The installations seemed as attractive as the steeples of village churches.

People put pictures of old Dutch wind mills on postcards and souvenirs. Any remaining ones are carefully preserved as tourist attractions. Single modern machines can look very attractive, though perhaps more to engineers than artists. Effects which seem offensive even to an engineer are:

- Seeing the moving blades of machines through the swept area of others. This can look like the spears of an advancing army or sea gulls fighting on a rubbish tip.

- Thinking that wicked absentee landlords are making a fortune from subsidies, paid from your taxes, while you have to pay high rates for your own electricity.

In Denmark they do not seem to have wicked landlords. There is much more local community ownership, with one-farm one wind-turbine and a perception of local benefits.

The big developers claim that tight clusters of machines are needed for economic reasons and that dispersed ones would be impractical. If this was really the case it would not be economic to distribute power and telephone cables to individual houses, only to factories and tower blocks.

The review committee investigated the relative costs of overhead and buried cables. All the sources were emphatic that the ratio was very large, ten to twenty times more for buried cables, especially for the higher voltages needed for long distance transmission.

Many places in Scotland are so beautiful that we should pay for underground cabling. Buried cables are more reliable than overhead lines but take longer to repair if they ever do go wrong. Vegetation has to be cleared from a 40 metre wide path along the burial line so the environmental impact is not zero.

We have not had time for full investigation of the option of tunnelling. This is easier in hard rock than soft mud, can use the same techniques under land or water and, if subsidence can be avoided, has very low impact at the surface. We are looking at a new development by Sam Kingman [25] on the use of microwaves to weaken rock by differential heating. This may reduce tunnelling costs enough to allow an underground grid.

There must have been similar concerns about pylons for the hydroelectric schemes built in the 40s and 50s. The now dearly remembered North of Scotland Hydroelectric board managed to plan the lines with considerable sensitivity and also brought electricity to people who had not had it before, so we know that compromises can be reached. What would happen if people who could see a turbine or a pylon from their house got electricity at half price?

In the last resort it may be some consolation to reflect that if the day ever comes when every croft has its own private cold-fusion generator, it will be easy to remove turbines and pylons leaving no visible trace. This is not true for atmospheric CO_2 or dispersed nuclear waste.

7. The nuclear question

Should we build more nuclear stations in Scotland?

Advocates claim that nuclear energy is cheap, firm, safe, and most importantly today, carbon-free.

Is it cheap?

Before privatisation it was taken as axiomatic that nuclear electricity was the cheapest of all sources. In the earliest days several eminent people said that it would be too cheap to meter. A recent paper published by the World Nuclear Association on the costs of Spanish nuclear output [26] claims that by 2001 the cost had fallen to just over one eurocent (about 0.6 pence) per kilowatt hour. This would be only about £100 a house per year, and barely worth fitting a meter or sending anyone to read it. It is a surprise that Spain has installed 9 GW of wind plant [27] and is increasing this at 2GW a year if their firmer nuclear electricity is so cheap.

But the too-cheap-to-meter claims were challenged in 1988 when a great admirer of nuclear energy, former Prime Minister, Margaret Thatcher, put the British electricity system up for privatisation and the City analysts looked at the books in detail. The privatisation of British Energy was deferred. When it finally took place in 1996 the investors were given a ‘buy-one-get-eight-free’ deal for the existing, fully-operational power stations. Despite this they have still needed Government bail-outs. How could the Spanish, with little background in nuclear energy, do so much better than Britain?

One interesting calculation can be made on the basis of a figure, recently announced by the Nuclear Decommissioning Authority, for the cost of cleaning up waste from our present stations. Estimates have been increasing faster than inflation and the latest from the UK Treasury [28] is £90 billion. From the DTI Energy Trends website [1] we can see that the total amount of energy ever generated by all British nuclear plant from the start up in 1956 up to 2004 was 2,065TWh. It would be fair to add on twice the 2004 generation to bring the figure up to 2006, giving 2,212 TWh.

If we divide the £90 billion clean up bill by the total nuclear energy generated we get an astonishing 4.07 pence per kilowatt hour for the clean-up cost if all accounts were squared up today. But the World Nuclear Association [29] says that the amount utilities are putting aside for clean up is 0.1 to 0.2 US cents per kilowatt hour. The upper figure of 0.2 cents is nearly 40 times lower than the one calculated above. How can this financial magic be done?

If, after his coronation 700 years ago, Robert the Bruce had invested one penny at the traditional UK interest rate of 5% on behalf of the Scottish people, every man, woman and child in Scotland would now be a millionaire. But this growth assumes safe investments and the continued steady expansion of the world economy with no Black Death (Europe 1347), hyperinflation (Germany 1922), world depression (1929) or Chancellors of the Exchequer raiding the pension funds (UK 1997). The world economy was fairly flat until we had cheap energy. Perhaps it would be prudent to clean up the mess as we go just in case there are hard times ahead. After all cleaning up your mess as you go is what city councils urge every dog owner to do.

The problem is that the value of money changes enormously depending on whether you are looking backward or forward in time, rather like the different views from each end of a pair of binoculars. It is interesting to try to do the calculation the other way about and try to work out the value of a hypothetical fund that had invested all the research money which went into the UK Atomic Energy Research Establishment (later the Authority). This is extremely hard to disentangle from the secret military side but an informed source suggests that it was probably about £1 billion a year, every year from 1946. Perhaps the Freedom of Information Act could be used to get a more accurate value (and perhaps not.).

If the guess was right and we had invested this sum every year until 1996 it would now be worth £135 billion. If we divided that by the total nuclear generation to date, the result would be 6 pence per kilowatt hour. Even halving this to allow for future output from remaining stations it is about five times more than the Spanish claim.

Is it firm?

The journal *Nuclear Energy International* used to publish month-by-month output of all the world's nuclear stations. The range of capacity factors was fairly evenly spread from almost zero for some designs (which need not be named) to the very high nineties for the Canadian CANDU system. The recent availability of stations operated by British Energy is about 75%, somewhat better than the world average but not as high as they would like and will fall as a result of graphite cracks.

Some of the outages for replacement of fuel rods or other maintenance are planned well ahead and can be done in the summer. But there can also be unplanned emergency shut-downs, losing all output at very short notice, which can last for months. British Energy had two units out at the start of one winter.

The shortness of the notice of some unplanned outages compares unfavourably with the slower, more partial outages of wind and waves caused by weather, where there is at least a warning period which is long, relative to the planning and pricing time of networks. The system works because of the diversity of the grid but British Energy still thought it worthwhile to buy a large coal-fired station at Eggborough. On a percentage basis British nuclear energy is fairly firm but some of the lack of firmness can have an unpleasant abruptness.

Is it safe?

At the peak of British coal production of 300 million tons in 1906 there were more than 20 miners killed in British pits each week [30]. After nationalisation there was a sharp reduction but we still killed about 50 a year. In comparison with these dreadful numbers the British nuclear industry is very safe indeed. But the safe British reactors will be judged by the standards of the most dangerous single reactor in the world which may be an entirely different design, operated by differently trained people, under different safety regulations.

The more reactors, the greater the chance that something bad will happen to one of them and all the others, however good, will suffer. There have been nuclear accidents at Windscale, Kyshtym, Three-mile Island, Dounreay and Chernobyl - about one every ten years. Only two were really serious but all might well have been. With a dash for nuclear in less technically advanced countries the rate will not reduce. British reactors may be safe but they will not be seen to be so and that is what matters to investors and voters.

A second concern is that reactors, and particularly the unprotected pools used for storing reactor fuel, could be attractive targets for terrorists. We now have the capacity with bunker-busting bombs such as the BLU 113 to go through 6 metres of concrete or 100 feet of earth [31]. To make reactors and fuel ponds safe enough needs 24-hour fighter cover or the increased capital cost of deeply-buried reactor designs. Neither comes cheap. It looks as if the safe ones will not be cheap and the cheap ones will not be seen to be safe enough.

Is it carbon free?

Many political advocates for nuclear energy claim very low emissions of CO2. Some, including senior figures in the DTI, even say zero. If one considers only a working power station itself the emissions are mainly from the petrol used by staff driving to work and could be claimed to be nearly zero.

A paper written for British Energy about their station at Torness by Daniel Forster of AEA technology [32] includes quite detailed calculations for CO2 from fuel production but has unsupported figures for later emissions involved with waste disposal. His figure for the amount of CO2 is only 6.85 grams per kilowatt hour compared with combined-cycle turbines running on natural gas of 400 grams and coal at 900 grams. This would mean nuclear energy produces one-sixtieth of the CO2 from gas. A second source gives a much higher amount for the whole nuclear cycle, ranging from 73 to 230 grams of CO2 per kilowatt hour [33].

But a paper by van Leeuwen and Smith [34], bitterly contested by the nuclear industry [35], contains a joule-by-joule analysis of CO2 production though the whole nuclear cycle, with three pages of references. It shows that the CO2 produced with present ore grades is 80 grams per kilowatt hour ignoring dismantling and 140 gm per kilowatt hour if that is included. (It is hard to see how you could spend £90 billion plus the usual estimate-creep on waste disposal without releasing *any* CO2 at all.)

Van Leeuwen and Smith also point out that the problem is not CO2 alone but the whole basket of other greenhouses gases. These include chlorine, fluorine, organic compounds containing them and compounds they can form when released into the atmosphere. These can be ten thousand times more powerful as greenhouses gases than CO2. For example, data from America [36] show that US enrichment plants released 405 tonnes of Freon 114 which has a global warming potential nearly 10,000 times greater than CO2. If we divide the Freon CO2 equivalent by the US nuclear output for the same year of 769 billion kWh [37] we get 5 grams per kilowatt hour. This, added to the Forster figure, nearly doubles it.

The 140gm figure from van Leeuwen and Smith still gives nuclear an advantage relative to combined cycle gas turbines using natural gas but only by a factor of about three.

However, the amount of energy needed to get uranium fuel will depend on the ore grade, the depth of rock in the overburden and the strength of the rock containing the uranium that has to be crushed.

Rich ores tend to be in shale and sandstone which are easily crushed but lots of the weaker ores are in much tougher granite. Furthermore the fraction of uranium which can be recovered falls with lower grades so that the increase in fossil fuel requirement is faster than the fall in ore grade. The three-fold advantage will narrow as the world uses more uranium. Their estimates for the rise in CO2 as a function of ore grade are given in the figure 3 taken from their evidence to the International Panel on Climate Change and reference [34].

The van Leeuwen and Smith paper was based on the present grade of ore which is around 1500 parts per million or 0.15%. They predict that at ore grades below about 300 parts per million, the energy for fuel production shoots up and that by 100 parts per million (or 0.01%) the CO2 from the whole nuclear process is equal to the amount from gas turbine generators producing the same energy.

If uranium use continues at its present level the crossover is about 50 years away but if there is a dash for nuclear reactors it will be very much sooner, within the life of reactors we might be planning now.

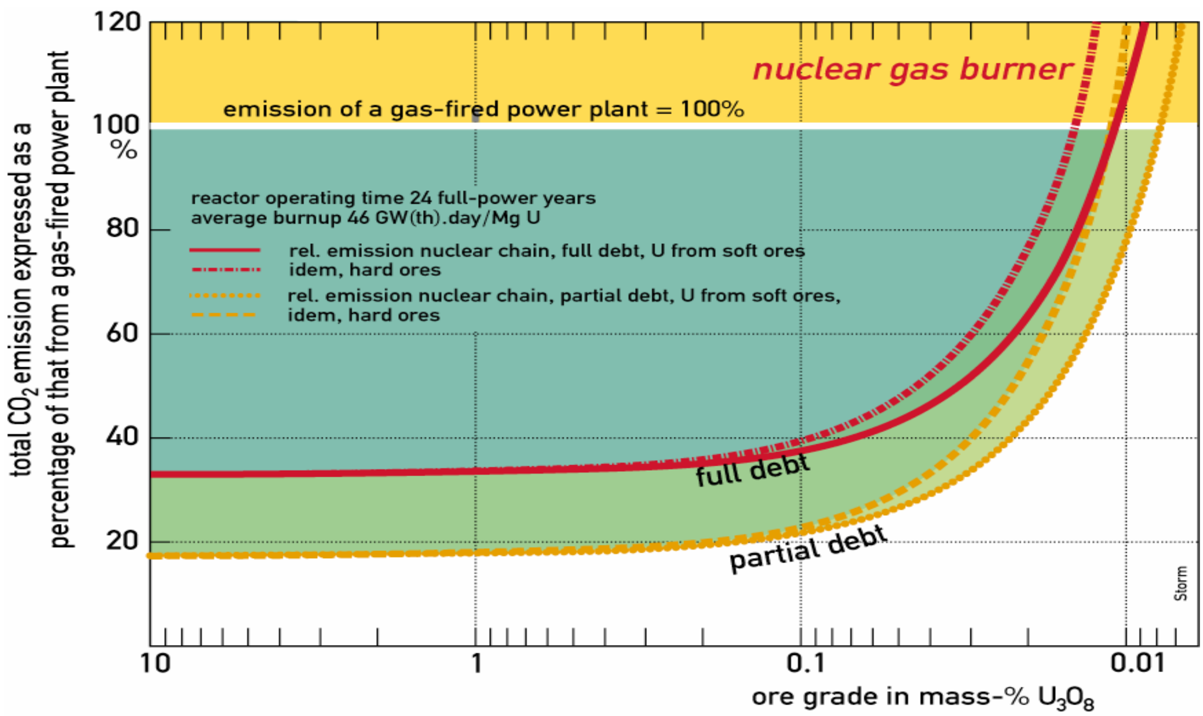

Figure 3. Estimates from Leeuwen and Smith of the amount of CO2 released from fission generation as a fraction of that from equivalent gas-fired plant plotted against uranium ore grade. We will not be on the flat part of the curve for much longer.

According to Kathryn McCarthy, in an otherwise pro-nuclear presentation [38], world-wide uranium use with once-through light-water reactors will exceed proven reserves in 2030. It would exceed the 'yet-to-be-discovered but probable reserves' by 2060. In contrast Ian Fells, former Chairman of the New and Renewable Energy Centre, writes that nuclear energy is carbon-free and can last for one thousand years [39].

Scottish decision makers must decide where the truth lies between these extremes. The review committee thinks that the carbon release from nuclear plant is fairly low now but not zero, and that it is likely to rise very fast within the lifetime of plant planned now to become equal to the carbon released from gas-fired plant of the same electrical output but lower cost.

The history of uranium costs looks like a roller coaster ride but the upward slope is now steep. Annual demand is now running at about 67,000 tonnes but production is only about 40,000 tonnes with the shortfall coming from recycled weapons. Some old, exhausted mines are being closed and mines are now being opened with ore grades of only 400 parts per million [39], fifty times lower than the first early ones and uncomfortably close to the danger point.

This was very well known by the UK Atomic Energy Authority, hence their determination to develop fast-breeder reactors. Advocates for new designs of reactor will claim that from now on they will now be safe and efficient and easy to clean but that was exactly what their predecessors said about the old ones.

Storm van Leeuwen and Philip Smith were both former nuclear engineers and have little to gain from their work while the Nuclear Industry has much to lose if their conclusions are true. Is it possible that a public company could release information with distortions of such large factors? Regrettably the answer is yes. Some examples are given in appendix A.

Fusion

Hydrogen bombs are much more powerful than the fission bomb used at Hiroshima but a fusion reactor would be very much less dangerous than a fission one. Instead of having a hundred tonnes of fuel and waste products under high pressure, a fusion system contains a tiny amount of fuel at atmospheric pressure and the reaction stops the instant that this is not supplied.

There is a small amount of radiation produced in the wall but it is about one thousandth of the amount from fission waste of an equivalent sized reactor and has a much shorter half life.

There are absolutely no concerns about limited fuel supplies.

Instead of having to be clever about not letting a fission reaction run away, you have to be even cleverer to keep a fusion reaction going.

Sadly fusion has suffered from over-optimistic claims from the early days which led to the belief that it was at least 50 years away and 'always would be.' But a graph plotting the achievements of the series of experiments shows steady progress towards the necessary containment periods needed for a viable system. The cost of building the next experiment might be £5 billion, but when this is shared by the international community it is very small compared with what they are already spending on energy and what we will all have to spend on cleaning up fission.

The remaining potential show stoppers are the need for a wall material which can withstand high bombardment from neutrons and a shortage of engineers good enough to make the system reliable. Even if success lies too far in the future to affect immediate Scottish policy, the pay-off for a successful outcome is so large that we should give them time to do the job properly.

8. Conclusions

Scotland has lots of coal left. **Carbon dioxide sequestration is already working elsewhere.** Independent geological advice is optimistic about its success in Scottish geological conditions. **This would allow us to use more coal and, in the process, release more oil.**

The Peterhead project which is both world leading and capable of being pursued now is of enormous importance in developing this technology and showing how it can enhance oil recovery.

At least half the original amounts of Scottish oil and gas are still there and there are many ways in which more can be recovered. The cash value will rise as world resources decline. We must decide how much should be left to future generations.

Onshore wind is now mature but running into problems with visual intrusion of turbines and pylons. These may be reduced by sensitive planning and more local ownership. **Onshore wind is choking the development of younger renewables and much of the subsidy is going overseas. However offshore wind offers much better prospects.**

Marine currents are not quite as predictable as has been supposed but are still predictable enough to be very attractive to network dispatchers. The size of the resource in the Pentland Firth may be larger than that predicted from studies which assumed only shallow water turbines and ignored bottom friction losses. **With turbines designed for deployment in 70 metres depth the resource could exceed present UK nuclear capacity.**

Wave technology is still immature. **The Scottish offshore wave resource is enormous and could be extended beyond the Scottish sea front with few environmental conflicts.** There is a need for reliable components and cheaper installation techniques.

Scotland is one of the BEST countries in Europe to exploit solar power because of the need for summer heating.

At present nuclear energy has an advantage over fossil fuel with respect to **carbon emissions but the emissions of the whole nuclear fuel and disposal cycle are certainly not zero and the advantage may not be as large as has been claimed**. It will decline fast if there is a rush for uranium and a consequent reduction in ore grades.

There is a wide range in the estimates of nuclear costs depending on accounting methods used for research, third party insurance and waste disposal. There will also be a rise in new nuclear construction costs if extra security is needed to protect reactors and fuel ponds from recently developed penetrating munitions and others still to be developed. **There is no need in Scotland for replacement nuclear stations and the working life of the current reactors should only be allowed to be extended after careful inspection.**

The problems of matching energy from diverse, variable inputs to the diverse, **variable patterns of electrical demand are not insuperable, especially if conventional hydro power, biomass and pumped storage can be combined** with intelligent, automatic load-management.

We believe there is a strong case for the inclusion of micro-renewables as a requirement in all new building schemes.

Electricity represents only about a sixth of final energy use. **Scotland will have to build plant for the manufacture of synthetic liquid fuels suitable for transport, combined-cycle gas turbines and domestic heating.** Fuels can be made from electrolytic hydrogen combined with carbon from coal, biomass or refuse and would absorb excess electricity from large renewable but variable sources.

While God has been very generous to Scotland with regard to renewable energy sources the devil has done his usual bit for the transmission network. There are political problems about resolving the conflict between tourism and power lines. **Even though buried or tunnelled cables are more expensive, it will be essential to pay the extra in areas of outstanding natural beauty.**

Recommendations for Action

We recommend vigorous and sustained action aimed at achieving the following seven main goals:

Coal: To bring our huge coal reserves back into use with minimal environmental damage through carbon sequestration, and to make Scotland a leader in sequestration technology.

Oil and gas: To use our remaining – and still large – oil and gas reserves wisely and with restraint, instead of squandering them on purposes that other resources can serve. Carbon capture projects linked to enhanced recovery can be particularly important.

New liquid fuels: To make Scotland a centre for the development and manufacture of synthetic liquid fuels using electrolytic hydrogen and carbon-neutral biomass.

Hydro: To exploit all our good hydro resources, both for generation and for pumped storage. This will require investigation of the effects of salt leakage from basins working to the sea.

Waves, tides and offshore wind: To put Scotland firmly in the vanguard with respect both to the commercial exploitation of these vast resources and to the fundamental research still needed to establish the technologies securely. Most immediately we must understand the effects of bottom friction on the flow impedance of the Pentland Firth.

Electrical transmission and load-management: To build an excellent transmission system that can bring electricity from remote places with minimal impact on the beauty of our country; and to have an intelligent load-management system.

Micro-renewables and conservation: To make Scotland a country where people know how much they can do for themselves as individuals or small communities by using wind, sunshine, seriously good insulation, heat pumps, combined heat-and-power systems, more efficient car engines and the like; and where it is the rule rather than the exception for these things to be done.

Appendix A – Measuring Energy

(Skip this if you know the difference between an ohm and an ampere)

Physicists will tell you that distances should be measured in **metres**, that amounts of material in objects should be measured in **kilograms** and that time should be measured in **seconds**. Engineers make fewer silly arithmetical mistakes if they take this very good advice and build up more complicated units from these basic ones.

Force is something that can accelerate masses, oppose friction or fluid drag, move electrical conductors in magnetic fields, and stretch, bend or break solids. We could have picked any of the above list to define the unit of force but the one decided on was about accelerating mass. We call the unit of force a **newton** in honour of Sir Isaac and define it as what will accelerate one kilogram at one metre per second per second.

If you applied absolutely no force to a one kilogram weight, gravity would accelerate it downwards at about 9.8 metres per second depending on exactly where you were on earth. If you did not want your kilogram to fall in this way you would have to give it an equal and opposite acceleration by applying an upward force of 9.8 newtons. It is helpful to remember that if 9.8 apples weigh one kilogram (which they roughly do) then the gravitational force on one apple would be one Newton.

One of the many forms of energy is a force working through a distance. If we are wise enough to obey the advice from physicists, the unit of energy would be a force of one Newton working through a distance of one metre. We call the unit a **joule** in honour of another famous physicist who sorted out the relationship between heat and work. So if the apple trees in Sir Isaac's orchard were three metres high, physics got a major boost through the expenditure of three joules of potential energy.

Power is the rate at which joules are moved or changed from one of their many forms to another. The unit might have been joules per second but we have chosen to honour yet another great man, this time an engineer (and Scottish of course) by calling the unit a **watt**. If you confuse energy with power by talking about megawatts of energy, engineers and scientists will despise you.

Discussions about energy involve VERY big numbers. Engineers like to get a better gut feeling for the numbers they use and have imaginations that go up to about a thousand. Accordingly they use a prefix which gears up unit values in steps of one thousand. For example one bar of an electric fire delivers a thousand joules of heat every second which we call a kilojoule and has a power rating of one kilowatt. In steps of one thousand the prefixes are called **kilo, mega, giga, tera, peta, exa, zetta** and **yotta** but we do not often need to go beyond tera for one million times one million or 10^{12}. Wind turbines now have power ratings of a few megawatts and big power stations a bit over one gigawatt. Often we use just the capital letters MW and GW.

This beautiful structure went sour, and silly mistakes became easier when accountants wanted consumers to buy electricity in kilowatt-hours ie 3,600,000 joules and for wholesale electricity to be traded in megawatt hours, at prices from about £20 upwards (and upwards.) Annual energy consumption for a whole country could be measured in Terawatt hours abbreviated TWh. This allows us to handle sources which do not work the full 8766 hours in a year. The admirable DTI publication Energy Trends [1] shows that the whole UK needed 2765TWh in the year up to March 2006. Scotland needs about one tenth of this.

Although electricity is very convenient and gets most of our attention it represents only about 15% of the final energy use and its generation from thermal plant is inefficient. We have become addicted to liquid fuel for transport and to gas for domestic heating. Liquid fuels are valuable because of the convenience of pipes and pumps to move them around and the very large amount of energy they can store.

For example one litre of petrol has about 33 megajoules of chemical energy. In contrast if you wanted to warm up your bath water by jumping into it through an air-drag free lift-shaft, you would have to jump from a height five times that of Mount Everest. This is not a good way.

Appendix B –

Accuracy of Evidence

During the first British Wave Energy Programme consultants working for the Department of Energy under day-to-day control of the UK Atomic Energy Authority produced reports on the performance and cost of various wave devices. In these reports they adjusted their own figure for the failure rate of static seabed marine cables from 330 kilometre years of operation per fault to 10 kilometre years. The figure for Norwegian cables was easily obtainable and was 600 kilometre years per fault. The consultant's adjustment is by a factor of 33 relative to their own first estimate and 60 compared to Norwegian data. It was particularly serious for deep-water offshore devices.

Officials in the UKAEA were 'against device teams contacting consultants' and wave energy developments were delayed by twenty years.

In the summer of 1982 a 43 kilometre cable was laid from the mainland to Orkney. It has now completed over one thousand kilometre years with no fault, already one hundred times better than UKAEA consultants had predicted.

A second example involves an enquiry by Sir Douglas Black into a cluster of child leukaemia cases around the BNFL plant at Sellafield *.

Paragraph 4.88 on page 81 of the report concluded:

> *'… to attribute these additional deaths from leukaemia to radiation would require that the total discharges from Sellafield site had been in fact at least 40 times greater than reported.'*

In other words if even more children had died from leukaemia, BNFL would have been even more innocent.

This conclusion was followed by a letter from one Dr Jakeman **, who had been in charge of measuring radiation round Sellafield, to say that his radiation measurements had been reduced by a factor of 40. This was later admitted by BNFL. Despite this admission Sir Douglas was not willing to change his conclusions about the leukaemia cluster but people learned a correction coefficient for information from the nuclear industry which may have bearing on the question about building more nuclear stations in Scotland.

The factor 40 is also the ratio of UK cleanup costs to the amount put aside in the United States [29].

Correction coefficients of similar or larger size exist about deaths and mutations following Chernobyl. The ratio of the IAEA figure of 4000 to the Russian Academy of Sciences National Commission for Radiation Protection in Ukraine figure of 500,000 is 125.

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