The Royal Academy of Engineering

Nuclear Power: Economics and Climate-Protection Potential

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Speaker:
Amory Lovins
CEO, Rocky Mountain Institute Inc

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INTRODUCTION

Sara Parkin
Forum for the Future

Good evening, everybody, and welcome to this meeting hosted by the Forum for the Future and the Royal Academy of Engineering. We are in partnership on the Engineer for the 21st Century initiative and this event is the first of what we hope will be many.

Sustainable development is a top challenge for us all. Some of those solutions, and perhaps many of them, lie with political will, but some lie with technology - either by applying known technology intelligently and in a modern way, or by revisiting the scientific principles to design new products and processes. Both will require absolutely top class innovation and some outcomes will be controversial, and this is why Forum for the Future is absolutely delighted to be in this partnership with the Royal Academy of Engineering, to provide a platform for public debate on the key issues, where technology and innovation are at the heart.

Where better or more timely to start than with energy? The UK is simultaneously reviewing its energy policy and its climate change strategy but how compatible these will be with each other or with the larger goal of sustainable development, I do not know. This is first because, personally, I do not think that the energy review is asking the right questions. For me, that includes how do I, as a consumer, obtain affordable, secure supplies of heat, power and light? It is the services of energy that I am interested in, more than the sources. These could be delivered differently for me, depending on where I live. Because those questions are not being asked, I am not quite sure how we will come up with a solution that provides that security, without harming either the environment or my health.

The second point is that for climate change sustainable development, or our energy futures, I am actually quite worried that there is not nearly enough investment in building the knowledge, skills and sustainability literacy that society needs so much. This last concern is one that features in Forum for the Future and the Royal Academy of Engineering's Engineer for the 21st Century partnership, where we are working with government, with engineering employers and with institutions to equip the new generation with the skills and modernised processes that they need to tackle these sustainable development challenges. Several of the young engineers who have participated in this programme are here today but I hasten to underline, patting my grey hair as I do so, that this is very much an inter-generational project and we have to stand on the experience of my generation so that the best of that can be taken forward by the next.

The first concern that the future energy debate is starting in the wrong place may be dealt with tonight. Therefore, with no further ado, let me hand over to our chairman for this evening, Professor David Fisk. David was Chief Scientist at the office of the Deputy Prime Minister until December and he is currently chair of Sustainable Development at Imperial College. I will hand over to David, who will introduce Amory Lovins.

Professor David Fisk: First, let me give an apology from Lord Broers who would have been delighted to have chaired this evening's meeting but, unfortunately, he is out of the country at the moment. He asked Philip Greenish to send the Academy's best man, but I am afraid he was not available either, so I am your chair.

It is a great pleasure to introduce Amory. I have had the opportunity to listen to him on a number of occasions over the last few years and never once has it been anything other than an extraordinarily stimulating evening. I am guessing that is why this room is so packed and full, and we will do our best to provide as much opportunity as possible for questions afterwards.

Amory almost needs no introduction. He is a MacArthur Fellow and a consultant physicist; friend and foe of the US DoE and the US DoD. He has 29 books to his credit and many of the people in the audience, whose faces I recognise, have well-thumbed copies of several editions of that great book, *Natural Capitalism*.

Amory will talk to us tonight about an article that he wrote just before the end of last year, which raises some issues about the competition that the nuclear industry faces in the way of doing things, and what it can provide.

NUCLEAR POWER:

**COMPETITIVE ECONOMICS
AND CLIMATE-PROTECTION POTENTIAL**

**Amory Lovins
CEO, Rocky Mountains Institute, Inc**

Thank you very much, Sara and David. Let me pay tribute to both the Forum for the Future and the Royal Academy of Engineering. It is terrific that they are in this partnership and it will be very important for the future of British engineering and much more.

I am here to describe the competitive economics of nuclear power and its potential to protect the climate. In that article, *Mighty Mice*, in *Nuclear Engineering International* last December, I opened with the very old story of two men who are out on a wild and barren plain. One of them spies a large bear running towards them at full speed and immediately started lacing on his running shoes. The other chap said, ‘What are you doing? You can’t outrun that bear!’ The first guy said, ‘I don’t need to outrun the bear!’ [*Laughter*]

It is very important to know, in any competition, who we are competing with and what it takes to win. I wrote the article because I did not feel that the nuclear power industry understood very well who its competitors are. As I go through the argument, perhaps you might form a view about that.

Q. How is climate protection like the Hubble space telescope?

Let me start with the context for the current nuclear debate, which is the absolutely correct and justified concern about climate change. There is not a problem with that, but climate protection is rather like the Hubble space telescope. How is that? Well, they were both spoiled by a sign error. You may recall that someone mixed up a plus and a minus sign in the formula for the curvature of the mirror, and this required a rather expensive partial repair.

Climate protection is similar, because the debate about it is all about cost burden and sacrifice and yet protecting the climate, as you will see, is not costly but profitable, because it is cheaper to save fuel than to buy it. Efficiency is cheaper than fuel. It is therefore correct to talk about an investment to save energy but there is also a return, and a very handsome return, on that investment. We seem to have forgotten the return, in talking about the investment. If, of course, climate protection is not about cost but about profit and competitive advantage, then that changes the politics quite fundamentally.

Global corporate leadership in profitable climate protection

Corporations generally understand this, and I will give a few examples of how they are acting on that understanding. ST Micro-electronics, for example, set a goal that by 2010 it would be emitting zero net carbon, despite making then about 40 times the chips that it made in 1990. We helped them to figure out how to cut their carbon-per-chip by 90-odd per cent, profitably. In fact, they have reduced their electricity use per standard wafer produced by six per cent a year, at a net profit so far of $50 million, and the average payback is two and a half years on the investment in improving their existing plant.

IBM similarly has cut its CO_2 emissions by 5.7 per cent a year so far, at a nice profit. DuPont set a goal that, in this decade, it would increase its energy productivity at least six per cent a year and make a major shift towards renewables for energy and feedstocks, and would reduce its greenhouse gas emissions by 65 per cent below the 1990 level. How are they doing? So far, they are 72 per cent below the 1990 level and, by the way, they have also met their quarter renewable feedstocks goal. They are producing 30 per cent more product with seven per cent less energy and so far they have made $2 billion on that deal.

BP has met its operational carbon reduction goals seven or eight years early at, they have actually said, zero net cost. Later on, they admitted that they had made $650 million by substituting efficiency for fuel.

As far as we know, every firm, or sub-national government, that has been trying to cut CO_2 emissions through energy efficiency has made money on it. So why is approximately 100 per cent of the political debate about cost rather than profit? It is as if the politics and the empirical evidence of business behaviour were on two different planets.

The climate problem is caused by one percentage point

Another interesting point about climate is that you could say that the problem was caused by one percentage point. Thus, modelling on Marty Hoffert's nice paper in *Nature* in 1998, Professor Kaya shows us that the rate of emitting CO_2 is the product of the population times GDP *per capita*, times the energy intensity of GDP, times the carbon intensity of energy. The economical assumptions for 110 years of average annual compound growth in these quantities are as shown here, and they net out to a one per cent net growth per annum in the rate of emitting carbon, which roughly triples the emissions by 2100 – heading rapidly towards Venus.

There is much debate about nuclear versus renewables and I will get into some of that later. That is the carbon-free energy term, or at least low-carbon energy term over here. However, I would like to focus for a moment on the four-fold bigger energy intensity term –

how rapidly can we reduce the energy consumed, to produce a dollar of GDP? Obviously, if that intensity decreased not by one per cent a year, as is normally assumed by economic theorists, but by two per cent a year, then that would cancel out the growth in carbon emissions – they would not grow. If you could have a little more than a two per cent a year decrease in energy intensity, then carbon emissions would shrink and we would be stabilising the climate, rather than simply experimenting with it at a slower rate. How plausible is it that we could profitably cut energy intensity not by one but by two per cent a year, or a little more?

How quickly have various economies cut energy intensity?

Here is how various economies at various periods with various price changes in energy have actually done so far. You will see that those shown in italics have achieved well over a two per cent a year decrease in energy intensity – China has actually averaged over five per cent a year for over 20 years now, and that was before they made energy efficiency their top national development priority last year. Thus, it is not at all clear that we are constrained to just one per cent a year for ever.

Reducing energy intensity

In fact, there are many ways to do this. Not only have advanced economies that paid attention sustained several per cent a year intensity reduction for years, and major firms six per cent a year, but you can do this through composition of output shifts – that is, less steel and cement per dollar of GDP, and more software and symphony tickets and insurance policies. There could be more sensible land use, so that you are already where you want to be and you do not need to go somewhere else; more mindful individual behaviour; more efficient energy conversion and energy distribution, as well as energy use, which is typically the biggest and cheapest opportunity. When you combine all of these things, it would not be so difficult to achieve well over two per cent a year of profitable reduction in energy intensity.

Nuclear power and oil are unrelated

I would like to make a number of comments about nuclear power. The first obvious point is that it is not significantly related to oil, even though the two are sometimes conflated. In the United States, less than three per cent of our electricity is made from oil and less than two per cent of our oil makes electricity – both declining. In the UK, those figures are both around one per cent, which actually includes some things that are not even oil, such as refinery gas, that are not broken out in the statistics. Worldwide, those figures are around seven per cent and falling. Note, that you can only displace oil-fired electricity once, and we have already done that.

Moreover, in the US – and I cannot obtain the figures for the UK – only one tenth of the oil that makes that three per cent of electricity is actually distillate and most of it is the gooey bottom-of-the-barrel, called 'resid'. Furthermore, oil fired power plants in general do not run much of the time, partly because oil is dearer, while nuclear plants must run steadily, for economic and technical reasons. Most oil-fired utilities and the grids that have them tend to be too small for standard nuclear plants and very small ones tend to become very dear.

It is quite true that nuclear could free up some gas, used to make electricity, although, once again, many of the same issues apply – especially in that many of those gas plants do not run that much of the time. However, this is not a competitive way to free up gas and there are much cheaper ones, that I will mention. There is also a much better oil solution anyway. More broadly, however, notice that power plants release two-fifths of US and global CO_2 and 30 per cent of UK CO_2. An all-sectors approach saves 2.5 or, in the UK, 3.4 times as much CO_2 as an approach that only does something about electricity. You need to deal with things like transport and buildings, and not just electricity and industrial process use.

Winning the oil endgame

So, more about oil. My colleagues and I put out an independent peer-reviewed study in September 2004. It is transparent and, so far, has not been argued with technically. It was co-sponsored by the office of the Secretary of Defense and the Chief of Naval Research in the US, and written for business and military leaders, based on competitive strategy, for cars, trucks, planes, oil and military. This can be obtained free and there have been over half a million hits on the download site so far, at oilendgame.com, along with the technical back-up. If you would like to hear more about it, I shall be giving a talk on it at Chatham House on 13 May at 1300.

Its thesis is arrestingly simple. It shows in detail, with 24 technical annexes behind it, that over the next few decades, say by the 2040s, the US could get completely off oil and greatly strengthen its economy, led by business for profit. We studied only the US but, working in 50-odd countries and having lived in this country for 14 years and kept up with it, I do not see any reason why very similar conclusions would not apply in the UK as well. Many of the technologies used to do it are completely fungible.

A profitable US transition beyond oil …

This slide shows what the US transition would look like. The use and imports of oil, instead of rising, would be turned downwards by redoubling the efficiency of using oil. This has an average cost of $12 per saved barrel – that is your $2000, ??revalised to five per cent real discount rate. I am assuming here that efficiency is adopted two-fifths more slowly than it was when we last paid attention.

We could then replace the other half of the oil with a combination of saved natural gas and advanced biofuels – chiefly, the cellulosic ethanol emphasised in the President's State of the Union message recently. Both have an average cost of $18 a barrel and so, obviously, with an average cost overall of $15 to save or displace a barrel, that is only about one-quarter of what we are paying now.

We know that this sort of thing works because we have done it before. The last time that the US paid attention to oil was in 1977 to 1985. In those eight years, GDP grew 27 per cent while oil use fell 17 per cent. Oil imports fell by 50 per cent, and oil imports from the Persian Gulf fell 87 per cent and would have been gone in one more year if we had kept that up. In fact, because so many countries saved so much oil so fast, it dropped OPEC's exports by half and it broke their pricing power for a decade because, as it turned out, countries like mine and indeed yours are the Saudi Arabias of negabarrels. We have more market power than OPEC, but ours is on the demand side: we can actually save oil faster than OPEC can conveniently sell less oil. We can run that old play much better with today's technologies: that was practice and this is real, and now you are here.

If we make the right choices, then by 2025 we could have invested, say, $180 billion in the US off-oil transition, half of it to re-tool the car, truck and plane industries, and half to build a modern advanced biofuel industry. This would have a gross saving of $155 billion a year and a net saving of $70 billion a year if what we saved was oil costing $26 a barrel. That was the official forecast for 2025 issued two years ago, when we started writing the report. You might think that is low now, and I do not think anyone knows what it will be, but everything on the margin is robustly competitive against $26 oil, refiners and acquisition costs. That was our benchmark. Notice, it is $70 billion a year cheaper not to buy the stuff. Assuming that all its externalities are worth zero – I know that zero is the wrong number, but it is a conservatively low number.

As a free by-product of profitable oil savings, by the way, we would cut CO_2 by 26 per cent. We would have a million new jobs, three-quarters of them in rural areas, and we would save one million jobs now at risk, chiefly in auto-making. That is quite an interesting proposition. Since the business logic is so compelling, we figured that it could actually be done without new fuel taxes, subsidies, mandates or even new national laws – but all administratively or at a state level. It would not be necessary but certainly helpful to have public policy that supported, not distorted, the business logic. However, overall this is very much a business-led transition, and it has been very well received in early stages of implementation by the five sectors concerned.

Vehicles use 70% of oil, but integrating low mass and drag with advanced propulsion saves ~ 2/3 very cheaply

The key to this, technologically, is to treble the efficiency of cars, heavy lorries and jet aircraft. This turns out to have quite a low cost of saved energy, which is very competitive with present fuels. You do this basically by ultralight weight with modern materials, with very low aerodynamic drags and, for wheeled vehicles, rolling resistance, and advanced propulsion, such as hybrid electric drive for cars.

These are just for illustration for carbon fibre composite concept cars, with some interesting properties. This particular one does 250 km/hour and uses 2.5 litres per 100 km, although not simultaneously. Our big analytic surprise was that the ultralighting with, say, carbon composites or, for that matter ultralight steels, that doubles the efficiency of these vehicles beyond, say, hybrid alone, is free. This is because the cost of your materials is paid for by simpler auto-making and by a two- or three-fold smaller propulsion system – because that is all it takes to make it go.

These demand-side technologies are continuing to improve much faster than even the stunning advances in finding and lifting oil and so the efficiency resource as a whole, whether for oil or electricity or gas, keeps getting bigger and cheaper, because the technologies and knowledge of how to apply them improves faster than we use them up.

[*Slide*]

By the way, here is what a particular version looks like. This is a design that we did with a British tier 1 engineering firm and another in Germany in the year 2000. This is the basic, uncompromised, five-adults in comfort, two cubic metres of cargo suburban assault vehicle that can haul half a tonne up a 44 per cent gradient, has quite respectable acceleration – raised 47 per cent as much as the steel version, but is safer even if it hits one, because these materials can absorb up to 12 times the crash energy per kilo of steel. The fuel cell version would get 136 miles per UK gallon with a fuel cell, or 80 with the petrol hybrid. The petrol hybrid version would have a dealer price, a retail price, $2,500 higher than today's equivalent steel version, and that would be a one-year payback at British fuel prices, or two years at US fuel prices.

2025 US oil demand-supply integration

Here is how all the pieces fit together. Rather than the officially forecast need for 28 million barrels per day of petroleum products in 2025, we could knock off nearly eight of that with $12 per barrel efficiency by then, and still be in the process of saving another seven, as we gradually turned over the light vehicle fleet. We would need 20 at that point, of which six could come from biofuels, bio-materials, bio-lubricants. Nearly two would be displaced by substituting saved natural gas – we can save half the gas in the country at under $1 per gigajoule, which is about one-fifteenth of the recent price.

Then we are projected to get about eight of domestic production, not counting areas like the Arctic National Wildlife Refuge, which is not yet allowed. We would still need five from somewhere else, and there are a number of ways to do that. We could buy more efficiency, since we are paying an average of $12 for it, to save oil costing much more. Perhaps we should wait a little longer and get the rest of the efficiency implemented, or we could continue to buy oil from, say, Canada and Mexico, or by then WTO will have dropped the discriminatory tariff that the US illegally uses to protect its maize farmers and so then we would let in Brazilian ethanol that they would love to sell.

I have not yet accounted for two-thirds of the saved natural gas. That two-thirds – because we only used one-third up here [*on slide*] – could actually replace this balance term or, if more profitably and efficiently we converted it to hydrogen, it could also displace the domestic oil.

There are other ways to do that, too. For example, wind power just in North and South Dakota, could make 50 million tonnes a year of hydrogen, which would be enough to run at these levels of efficiency every highway vehicle in the United States. There are also other options but, at any rate, this is a large and varied menu.

Two 1989 climate-strategy cases that scope the world conditions

There is an equally large and varied menu of ways to solve the climate problem. Let me just cast your mind back to 1989, when there were two nice studies that pretty much scoped the range of the world's conditions. One was for Sweden, from the state power board, Vattenfall. Birgit Bodlund *et al* published *The Challenge of Choices*, a rigorous analysis for a country that is cold, cloudy, northern, full of heavy industry and rather efficient to start with. They found that half of Swedish electricity, using late-eighties technologies, could be saved at a four-fold lower cost than making more. If you combined that doubled end-use efficiency with a little fuel switching and operating most of the plants that emit the least carbon, you could achieve the forecast economic growth, shut down the nuclear half of the power supply – as 81 per cent of Swedes said they wanted in a referendum in 1980 – and you could reduce meanwhile the heat and power sector CO_2 emissions by one-third and cut the cost of electric services by $1 billion a year.

When the CEO read this, he ordered to be removed from it the usual disclaimer saying that it did not represent their official view. Nonetheless, the support was largely suppressed by other interests and it is little known. In fact, three years later, the Swedish parliament's energy committee had never heard of it.

In India, there are pretty much opposite conditions. Professor Amulya Reddy at the Indian Institute of Science, did a nice roadmap for the state of Karnataka. He showed how a little efficiency, which was nothing like the Swedish case; some natural gas and some CHP from sugar cane residues; a little biogass and producer gas; a little solar water heating and small hydro - from far from a comprehensive menu in other words, could achieve much more and faster economic development. It would have three-fifths lower electric demand, two-thirds lower cost and only two-hundredth as much fossil fuel CO_2 as the utilities' official plan, which was rejected – but unfortunately so was his.

In both cases, however, it is interesting that the efficiencies monetary savings – it being cheaper than any sort of supply – more than paid for the renewables. Therefore, major carbon savings in both scenarios, for both countries, were better than free. This is a very general conclusion that has turned up in many countries that have done such careful analysis. This is all with 1980s technologies and it is without design integration, which I shall talk about a little more later.

Global nuclear expansion is coasting to a halt

Meanwhile, nuclear expansion has been quite ambitious during the seventies and eighties, but it is coasting to a halt – whether you look at the number of reactors in operation, or the orange curve [*on slide*] which is their installed capacity. This continues to drift up a little as reactors are uprated, and they also tend to be operating a little more reliably.

Average reactor in 2005 was 21 years old

Unfortunately, however, they are growing old – with the average reactor last year being 21 years old, as, coincidentally, was the average one permanently retired. When you have this sort of age distribution in the demography of the power plants, they start to retire after a while. In fact, to offset the planned retirements over the next nine years, 73 reactors not yet being planned, plus all the ones now scheduled, would have to be built – but I do not think anyone expects that could happen. In fact, if China built all of the 32 new units that its more enthusiastic planners talk about to 2020, which would be an heroic task, this would scarcely cover 10 per cent of the plants that, by then, will reach the age of 40 worldwide. This, by the way, is from a nice paper in *Nuclear Engineering International* last June.

Global nuclear capacity is about to start a long, inevitable decline

The obvious conclusion is that, starting late in this decade, the global nuclear capacity starts a long decline, which goes faster in a mirror image or an echo of the original construction peaks in the seventies and eighties, and then gradually tapers off until they are all gone by 2050. This assumes that a plant retires after 40 years of mean lifetime, or 32 years in Germany as required by law.

Nuclear's 'small slow' decentralised supply competitors are growing far faster

What is happening meanwhile in competition from micropower? Here is what happened in the empirical data through 2004, and what the respective industries projected would happen after that, as of the middle of last year. For comparison, nuclear is shown in the heavy red line on this slide, and the vertical access shows how many net gigawatts of capacity were added each year. You can see that this is projected to decline to very nearly zero by 2010. Remember, that is net additions – net of retirements – and so that is consistent with what I showed you earlier about the demographics of the fleet.

As a leading indicator of whether we might make up for that by new build, this little dash-line is the new nuclear construction starts. Thus, if you add five or six more years to that, you would then get the construction resulting from that, and nothing we can do now will affect how much is built in 2010 – or at least, not affect it upwards.

Meanwhile, here are the annual capacity additions for wind, for decentralised fossil fuelled combined heat and power (CHP), and the black line is the geothermal biomass and small hydro, while the blue line indicates photovoltaics which, this year or next, will probably exceed the new nuclear construction starts in capacity. That is not bad for the most costly and futuristic of the renewables. Of course, you have to add all these up, because these are individual technology curves. Therefore, in 2004, these micropower supply side competitors added 28 gigawatts, whilst nuclear added 5 gigawatts. In 2010, the base forecast is 84 versus 0.5.

Market reality: low-/no-carbon decentralised sources have eclipsed nuclear power

If you then look at the graphs, both historic and going forwards from 2004, then for capacity worldwide and annual electric output worldwide, the brown part is the CHP. Two-thirds of that is gas-fired, and so that reduces carbon emissions per kilowatt hour by a factor of at least two, compared to what it replaces. For those wondering what micropower is, the CHP counted includes gas turbines up to 120 megawatts, engines up to 30, and steam turbines of any size but only if they are in China – otherwise they are omitted altogether. We do not have that information yet, so this is an undercount. The turbines and engines counted are only if they do CHP and not if they are just pure generators. Also, anything under 1 megawatt is omitted.

The coloured parts at the bottom are the renewables but we are only counting hydropower up to 10 megawatts electric. The small hydro is the red part; wind is denoted in blue; green is biomass and waste; and the others are geothermal and photovoltaics. You will notice that, in 2004, these low- or no-carbon options added three times as much output and six times as much capacity worldwide as nuclear power added. In fact, they surpassed nuclear power in capacity in 2002 and, in output, in 2005.

The industry projections show that, by 2010, micropower supply would be adding, on average, about 160 times as much capacity as nuclear will add in that year – and, remember, it is too late to change that. Here, I am not counting savings of electricity, which are probably bigger than the micropower additions, but we do not know that for sure because no one is tracking them carefully. However, it is obvious from the national data that we have that the total decentralised capacity additions in 2004 were at least 10 times as big as the capacity that nuclear power added.

So, first of all, anyone who claims that decentralised options – supply side, demand side or both – are small, slow and futuristic, should really examine the data. In fairness, we only published the data last June and nobody had added them up before. Then Eric ??Martineau, formerly of Lawrence Berkeley National Laboratory, and now of Xinghua university in Beijing, published a very similar and even more detailed assessment in November. He came up with the same numbers within a few per cent – except that he used the Chinese convention that small power goes up to 30 megawatts, so he got a little more. Notice that all of this happened also without carbon taxes or trading. Kyoto had not yet entered into force.

Nuclear power's fatal competitors

In search of a hypothesis for why micropower might be walloping nuclear so badly in the market place, I thought it would be useful to plot a graph showing the levelised cost in 2004 dollars of delivering a kilowatt hour, or of saving it, either from remote sources which require a nominal distribution cost to get to your meter, or from onsite sources which are already delivered, so that they do not incur that 2.75 cents charge which, by the way, is certainly an understatement. Your actual costs may vary but I did the analysis in a way that favours central plant. That is all that most analyses consider and, to be extra conservative, I baked into the numbers whatever subsidies these plants in the US already had in 2004, which are often very large, and I have not counted any reserve margin. I will come back to that later.

The economical study, the most careful one done from empirical data, is by an MIT team in 2003, led by two former Deputy Secretaries of Energy. It was very carefully documented and it shows about a 7 cents cost of producing a new kilowatt hour and then, when you add in the delivery cost, you come close to 10 cents – delivered to your meter. If the new subsidies just added roughly 3.5 to 4 cents per kilowatt hour, and were extremely successful in reducing cost and construction time and eliminating the market risk premium on nuclear, and cutting operating costs, then you would get down – said the MIT study – to about here [*on slide*]. There are differing views as to whether that is plausible or not.

Meanwhile, they said that a coal plant was already a little lower than that but, if you had a $100 per tonne of carbon tax on the emissions, then it would rise to roughly where nuclear started. Similarly, combined cycle gas would become dearer, although not by as much, because it is not as carbon intensive, if you had that $100 per tonne carbon tax. These, however, are not the only competitors, even though they are the only ones that the MIT study looked at. In fact, the ones that are doing better in the market are not in there at all, so let us look at those.

Let us start with windpower. I have assumed a busbar cost of 3 to 3.5 cents per kilowatt hour, because the last 2.7 gigawatts installed in the US had a median of 3.37. Some of them, however, were as low as 1.5 cents, so that there is considerable scatter, with some of them up around 5 cents. That is all busbar. You then have to add the delivery costs, because the wind farm is some way off. Then, to make it fully comparable with central station, I added more than enough money to firm this into a fully despatchable resource, as a number of our utilities now do, or you can do it in virtual peakers based on demand response. This means that you can have the power whether the wind is blowing at the time or not, so that is already included there.

If you were to take away the production tax credit, the modest subsidy wind receives to help it compete with the larger subsidies to central plant, you would be back here. Note, however, that I have not subtracted the subsidies that the central plants already have: for nuclear, that is about 0.8 to 4.2 cents, so it would be somewhere up in the ceiling. Meanwhile, wind is becoming cheaper – within one nuclear lead time, both industry and government expected it to be down here, and some are already a good deal cheaper than that.

I take wind here as a surrogate for all renewables but obviously, if you look at how well a diverse portfolio of renewables is doing in the market place, you will have to conclude that there are many others that the market perceives as cost effective as well.

Then there is CHP. If they pay $1 per gigajoule more for gas than the utilities pay for a combined cycle plant, then garden variety industrial co-generation is here. If you make heating and cooling and power together in a building, it is about here [*on slide*], depending how good you are. If you use recovered waste heat in industry, then actually it is often a negative cost but, to be conservative, instead of that – which might confuse people – I showed the all-in price that actually projects sell power for, the difference being a very juicy margin.

The cheapest competitor is then typically end-use efficiency. In business sectors, it is about 1 cent per kilowatt hour or less but, if you do a lot of residential shell retrofits, or are not as good at it, it costs perhaps a few cents per kilowatt hour and if you are very good at it, new or retrofit, it often has a negative cost. Once again, these are all empirical data and it is obvious, just from looking at this, that you have to look at the whole competitive range, otherwise you are like the chap trying to outrun the bear.

Renewable energy cost trends

This may indeed be a lot of mice but, if there are a whole lot of them, perhaps you should worry about them – especially because they are becoming cheaper all the time. This was updated in December and it is the National Renewable Energy Laboratory analysis in the US, of how various renewable power prices are continuing to fall and are projected to fall further. Actually, this does not count any of the breakthroughs that are now clearly in view. For example, here is an Australian photovoltaic concentrator design, that its inventor thinks is about 8 US cents per kilowatt hour in private production, and 2 cents per gigawatt scale.

Electricity supply (and more): what's the right size for the job?

This raises the question: what is the right size for the job? In the first century of the electricity business, power plants cost more but were less reliable than the grid, and so it made sense to build a bunch and have them back each other up through the grid. In the past few decades, however, that has stopped being true and now power plants are cheaper than the associated grid, but much more reliable. So now, if you want to have cheap and reliable supply delivered to the customers, you should make it near them – that is, in distributed fashion. That may help to explain the observed market behaviour in the decline of the attractiveness of central thermal plants, especially in the North American market. Conversely, distributed generators have a very substantial market share in a wide range of industrial and developing countries by now, because they are not just cheaper but they are faster and they have lower financial risk – something that investors rightly care about.

"Distributed benefits" change the game

In fact, if you look at our *Economist* book of the year, *Small is Profitable*, that came out in 2002 – and you can obtain it at smallisprofitable.org – you will find a quantification of 207 so-called distributed benefits, hidden economic benefits of making electrical resources the right size for the job. These collectively increase their economic value by about a factor of 10 – although, of course, the details are site-specific. Then my colleague, Dr Joel Swisher, who is a civil and mechanical engineer, did a specific application of this to fuel cells and showed that, even hand-made by PhDs on a lab bench at $3000 per kilowatt, you can make those compete nicely if you put them in the right place and use them in the right way, even in rather large applications like retrofitting into existing chip-fabs.

Whence the order-of-magnitude typical value increase?

Where does this big 10-fold value increase come from? Most of all, it comes from financial economics, of which I will give an example in a moment. This is often worth close to a factor 10 increase in value on its own for renewables, and about half of that for non-renewables.

There are roughly factor two or three increases in value from electrical engineering, with things like graceful fault management; avoiding distribution investment and losses; sharing loads more evenly across circuits so that you reduce heating and make equipment last longer; reducing tap changes to extend equipment life; getting free reactive power control, and so on. These all have quantifiable values, but the value is actually much higher if you have a congested distribution grid, or if you need particularly high quality or reliable power – for example, for digital loads.

There are dozens of miscellaneous benefits that, collectively, are worth about a factor two in value, or more if you can use previously wasted heat. There are then externalities, which may be important or even decisive in actual citing and investment choice, but I have not counted those here.

207 distributed benefits: ~ 10 x value

Just to dig into the financial and economics benefits, I will give one case. This is the art of minimising regret – that either what you did, you wish you had not done, or what you did not do, you wish you had done. Using the tools that portfolio managers use to manage their assets, you can find, for example, in a closed forum analytic solution, as Tom Hoff has done, how much it is worth paying to reduce financial risk by buying small, fast options, rather than big, slow ones.

If it is slow, then you are more exposed to things changing. You may find changes in expected demand patterns, interest rates, regulatory rules, competing technologies and so on. Financial risk is lower if you can get built quickly and start producing revenue straight away. For example, if you are willing to pay $1000 per kilowatt for a 50 megawatt unit that takes two years to install, then it turns out in a typical substation support application that you should be equally willing to pay 2.7 times as much - $2700 per kilowatt – for a 10 kilowatt resource that you can install over the weekend. This will give identical financial performance when properly adjusted for financial risk.

That is just one of many phenomena that make financial risk lower for small, fast units. Another, for example, is that renewables are not exposed to fuel price volatility. Wind developers who sell their wind at a long-term fixed price contract have roughly an extra 2 cents per kilowatt hour for it, because they shield their customers from that financial risk of gas prices running crazily up and down. There are many more.

Note that the analysis that I presented earlier, that wonderful chart of all the competing costs, does not count any distributed benefits of the decentralised ones. That would just make the case a good deal stronger – roughly a factor of 10 stronger. Instead, I did their conventional engineering economics and left out all these 200-odd benefits of distributed techniques.

Two 1990 supply curves for saved US electricity

Let me turn for a moment to end-use efficiency, which you might have been wondering about. For example, how big is it and how expensive is it? In a joint scientific American article back in about 1990, the Utilities Think tank in the US, the Electric Power Research Institute (EPRI) and I presented our respective findings. EPRI said that by 2000, you could get the amount of savings shown here on this slide in US electricity use, plus a further nine to 15 per cent that they thought would happen anyway. So, add nine to 15 visually to this graph – the percentages are shown here – and you have about 40 to 60 per cent saving, at an average cost of somewhere around 2 cents a kilowatt hour.

Our assessment showed a long-term potential for retrofit that was even larger, and the differences are largely methodological and we agree what they are. In other words, it does not really matter who is right, because these are both very large sets of savings at very attractive costs. In case you are wondering where our numbers came from, they are measured cost and performance data for about 1000 technologies, exhaustively documented in the late eighties and early nineties. Once again, this is all old stuff – this is 1989 technology and so now, 17 years on, we are finding that the savings are becoming bigger and cheaper.

[*Slide*]

Let me give a few examples of how that is going – and, by the way, there are similar findings in Sweden, Denmark, Germany and the UK, by very careful analysts.

Why is the efficiency resource getting bigger and cheaper even as we use it up?

Why is this efficiency resource getting even bigger and cheaper? It is because most of the technologies involved are doing the same thing as the consumer electronics do. We are mass producing them, often in Asia. The electronics become cheaper when you make a lot of them – there is more competition and there are better technologies. Here are examples, without even correcting for inflation – and these are all in nominal dollars.

Compact fluorescent lamps have come down by a factor of [?4:10] in price over 20 years; electronic lighting ballast by a factor of roughly eight, and they are more efficient. The most optically efficient kind of lighting fixture was the dearest option but now it is the cheapest. Industrial variable speed drives are a factor of three or so cheaper – so cheap, in fact, that for small and intermediate-sized motors the contractor, in competitive US markets, will often give it to you for free - otherwise, he would have to pay more for the self-start, to buy some protective kit.

Window air-conditioners are two-fold cheaper but more efficient. Window coats that let in light without heat are four times cheaper than five years ago. Also, the delivery process is becoming cheaper, just through scale-up and learning. The biggest and least exploited resource is the proper integration of efficiency technologies, which typically makes very big savings cost less than zero. Let me give an example or two.

-44º to + 46º C with no heating/cooling equipment, less construction cost

If you come to visit me in the Colorado Rockies at 2200 meters elevation, where the temperature can go to -44º Celsius, if you come into the middle of my house, in a climate that can have frost any day of the year, and 39 days continuous mid-winter cloud, there you are in January in my passive solar banana farm where I have harvested 28 banana crops so far – and, by the way, I have no furnace. I did not put in a furnace because I did not need one, and it was cheaper upfront not to have one, because the heating system would have cost more to install than I paid to install super-windows and super-insulation and ventilation heat recovery. So the house became cheaper to build, using only one per cent of the normal amount of heat. I get that last one per cent for a wood stove, because I have to burn the energy study somehow! [*Laughter*]

I reinvested that, plus a further $16 per square meter, to save also 99 per cent of the water heating energy and 90 per cent of the household electricity. So, if I bought that at the utility 7 cent tariff, rather than making it with solar as I do, it would cost about £3 a month for 372 square meters. I know that is a large amount and we could actually save two-thirds of that now, but I have not bothered yet. In fact, all of the savings were 10 month payback, put together in 1983 – but now we can do much better.

[*Picture*]

Here is an ordinary looking, ugly American tract house, with a big garage in front saying, 'cars live here'! This is in a climate that can go to 45 or 46 degrees, and this one provided comfort with no air-conditioner and, if not a one off but a general practice, would have cost less to build and maintain than a conventional house of that size and style. It would have saved a factor of five against the strictest standard in the country, or a factor 10 against a normal US house.

[*Picture*]

What about a hot humid climate? That is where most of the world's people live. In Bangkok, here is a lovely new 350 square meter house built a decade ago, using one-tenth of the normal air-conditioning energy to provide superior comfort at no extra construction cost. So, here we have pretty well scoped the range of the world's climates and, for houses that have a large surface to volume ratio, so that they are particularly hard to do this with. In every case, integrated design – getting multiple benefits from single expenditures – makes very big savings cheaper than small ones, or no savings.

Old design mentality: always diminishing returns

We are not confined to diminishing returns and the economic theory that says that, the more energy you save, the more and more steeply the cost of the next unit of savings goes up, until it becomes too dear and you have to stop. That is sometimes true for components, but often not, and it is definitely not true if you properly combine them. At first, to be sure, as I add insulation to my house in the Rockies, I have diminishing returns, because that is how insulation works. However, when I add so much insulation that I no longer need a heating system, then I save its entire capital cost, which is even larger, and therefore I end up with a 99 per cent saving on space heating energy, at less cost than if I had set out to save little or nothing. Rather than getting to it the long way round, we can tunnel through the cost barrier, heading straight for that design destination – and we do.

Examples from RMI's industrial practice (>$20b of facilities)

For example, in industry, I will give a few examples from our practice which has redesigned over £20 billion worth of facilities in 22 sectors so far. You can save about half of motor system electricity with about a one-year payback by doing the right seven things first and getting 28 more savings as a free by-product.

You can achieve similarly rapid returns, saving over half the energy used to produce chilled water and clean air in existing chip-fabs – eight so far. Texas Instruments is finishing a new fab next month, which will save about one-fifth of the energy and one-third of the water, but will cost 30 per cent less to build, and that is why it is being built in Texas and not China – because it was cheaper, saving 1000 high-tech jobs. The next one, using a couple of further measures – I am sure that the biggest ones will save over half the energy and cost even less to build.

The most efficient oil refinery in Europe could be retro-fitted, we have found, to save 42 per cent of the energy with about a three-year average payback. A typical North Sea oil platform could be retrofitted to save half its electricity and to get the other half from stuff being thrown away. A $5 billion Fisher Tropes plant could be built for of the order of one-fifth cheaper, and saving over half its energy, if re-designed.

A very large gas liquefaction plant could save over 40 per cent of its energy on retrofit. If it were new, there would probably be about a 60 per cent saving at lower capex. The world's biggest platinum mine could save about 43 per cent of its energy with a two or three year payback and better worker productivity, health and ergonomics, and better value recovery.

A new data centre could save a factor of nine on energy, become more reliable and be quicker and cheaper to build. A new supermarket could save 70 to 90 per cent, while a new chemical plant could make 75 per cent savings at about one-tenth cheaper and faster to build. The list goes on like this.

My very favourite example was that of a run-around pumping loop for heat transfer to a factory. They observed a 92 per cent saving in pumped energy by the radical expedient of using fat, short, straight pipes, rather than thin, long crooked pipes: this is not rocket science but it is good Victorian engineering rediscovered. By the way, we discovered afterwards that the design was messed up and we did not optimise properly – had we done so, we would have saved more like 98 per cent and it would have cost even less.

Here, I am not counting all the other nice things you can do for better processes, catalysts; pinch; microfluidics – shrinking chemical plants to the size of a water melon; producing things the way nature does; dematerialising our products and making them last longer; recovering materials. When you add all of this, there is no end – for at least a century – to radical savings in industrial energy at a profit.

Efficiency works in California … and similarly in New England

By the way, efficiency actually works, and this is not just theoretical. If you look at the US generally versus California, for example, the *per capita* use of electricity, whilst growing in most of the country, has stayed flat in California for 30 years. This is because they rewarded their utilities for cutting your bill and not for selling you more energy, as most places do.

They put in better appliance and building standards earlier than the rest of the country. In Vermont, this *per capita* use is actually going down, because they are serious about capturing the opportunity.

Levelised cost of electric end-use efficiency

We have a good deal of data – with which I shall not bore you – on the actual costs of end-use efficiency. Notice, for example, that for the big Californian utilities, they are all converging on about 1 cent per kilowatt hour for the non-residential cost of savings. There are many other programmes – such as the 237 commercial and industrial programmes of 58 utilities – and all of the programmes worked out here to about 0.3 or 0.4 cents per kilowatt hour. Utility costs are about twice that, so still under 1 cent societal cost. There is thus a great deal of experience with what these programmes, carefully audited, actually do cost. Obviously, we should build on the best ones, even though what is shown here is typically more of an average.

Efficiency is a rapidly moving target

Efficiency is also a rapidly moving target, as is illustrated by what happened to refrigerators. The energy use of a typical US refrigerator kept going up and up and up, partly because they were getting bigger, as indicated by the red curve on this slide. However, then California, followed belatedly by the national government, introduced standards, and energy use started to go down significantly. In fact, that is now the standard worse than which you cannot sell. By the way, this was the standard 1995 model on the Japanese market, but the latest Japanese model is down here because they started paying attention.

[*Picture*]

However, there is still some way to go. That is what I have had in my house since 1983, and that is the state of the art, which is Dutch.

Efficiency standards needn't raise costs

By the way, these improvements do not increase costs. This is what happened to the real price of a fridge – shown by the magenta points – even while the energy use fell radically. There are some interesting lessons here.

Nuclear power's fatal competitors

Let us go back to this graph, which looks a little busy when it is all in place – but I presented it bit by bit, so I hope it is clear what I did there, and that these are all the same numbers.

There is a rather important point about these differences in cost, which is that they give you different amounts of climate solution per dollar. Suppose, for example, that you spend 10 cents to buy and deliver a new nuclear kilowatt hour. That will displace one kilowatt hour of coal power and they are pretty much equivalent, except in carbon emissions and some other attributes that I will not worry about here.

The trouble is that if, instead, you had spent that 10 cents to buy something cheaper, you would have got more of it. That is what cheaper means. Properly correcting for the carbon emissions from the fossil fuelled – typically gas-fired – co-gen here, notice that you would have several to many times as much coal displacement per 10 cents spent if you bought something cheaper than if you bought something dearer.

This is a rather important because, if climate is a problem, then we need to buy the most solution per pound sterling, and the most solution per year. If we buy a dear solution rather than a cheap one, we are actually making the problem worse than if we had bought the cheap one first. The order of economic priority is the order of environmental priority: this is a very basic matter, which economists call 'opportunity cost', whereby you cannot spend the same pound on two different things at the same time. When you buy one thing, you forego buying another thing instead. That argument needs to be addressed by those who believe that nuclear power will help to abate climate change. On its own, it would do but, in competition with everything else on offer, it would not – it would make things worse.

All options face implementation risks: what does market behaviour reveal?

To be sure, every option for protecting the climate or for keeping the lights on presents risks of implementation. Dry hole risks, you might call them – perhaps it will not happen, or it will not happen on time. What does observed market behaviour actually reveal about that risk?

There was an interesting experiment in California in the eighties, when they had a pretty level playing field for four years. At the time, they had a peak load of 37 gigawatts. Within those few years, they were offered, or had actually signed up, 143 per cent of their entire peak load in alternatives – both supply side and demand side. Notice that new offers of generation – most of it renewable – equivalent to one-fourth of their total peak demand were arriving every year, and all of this at attractive prices. In April 1985, they actually had to suspend the bidding because, if it had gone on one more year, they would have had to have shut down every fossil fuelled nuclear plant in the state which, in hindsight, might not have been such a bad idea.

If you are wondering about what is the ability of the competitors who are doing so well in the market to displace nuclear over the long-run, what is their ultimate size and what can they do? Well, if you believe the Electric Power Research Institute, then end-use efficiency - 40 to 60 per cent of US electricity at less than the cost of running a thermal plant and delivering its power – even if building the plant were free – can come from end-use efficiency. Or, if you believe me, it is more like four or five times instead of two or three times nuclear's 20 per cent market share, but it does not matter who is right, because these are both very big figures. Efficiency alone is several-fold bigger than nuclear, even assuming nuclear capital cost is zero.

CHP in industry alone is comparable to nuclear, and not even counting buildings – which is a very large potential, especially now that it can go to domestic scale.

Wind power has recently been shown to be at least twice as big in US practical potential in high quality sites as total electricity use, in both the US and China and, globally, about nine times total electricity use. That counts offshore, out to 50 metres depth.

I am not counting here other renewables which are collectively even bigger than wind, with photovoltaics in particular being almost unlimited.

This brings me to a concern that has often been expressed about what happens with variable resources. The wind does not always blow and the sun does not always shine, but I would argue that if you have diverse, dispersed and properly forecast variable resources that are properly integrated with both the supply and demand side on the existing grid, then the variability and indeed land use concerns become important. It is important to understand that all sources of electricity are variable or intermittent. 'Intermittent' means that they stop altogether from time to time, while 'variable' means that they go up and down and that there is some distinction. They differ in this regard only in how big their failure is, for how long or for what cause, and how predictably: there is no perfectly reliable source of electricity.

Baseload ≠ "big thermal plant" (cf Telephony and Computing)

It is quite fallacious to equate the so-called baseload demand, which is usually misdefined in the first place, with a big thermal plant. It is as if you had said that you could only do telephony on a national scale with tens of millions of people by having large switching stations handling landlines. That is what we used to think that, but we not longer think it because of mobiles.

It is as if you said that we have a lot of computing to do, so that we can only rely on mainframe computers run by high priests – and we used to think that, too. Are any of you from the paper, tape and punch-card days? I remember those days, when you would get your job back a few days later. However, we now know that distributed computing works just fine and, of course, arithmetically, a 1000 megawatt power plant does exactly the same thing in producing electrons as a 1000 x 1 megawatt units, or 1 million x 1 kilowatt units. Except, actually, it is better than that because, in practice, if you have many small units they will be collectively more reliable than a few big ones, even if they are all equally reliable. The reason is that you will not have a big unit failing all at once – or rather, I should say, you will not have all the little ones failing all at once, at the same frequency, as the big unit will certainly fail from time to time.

By the way, generating near the customers saves you the dominant source of failure, because 98 or 99 per cent of outages in the US – and I dare say that it is probably not very different in the UK – originate in the grid. About 95 per cent are in distribution, which is closest to the customers, and so you have to get quite close to the customers in generation in order to avoid that dominant cause of power failures and glitches. Distributed generation does that, while remote does not.

It is quite true that wind array sometimes shuts down, and I will show you the statistics in a moment, but they are not the only ones that do. The average US nuclear plants shut down for an average of 37 days at intervals of every 17 months, which is chiefly – but not entirely – for planned refuelling, and sometimes it is a forced outage. Also, many nuclear units can go down simultaneously, without warning.

This is what happened in August 2003 to nine US nuclear units. We had a sudden black-out, owing to bad grid management and these 7.8 gigawatts/nine units were humming along, perfectly fine, as they often do. They were quite reliable except that they then failed – and then look at how long it took to get them back into service. It took a fortnight altogether. In the first week, they were 59 per cent low on capacity; the first three days, 97.5 per cent low. That is not a terribly reliable resource when you are trying to re-establish the grid. If you have very much of it down for that much, you just cannot get the supply-demand balance back to start the conventional plants, while you are busy coping with zenon and samarium instability and the other bad things that happen if a nuke shuts down rapidly and without warning.

Same for UK reactors

The same is true in the UK. Their availability varied widely and the average has been about 74 per cent so far, but all central stations here – as everywhere – are intermittent. The forced outage rate on US fossil units has averaged about eight per cent over the years and, in recent years, for British reactors, it has been something over nine per cent. As you can see, Hinkley has a better average cumulative capacity factor than the average UK reactor, but look at what alas happened in March 2004 with an unplanned outage. They were doing power ascension and re-start and they had another problem which then lasted longer than expected.

I do not think any wind farm in the UK would have such a long outage, let alone without being able to forecast it. This makes me wonder therefore, for this nuclear plant, or any nuclear plant, or any central plant, what is the balancing cost? It is not zero, as is sometimes assumed. We call it the 'reserve margin', and 'spinning reserve' and things like that, but it is not zero. It is better to be approximately right than precisely wrong. We should count balancing costs for all resources and compare them symmetrically.

34 years of UK wind data from 66 onshore sites (>15M site-h)

A wonderfully definitive paper was recently published by Graham Sinden of Oxford, on British wind data from 66 onshore sites – over 15 million site hours of data, and it is in press at *Energy Policy*, but you will find it on his website. It is quite encouraging that the realistic long-term capacity factor at the current stage of UK wind development is 30 per cent. However, this rises later on – perhaps to 35 per cent, although that is not clear yet – as you go more offshore, and more to Scotland, where there are better wind regimes, and perhaps also with technological improvement.

The annual range, if you are looking for year to year fluctuation, has a standard deviation equal to 7.5 per cent of the average annual production, which is not too bad. That is much less effect than you have from things like coal strikes, gas prices or nuclear problems. Also, both seasonal and diurnal variations of wind output correlate very nicely with loads. One-third of the entire annual output is during the three winter months, compared to only one-sixth during the three summer months, which have much lower load. Wind is also a little stronger in the day time than at night.

The correlation of the sites between the output at different sites falls with their distance, and I will show you a graph later. If you diversify sites, therefore, you can smooth the output and you can deliberately maximise this by going for sites that are least correlated with the ones you already have. Interestingly, the extreme conditions turn out not to be problematic. Not for a single hour in the 34-year record here was the entire UK becalmed nor too windy for the machines to operate.

Of the 20 per cent of output hours that would have zero output at a given site, about 99 per cent are because there is not sufficient wind and not because there is a fierce gale which means that you have to shut down the machine for its own protection. Under-speed, not enough wind, affects over half the country for less than 10 per cent of all hours - over there-quarters of the country, for 0.8 per cent, but only 0.2 per cent in winter when there is higher load. Over 90 per cent of the country, it is for only one hour a year, and for under 20 per cent of the country, for over 60 per cent of the hours. This is actually a very nice wind regime. The most extreme over-speed similarly affects 43 per cent of the UK for only an hour every 30 years. It affects over 30 per cent of the UK at once only during periods of very low load. Strong winds actually affect only less than one-tenth of the UK at any one time.

Correlation between output from UK wind power sites

Here is that graph between wind power sites showing the correlation between their output, with over 2000 pairs of sites. If you work on a meso-scale of hundreds of kilometres, then the correlation is very low. Therefore, diversifying where you put the wind machines very much smoothes their output.

UK wind resource matches loads well, increasing its dependability and value

It is also fascinating to look at how well the UK wind resource matches loads. If you look at going from zero to maximum demand – and these are percentile rank of the demand hour – here is the average which, for these years, was 28 per cent but, over the long-run, it averages 30. You will notice that, for the higher load periods, you are always above average on how much wind is available, which is a good thing. Wind power correlates well with electric loads and, during the highest demand hours, the wind machines are nearly three times more productive than during the lowest demand hours. In the highest 10 per cent demand hours, 82 per cent of the sites are actually working. Low wind speed correlates well with low load, conversely. Thus, if you are using annual average metrics to look at a wind site, you will very much understate windpower's capacity value for meeting peak loads. You have to do this probabilistically with a real analysis.

Diversifying renewables beyond just wind power

Suppose you look at diversifying renewables beyond just wind. Here, I will call on Graham Sinden's paper on *Diversified Renewable Energy Portfolios for the UK*, which he put out last September. Wave power is even more correlated than wind is with load and they are correlated under half with each other but neither really with tidal current power. Therefore, if you include that as well, which is predictable 100 years ahead – just look up the tide tables – then you actually have quite a firm resource. He therefore constructed a diversified portfolio of all three, that would meet one-fifth of UK electricity demand. This could meet the same load, with the same reliability, using 76 gigawatts of conventional capacity. If you did all of that with wind, you would need 3 gigawatts more, because wind is less diversified and therefore less reliable or more variable.

If you had no renewables, you would need 84 gigawatts: you have just saved 8 gigawatts by using a diversified portfolio to meet one-fifth of your load. Also, the balancing cost declines rather dramatically, according to Millborrow's work. Clearly, if you diversify therefore by technology and by site, then you are reducing variability and you are raising capacity credit, and you are cutting balancing cost, all at the same time.

Or combine offshore wind, PVs and domestic CHP (65/10/25%)

Another diversification scenario combines offshore wind with photovoltaics and domestic CHP, in an output mixture of 65/10/25 per cent. This is from Sinden's House of Lords testimony in ?Oct '04. Here, he looked at a scenario of providing one-tenth of the England and Wales annual electricity, but a little more on-peak and less off-peak because of the load correlation. The system would actually be producing power every hour of the year, based on 21 years of data.

Of course, you only need additional back-up capacity when two things happen at once: the variable sources are putting out very little electricity, and demand is high. Otherwise, you have the conventional capacity already there. It turns out that the peak load over the 21-year period, which was 51-odd gigawatts could have been met with under 48 gigawatts of available conventional capacity if you had put in one-tenth of the annual electricity in these three variable resources, and thus displaced 3.5 gigawatts of conventional capacity. However, in that worst-case hour, you would have needed only 400 megawatts of additional conventional capacity, which is to serve a peak load that occurs two hours in the 21 years. Actually, the back up would be used on average just one hour every five years, and zero hours in four out of five years. There are other ways to do this, like load management.

Also, if you did it with all offshore wind, just to show the value of the diversified portfolio, you would instead need three-odd gigawatts of back-up. Compare that with 400 megawatts and you can see that diversifying into these three sources reduces the back-up requirement by 87 per cent. It is just like a financial portfolio diversification, with similar mathematics.

Of course, the more diverse your types and sites are, the more you reduce the back-up. By the way, we have not yet counted the existing back-up capacity that is already on the grid and what you need is much less than that. If you sought to meet not 10 but 20 per cent of the annual need with variable supply, you would need about two gigawatts of back-up for one hour a year but, again, that does not count the existing back-up capacity. That is a big number and we call it the reserve margin – it is normally around 15 to 20 per cent of the capacity on the grid. This does not look like a problem.

A 10%-variable-generator scenario in the 1980 – 2000 peak period

In fact, here is how the numbers work out for the 10 per cent scenario. The grey would be met by existing conventional plant after you retired 3.5 gigawatts of it and then the domestic CHP is the dark grey, the yellow is the photovoltaic and the blue is wind, while the red denotes total demand. You can see that in the most extreme condition that occurred for an hour in 21 years, you would be going from the peak daily demand, shown in grey, to the peak net daily demand – net of the variable resources that you have just added, shown in orange on this slide. The maximum back-up level would only take you up to here. It is clear that the additional back-up capacity in this scenario, the 400 megawatts, is less than one per cent as big as the peak load and it is far below the reserve margin already on the grid.

Even photovoltaics show UK promise

Curiously, even in the often cloudy UK – and I lived here for 14 years – even photovoltaics show promise. There is a nice paper in *Nature Materials* by Keith Barnham and two colleagues, who I think are here tonight, pointing out that Japan and Germany boosted their photovoltaic production nearly two-thirds during 2003/4, as they completed ambitious solar roof programmes – far more ambitious than the British one, which was cancelled halfway through. Partly for that reason, BP Solar, which was the world's No. 3 solar maker in 2004, no longer manufactures in the United Kingdom. I feel this rather keenly, because the United States had over 50 per cent market share worldwide in photovoltaics not long ago, and it is now below eight per cent and falling, while the Japanese have over a 50 per cent share.

Japan plans to have installed about 100 gigawatts of photovoltaics – about twice the size of the British grid capacity – by 2030. Germany, in the past 12 years of photovoltaics – just their history implies about 12 gigawatts in 2010, four years from now. So, as the article states, if the average trend of the past 12 years continues, Germany will have installed more photovoltaic capacity than the entire current UK nuclear contribution, which is 12 gigawatts, well before the next UK reactor has produced a single kilowatt hour. Germany is not all that sunny either, by the way.

The article also points out that UK buildings have, falling on them, about seven times as much solar energy as the electricity they use. If you therefore had one-seventh efficient photovoltaics on about one-third of the roof and south-facing wall area, you could replace Britain's annual nuclear output. The latest cells that the Imperial Group and others have been working on are over 30 per cent efficient, so they are over twice as good as that, and they can be integrated into a new kind of light-diffusing window that still lets the diffuse light through for daylight, displacing lighting energy. They block excess heat, reducing air-conditioning energy in the summer, and they would make a south-facing London office self-sufficient in electricity. If you had the sort of feed-in rules that now obtain in, say, Spain, or the new one in Italy, they figure that you would have about a two-year payback on that investment because of its multiple benefits. Those are interesting figures for a British climate.

What about nuclear power's commonly discussed issues?

I would like to conclude with a few remarks about nuclear power in this context of competition. Steve Kidd, who runs Strategy for the World Nuclear Association had a nice article in *Nuclear Engineering International*, pointing out the kinds of issues that concern investors and the public: proliferation; terrorism; accidents; waste; decommissioning; releases; risk; common mode shut-downs, and so on. You will notice, however, that in this talk I have just considered economics because, after all, if nuclear power is unnecessary and uneconomic, we should not be debating whether it is safe – we just should not be building more of it. In that view, therefore, putting economics first, as the first hurdle that must be overcome in a liberalised market economy, the kinds of issues that normally dominate the nuclear debate seem to be not a minor counterweight to enormous advantages but rather, as I wrote in 1980, a gratuitous supplement to disadvantages.

Those become rather large if nuclear does enough to displace much coal. If, for example, you doubled today's global nuclear capacity – that is, adding about 1200 plants, if they last 40 years – you would also have to add about 15 enrichment plants, and you would need 14 Yucca mountains to put the waste in. They would contain hundreds of thousands of bombs' worth of plutonium, or you could use 50 reprocessing plants to extract it, not one of which could keep track of its inventory or throughput within, I dare say, one per cent – which you could calculate, therefore, as thousands of bombs a year altogether. It would cost $1- 2 trillions or more of capex, but it would cut global average temperature rise by about one-fifth of a degree Celsius. So that would be heroic efforts for not much result.

Nuclear power disguises and greatly facilitates nuclear proliferation

The concern that would be at the top of my list, if nuclear could cross the economic hurdle, would be proliferation. If you look at up our article in *Foreign Affairs*, summer 1980, called *Nuclear Power, Nuclear Bombs*, you will see an argument that has stood the test of time very well. In fact, if it had been accepted at the time, we would not be worrying today about Iran and North Korea. It goes like this. Nuclear power makes widely and innocently available all the key ingredients of do-it-yourself bomb kits, whether it is the fissile materials, the technologies, the knowledge, the skills – they all come from civilian nuclear power. That is not the only place you can obtain them, but it is the only place you can have them and claim to be just making civilian electricity, as Iran is claiming. It is the only place where the vendors will push upon you, with great verve and large subsidies.

The new reactor types proposed – pebble bed and so on – are actually much worse in this regard. They require much more and cheaper enrichment, for example, which is not at all what we want to be spreading around.

Notice how the logic works. In a world that took economics seriously, we would not have commercial transactions in all of these ingredients of the do-it-yourself bomb kits, and so they would be harder to come by. It would be more conspicuous to try to get them, and it would be politically much costlier for both the buyers and the sellers to be caught trying to obtain, because there would be no doubt at all that what you were up to was making bombs. You would not be able to claim that you were just making electricity.

A world, therefore, without significant nuclear commerce, a world that took economics seriously, would not make proliferation impossible, but would make it a great deal more difficult. It would be much easier to detect in a timely way, because you could concentrate your intelligence resources on needles, not haystacks.

The British and American examples are absolutely critical in this regard because, if countries with such wealth and technological skill and fuel resources say that they cannot get by without nuclear power and reprocessing, then it is very easy for any other country, less favoured, to make the same argument.

Whether in the case of India or Iran, by the way, the very logical conclusion from this is that we should re-interpret the Non-Proliferation Treaty's Article 4 bargain, that you can have access to nuclear technology for exclusively peaceful purposes – they often forget that part – if you are a signatory to the treaty. Let us recall that the purpose of that was affordable energy for global development, but the clause was actually written in around 1969/70, by nuclear experts and in a nuclear context, at a time when nuclear power was widely believed to be cheap and indispensable. However, the market is now telling us differently.

Technologies have changed and there are now better and cheaper ways to do the same thing. If countries like yours and mine were to provide those kinds of inherently non-violent and, by the way, cheaper and faster technologies, to provide affordable energy for development – especially for the 2 billion people not on the grid – then that would fully meet the purpose and the intent of Article 4, and it would smoke out the proliferators. If they wanted specifically nuclear technology, they would have to explain why.

Nuclear power – policy questions

All of this raises certain questions in my mind about policy choices. Why do you want to pay a premium to incur the special problems of the only energy technology requiring an international safeguards regime? Or bearing such a large risk of terrorist attack? Or being guaranteed unavailable when you most need it, after a black-out, which is a sort of 'anti-peaker' attribute.

Why incur the opportunity costs of buying less climate solution per pound spent and per year? Why divert further public resources from winners to losers? The losers, by the way, are already heavily subsidised – and this particular loser has already been bailed out twice, at considerable public expense in the UK. The global vendor revenues for renewable electricity generating equipment in 2004 were about $30 billion and they were probably more than that for CHP and efficiency, but they were much smaller than that for nuclear – although I do not think the figure has been published. It is probably single digits, and it is probably rather low in single digits. I am not even aware that any vendor in the world has cumulatively made money from selling reactors.

Clearly, you cannot do nuclear build in the UK without public subsidies. How can you thread that between market liberalisation – one of the pillars of British and indeed European energy policy – and, on the other hand, the EU's anti- subsidy rules? The subsidy to finance the Finnish reactor is already being litigated by vendors who have been hurt by that subsidy.

If you think that we need everything so that we do not need to make choices – and one sometimes hears this argument – then I am curious to know what is the analytic basis for that belief. How do you propose to pay for buying everything? And how can avoid the Chinese restaurant menu problem, where you have a restaurant with a beautiful big menu, and everything looks good – so you pick one item from each section and spend your money, mostly, on a little bowl of shark's fin soup and other delicacies, and you end up not being able to afford the rice and you go away hungry. You really need to be more discriminating than that and look at the prices.

Nuclear power – more policy questions

A few more policy questions. What does it mean, exactly, to keep the nuclear option from the 2003 White Paper? Does it mean continued massive investments in a mature technologies research? In OECD, nuclear has had the lion's share and, in the US, it is even worse. Does it mean even bigger taxpayer subsidies, to try to steer into nuclear the private investment that is lacking so far? It is interesting that the US proponents of new nuclear build have almost $0.5 trillion of annual revenues and they will not commit a penny from their own funds. They do not intend to put any of their own capital at risk: what does that tell us?

The most authoritative student of energy subsidy says that nuclear in the US already had a 0.8 to 4.2 cent/KWH levelised subsidy and the new subsidies, added, are about 3 to 4 cents/KWH for the next six units to be built. That is basically equal to their entire capital cost. Does it mean heroic life-support measures, to try to divert still more investment where it would not go in a free market, and away from competitors? And what is the opportunity cost? What options do we forego, if we distort the market in this way?

You could ask more generally. We have been trying to make a go of this for half a century and a great deal of talent and effort has gone into it, by people sincerely trying to solve energy problems. I pay them great tribute because this is a difficult thing to do and they have done remarkably well at it. But are we there yet? Have we met the goal? When will we know? When can we stop subsidising and say that this technology has had a fair go, but that it has to make it on its own? Will they agree to de-subsidise the whole energy sector – everybody, without discrimination?

Nothing can save nuclear power from dismal fundamental economics

As a student of this subject for 30-odd years, I do not know anything that can save nuclear power from its discouraging economics – certainly not regulatory change. The US has had a regulatory system, of the nuclear industry's devising, for the past quarter century, with no orders. France has tried the same thing.

It is not new types of reactors. If the nuclear steam supply system were free, the rest of the plant would still cost too much to compete. It is not a carbon tax, because that would equally or largely advantage nuclear's main competitors, which are at least equally low-carbon or no-carbon; not hydrogen, because any form of thermal electricity is a very uneconomic way to make it, and even nuclear heat is very uncompetitive with reformation, whether it is based on natural gas, coal or whatever.

And it is not the increase in subsidies. You know that the new US subsidies are at least $13 billion over the next six plants, equal to their whole capital cost, and yet just after that was voted, Standard & Poor's put out two reports saying that those new subsidies would not materially improve the builders' credit ratings – because most of the risks that the market worries about are not yet dealt with. I do not think that the market yet understands very well the competitive risk that I have emphasised here, because they are thinking about all the other stuff. In fact, the effect of these subsidies will be roughly the same as what you get by defibrillating a corpse – it will jump, but it will not revive. [*Laughter*]

Ultimately, markets prevail and the best buys win, sooner or later. There is a long history in the US that, whenever a President has placed nuclear energy, or any other pet technology, at the centre of energy policy, that has been bad for that technology. The only thing that has made nuclear better is rigorous market discipline. Favouritism has tended to make it mess up in many very expensive ways.

"If a thing is not worth doing, it is not worth doing well"

I conclude with a quotation from Lord Keynes that, 'If a thing is not worth doing, it is not worth doing well'. [*Laughter*] We have here a technology which, despite sincere, devoted and prolonged efforts, at great expense - public and private – has died of an incurable attack of market forces. There is no credible prospect of its revival and, the more we try to deny that, the more we waste money and time and the more we reduce and retard carbon emissions by not buying the cheapest things first.

The alternatives are clearly cheaper and faster and more abundant, and they are now bigger. In God we trust: all others bring data. The market agrees with this, and private capital is financing that huge growth in micro-power. Private capital is financing zero nuclear projects and those are being bought only by central planners, chiefly in Asia. How on earth can we claim to adhere to market principles and say that we are therefore going to buy the thing that central planners are buying and the market is rejecting?

If we actually let all ways to save or produce energy compete fairly, at honest prices, no matter which kind they are, or what technology they use, or how big they are, where they are or who owns them, then we would see the climate problem and the oil problem, and most of the proliferation problem, fade away. These are artefacts of an economically inefficient energy policy. If we really take climate seriously, then we need the best buys first: it is not a matter of the more, the merrier, but of making judicious, discriminating choices, until we get the most solution per pound and per year.

I thank you for your kind attention. If you want to know where to find the original *Nuclear Engineering International* article, summarising what I have just told you, it is at this URL. The one above it, at the top, gives the full documentation. Thank you. Let us see if I have said anything controversial. [*Applause*]

Questions & Answers

David Fisk: Let us see whether Amory has said anything controversial. First, however, let me thank him for an enormous repartee, which was tremendous.

Walt Patterson (Chatham House): Amory, every time I listen to you – and I have been listening to you now for nearly 35 years – my immediate reaction is, 'Of course, why don't we get on and do this?' I would really like you to tell me what you think is the reason why we do not get on and do this. Could we, for example, have a whip-round here, to arrange an audience for you not necessarily with our Prime Minister, but with Sir David King, his adviser, who seems to feel that nuclear power is an answer to climate? [*Applause*]

Amory Lovins: I have actually sent Sir David, whom I know, the relevant papers, but I have not heard back. I hope he has read them because they would help him to give better advice. I am happy to talk to anyone you think it would be useful for me to talk to. At this point, however, it is largely a matter of theology on both sides. I thought it was perhaps simpler to focus just on the economics – you will notice that, other than a little on proliferation, I did not talk about the other issues. We do not need to do that, because there are capable people trying to deal with the other issues and I trust that they will do the best they can. However, the question of new nuclear build should at least fall at the first hurdle, if it is not cost-effective, and then we avoid all the rest of the argument.

We are suffering from recurrent amnesia. You are the best historian of the subject in the country. For those of you who do not know, Walt is a Canadian nuclear physicist who has lived here a very long time and written a classic book on nuclear power, and some others after that, and that is widely used in the industry as a text to understand their own business. It is a jolly good book, which I hope you will all read, and you will find in there that we have been here before, and many times. This is nothing new.

Keith Barnham (Imperial College): That was a great talk, Amory, and thank you very much for the plug for our photovoltaic work.

Carrying on, let us come a little closer to home. I would like to raise this report. I would like to thank the RAE for organising this meeting, which is excellent, and for bringing Amory here. Does this indicate a change of heart? Photovoltaics, in this report of just two years ago, merited *five lines*, while many pages were devoted to nuclear power, and it rather ignored the waste cost as well. Do you feel that there should be a revision of this, which should be submitted to David King and the energy review that is going on at the moment?

Amory Lovins: Is this the Royal Academy of Engineering's report on the costs of making electricity? [*Yes*]

No, I felt that the report was not really consistent with modern evidence on the subject. The policy review would be a very good opportunity for the Academy to revisit this subject and produce a sound and transparent analysis. I am sure that, with its skills, it could go well beyond the modest summary that I did here.

Jim Kennedy (Retired consultant): As an octogenarian, I am no longer affiliated.

My question has been partly but not wholly pre-empted by the first speaker. You spoke about your reluctance – if I understood you correctly – to go to the office of the Prime Minister, because this was more of a 'theological issue', which was the term that you used. I would point out that not a few visiting, distinguished American economists are granted an audience not with the office of the Prime Minister, but with the Prime Minister himself. Given that your argument is fundamentally economically-based, I wonder whether it would not be appropriate for you to contact the office of the Prime Minister himself during your visit.

Amory Lovins: I do not know the Prime Minister. Should he wish to talk to me, I would be honoured to talk to him. I expect that my views are somewhat known around Whitehall, and they will be better known in the morning. I am not an economist – I am a recovering physicist – but I try to take economics seriously and not literally. Markets make a wonderful servant a bad master and a worse religion.

David Fisk: For a terrible moment, I thought the theology thread was going to lead to a suggestion that you visit the Pope. [*Laughter*]

?Ole Steuernagel (University of Hertfordshire): Could you briefly explain how the use of nuclear energy in France affects the French economy?

Amory Lovins: It is very hard to say, because the basic French economic data, especially on subsidies, remains secret. In principle, electricity should be transparent, under the Treaty of Rome, but it is very hard to get good historical or even current data that are transparent and trustworthy out of Éléctricité de France, to know some of the complexities of debt forgiveness by treasury and so on.

The best historic work on this is by Jean-Claude Derian and Irvin Bupp, who was then at Harvard Business School, called *Light Water: How the Nuclear Dream Dissolved*. My own reading of this is that EDF would probably have been better off, economically, from burning oil all this time, although that was not the alternative. In fact, France is the richest major industrial country in renewables, except Japan, and it had plenty of other options which, however, were not aggressively pursued. I would say that, broadly, the programme has severely damaged Éléctricité de France financially. The Cabinet has been split down the middle since the seventies as to whether it was a good idea, and no doubt it remains split on whether new nuclear build would make sense.

If someone has good information on the proposed new French nuclear unit, modelled on the Finnish one, then I would be interested to know the proposed turnkey price – which I was told was greater than that of the Finnish plant, which was already rather high and yet clearly a loss leader. I expect they will lose their shirts on it, especially given what steel prices are. I would say that the French experiment with nuclear has been impressive but not successful in economic terms. It is very much a centrally planned electricity system and I believe that it is still a crime in France to oppose planification.

The only way they could sell that much electricity was to cross-subsidise its extensive use for electric heat, which is a grossly uneconomic way to heat your house. This means having rather high heating bills, or other bills, depending on who bears the cross-subsidy. The electricity tariffs are in the middle range for Europe, despite being assisted by some rather lucrative exports at peak. This is a complex situation and I certainly would not use it as a model for a competitive system.

Robert Hawley: I am not an economist and I am not against windpower, but we need a mix of all the various things. I would like an answer to a very simple question. In the House of Lords, we were given a figure for the subsidy for windmills to the year 2030, which was £30 billion. The cost of a new nuclear replacement programme is £10 billion. What are your views on that?

Amory Lovins: I would need to know what the numbers meant, before I could comment on them. I have not heard those particular numbers and they do not sound at all consistent with any numbers that I understand. If you would be kind enough to tell me later on, I could try to react.

Anthony Kelly (University of Cambridge): That was a magnificent performance. Do you have any comments to make on the future of coal? As I understand it, that is more or less the fuel of the future, when oil runs out, and yet you hardly mentioned it.

Amory Lovins: Yes, that is not because I am not interested in it, but because the objective usually proposed for new nuclear build is to protect climate by displacing coal.

The carbon sequestered options for coal may well prove attractive as central plants go but central plants – even today, without the extra 1 cent or perhaps 2 cents per kilowatt hour for collecting and sequestering the carbon – are uncompetitive with the other distributed options I have described, such as certain renewables, CHP and end-use efficiency.

That said, the greatest long-run value of coal may be its excellent performance in pulling hydrogen out of steam. This can be done in a carbon-sequestered way that could be quite attractive. It could be the best long-run way of making hydrogen and at least two of the world's top five coal producers are already viewing their coal assets through the lens of the hydrogen value chain – which is the right way to do it. If they are to be carbon-constrained, they will make more money that way than they could do by just burning steaming coal, and sending the carbon up the stack.

In general, in case you were wondering about my views on oil depletion as well – because you mentioned oil – I think oil will become uncompetitive, even at low prices, before it becomes unavailable, even at high prices. That is what our *Winning the Oil Endgame* analysis for the Pentagon confirmed. Fortunately, however, even if you own a great deal of oil in the ground, you will make more money in a world that buys no oil. This is because the hydrogen in your hydrocarbon will be worth more without the carbon than with the carbon – even if no one pays you to keep carbon out of the air. That is, you will make more money by taking hydrogen out of your oil or natural gas in a reformer, than putting more in, in a refinery.

Kirsten Gogan (Town and Country Planning Association): I notice from the list of delegates that the Prime Minister's office have sent a delegation here tonight.

Could you be so kind as to expand on the role of hydrogen in a de-centralised energy system, please?

Amory Lovins: That would be a longer conversation than we could do here, but if you go to RMI.org and then click on 'library', and then 'energy', you will find a hydrogen section, containing what has now become the industry standard white paper. It is called *20 Hydrogen Myths*. Hydrogen was canvassed in *Winning the Oil Endgame* as an option and not as a requirement for getting the US completely and profitably off oil. It would be the most profitable and efficient way to use saved natural gas, of which we will have a great deal if we use gas and electricity in a way that saves money. This is because if you save one per cent of US electricity, including peak hours, you will thereby save two per cent of the natural gas in the country and cut its price by three or four per cent. That huge leverage arises because peak electricity is made almost entirely from natural gas burned in extremely inefficient, simple-cycle peakers. Displacing those therefore has enormous leverage in saving gas and money.

The hydrogen economy for vehicles makes sense if, and only if, you have very efficient vehicles so that they are ready for the hydrogen. The tripled efficiency car that I showed briefly illustrates this. That SUV would have a 530km driving range, with quite small tanks which package well, using existing technology – you do not need any breakthrough in storage because, when the vehicle is half as heavy and lower in drag, the tanks are three times smaller for the same range. When the fuel cell is three times smaller, you can afford it much earlier, because you can afford to pay three times more per kilowatt. How much earlier? If you had an 80 per cent experience curve, which is a standard assumption, then you would need 32 times less cumulative production volume to reach your price point. That is a lot of years.

David Fisk: I am conscious that we scheduled this meeting to finish at 8.30pm. We have time to take two more questions and I would be grateful if you could make them short if possible, please.

Tom Tibbits (Green Party): Thank you for your talk, Amory. In the UK, up to 45 per cent of all the carbon dioxide emissions are associated with our building stock, both domestic and industrial buildings. Could you expand on the retrofitting technologies available, to reduce rapidly those emissions? Rebuilding the entirety of the UK's building stock to a very high insulation standard would take a very long time.

Amory Lovins: Not doing it takes a long time, too. Having lived here for 14 years, at a time when thermal building standards were higher for piggeries than for houses, I am conscious of the rather modest rate of progress since. The otherwise comfortable hotel that we were staying in last night, for example, was in need of very basic draught-proofing –

closing an open door, and things like that. It is not just a question of lagging, but of attention to detail. For a central London, good quality hotel to have 1cm cracks around the windows and doors seems a very juicy opportunity to me.

There are of course institutional barriers and it takes a long time but, if you use either roving specially equipped vans, such as we used to retrofit the frequency of the electric grid in Los Angeles, Toronto, Montreal, or community-based programmes as in Minneapolis St Paul, retrofitting the city block by block, we could get a lot of good weatherisation done by very conventional means.

There is a very important missing technology for the UK building stock, and that is efficient windows. I have just looked on the Pilkington site because, after my ?H..... lecture a few years ago, I had a chat with a Pilkington director, who said that he would fix their not making super-windows. Well, they still do not make them. You are lucky to get K 1.1, or 1.2. I can buy 0.3 in Colorado – it has been on the market for a long time. If I really want to, I can buy 0.2. Most of the ones sold here are 2-point-something, or worse. What is wrong here? It just takes some attention and, if Pilkington will not do it, somebody else should.

Also, you should look carefully at the Scandinavian techniques – especially Danish and Swedish – for putting a 'tea cosy' round existing buildings – 'outsulation'. If it is a listed building, then of course you can do super *in*sulation inside and give up a little room space, but not much, and greatly improve comfort. Yes, you have to pay attention to damp and all the other British issues. I have seen David Strong here, from the BRE, and they have a couple of hundred people who are very good at those things.

David Fisk: And I guess that condensation from chip pans would be the other thing that you would go for.

Gary Foster (The Carbon Trust): In your vision of a decentralised energy system, how would you meet the needs of larger energy users – the energy-intensive sectors like aluminium smelting, pulp and paper manufacturers, ceramics manufacturers and so on? How would you cope with that in a de-centralised system?

Amory Lovins: Exactly the way you do now. They receive electrons through the grid. They do not care where the electrons come from, but they care about whether the electrons are cheap and reliable. The electrons are not labelled according to whether they came from a big or small generating unit. For example, you care about whether your mobile phone works, without worrying what is behind the curtain in the technical system that the boffins use to get the signal to you.

We already have a fair amount of big hydro in the UK, and smelters tend to be near that. There is the Anglesey smelter in ?Rilper, and that will be decommissioned and we will do something else. We have some balancing schemes, like the Dinorwic, 'things that go *pump* in the night'. We will no doubt have some large fossil fuel and indeed nuclear plant for a long time, but the question is what to build on the margin. The evidence I see says that, on the margin, it is the small, fast, cheaper options that are winning and investors who want to make money, and not lose money or run undue risk, should pay careful attention to that market outcome, and the reasons why it will probably intensify.

That said, all of the big process plants that you mention have major opportunities to save electricity – I know, because we work in many of them. As you saw from the industrial examples I presented, that is definitely the thing to do first and, afterwards, most such facilities will do fine with CHP. In fact, the US pulp and paper industry already makes most or all of its electricity from its own waste products.

David Fisk: Thank you very much. I reluctantly call our meeting to a close. Very few people have had to leave to catch trains but, otherwise, you have all stayed absolutely riveted in your seats. We had a tremendous presentation from you, Amory, and we are all very grateful to you for giving such a rounded attack of your position, right across the board. My head is spinning with cents per kilowatt hour!

Let us thank Amory for giving us the really big picture here. [*Applause*]

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