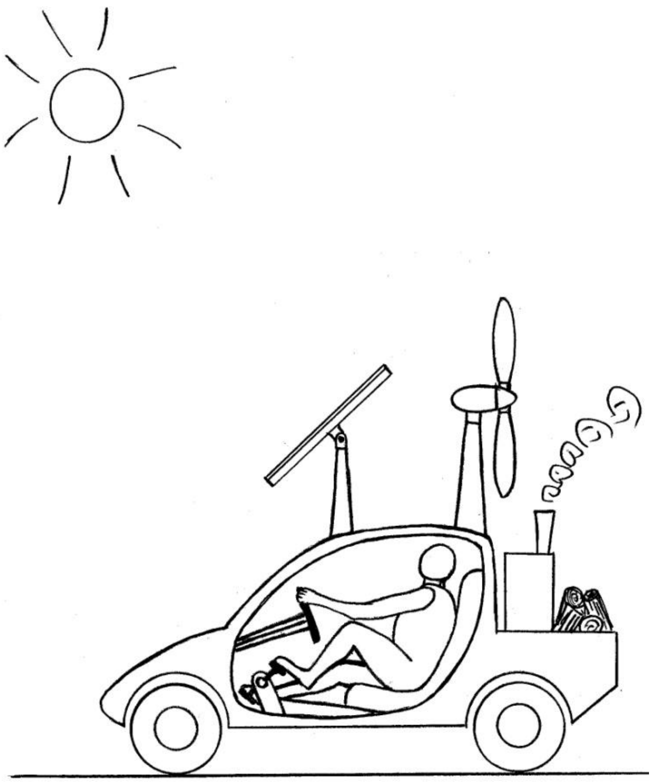
Energy & Climate:
Time We Took Out Insurance?



David L.J. Dunbar

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The Main Points

- Impending fossil fuel shortages and man-made climatic changes are not proven, but there is enough evidence to suggest development of sustainable alternative energy sources would be a sensible insurance policy.
- We can reduce our overall energy needs by good design and practices without major lifestyle changes, apart from a possible reduction in air travel. But even that requirement is open to question with future sustainable fuel production concepts.
- There is insufficient space in the UK for any of the proposed on-shore sustainable energy concepts, even in combination, to meet more than a minority of total requirements, even following energy usage reductions.
- Fully exploiting the potential offered by our territorial waters for installation of off-shore wind, tidal current and wave power facilities, along with the realistic contribution of other sources, would theoretically meet our needs.
- Under these circumstances, about 85% of our energy would come from wind power. This is extremely dependent on one unreliable source.
- An easily switchable reserve power source would be required to cope with wind power interruptions. It is proposed that this be methanol-based fuels produced from CO_2 extracted from the atmosphere, using electrical power generated in off-peak periods.
- Methanol-based fuels would also be used for land-based “mobile” applications that don’t lend themselves to electric power.
- The heavy reliance on wind power can be reduced by incorporation of nuclear power. Future enhancements presently under development will greatly improve fuel efficiency, toxic waste production and long term sustainability of nuclear power.
- Long haul flying at near-present levels could be sustainably maintained by adopting methanol-based fuels produced by solar powered plants in tropical regions. The energy demand would be too high for aviation fuel production in temperate regions.
- Other countries around the world generally possess their own geographical or climatic characteristics which can be exploited to support their sustainable energy needs.
- Proposed short term action would focus on progressing sustainable energy schemes already under development, and doing the groundwork to support timely implementation of longer term developments.
- Given the commitment and resolve, the human race is capable of progressing to a sustainable energy future with little hardship or undesirable lifestyle changes. The financial cost will be high, but within the bounds of reason.

About the Author

David Dunbar has recently retired after 41 years working in the heavy, specialist and high performance vehicle manufacturing and operating spheres. As such, David can claim to be responsible for more than his fair share of fossil fuel consumption and CO_2 production during his career!

David’s engineering background has led to him taking a keen interest in the energy and climate change debates, from the early days of pollution concerns in the 1960s and the original oil crises of the 1970s.

This interest was recently galvanized into a more active desire to contribute to the debates after David read Professor David MacKay’s book: “Sustainable Energy – Without The Hot Air”. This paper is the result.

David’s engineering credentials encompass a degree in Mechanical Engineering gained at Hatfield Polytechnic, Fellowship of the Institution of Mechanical Engineers, registration as a Chartered Engineer and award of the designation European Engineer.

David’s main interests in life continue to exacerbate his high energy-consuming, CO_2-creating lifestyle. They include his 1934 Lanchester LA10 car, following motor racing and long-distance travel. He hopes this paper will go some way towards redeeming him!

The objective of David’s studies leading to this paper was to determine whether it will be possible for future generations to continue to enjoy the energy-hungry lifestyle available to David’s generation, but in a manner which would not run the risk of exhausting our fuel reserves or harming the environment.

David originally produced this paper in mid-2010. Time will tell how well it forecasts future developments.

Contents

1. Introduction

My efforts are unashamedly based on the data produced by Professor David MacKay in his book "Sustainable Energy - Without The Hot Air". I strongly recommend that anyone reading this paper, or any other discussion piece on this subject, obtains a copy of Professor MacKay's book, which lays down the fundamentals of this subject in far more detail and clarity than I could dream of emulating.

For those not wishing to shell out on a paper copy of the book, it is also available free online at: www.withouthotair.com.

Professor MacKay's book identifies and quantifies energy consumptions under the various categories of use (heating, transport, manufacturing, etc), and expresses the results as energy used per average person in the UK per day.

He compares these results to other countries worldwide, and goes on to calculate the potential energy production capabilities of the various possible forms of sustainable energy, including some which may be open to debate regarding their true worthiness to be included (eg. nuclear power, clean coal). These results, and a number of possible combinations potentially offering a solution to the UK's future needs, are also expressed as energy per person per day, so they can be directly compared to the demand figures.

The book contains a mass of background information and calculations illustrating the derivation of the various figures in the demand and potential production estimates. This makes it an indispensable tool for anyone wishing to continue the discussion and put forward their own proposals for meeting our future needs: an outcome actively encouraged by Professor MacKay.

This paper contains my humble attempt to build on this work by putting forward my views on how each of the various demand categories may develop in future, and how the resulting total energy requirements may be met. Like Professor MacKay, I have notionally based my estimates on possible circumstances 40 years hence, in 2050.

The main body of my paper is arranged in 2 sections: discussion of the usage categories, and theoretical proposals for sustainably satisfying the resulting total demands. I then conclude with a final section considering the practicality of the proposals and possible compromise scenarios which would ease our transition to a sustainable future.

When discussing the respective usage categories, I have assumed that all requirements will be distilled down to two energy supply concepts: those serving static or near-static demand centres (buildings, industrial complexes, etc), and those serving mobile equipment (vehicles, aircraft, ships, etc). In a nearly or completely fossil fuel-free world, the logical means of supply for the former demand group is mains electricity. I discuss the forms the latter supply concept may take in the main paper.

When determining what constitutes "sustainable" energy, I have taken into account not only the possible affects on the environment and depletion of global reserves, but also the practicality of supply to the UK. This has caused me to eliminate or greatly reduce the significance of some energy sources which could otherwise be considered significant future players.

My ideal target for future CO_2 emissions by the UK is taken from Professor MacKay's book: 1 tonne per person per year. This figure results from the estimate of sustainable global emissions divided by the world population, assuming an equal world in which all have the same access to energy sources and produce the same level of emissions. It compares to current UK emissions of approximately 11 tonnes per person per year.

I'm the first to agree that the world isn't equal. But as we move forward in the coming decades, and nations such as India and China continue their relentless industrial and commercial development, we must assume that the inequalities of previous centuries will be eroded. We must expect to have no more than our fair share of the energy and emissions cake.

Please note that I have not selected the 1 tonne per person per year CO_2 emissions target because I am personally totally sold on the worst predictions promulgated by climate change campaigners. I have based my proposals on this figure in order to illustrate the full implications of responding to this scenario, among the many theories about possible future climatic causes and effects.

It should be noted in this context that global warming is not the only hazard potentially facing us. There is a strong but under-reported belief in some highly respected circles that we may in contrast be heading for a period of prolonged global cooling: that would present a whole new set of challenges potentially even more difficult than those highlighted by the global warming lobby.

I would put my personal position regarding climate change in about the middle of the spectrum, between the "we're all doomed" world view and the "what's all the fuss about?" attitude to the climate debate. Time will surely tell who was right. In the meantime, I feel a healthy scepticism about the outputs of all individuals and bodies with vested interests to protect and promote, along with intelligent concern based on a balanced view of the comments of responsible commentators, is the appropriate course, hence this paper.

I have put forward some quite ambitious proposals, in both the way that our energy consumption may be reduced in some of the usage categories, and the means by which it can be produced, stored and transmitted. I acknowledge that some of these may appear fanciful at this juncture, but I ask the doubter to consider whether anyone in 1929 seriously believed that man would be walking on the moon in just 40 years' time. Given the need, the focus and the commitment, the scope for human initiative and endeavour is far from exhausted, and I am confident that at least some of my proposals are achievable over the next 40 years.

I have based my proposals on the assumption that not much energy saving will result from lifestyle changes, other than methods of communication and levels & means of long distance travel. Should there be a major shift in other lifestyle aspects, there could be a commensurate additional reduction in energy requirements, and the progressive increase in energy costs will undoubtedly result in some reduction in consumption. But I believe any changes involving a significant erosion in living standards will meet with considerable resistance, not least from me!

Similarly, I have paid little heed to the potential for energy production at an individual domestic or community level. Any tangible contribution by these will of course reduce the challenge at the national level.

I should also stress that this is a theoretical analysis. Practicalities, economics and many other factors not considered in detail in the paper may well lead to actual future developments taking a different path. Nevertheless I feel the analysis is worthwhile, to establish whether it is possible to foresee a future in which continuation of our present lifestyle is compatible with a more sustainable energy scenario.

Finally, a word about the elephant in the room: population. Professor MacKay based his future projections on current population figures for both the UK and the world, namely approximately 60 million and 6 billion respectively. The actual population figures presently being forecast for 2050 by various bodies are up to 75 million and 9 billion respectively.

There is some evidence to suggest that the rate of global population growth may be levelling off, and it is hoped that it will eventually stabilise at not much more than the 9 billion presently forecast for 2050. I earnestly hope that this proves to be the case, because I very much doubt that our governments and international bodies will ever agree a strategy to control it reconciling the many and varied social, cultural and religious convictions to be found on our planet.

However for the sake of this paper, I am assuming that UK population growth will ease off, and my energy calculations are accordingly based on an estimated population figure of **70 million**.

I offer my proposals in the hope that they will help to stimulate further discussion of the practical means by which we may meet our future energy requirements, and as a possible basis for the development of alternative approaches which may achieve these aims at lower financial and environmental cost.

I have not included a formal bibliography, but please contact me (email address at end of section 4.6) if you’d like to investigate the origins of any of my statements.

2. Energy Demand

Professor MacKay identified the following usage categories and figures for current energy consumption, expressed in kilowatt hours per day per average person in the UK:

Car usage	40 kWh/d/p
Flying	30
Heating, cooling	37
Lighting	4
Powering gadgets	5
Food production	15
"Stuff"	48
Transport	12
Defence	4
Total	**195 kWh/d/p.**

"Stuff" constitutes manufactured goods of all sorts, the bulk of which are presently made elsewhere and imported into the UK, but they are nevertheless included as their consumption takes place in the UK.

One could argue the case for the inclusion of one or two other categories, eg. building and infrastructure construction, etc. However, the above total is already somewhat higher than data from other sources. Therefore I am going to assume that these other energy usages are adequately covered in generous estimates for some of the categories already identified above, thus erring on the pessimistic side overall.

Not all the above energy is consumed within the UK, a significant proportion being embodied in imports. I have accordingly notionally broken the respective energy usage categories down between home energy consumption and overseas consumption as follows:

	UK	**Overseas**
Car usage	40 kWh/d/p	0
Flying	18	12 kWh/d/p
Heating, cooling	37	0
Lighting	4	0
Powering gadgets	5	0
Food production	5	10
"Stuff"	12	36
Transport	10	2
Defence	3	1
Totals	**134 kWh/d/p**	**61 kWh/d/p.**

There now follows a discussion of how each of the usage categories may develop between now and 2050.

2.1. Car Usage

(current usage 40 kWh/d/p)

I don't believe there will be a mass general movement from cars to public transport. Apart from the loss of flexibility and privacy, the public transport networks are far too limited to cope with a significant transfer, and can't realistically be expanded to the scale required to absorb a substantial change in travelling habits. People will continue to prefer the benefits of private transport, particularly in rural areas and especially as the substantial energy savings implicit in public transport are not reflected in commensurate fare price economies.

This is not to say that there isn't scope for further development of public transport in urban areas and over longer distances. But the majority of car journeys in the UK will not be influenced by this. I therefore predict that car usage per person will remain approximately as at present.

Presently envisaged improvements in car design (weight reduction, driveline efficiencies, general downsizing, etc) are anticipated to trim a total of about 20% from current fuel consumptions. This would bring total energy usage down to about 32 kWh/d/p based on existing propulsion concepts.

However, the potential benefits offered by electric propulsion are starting to become evident, to the extent that we are nearing the point where solely battery powered cars for urban use and plug-in hybrids for mixed distance travel are almost at the point of general viability. There is concern about the future availability of lithium, which is a critical constituent in the majority of current high energy density battery concepts, but I am confident that future developments in this field over the next 4 decades will produce other battery concepts using alternative materials.

Bearing in mind the range limitations of battery powered cars (about 200 km appears to be a sensible limit, beyond which the weight of the battery as a proportion of the total vehicle weight would become excessive), I believe about 75% of future car journeys could be by electric power. This would lead to approximately **8 kWh/d/p** still being consumed using a "mobile" fuel requiring the general characteristics of existing petroleum products, and the other 24 kWh/d/p being reduced to just 6 kWh/d/p due to the greatly superior efficiencies implicit in electric propulsion. If we add a 50% margin to this for battery charging, discharging, etc, the "static" mains electrical load at the charging points will be about **9 kWh/d/p.** Virtually all of these energy demands will be consumed within the UK.

2.2. Flying

(current usage 30 kWh/d/p)

Flying is a major problem, or rather the energy consumed and CO_2 emissions are a problem. At the current average rate of 30 kWh/d/p, and CO_2 emissions of 240 g/kWh for kerosene fuel, flying alone accounts for 2.6 tonnes per person per year. This is over twice the proposed target CO_2 emissions level of 1 tonne per person per year for safe emissions in an equal world.

Airline travel has enjoyed a recent dramatic upsurge due largely to the cheap fares on offer. This has resulted in air travel changing from a luxury to be enjoyed by the wealthy few to a commonplace experience for everyone. Thus, a businessman will happily hop on a plane for a meeting half way round the world, and overseas holidays as far afield as Australia are taken for granted.

All this has been made possible by cheap fuel. I'm going to make a major assumption at this point: as fossil fuels start to become more scarce and difficult to extract, fuel prices will escalate to the extent that airline passengers reconsider their destination choices or their need to travel. Airline travel will once more revert to being the preserve of the relatively affluent, or an occasional luxury for the rest of us.

This isn't to say that we'll all stop travelling altogether, or taking holidays in nice locations. But the degree to which we do these things with long flights will be much reduced.

How will this happen?

I think inter-continental travel will be slashed, by as much as 50%. Instead of holiday-makers casually jetting off to Africa or the Caribbean, they will often settle for the closer delights of Europe, and get there by high speed surface transport. Likewise, the cost of flying will make this a less common occurrence for the business community. Teleconferencing etc will take its place in many instances. Flying to far flung destinations will become a last resort, for occasional indispensable visits.

In Europe, maybe as much as 75% of current air travel will become the preserve of high speed surface transport, resulting in the total amount of flying being significantly reduced, to about 10 kWh/d/p at present energy consumption levels.

This represents a reduction in the average annual aviation mileage per person from approximately 27,000 km to 9,000 km. Unreasonable? Well, we all managed with this level of flying until quite recently, and I should stress this is an average. Many people won't fly at all in a year, while others will do considerably more.

A 9,000 km return flight would be enough to travel to North Africa, or would get one to north east Canada. By 2050, there could be high speed surface links throughout North America, enabling continuation by this means to any destination.

On top of that, there is some optimism that air travel efficiency can be improved. Boeing are making claims that the B787 will be about 20% more efficient than previous aircraft designs. Assuming this proves to be over optimistic, there is still time for a further generation of aircraft design in the next 40 years, and with the benefit of two bites at the challenge, the 20% improvement should come to pass. The airliner energy usage figure would therefore come down to about **8 kWh/d/p**, split equally between UK-based and overseas fuel supply locations.

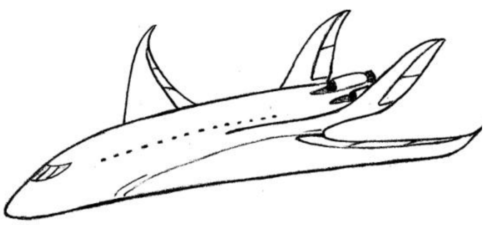

Fig. 2.2. Son of Dreamliner?

This reduction in energy demand would also mean that our CO_2 emissions due to airline travel would fall to about 0.7 tonnes per person per year, ie significantly less than the "equal world" target of 1 tonne/p/yr.

I'd like to stress at this point that I believe this change could come about purely through market forces, driven by the cost increase in flying implicit in the escalation of fossil fuel prices, combined with investment in the alternatives. I don't believe there is any need for government action etc to force people to change their habits, and I don't think there's any chance that the international community would agree what form any action should take, or would adhere to it.

Assuming the eliminated European flights are largely replaced by high speed rail, rail will be about 10 times as energy efficient as flying (ref. following paragraph in italics for justification). Therefore the energy required for these journeys will be reduced from about 20 kWh/d/p to about **2 kWh/d/p**. Rail networks can be regarded as "static", in that the permanent way doesn't move, and they accordingly lend themselves to mains electric power. The notional split for this item is 1.5 kWh/d/p within the UK and 0.5 kWh/d/p overseas.

Ref. Professor MacKay: typical airliner energy consumption: 40 kWh/100p-km, typical high speed rail energy consumption: 3 kWh/100p-km. I've assumed that whereas airliners tend to fly with near-100% load factors, trains are more likely to be part empty (assumed 75% full). This increases the train's energy consumption to about 4 kWh/100p-km, ie. a tenth that of the aircraft.

I have painted a rather harsh picture for the future of flying here, and revisit it from a different perspective in section 4.3.

2.3. Heating, Cooling

(current usage 37 kWh/d/p)

We really haven't yet tried very hard in the UK to properly insulate our homes and reduce our heating bills. We are approximately half as good as Swedish practice in this respect. I think this is understandable: until recently we enjoyed very cheap fuel courtesy of the North Sea, and this rendered the pay back period for improving insulation etc unacceptably long.

That's all changed now, and we can expect our future energy costs to go even higher than they are at present. This will lead to the question of insulation and energy saving being approached with much more enthusiasm than hitherto.

Looking at the data assembled by Professor MacKay, if we closed the gap between us and best practice in Sweden by just half, we'd be looking at a saving of about 25% overall in our heating and cooling requirements. This would bring the total usage down to about 28 kWh/d/p. Remember, we've got 40 years to do it!

If we now assume that 50% of this requirement will be met by solar water heating and heat pumps at a conservative (for 2050) coefficient of performance of 4.0, the energy usage for heating and cooling will come down to 14 kWh/d/p for conventional methods and about 4 kWh/d/p for the newer technology. Ie. a total of **18 kWh/d/p**, which falls in the "static" supply category, and would all be consumed within the UK.

2.4. Lighting

(current usage 4 kWh/d/p)

As with heating & cooling, I'm going to assume that just 50% of our total lighting requirements can benefit from lower energy bulb technology. The remaining 50% will be constrained by the nature of the application, lighting system design aspects, etc.

Assuming an energy saving of 80% where low energy bulbs etc are used, the requirement will come down to 2 kWh/d/p for the remaining conventional lights and 0.4 kWh/d/p for the low energy units. Ie. a total energy requirement for lighting of approximately **2.5 kWh/d/p**. Lighting obviously falls in the "static" supply category, the vast majority already being electric, and it will all be consumed within the UK.

2.5. Powering Gadgets

(current usage 5 kWh/d/p)

It's difficult to predict what's likely to happen with this category. Further advances in computer technology, communications, games concepts, etc not yet dreamed of by their inventors could have a dramatic affect on future energy requirements, for better or worse.

For the sake of this analysis, I am therefore going to assume that energy consumption for this category remains at its current level, ie. **5 kWh/d/p**. I am basing this assertion on the theory that, for any future expansion of the capabilities of gadgets, there will be an equal saving in energy demand due to smarter design, etc. The vast majority of gadgets will be used in the home, office, etc, or are recharged from the mains, therefore they fall into the "static" supply category. The overwhelming majority of consumption will be in the UK.

2.6. Food Production

(current usage 15 kWh/d/p)

It is assumed that food production techniques will remain approximately as at present, but the same energy efficiency advances as seen in other areas (cars, heating/cooling, lighting, etc) will also apply to the mechanised and industrialised elements of the growing and supply chain.

It is accordingly proposed that an overall energy reduction of 20% will accrue, resulting in the total energy requirement falling to 12 kWh/d/p.

Although the majority of our food is presently imported, I'm going to assume that by 2050 a substantial part of it will be produced in the UK, thus eliminating the need for transport over long distances, and assisting our economic position. I acknowledge that this will raise renewed issues over GM crops etc, to get the necessary yields per hectare. The above energy requirement will accordingly be met largely from UK-based sources. For this analysis I have assumed that the UK production vs. imports split will be approximately two thirds UK production and one third imports. Ie the UK share will be 8 kWh/d/p.

Of this total, it is further assumed that 50%, ie **4 kWh/d/p**, is consumed in static facilities which would be supplied from the electrical grid, while the other **4 kWh/d/p** goes to mobile farm equipment etc, which would accordingly fall into the "mobile" energy supply classification.

2.7. "Stuff"

(current usage 48 kWh/d/p)

The majority of the energy demanded for producing "stuff" is consumed in mining raw materials, recycling waste, processing materials, assembly and packaging.

All these functions (even mining) are fairly static, and lend themselves in most cases to electrical power from the grid. Also, as we move forward, increased levels of recycling should progressively reduce the amounts of raw materials required.

Assuming similar efficiency improvement levels to those proposed for other categories, it would be reasonable to expect a 20% reduction in energy consumption, bringing the total down to about 38 kWh/d/p.

Most of the "stuff" consumed by the UK is presently imported, therefore this item does not contribute as much to UK domestic energy requirements as may be expected. However, it is proposed that future economic conditions will force the repatriation of a considerable proportion of the manufacturing burden of our "stuff", as well as some production for exports.

It is therefore assumed that an estimated 50% of future manufacturing will be in the UK, leading to a demand of approximately **19 kWh/d/p** from UK sources, while the remaining **19 kWh/d/p** will continue to be consumed overseas.

2.8. Transport

(current usage 12 kWh/d/p)

Professor MacKay calculated that the goods transport category comprised the following elements:

Road transport in UK:	7 kWh/d/p
Shipping:	4 kWh/d/p
Other aspects:	1 kWh/d/p.

If we assume that road transport could enjoy the same efficiency gains as cars over the next 4 decades, this element will come down by about 20% to approximately 5.5 kWh/d/p.

If we repatriate 50% of production of "stuff" to the UK (ref. Section 2.7.) and replace our current fossil fuel imports with locally generated energy from sustainable sources, it is reasonable to suggest that the UK's demand for shipping will also fall by about 50%, to 2 kWh/d/p.

I will leave the other transport aspects identified by Professor MacKay at the figure of 1 kWh/d/p that he calculated.

The total transport energy requirement will therefore come down to approximately **8.5 kWh/d/p**, the overwhelming majority of which will be in the "mobile" supply category. For this analysis I have assumed that the shipping element (2 kWh/d/p) will be equally split between UK and overseas-sourced fuel supplies.

2.9. Defence

(current usage 4 kWh/d/p)

Assuming we maintain our defensive capabilities roughly at their present level, I would expect any increase in operational performance (larger, faster ships, aircraft, vehicles, etc) to be approximately cancelled out by efficiency improvements similar to those anticipated in some of the other categories.

I estimate that about 25% of energy usage is in static installations etc. Therefore approximately **1 kWh/d/p** will fall into the "static" supply category.

The remaining **3 kWh/d/p** will fall into the "mobile" supply category. Some of this is presently served by nuclear power (submarines etc), but this is a tiny part of the total energy requirement for this category, and I won't get into a discussion about the future of this aspect in this paper. For the benefit of discussion later in the paper, I'll assume that the 3 kWh/d/p is split equally between military aviation, shipping and land equipment, and that approximately 2 kWh/d/p of this is drawn from UK supplies, with the remainder supplied overseas.

2.10. Summary

Summarising the above analysis, I estimate that the UK's total energy requirements in 2050 will be as follows:

Usage category	UK	Overseas
Car usage	17 kWh/d/p	0
Flying	4	4 kWh/d/p
Surface transport	1.5	0.5
Heating, cooling	18	0
Lighting	2.5	0
Powering gadgets	5	0
Food production	8	4
"Stuff"	19	19
Transport	7.5	1
Defence	3	1
Totals	**85.5 kWh/d/p**	**29.5 kWh/d/p**
Total UK + Overseas		**115 kWh/d/p.**

Ie. the total anticipated future energy requirement per day, per person, of 115 kWh/d/p represents a **41% reduction** from the current level. The saving would largely come through efficiency gains in the various usage categories and a significant reduction in the amount of flying we do.

The split between "mobile" and "static" energy consumption within the UK would be as follows:

Usage category	"Mobile"	"Static"
Car usage	8 kWh/d/p	9 kWh/d/p
Flying	4	0
Surface transport	0	1.5
Heating, cooling	0	18
Lighting	0	2.5
Powering gadgets	0	5
Food production	4	4
"Stuff"	0	19
Transport	7.5	0
Defence	2	1
Totals	**25.5 kWh/d/p**	**60 kWh/d/p.**

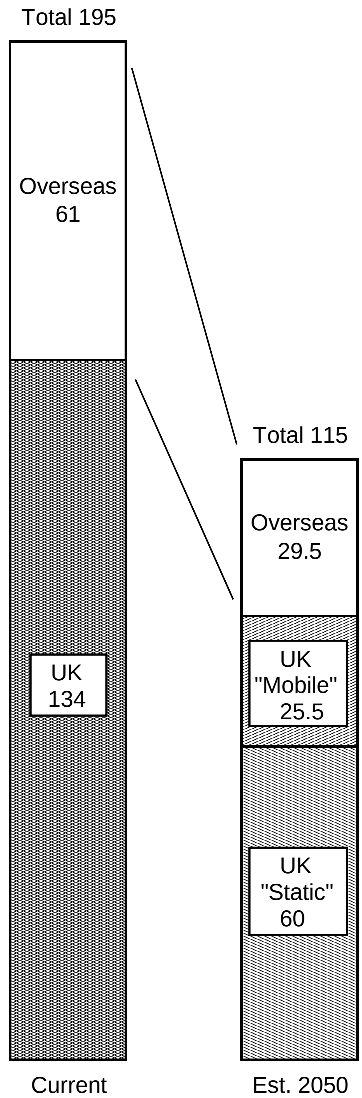

Fig. 2.10. Current vs. future energy requirements (kWh/d/p)

In the next section we will discuss the means by which we could sustainably meet this energy demand level.

3. Power Generation Proposals

In the previous section I concluded that our total energy requirements in the UK may in 2050 be as follows:

"Mobile" supply requirements:	25.5 kWh/d/p
"Static" supply requirements:	60 kWh/d/p
Ie. Total energy requirement:	85.5 kWh/d/p.

I will exclude the additional overseas energy requirement of 29.5 kWh/d/p, used in the supply of goods etc for UK consumption, from this part of the discussion.

At this point I will diverge from the procedure followed by Professor MacKay in his book, in that from here forward I will consider the above requirements primarily as the total for the nation as a whole.

To convert the energy per day per person to energy per day for the total nation, one must multiply the above figures by the anticipated UK population in 2050, ie. 70 million.

The total UK energy requirements per day therefore come to:

"Mobile" supply requirements:	1.79 billion kWh/d
"Static" supply requirements:	4.20 billion kWh/d
Ie. Total energy requirement:	5.99 billion kWh/d

To convert kWh/d to <u>average</u> power requirements in kilowatts, divide by 24.

The <u>average</u> UK power requirements therefore come to:

"Mobile" supply requirements:	75 million kW = 75 GW (gigawatts)
"Static" supply requirements:	175 million kW = 175 GW
Ie. Total <u>average</u> power requirement:	250 million kW = **250 GW**.

I will now consider how the above energy/power requirements can sustainably be met.

3.1. "Mobile" Power Requirements

The "mobile" power requirements are needed to power all mobile equipment not able to receive all its power from a static supply grid, as are electric trains for example. This grouping therefore encompasses cars, buses, trucks, aircraft, boats, ships, mobile construction equipment, etc.

The vast majority of these users currently derive their power from fossil fuels (lpg, petrol/gasolene, diesel fuel, jet fuel/kerosene, heavy fuel oil, etc). A sustainable alternative to all these types of fuel must be developed.

The following options have been touted by various parties:

Battery electric power
Hydrogen-based systems (fuel cells etc)
Naturally occurring propulsion (wind, tides).

All the above options have serious drawbacks, as follows:

Battery electric power is limited by the capabilities of the batteries. While it is beginning to look feasible for short range road vehicles (city cars, delivery vehicles, etc), the implications for longer journeys (battery weight, range, recharging times, battery exchange logistics) look quite daunting, and it is of course out of the question for aircraft and long distance shipping. On top of that, we need to have a regard for the future supply of the materials necessary for manufacture of high energy density batteries.

Battery electric power does have a future part to play in the overall scheme of things, in the areas already identified where its limitations are not too constraining, and these can be extended by operation in conjunction with other power sources in hybrid drivelines. But it cannot in isolation provide the wide scale solution to our mobile energy needs.

Hydrogen-based systems are dealt with comprehensively by Professor MacKay in his book. I agree with his conclusion that they are unacceptably energy intensive and impractical due to the difficulties of storage and transfer of hydrogen. I cannot better Professor MacKay's comments, and would advise any reader wishing to promote the cause of hydrogen to turn to the relevant section of his book.

Naturally occurring propulsion may have a part to play with wind and tidal current assistance for slow moving ocean-going ships. It is of course already exploited by trans-Atlantic airliners, whose routes and operating altitudes are selected to either enjoy the assistance or avoid the resistance of the jetstream winds.

However, the speed constraints and/or unreliability of winds and tidal currents will limit their role to no more than small scale assistance in the propulsion of craft still needing a primary power source produced by other means.

I therefore conclude that none of the above options can provide a total solution to our future mobile power requirements.

3.2. Alternative "Mobile" Energy Sources

Before trying to identify what alternative power concept could fulfill these needs, it may be helpful to remind ourselves of the characteristics needed to render it a practicality. I have summarised these in the following list:

Capable of large scale production
Non-polluting production and use
Lends itself to economic production
Does not require resources in limited supply
Lends itself to ease of storage, transport and delivery
High energy density level
Does not rapidly degrade in storage etc
Benign effect on production, storage, transport and user systems
Acceptable levels of toxicity, danger through accident, misuse, etc.

This is an awesome list of requirements, and it's easy to see how petroleum products have risen to their level of pre-eminence in view of their near-unique ability to meet most of the requirements. Identifying a replacement will not be easy.

Of all the "mobile" usage categories, the most difficult ones to find an alternative, sustainable fuel to power are flying and shipping. I am therefore proposing that for these categories for the time being we "use" our target limit for CO_2 emissions from fossil fuels of 1 tonne per person per year.

The total future flying energy requirement is estimated to be as follows:

Civil aviation:	8 kWh/d/p
Military flying:	1 kWh/d/p
Ie. total flying energy requirement:	9 kWh/d/p.

The CO_2 emissions from kerosene jet fuel are 240 g/kWh.

Therefore the emissions per person per year from flying will be:

9 kWh/d/p x 365 d/yr x 240 g/kWh ÷ 1,000,000 g/tonne = 0.79 tonnes.

The future shipping energy requirement is estimated to be as follows:

Transport:	2 kWh/d/p
Military shipping:	1 kWh/d/p
Ie. total shipping energy requirement:	3 kWh/d/p.

The CO_2 emissions from heavy fuel oil are 260 g/kWh.

Therefore the emissions per person per year from shipping will be:

3 kWh/d/p x 365 d/yr x 260 g/kWh ÷ 1,000,000 g/tonne = 0.29 tonnes.

Ie. total estimated CO_2 emissions for flying and shipping: **1.08 tonnes/p/y.**

OK, I failed. This exceeds the target limit of 1 tonne per person per year by just 8%, but I'm going to allow this as it's such a big reduction from our current emissions, and numerous figures in the calculations are probably over- or under-estimated by much more than 8%. But even to achieve this, all other "mobile" energy supplies must be 100% carbon neutral. Hmm.

3.3. Proposed Future "Mobile" Energy Medium

During general background reading, I did hit on a possible candidate able to meet this requirement, and I would like to propose its adoption to meet our land-based mobile power requirements. I am no chemical engineer, and my present level of knowledge is extremely limited, but I have decided to go ahead and base my proposals on this option in the belief that it could become a practical alternative to our present fuel supplies.

The alternative fuel source I am proposing for land-based mobile uses is: **Methanol**, and its related compounds.

Methanol is a compound of carbon, hydrogen and oxygen, and has physical, combustion and energy density characteristics very similar to the lighter fractions of the current petroleum products. It is also chemically related to a number of other compounds which are possibly even better suited to some of the applications, and could be produced by similar processes.

What particularly excites me about this option is the belief (I won't put it stronger than that for now) that it can be produced reasonably economically from carbon dioxide extracted from the atmosphere, and water. It is therefore potentially a 100% carbon neutral energy source.

The other element of the methanol production equation is electrical power (the production process is based on electrolysis), and the sustainable generation of this electricity must also be addressed. I'll discuss that in the following section.

My background reading has uncovered numerous proposed production processes for methanol and its relatives with widely varying claims regarding their energy efficiency. All these processes are in their infancy and I am certainly not qualified to pass judgement on them, but I am going to assume that 40 years of further development will generate a commercially viable process. Regarding energy efficiency, for the sake of this analysis, I am going to assume an approximate mid-point in the range of current claims (between about 40 and 65%), ie. 50%. Put another way, for each 1 kilowatt hour's worth of methanol (or related product) produced, an energy input of 2 kilowatt hours will be required.

Looking at the above list of required characteristics for a new mobile power source, methanol and its relatives appear to tick pretty much all the boxes. In particular, their close similarity to some of the fuels currently in widespread use means that the existing storage, transportation and delivery systems could be amended to handle the new fuels with very little additional investment. Methanol is a proven fuel in several existing applications, and it has even been suggested as an alternative to hydrogen in fuel cells.

The big issue concerns production. Can any of the proposed processes, which presently only exist in laboratory conditions, be up-scaled to the extent necessary for widespread use of methanol and its relatives within acceptable levels of input power and financial investment?

While seeking an answer to this issue and confirmation regarding my other assumptions, I'm proposing methanol as the carbon neutral mobile fuel of the future.

After subtraction of the UK-sourced flying and shipping requirements (flying 4 kWh/d/p, shipping 1 kWh/d/p, defence flying & shipping elements 1.3 kWh/d/p, ie 6.3 kWh/d/p = 440 million kWh/d = 18 GW average power), the land-based mobile energy requirement will be 1.35 billion kWh/d = 56 GW average power.

Regarding production power requirements, a calculation based on an energy efficiency of 50% would result in an electrical energy input of **2.68 billion kWh/d**, or an <u>average</u> input power of **112 GW**. This would satisfy projected UK land-based mobile energy supply needs, covering all forms of demand from cars and trucks to agricultural vehicles and armoured fighting vehicles.

Regarding cost, artificially produced methanol and its relatives are bound to be more expensive than our current fuels, the raw materials for which we effectively get for free from under the ground. However, this must be viewed from the perspective of total fuel prices at the pump. In the UK, approximately 75% of the pump price is tax. If we assumed that the intricacies of manufacture would double the total ex-tax cost of the fuel, including production, storage, transportation, retailing costs, profit, etc, and the tax take remained at present levels, the pump price would go up by 25%. OK, this is quite a hike, but it would disappear into insignificance if spread over a few years, when compared to recent price rises.

The scale of the production facilities for methanol and its relatives would be on a par with current oil refineries, but they would of course be considerably less polluting. It is possible that in some instances the sites of existing oil refineries could be converted with no additional intrusion into the landscape.

In the short term, relatively small scale methanol production could be based on methane captured from landfill sites etc and naturally escaping methane gas. This would be much less harmful to the atmosphere than allowing it to contribute to greenhouse gases.

3.4. "Static" Power Requirements

The medium for supply of power to static installations would be mains electricity, supplied via a grid as at present.

The total "static" energy requirement for the UK in 2050 is estimated to be 4.2 billion kWh/d, or an average power demand of 175 GW. However, we must add to that the electrical power required to operate the proposed methanol production facilities discussed above, making a total electrical energy requirement of 6.88 billion kWh/d, or a total average power demand of 287 GW.

These energy/power demand figures were all calculated at the point of usage. If we add a margin of 5% for transmission losses for the mains electricity and distribution energy requirements for the methanol-based fuel, the final total UK requirements, at the points of power generation, would be:

Energy: 7.22 billion kWh/d

Average power: 301 GW.

Although the total UK-sourced energy requirement per person, including the flying and shipping requirements and even including the efficiency losses inherent in the methanol production process, is significantly less than our estimated current usage (it converts to approximately 110 kWh/d/p, compared to the current figure of 134 kWh/d/p excluding overseas sourced goods and services), the nature of the required energy will be totally different from current practice.

The above figures for future requirements relate to overwhelmingly electrical power generation. Currently, the majority of our energy needs are met by other media (petroleum-based fuels, gas, etc), and only about 18 kWh/d/p, or 1.1 billion kWh/d for the UK as a whole, comes to us as mains electricity. This is only about one eighth of our total energy consumption. The vast majority is consumed in oil and gas.

Therefore, in order to meet our future energy requirements along the proposed lines, we will have to increase our electricity generating capacity about **7-fold**!

This would be a massive undertaking even assuming we were adhering to current energy sources (coal, gas, oil, etc). To achieve this result from sustainable sources adds an extra dimension to the challenge.

3.5. Electricity Generation Options

Professor MacKay identifies 15 distinct sustainable methods of generating power, with widely varying potential contributions to the total energy requirement.

When viewing their potential outputs, the options fall into two basic categories. There are the big hitters, which are able to make a significant impact on our total needs, and comparative minnows which would not be able to make much of a contribution to the overall picture.

The big hitters comprise the following options:

On-shore wind power
Off-shore wind power
Tidal currents
Tidal barrages and lagoons
Energy crops
Photo voltaic power
Nuclear power
Clean coal.

Clean coal is not strictly sustainable, but I've included it in the list because it could have a significant transitional role, particularly as a supply of concentrated carbon dioxide for the proposed methanol-based fuel production facilities, as would the continued short term use of oil and gas.

Nuclear power is also contentious because of its associations with nuclear weapons and toxic waste. However I have included it at this stage because the inherent shortcomings of other options may prevent its elimination.

For the record, here are the comparative minnows:

Wave power
Hydro electric power (in UK)
Waste incineration
Wood burning (in UK)
Landfill gas
Waste food digestion
Geothermal energy.

All of the above will have their parts to play in localised or small scale applications, but even taken together they are too small to make a significant impact on our overall requirements.

Returning to the big hitters, there are 3 options which I would again discount from large scale plans because they will be too intrusive for development on anything like the scale necessary to make a significant impact. They are: on-shore wind, tidal barrages & lagoons and energy crops. In addition, I would demote photo voltaic power due to the limited space available in the UK, the technical and cost implications of transmission of imported power to the UK, and the uncertainties over supply security implicit in reliance on the regimes of some of the potential overseas supplier states.

This whittles down the list of potential large scale sustainable energy sources in the UK to just 3 candidates:

Off-shore wind power
Tidal currents
Nuclear power.

I'm now going to put nuclear power to one side and try to establish whether we can theoretically answer all our future energy needs with just the two remaining large scale options: off-shore wind power and tidal currents, supported by the smaller scale options in realistic quantities.

In this investigation I will push at the accepted boundaries of these options' capabilities. I feel justified in doing this because I believe there is considerable scope for the enhancement of our capabilities in the coming decades, particularly when motivated by the critical need to do so. But I will not exceed what I believe to be the realistic limits of what can be achieved.

First a brief resumé of what we can expect from all the other small scale sustainables:

3.6. Summary of Small Scale Energy Sources

In the interests of keeping the main body of this paper reasonably brief, I've calculated the potential contributions of the small scale energy sources in Appendix 1 at the end of the paper. The results, rounded to the nearest half gigawatt, are summarized below:

On-shore wind:	10 GW
Tidal barrages & lagoons:	8
Energy crops:	5
Photo voltaic power:	4.5
Wave power:	2
Waste incineration/landfill gas:	1.5
Hydro electric power:	1
Geothermal energy:	1
Wood burning:	0.5
(Waste food digestion:	0.1)
Total:	**33.5 GW**

These contributions are not to be dismissed: together they add up to about three quarters of our current mains electricity consumption.

But they do pale beside our total future needs after substitution of oil and gas (they add up to only about 11% of our total energy requirements).

Can off-shore wind and tidal currents fill the breach on their own?

3.7. Off-Shore Wind Power

We are uniquely fortunate in the UK in being bordered by large areas of sea, the majority of which is comparatively shallow. These seas have come to our aid on many occasions throughout history, providing defence against invasion, food from fishing and energy from the North Sea oil and gas fields. I believe the sea will once again come to our rescue, by providing the locations for large scale off-shore wind power installations.

On-shore wind farms on anything like the necessary scale are not possible in the UK, because of the dire shortage of unused land suitable for their installation.

The sea, however, provides empty space aplenty, with very little call on it for other uses, apart from fishing and the provision of shipping lanes.

A number of pioneering off-shore wind power developments have already been established, on a fairly small scale up to now. The hostile environment has thrown up plenty of problems, but I am confident that these will be overcome as experience grows, just as with other marine endeavours (shipping, oil rigs, etc).

Current thinking has it that these technical considerations will limit the water depth in which wind farms can be located to about 25m, with 50m seen as a maximum future limit. This would constrain wind farms to a total offshore area of about 76,000 sq km, much of it close to shore and therefore unusable because of other needs (coastal shipping etc) and the visual blight of lining the coastal skyline with wind turbines.

Assuming that these considerations would halve the possible area for the location of wind farms to 38,000 sq km, and based on the average power density of 2.5 W/sq m (or 2,500 kW/sq km) shown by experience of existing off-shore wind farms to be achievable, this area could generate an <u>average</u> output of 95 GW. This is roughly 30% of the total estimated future average UK power requirement: a good start, but far from the total solution.

I believe we must be more ambitious in our thinking about the depth of water in which we can establish wind farms. Here in the UK, we have a world lead in the technology involved in the construction and operation of the complex machinery and installations required for operation of oil rigs and production platforms in the extremes of hostile conditions in the North Sea and beyond. Coincidentally, this expertise has been gained over the past 40 years. I believe that, given the motivation, we should be able to build on this knowledge to the extent that in another 40 years we are able to construct and reliably operate wind farms in water depths up to 100 m.

Looking at a map of the North Sea, the depth of the water remains less than 100 m all the way northwards to a line running approximately eastwards from the southern shore of the Moray Firth. Taking the UK's share of this area, and assuming an exclusion band of 30 km width out from the coast, this creates an area of approximately 80,000 sq km. There is an additional area of approximately 50,000 sq km of similar depth down the west side of the UK mainland and up the English Channel, making a total potential area of approximately 130,000 sq km.

Fig. 3.7. UK territorial waters

In view of the remoteness of much of the northern North Sea, I think it would be reasonable to assume that up to 75% of its area at this depth would be suitable for the establishment of wind farms. The remaining portion would be given over to shipping lanes, wildlife sanctuaries, etc. The area open to development would therefore be 60,000 sq km. The Irish Sea etc are more congested: we'll go for 50% of that area being available. This results in a total of about 85,000 sq km between 50 and 100 m deep available for wind farm development.

Based on the same average power density figure as before (2.5 W/sq m or 2,500 kW/sq km), the average power generated in this area would be 212 GW.

When combined with the output from shallower regions, we are now up to an average power output of **307 GW**, slightly in excess of the total average requirement.

There are several major issues associated with a development of this scale and complexity. In addition, we must address the matter of continuity of supply from a notoriously fickle element (the wind). I'll come back to these issues a little later.

3.8. Tidal Currents

All the sea around the UK is subject to the tides. Unlike wind, these are very predictable, but vary in intensity according to the positions of the heavenly bodies, and don't always provide peak output at times coincident with peak demand.

The scope for power generation also varies according to location, the peak and average flow velocity varying considerably from point to point. Professor MacKay identifies 6 areas round the UK offering particularly good power generation prospects. These are as follows:

English Channel south of Isle of Wight
Bristol Channel
North of Anglesey
North of Isle of Man
Between Northern Ireland, Mull of Kintyre and Islay
Pentland Firth

Together, these areas offer the potential for generating an average power of 22.5 GW, about 7% of the total power requirement.

This doesn't sound very much in isolation, but I think there is considerable potential for increasing the tidal current power generation contribution by exploiting the installations proposed for off-shore wind power. Many of these would be in locations where there may not be sufficient tidal flow to justify the establishment of facilities solely dedicated to tidal current power generation, but if combined with wind power in a dual purpose facility, the economics could look very different.

Referring again to Professor MacKay's book, the total average tidal power impinging on the North Sea, west coast of Scotland, Irish Sea, Bristol Channel and English Channel from the Atlantic is 250 GW. Not all of this is in UK territorial waters: we could reasonably claim access to about 160 GW in "our" portions of the sea. The specific proposals for tidal current generation referred to above already claim 22.5 GW of this power. If we identified those remaining areas featuring relatively high flows, we may be able to extract up to about 10% of the remaining power, ie. about 14 GW average power. Combined with the specific proposals previously identified, tidal currents could therefore contribute **36.5 GW**, about 12% of our total power requirements.

3.9. Total Power Generating Capacity

Combining the above tidal current power with the potential capacity of off-shore wind farms, we have a total average power output of 343.5 GW. Adding a further 33.5 GW derived from practical development of all the on-shore sustainable energy sources, wave power, tidal barrages & lagoons, this takes our total average power generating capacity up to **377 GW**, which exceeds the estimated requirement of 301 GW by about 25%.

Job done.

Well, not really.

So far we've glossed over some major issues which have to be resolved to make this a viable energy policy. Here are the issues:

Energy demand fluctuations
Prolonged periods of low or absent wind
Technical and design issues
Reliability & maintenance issues
Resource demands
Financial aspects.

I'll discuss how the above issues may be addressed in the following paragraphs.

3.10. Energy Demand Fluctuations

Peak electricity demand, during weekday evenings in the winter, is shown in Professor MacKay's book to be approximately 50% up on average consumption.

If we assume that consumption of other current energy supplies (gas etc) follows the same characteristic as electricity, the peak demand from "static" energy users would be 50% greater than the average consumption, ie 1.5 x 175 GW = 262.5 GW.

This is significantly less than our total target average electricity generating capacity, the remaining capacity being required for producing the methanol-based fuel to be used for land-based "mobile" applications.

I therefore propose that daily demand fluctuations be accommodated by varying the amount of energy drawn off for methanol-based fuel production. This would be made up by running the fuel production facilities at maximum capacity in off-peak periods, for example at night and in summer months.

3.11. Prolonged Periods of Low or Absent Wind

A worst case scenario would be a prolonged freezing period with an anticyclone stationary over the country for several days, and therefore little or no wind, as occurred in January 2010. Energy demand for heating was exceptionally high, including daily peak demand periods well above the average power consumption. This cold snap provided a timely reminder of the limitations of large scale wind power generation in real world conditions.

An alternative energy source must therefore be available at short notice, with sufficient capacity to fulfill peak power requirements, for the duration of the period of no or low wind.

I propose that this alternative energy source again be methanol-based fuels, reserves being drawn from the supplies primarily produced for land-based "mobile" applications, and used to power generating equipment very similar to existing gas turbine generators currently powered by natural gas. These stand-by power plants can be turned on and off very quickly, and to some extent already exist, therefore their adaptation to this new role will be comparatively straightforward and economical.

For the purposes of this analysis, I will assume that we have a period of no wind at all lasting 10 days, coincident with deepest winter conditions.

Peak electrical power demand will be 262.5 GW, as defined in the previous section, and average power required during the winter period is assumed to be 25% greater than the yearly average, ie 219 GW.

Gas powered generators are claimed to be up to 70% efficient, and I will assume that methanol powered generators will match this figure. The energy content of the methanol required to supply the generators must therefore be uplifted by 43% to allow for this.

The overall efficiency of the electricity-methanol-electricity process will accordingly be 35%: not particularly impressive in absolute terms, but not so bad when one compares it to typical coal fired power stations (about 33%), and when one accepts that this is a back-up system for use only when the primary energy sources fail to deliver sufficient power to meet demand.

Before calculating the reserves of methanol required to supply this demand, we must also add the ongoing requirements of land-based "mobile" users, ie an average of 56 GW.

I'm going to assume that all the land-based sustainables, other than on-shore wind, plus wave power are working at maximum capacity. Also, tidal power will be making its contribution every day, although not necessarily at peak demand periods. Therefore the energy content of the methanol reserves required to keep us going during the no/low wind period will be:

((average winter electrical power demand minus (small scale sustainable power output ex. wind + tidal power)) multiplied by 1.43,
plus land-based "mobile" power demand)
all multiplied by the no/low wind duration, assumed to be 10 days.

This comes to:

((219 – (23.5 + 36.5)) x 1.43 + 56) x 10 = 2834 gigawatt days.

This equates to 245 million gigawatt seconds, or 245E+15 joules.

(E+15 means 10 to the power of 15, or a "million billion").

The energy density of methanol is 18 MJ per litre.

Therefore to provide sufficient reserve energy to keep us going through 10 days of no/low wind, we need to store **13.6 billion** litres of methanol.

This sounds like a heck of a lot, but to put it in perspective, the capacity of some current fuel depots is approximately 250 million litres. Therefore the methanol storage facilities required to keep the whole United Kingdom powered up for a 10 day winter period of no/low wind would be equivalent to 54 depots of this capacity. Still a lot, but not unreasonable when one considers the enormity of the challenge, and reflects on the number and scale of existing industrial and storage facilities dotted around the country. (There are presently over 100 fuel depots of various types around the country, many of which would be rendered redundant in the post-fossil era).

Having exhausted this reserve, and returned to a more usual weather pattern, how long would it take to replenish the methanol stocks?

The average output of all our sustainable energy sources was calculated to be 377 GW, and the average power demand was 301 GW. The difference between these figures, 76 GW, would be available for production of the methanol required to replenish the reserves.

The energy required to produce methanol is assumed to be double the energy capacity of the resulting fuel, ie 490E+15 joules.

Our 76 GW input power is equivalent to 6.57E+15 joules per day.

Therefore it will take 75 days to fully replenish the reserve stock of methanol from our own resources.

I think this is a reasonable timescale in view of the extreme nature of the circumstances being guarded against. However a government wishing to avoid the embarrassment of a power shortage brought about by these conditions may decide it would be prudent to increase the size of the reserve stock over the 10 days' no/low wind's worth used in the above analysis. It would also be possible to replenish stocks during the no/low wind period or following it in less time if we imported some fuel, just as at present.

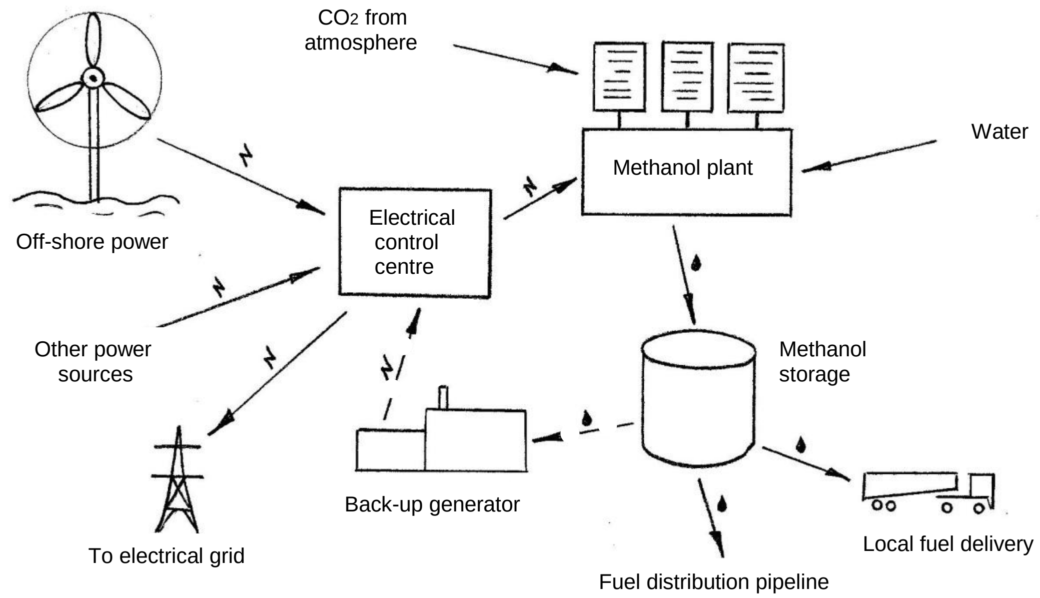

Fig. 3.11. Integrated energy supply & distribution process

3.12. Technical and Design Issues

The technical challenge implicit in establishing off-shore generating facilities on the proposed scale is enormous. The design and installation of equipment able to operate reliably in water up to 100m deep, and in the weather conditions to which these locations will be subjected, will certainly stretch off-shore engineering capabilities beyond their present limits.

Any structure capable of sustaining these conditions will have to be massively constructed, and mounted on very secure foundations. It therefore follows that, in order to recoup the technical and financial investment, the generating equipment mounted on the structure should be of a commensurate scale. I therefore propose that the size of the turbines be progressively scaled up, from the 90m diameter of typical present units to approximately 200m diameter.

Rated and average generating power of the resulting machines will increase in proportion to the square of the diameter, from the quoted 3 MW and 1 MW respectively for a 90m diameter turbine to approximately 15 MW and 5 MW respectively for a 200m model. Employing the five times diameter spacing rule for maximum efficiency, turbines of this size would be spaced at 1 km intervals, ie there would be one turbine per square kilometre of sea area.

Incidentally, there's a discrepancy between the above turbine performance figures and the accepted convention that the average power density of an off-shore wind farm would be about 2.5 W per square metre, in other words 2.5 MW per square kilometre. This appears to be due to the fact that in those wind farms established to date, the actual spacing between turbines is considerably greater than the "five times diameter rule", thus reducing the potential power density of the resulting farm. However, I will stick to using the latter, lower, figure for our macro calculations, thus if anything erring on the safe side.

One of the shortcomings of present wind turbines is their inability to perform at all in very high winds, thus wasting a great deal of potentially very useful energy. This limitation must be overcome, in order to maximise the potential output of these highly costly installations. I suggest that, if the main turbine cannot be made to withstand these conditions, a smaller diameter secondary turbine be coaxially mounted, possibly on the opposite end of the generator pod from the main turbine, and in extreme winds the main turbine be stopped and the secondary turbine take over.

In the interests of further enhancing the return on investment of these installations, many of them could be made to be dual- or even triple-purpose, in that as well as wind turbines, they are also equipped with tidal flow and wave power generators. They would thus exploit all three off-shore energy sources in one hit. The degree to which tidal flow and wave power can be tapped will depend on the locations of respective installations around the coast: in some positions, the available energy would be insufficient to justify the cost of this additional hardware. But those facing the full brunt of the Atlantic, and in areas of high tidal current velocities would be well placed to exploit these additional sources.

Regarding locations in very deep water, a development presently in its early stages involves the installation of turbines on submerged buoyancy systems anchored to the sea bed by cables. This could greatly increase the practical limit of the depth of water accessible to wind farms, and have a major influence on costs.

Further to the challenge presented by the generating equipment itself, the task of engineering a distribution and control system able to cope with regular demand fluctuations in addition to the vagaries of the supply side will be extremely taxing. It could well be that use of other energy storage media in addition to the proposed methanol reserves will reduce the required scale of the latter.

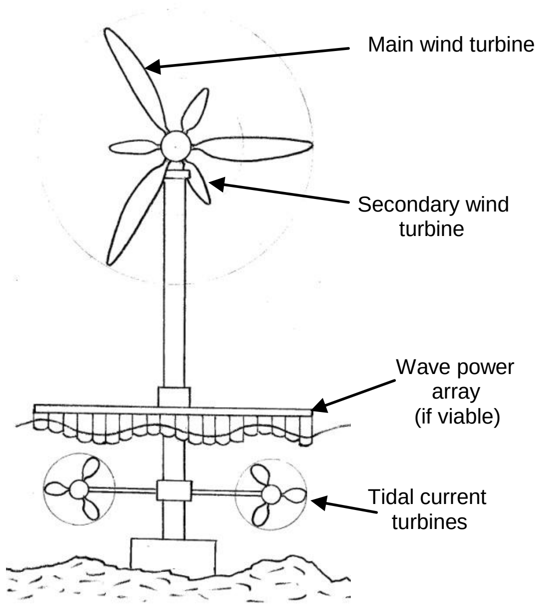

Fig. 3.12. Off-shore power installation

3.13. Reliability & Maintenance Issues

Nothing on the proposed scale has ever been attempted before in the conditions which prevail in the seas around the UK. However that was also the case before the large scale development of North Sea oil, and myriad other engineering advances down the centuries. I strongly believe in the saying “necessity is the mother of invention”, and this applies to the development and operation of new energy sources as much as other pursuits.

I accordingly believe that the reliability and maintenance issues implicit in these proposals will be rapidly resolved, and the knowledge and procedures gained in other marine applications will be brought to bear on the challenges to be encountered in this development.

There will inevitably be a degree of learning from experience, so the best way of starting the education process about any new issues will be to establish a number of pilot installations well ahead of the main body of generators. In this way, we will already be well advanced on the learning curve by the time full scale production and installation is commenced.

3.14. Resource Demands

The demand for all resources implicit in these proposals is going to be enormous. This will encompass concrete, steel, composites, electrical generation, switching and distribution equipment, methanol generating plant and storage facilities, installation and maintenance equipment for all aspects, and crucially the skilled personnel necessary for execution of all contributing parts.

Selecting just two of these resource categories, I’ll discuss the requirements for steel and skilled personnel. Similar considerations will apply to all the other resources.

Professor MacKay’s book quotes the weight of a “3 MW” (maximum capacity) wind generator with 90m diameter turbine as 500 tonnes, half of which is in the foundation. The foundation material would mainly be concrete, therefore the implied steel content is approximately 250 tonnes.

I’m going to assume that the extra material resources involved in the deeper water locations implicit in many of the proposed wind farms will offset the economies of scale deriving from their larger capacity. Therefore a “15 MW” turbine along the proposed lines will require 5 times as much steel as the “3 MW” design, ie 1250 tonnes.

Expressing the required steel as a weight per average unit power output, this equates to 250 kg per kW.

I will make a further assumption that the steel requirements per unit of generated power of the tidal current and wave power elements utilising the same structures as the wind turbines will also be 250 kg per kW. The weight of steel required for the entire system of off-shore facilities, generating an average of 345.5 GW (made up of 307 GW from wind, 36.5 GW tidal currents and 2 GW waves) will be **86 million tonnes**.

Current UK steel manufacturing capacity (diminishing even as I write this) is about 10 million tonnes/yr, and world steel production is presently approximately 1200 million tonnes/yr.

Therefore, assuming the bulk of the above 86 million tonnes of steel demand was spread over 20 years, it would account for about 43% of total UK steel output at current production levels, or about 0.35% of global steel production. Challenging, but do-able.

Just as a comparison, the “usual” demand for new cars in the UK is about 2 million per year. Assuming each contains 1 tonne of steel, that’s 2 million tonnes of steel per year. The annual steel requirement to facilitate the above proposal spread over 20 years (4.3 million tonnes per year) is a little over twice our year-in-year-out appetite for steel in our cars.

Turning now to “human resources”, the scale of the proposed development is on a par with all our existing power generation, North Sea oil extraction and fuel supply operations combined, and will demand equivalent levels of skilled personnel to support it. Skilled people on this scale are clearly not instantly available, and a massive training programme would have to be instituted to enable it to go ahead.

However, this would be no bad thing. For a start, we do already possess a core of personnel with these skills, presently employed in the existing industries, and these would form the basis for the development of the enlarged workforce needed to facilitate the proposed development, and support it post-installation.

In addition, this requirement could prove to be a veritable godsend. Successive governments have proved themselves devoid of any meaningful notion as to the future shape of British industry following our withdrawal from the traditional manufacturing sectors which have underpinned the economy ever since the Industrial Revolution. The talk from all sides is of “High Tech Sunrise” industries with no evidence of what they may be, or how they could support anything like the scale of employment necessary to compensate for the loss of jobs in the manufacturing sector.

This development would generate a massive demand for personnel with a wide spectrum of skills, at a stroke eliminating much of the present shortage in the UK of employment opportunities of this nature. It would additionally open up widespread potential for the subsequent exploitation of these skills in the execution of projects requiring similar expertise in other parts of the world, just as North Sea oil spawned a previous generation of internationally renowned oil production specialists.

3.15. Financial Aspects

Cribbing Professor MacKay's work yet again, the cost quoted for off-shore wind farms presently planned works out at about £1 million per megawatt of rated capacity. The average power output being one third of rated capacity, this works out at about £3 million per megawatt of average output.

Can we use the same figure for our 345.5 GW of combined wind, tidal current and wave generators? Will the additional complexities of the comparatively extreme locations of many of them outweigh the economies of scale implicit in their larger size, and deriving from the sheer volume of installations to be produced? Maybe, but let's do the sum based on the above figure as a guide to the order of magnitude of the total cost.

Therefore, the approximate total cost of our 345.5 GW of wind, tidal flow and wave power generators is estimated to be: **£1.04 trillion**.

That is a stupendous figure. It even puts the currently quoted UK government debt of about £900 billion in the shade. However, spread over 20 years it's about £52 billion per year. That's around 4% of current GDP. Still one heck of a hit, but more sustainable if the alternative really was the end of energy-hungry life as we presently know it.

Not only will the up-front installation investment be enormous, this will inevitably have a knock-on affect on fuel prices at the point of delivery. Energy costs will accordingly represent a much higher proportion of overall domestic and commercial expenditure than hitherto. This will in turn be a limiting factor on future demand, so we may therefore find that our total energy requirements are somewhat less than the figures arrived at in the above estimates.

3.16. Concluding Comments

This concludes the "can it be done?" section. I believe I've shown that theoretically we could create a sustainable energy strategy in the UK, but at enormous cost in terms of the impact on the seas around us, the demand for resources of many types, and the financial investment.

One of the criticisms which could be levelled at this analysis is that I have not taken into account any allowance for generating units being taken out of service for maintenance etc. I accept this, but believe that I have been conservative in some of my other estimates (eg. I have not allowed for any reduction in demand resulting from the inevitable rise in costs), so the maintenance downtime aspect would be compensated by these.

In the final section I'm going to look again at some of the implications and review whether arguments of practicality should lead to a compromise in some aspects of these proposals.

4. Final Thoughts

4.1. Is This Realistic?

I believe we showed in section 3 that it is theoretically possible to generate sufficient energy to meet anticipated future needs, sustainably and within the UK's land mass and territorial waters. The overwhelming reliance on off-shore wind and tidal energy would avoid the need for widespread development of on-shore wind farms, bio-fuels, bio-mass, etc.

However, there would be an enormous financial cost, and some awesome technical challenges dictating urgent further development of some of the technologies and skills first established during the original exploitation of North Sea oil and gas.

The figures suggest that up to 92% of our energy would come from these off-shore sources, which begs the question: is it wise to put so many of our eggs in this one basket? Would it not be wiser to spread our future energy needs more equitably over a wider selection of sources?

There are no other sustainable energy sources capable of meeting our requirements, apart from one.

It's time we revisited **Nuclear Power**.

Nuclear gets a bad press because of its original application to weapons of mass destruction, and the hype over toxic waste. I don't intend to re-run the arguments for and against here. Suffice it to say that the present stance by some bodies against its use in the UK is beginning to look a little forlorn in view of its widespread uptake elsewhere, including by a few governments we would prefer not to have it, and the fact that we actually import some of our present electricity needs from France, where about 80% of their power is generated by…….nuclear energy.

Professor MacKay does a very thorough job in his book of analysing the size of presently known uranium reserves, the scope for considerably enhancing their effectiveness through better reactor concepts, the potential offered by uranium dissolved in the sea, and the scope for development of fission reactions using other materials. On top of that, there's the holy grail of nuclear fusion potentially offering near-infinite energy supplies, if it can be made to work in a commercially viable process.

I'm not proposing we scrap all other options in favour of nuclear power, but I do believe that our future requirements will be better served by a more equitable mix of the viable options. I would therefore propose that we achieve our average power requirement of 301 GW, plus an excess of about 30% to cover supply interruptions etc (ie. a total of 400 GW, slightly more than previously calculated) as follows:

Small scale sustainables:	30 GW
Tidal currents:	35
Off-shore wind:	235
Nuclear:	100

This distribution would have the affect of reducing the need to position off-shore facilities in some of the more hostile areas of the sea, thus easing the technical challenge and ultimate cost. Regarding cost, presently available figures suggest nuclear installations are about the same price as off-shore wind farms pound per kilowatt, so the overall investment would be little changed by this adjustment.

Nuclear power partly shares the other principal sustainable options' drawback of not being easily switchable to reflect demand variations, although it doesn't suffer from wind power's unpredictability. It will therefore still be necessary to have a reserve energy facility to smooth demand fluctuations (and output variations from the remaining wind, wave and tidal elements). I therefore propose that this function again be accommodated by methanol-based fuels, as previously suggested, although the greater degree of reliability resulting from the contribution of nuclear power will reduce the scale of the methanol reserves required to meet the no/low wind condition.

Current nuclear power stations typically have outputs of about 1 GW. At this output level, we would need 100 nuclear power stations to generate the proposed 100 GW of power from this source.

This would require our coastline to be dotted with power stations. Spread equally around our 3,000 km coastline, there would be one nuclear power station every 30 km.

However, I don't see why future generations of nuclear power station shouldn't be a lot bigger. Why not 5 GW super-stations? At that size, not only would there be only 20 installations, some could perhaps be sited on artificial off-shore islands, in combination with power collection points from adjacent off-shore wind and tidal current generators and some methanol production facilities. Another opportunity to exploit our shallow territorial waters?

100 GW of nuclear power stations is certainly a big leap from the UK's current nuclear capacity of about 7-8 GW. However, it doesn't look so awesome when compared to France's <u>current</u> nuclear capacity of 55 GW. In addition, in 1975 the UK Atomic Energy Authority was reported to forecast that UK nuclear capacity would be 104 GW by the end of the 20th century, so we've been here before. I don't think we can realistically afford to ignore this option.

Ideally there would be another major sustainable option whose contribution would be large enough to reduce the combined share of on-shore and off-shore wind of 58% of the total burden to about 30-35%. However, this does not appear to be feasible at present, and we should count ourselves very fortunate that the presence of the extensive shallow seas around our coasts offers such a substantial potential source of energy.

I therefore conclude that considerations of practicality and reducing our reliance on just one energy source should lead to a significant part of our future energy requirements being met by nuclear power, in conjunction with the still dominant development of off-shore power.

4.2. Transition Period and Overall Energy Requirements

This paper has concentrated on the possible scenario in 2050, 40 years into the future. The change from fossil fuels to sustainable energy sources will not be sudden, indeed it may not follow this timescale at all.

However, assuming we are well on the way down the proposed path by 2050, we can expect that the various elements of this development will come about gradually: in fact, several have already begun.

Existing fossil fuels will continue to meet a large part of our needs for well into this transition period. In particular, we will still use petroleum products for much of our road journeys, and electricity will still be generated by coal and gas-fuelled power stations.

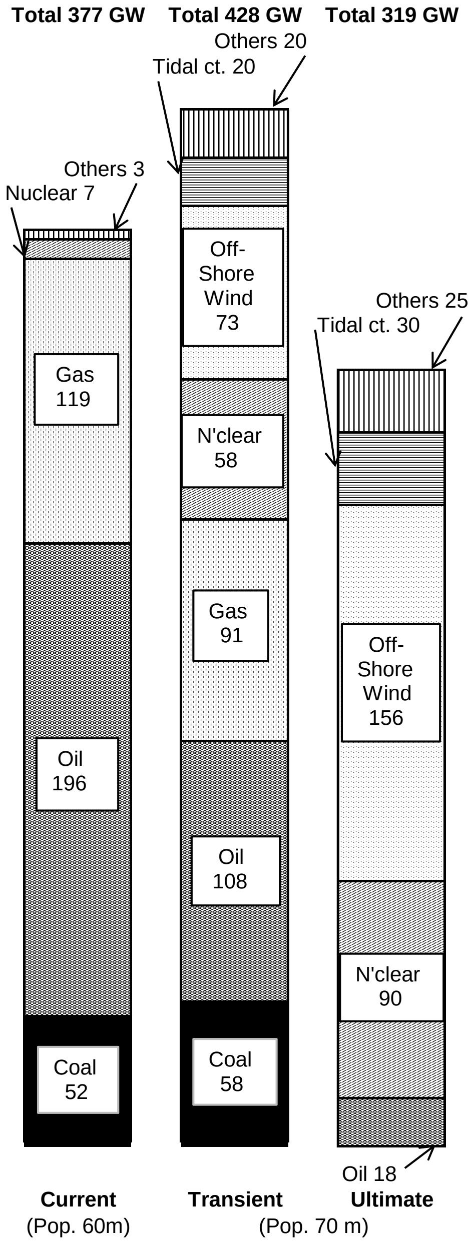

Fig. 4.2. Domestic energy requirements (av. GW)

The latter aspect actually represents a short term opportunity, in that the fossil fuelled power stations, along with a number of other chemical processing facilities, will be major sources of concentrated CO_2. There are already plans to capture the CO_2 and store it underground: how much better it would be to use it instead to supply methanol production plants to service some of the ongoing “mobile” fuel requirements, thus eliminating for the duration the difficult task of extracting it from the atmosphere.

I therefore anticipate a period of steady transition from our present overwhelming reliance on fossil fuels to an eventual sustainable future, exploiting opportunities along the way to adopt temporary expedients contributing to the journey to the desired destination.

The possible transition process in domestic energy requirements is illustrated in fig. 4.2. The data was drawn from a number of sources which I then combined in tables representing the 3 scenarios, arriving at the figures in the respective columns. As always in exercises of this kind, I encountered a few discrepancies, and I have prepared a separate note of explanation which is included as Appendix 2 at the end of this paper.

The apparent increase in overall energy requirements during the transient phase (which is actually just a notional snapshot of a continually evolving process) is explained by a number of factors. Firstly, the population is assumed to have grown by 17%. Secondly, I have assumed that a substantial proportion of our food production and manufacture of “stuff” will be repatriated from overseas to the UK. Thirdly, a significant proportion of our fuel needs for cars is assumed to be fulfilled by methanol in place of petroleum products, and the energy to produce it (at 50% process efficiency) is included.

The ultimate energy requirement is over 15% down from the current figure; this represents a 27% reduction in energy consumption per head of population. Taking into account the above factors, which in the ultimate scenario are taken a stage further than they are in the transient snapshot, I believe this represents a worthy aspiration.

4.3. Flying Revisited

In section 2.2, I suggested that we would greatly reduce our reliance on flying, through a combination of increased use of surface transport for journeys within Europe, and less frequent long haul flights. The latter would be replaced by increased business use of video conferencing etc and by holidays generally being taken nearer to home. I suggested that these changes would come about through commercial factors alone, driven by higher fuel prices.

This may be a little harsh, and would certainly not go down well in the aviation industry. It would also rule out the cultural benefits of young peoples’ gap year experiences travelling and working in developing countries etc. I’ve therefore given it some more thought, and come up with an alternative solution.

Apart from the energy consumption aspect, I was driven in my original analysis by the desire to try to meet the reduction in CO_2 emissions being mooted as necessary to stabilise the atmospheric environment, which would convert in an equitable world into an 11-fold reduction in the UK. I suggested that the remaining 1 tonne of CO_2 per person per year could be consumed by aviation and shipping, thus reinforcing the need for a substantial reduction in the amount of flying we do.

Of course, just as I'm proposing that all the numerous forms of land-based mobile equipment can operate sustainably in the future with a carbon-neutral fuel based on methanol generated with CO_2 extracted from the atmosphere, the same could apply to a future generation of aircraft. This would go a long way towards resolving the pollution issue, but the generation of the additional quantities of methanol would add considerably to our total sustainable energy requirements.

There would be some impact on aircraft design due to the reduced energy density of methanol compared to kerosene and other factors, but this would be nowhere near as marked as the implications of adopting hydrogen fuel, which has been suggested in some quarters.

If we accepted that our future flying requirements were to demand a more generous 20 kWh/d/p (compared to my previous suggestion of 8 kWh/d/p, and down from our present 30 kWh/d/p: we'd still use surface transport in Europe, video conferencing where possible, etc), this would create an additional energy requirement of 1.4 billion kWh/d for the nation, or an average power demand of 58 GW.

We then have to double this to allow for the anticipated 50% energy efficiency of future methanol production processes, leading to an average power demand of **116 GW**.

This is an additional power demand of **39%** on top of the previous total of 301 GW!

I submit that this is too much to accommodate within the UK's own sustainable energy resources.

However, this may lead to an ideal solution to the problem of cost effectively exploiting the solar power resources potentially available in areas of the world close to the equator. This could be a very valuable source of revenue to some of the nations in these regions, particularly as the scope for oil revenues starts to diminish.

The main bugbear stopping the practical exploitation of tropical solar power is the enormous cost involved in transmitting it to the principal potential users, in Europe and North America. However, if this power was used to locally produce methanol-based fuels, drawing CO_2 from the atmosphere, the transmission problem would be greatly reduced, and to some extent completely eliminated.

The methanol-based fuels can be transported by tanker far more easily than liquified petroleum gas, for example. But better than that, a considerable number of long haul flights traverse the tropical areas in question, meaning they could replenish at least some of their fuel requirements if they stopped there en route to their final destinations.

The route adjustments and extra landings would detract from overall fuel efficiency levels, but this would be compensated by the elimination of the need to transport the fuel taken on board at the point of production to another location.

I accept that this arrangement contravenes one of my original objectives, namely to be sustainable in terms of the place of origin of our energy as well as the means of production and its affect on the environment. However, the particular implications of long haul aviation merit some compromise on this score.

We therefore have a possible way of maintaining levels of long distance flying close to present conventions, doing it sustainably, and avoiding any additional demand on our future domestic power generation requirements. Too good to be true?

4.4. Other Countries

This paper has focused on the energy needs and potential future sources for the UK. It would be remiss of me not to consider what may happen in the rest of the world: a solution which applies to the UK alone will go virtually nowhere in resolving global energy and pollution concerns.

I don't intend to work my way through every country, but just as we in the UK have the particular advantage of shallow coastal waters and relatively high winds and tides around us, most other countries have local circumstances which can be turned to their advantage. These circumstances are many and various.

It is the case that some of the emerging economies are not as enthusiastic about the adoption of sustainable energy concepts to the desired scale as the established economies. This is understandable while they are playing catch-up with those nations that have built up a position of wealth on the back of widespread fossil fuel consumption over previous centuries. While it persists, this situation also of course renders the manufacture of goods in nations using high levels of expensive sustainable energy uncompetitive.

Some gentle persuasion may therefore be necessary to arrest the present near-exponential rise in consumption on the part of those countries rapidly developing their economies through exports of manufactured goods to the west. I envisage the possibility of a system of international tariffs, in which a duty is imposed on any internationally traded goods which are manufactured using fossil fuels, the value of the duty being equivalent to the cost penalty which would be inherent in the adoption of sustainable energy in their manufacture.

The establishment and operation of such a system will not be easy: indeed there are numerous examples of similar international agreements in the past failing due to local vested interests and corruption in the monitoring organisations. However, the stakes are sufficiently high to render it expedient to investigate the scope for such an arrangement.

4.5. Short Term Action

We've been focusing on the possible scenario in 40 years' time, 2050. But the achievement of the proposals, or any other plans with similar objectives, will take decades of intensive work, hence the need to crack on with initial actions without delay. I believe it would be good policy to commit to the following short term action:

- Progress off-shore wind farm developments already committed to.
- Accelerate tidal current and wave power system development.
- Survey sea bed of all UK territorial waters up to 100 m depth, and plan potential sites for extensive off-shore facilities.
- Design and development of "15 MW" wind turbine with integral tidal current and wave power elements, and capability of operation in extreme wind & wave conditions.

- Development of off-shore installation procedures, identification of equipment and resources requirements.

- Progress development of proposed tidal barrages & lagoons, and on-shore energy concepts.

- Plan for control, transmission and distribution issues inherent in highly dispersed and variable supply elements.

- Get on with short term plans for nuclear power stations and clean coal with capture and conversion of CO_2 to methanol-based fuels.

4.6. Final Final Thoughts

I don't know whether we are truly heading for a global energy shortage, or whether our fossil fuel emissions are truly causing potentially catastrophic changes to our environment. But in common with many people, I try to keep abreast of all the arguments and counter-arguments, and form a balanced view of their validity and implications.

So why have I written this paper?

Well, it seems good sense to me to at least be aware of the possibility that we may be heading for trouble, and if so have plans in place for its effective resolution. But I don't think it's enough just to maintain a watching brief. Such is the lengthy timescale implicit in the various suggested solutions, in comparison to mooted timings for possible energy shortfalls and climate changes, that I feel we should be taking out some insurance against any of these predictions coming about. The insurance takes the form of active development of the techniques and hardware necessary to replace fossil fuels with sustainable alternatives on the required scale, in readiness for widespread deployment if the evidence indicates they are necessary.

I owe much of the material on which I have based my proposals to Professor David MacKay's book "Sustainable Energy – Without The Hot Air". Professor MacKay includes in his book the invitation to readers to take his work forward by developing their own thoughts as to how we may resolve the energy conundrum. I would like to extend the same invitation to readers of this paper. Should anyone wish to discuss any aspects with me, in particular correcting my errors, I will be pleased to receive your comments at the following email address:

ddenergyclimate@gmail.com.

Appendix 1:
Evaluation of Small Scale Energy Sources

Maintaining my tradition of cribbing wherever possible from Professor MacKay's book, I estimate that the sustainable energy sources other than off-shore wind and tidal currents have the potential to contribute the following levels of power:

1. On-Shore Wind

Experience shows that on-shore wind farms can produce an <u>average</u> power output of 2 W/sq m, or 2 MW/sq km.

The total UK land area is 244,000 sq km.

Now, the big question: how much of this area could realistically be populated with wind turbines?

Professor MacKay suggests a maximum of 10%. I think this is unacceptably high. We could argue this point until doomsday, but I'm going for a figure of 2%, or 4,880 sq km. This is still a very substantial area: if grouped together in one circle, it would have a diameter of almost 80 km, and could cover all of Greater London and its surroundings out to about 10 km beyond the M25.

I therefore conclude that on-shore wind power could produce an <u>average</u> power of:

4,880 sq km x 2 MW/sq km = 9760 MW = **9.8 GW**.

Another way of looking at this output level is to imagine that it is all produced by turbines of the size of the installation adjacent to the M4 motorway in Reading, distributed uniformly throughout the country. The unit in question has a diameter of 70 m and an average output of 400 kW. Therefore we would require 24,500 turbines of this size, which if spread uniformly would lead to a density of 1 turbine every 10 sq km, ie if in a grid they would be just over 3 km apart. Smaller turbines would of course have to be more densely packed. When one allows for the vast tracts of land which would be denied to wind turbine installations, this looks quite a challenging prospect.

Wind power is of course subject to wide variations, therefore the above figure cannot be relied upon to provide constant power when it's most needed.

2. Tidal Barrages & Lagoons

Let's assume objections to large scale barrages and lagoons are overcome, and they're established in the best locations currently envisaged. Totting them up, and assuming they operate in both tide directions (not the current case for all proposed developments), the following figures would result:

Severn Barrage:	4.0 GW
800 sq km of lagoons:	3.6
Smaller scale developments (est.):	0.5
Total:	**8.1 GW**.

Tidal power is much more reliable than wind power, but it is again subject to large fluctuations which can lead to little or no output at times of maximum demand.

3. Wave Power

Based on the UK's 1,000 km of "frontage" facing the Atlantic, and an average incoming power of 40 kW/m, or 40 MW/km, the total average power contained in waves is 40 GW.

Of course, it's impossible to usefully absorb all this power. If we make a sweeping assumption that suitable structures are strategically located in the sea (their primary applications would be for other purposes: refer back to the main paper), such that 10% of this frontage is populated by wave power machines, and they are capable of converting 50% of the wave power into electricity, the resulting <u>average</u> power output would be:

10% x 1,000 km x 40 MW/km x 50% efficiency = 2,000 MW = **2.0 GW**.

Wave power fluctuates according to weather conditions in the Atlantic, so once again we wouldn't necessarily be able to rely on this source when we most need it.

4. Energy Crops

What proportion of the UK's land area could we turn over to energy crops? Not much I fear, because I feel we should be maximising our domestic food production potential in the interests of the UK economy, and reducing our dependence on long-distance transport of imported food.

Professor MacKay informs us that 75% of the UK's land area is presently devoted to agriculture. I suspect there's very little scope for growing energy crops on the other 25%, as it is largely taken up with urban developments and areas of natural beauty. So any energy crop production would have to come from the area presently devoted to agriculture.

But let's assume economic and other factors lead to 10% of the land area, or 24,400 sq km, being turned over to energy crops.

There are numerous different crops and processes under the "energy crops" umbrella, but for the purposes of this analysis I've assumed that all the available land area is devoted to the best performer, which Professor MacKay advises is Miscanthus. In northern Europe, this crop is capable of generating the equivalent of 0.5 W/sq m, or 0.5 MW/sq km, of usable energy. So our 24,400 sq km of land would generate a "power output" of:

24,400 sq km x 0.5 MW/sq km = 12,200 MW = 12.2 GW.

Unfortunately the process to turn the energy in the crops into electricity is only about 40% efficient, so the useable power output would be:

12.2 GW x 40% = **4.9 GW**.

If the crops are stored after harvesting, this energy source is available whenever required, making it very flexible in its application.

5. Hydro Electric Power

There are a number of schemes in the UK which serve as energy storage systems by pumping water from a low level reservoir to a high level one in times of low power demand, and then using the power generated when the water flows back under gravity to augment other power sources when demand is high.

Unfortunately these must be excluded from this analysis because they don't create any energy. They just act as a big battery which is repeatedly charged and discharged.

Professor MacKay does a theoretical analysis of the potential for hydro electric power assuming every drop of rain falling on the nation is perfectly exploited, with no evaporation, efficiency losses, etc. He produces a result of 1.5 kWh/d/p, which multiplied by his assumed population of 60 million would be equivalent to 90 million kWh/d for the nation, or approximately 3.8 GW.

Professor MacKay also notes that the actual power produced by hydro electric schemes in the UK today is 0.2 kWh/d/p, equivalent to 1.2 million kWh/d for the nation, or 0.5 GW.

What is a realistic target? I'm going to assume we can double the present figure, to **1.0 GW**. Much of the extra would be small scale local schemes in rivers, etc. This would be equivalent to extracting useful power from no less than 26% of our total rainfall: not bad at all.

6. Waste Incineration and Landfill Gas

I'll assume all combustible waste is incinerated. This will leave virtually no landfill gas to be collected.

Based on Professor MacKay's estimate that we produce 1 kg of waste per day per person, and the calorific value of 2.5 kWh/kg, the total energy produced across the nation would be:

1 kg/d/p x 2.5 kWh/kg x 70 million = 175 million kWh/d.

This is equivalent to a power of 7.3 million kW, or 7.3 GW.

Assuming the subsequent electricity generation process is 21% efficient (quoting Professor MacKay again), the resulting useable power output would be:

7.3 x 21% = **1.5 GW**.

To a degree this energy source can be operated in sequence with times of maximum power demand.

Waste incineration and landfill gas use are not carbon neutral, as one of the principal products of combustion is CO_2. However, this is a better way of disposing of waste than just letting it rot, which would result in the CO_2 being produced anyway, and passing into the atmosphere with no beneficial effect at all.

7. Wood Burning

We don't have enough forest in the UK for wood burning to be a major sustainable energy source. However, forestry maintenance and other clearance activities would generate a significant amount of wood each year, so let's assume it's all used productively.

Only about 12% of the UK's land area, 29,000 sq km, is wooded. Let's assume that 50% of this area is managed in the interests of maximising energy output.

Based on a power density of 0.1 W/sq m, or 0.1 MW/sq km (the bottom end of the quoted range for wood, probably appropriate to northern Europe), the power deriving from the wood would be:

50% x 29,000 sq km x 0.1 MW/sq km = 1,450 MW = c.1.5 GW.

Assuming the electricity generation process is 40% efficient (as with biomass), the resulting electrical power output would be:

1.5 x 40% = **0.6 GW**.

This assumes that none of the timber is put to other uses (carpentry etc). The cut timber could be stored until times of high power demand, making this a flexible energy source.

8. Photo Voltaic Power

(A note before we get into this source: I took solar water heating into account when estimating future energy requirements for heating, subtracting it from the input power requirement).

The logical place to put solar panels is on the roofs of buildings. It's sometimes possible to mount them elsewhere, but the general pressure on land use in the UK will prevent large scale photo voltaic installations at ground level, on dedicated structures, etc.

Professor MacKay states that there is 48 sq m of building area per person in the UK. It's assumed that this relationship will remain constant as the population grows.

If we assume that 25% of roof areas are in the arc facing southeast to southwest, 50% of that is rendered unsuitable for solar installations by other factors (roof construction, skylights, etc), and of the remaining area 50% is given over to solar water heating, that will leave 6.25% of the original area, 3 sq m per person, for photo voltaic installations.

Professor MacKay also reports that the average output of south facing solar panels in the UK is 22 W/sq m for a 20% efficient device. Therefore the total power generated would be:

3 sq m/p x 22 W/sq m x 70 million = 4.6 billion W = **4.6 GW.**

9. Geothermal Energy

Professor MacKay's comprehensive study of this energy source concluded that if we exploit all the UK's land area with deep drilling to reach high temperature subterranean zones, geothermal energy could provide the equivalent of 2 kWh/d/p based on a population of 60 million. This equates to a total power of 5 GW.

Local issues are bound to impact on some areas preventing the sinking of bore holes to extract the heat. I'm accordingly going to halve the potential value of this source to 2.5 GW.

It's very unlikely that the bulk of this energy could be put to any useful application in the UK, such is the distribution of potential drilling sites in relation to demand centres, other than powering electrical generators. Maybe the steam or hot water emerging from the ground would require further heating to give it the necessary energy to serve this purpose, but whatever the case, it would still be a useful energy source.

Assuming the subsequent processes are 40% efficient, the geothermal energy would contribute useful power equivalent to:

2.5 GW x 40% = **1.0 GW**.

10. Waste Food Digestion

The average household produces 4 kg of food waste per week. The food industry produces double this amount, leading to a total of 12 kg per household per week.

If we assume the average household has 3 occupants, the assumed 2050 population of 70 million will require 23.3 million households.

Total food waste for the UK as a whole would therefore be:

12 kg/wk/household x 23.3 million households = 280 million kg/wk = 280,000 tonnes/w = 40,000 tonnes/day.

Average energy content of food waste is 250 kWh/tonne. Therefore energy content of the daily food waste output would be:

250 kWh/tonne x 40,000 tonne/day = 10 million kWh/d = 0.4 GW.

Assuming that this energy can be converted into electricity at an efficiency of 21% (as for non-food waste incineration), the resulting useable power will be:

21% x 0.4 GW = **0.1 GW**.

Appendix 2: Derivation of Approximate Current, Transient and Ultimate Energy Consumption

1. Current Energy Consumption

The source data is drawn from Professor David MacKay's book: "Sustainable Energy – Without The Hot Air", and figures for 2007 electricity generation taken from the website: www.berr.gov.uk/files/file49480.pdf.

2007 is not quite "current", but looking at the trends in electricity generation over the previous 3 years, the year to year changes are quite slight, mainly reflecting a gradual reduction in nuclear output compensated by an increase in gas and renewables. The changes are sufficiently small for 2007 to be regarded as "current" for the purposes of this exercise.

Total electricity generation for 2007 was 396,142 GWh for the year.

This converts to 1,085 GWh per day, or **18.1 kWh/d/p** assuming 60 million people.

Percentage contributions of respective fuel types, and corresponding energy outputs, are as follows:

Coal:	34.5% = 6.2 kWh/d/p
Oil:	1.2% = 0.2
Gas:	41.5% = 7.5
Nuclear:	15.9% = 2.9
Others:	6.9% = 1.2

This totals to 18.0 kWh/d/p, the slight discrepancy caused by rounding the figures.

In addition, there were net imports of 5,215 GWh in 2007, corresponding to 14.3 GWh/d, or 0.2 kWh/d/p, but I have omitted these from the analysis in the interests of simplicity.

Reverting to Professor MacKay's data for current energy consumption, I produced a table showing the <u>estimated</u> distribution of energy sources for each of the usage categories. I'm the first to accept that this can contain inaccuracies, but hopefully the overall picture is not too wide of the mark.

The table is reproduced below: Table 1.

I then attempted to get back to our overall energy requirements by taking into account the conversion efficiencies of the respective electricity generation processes, in order to combine the raw material energy requirements with those used in other applications (eg. gas: some goes to electricity generation at an assumed efficiency of 65%, and some is used directly for heating & cooling). I have not done this in the case of nuclear energy: my justification here is that the raw material has no other significant application, so I have used the energy figure for the resulting electricity with no conversion efficiency. I acknowledge that this juggling with efficiency factors is a minefield open to misinterpretation, but I have tried to be logical in my approach.

Looking at the resulting figures, it's easy to spot a number of discrepancies between the respective total energy usages and those quoted in Table K.1 of Professor MacKay's book. I won't attempt to reconcile them: this is a hazard of drawing data from a number of different sources.

The figures in the bottom row of the table are used in the left hand column of fig. 4.2. in the main paper.

2. Transient Energy Consumption

By definition this is a changing scenario, so I have taken a snapshot of what I believe may be the position some way into the process from our current overwhelming reliance on fossil fuels to a more balanced position which may occur about a couple of decades hence. For example, I have assumed that car usage has started to go electric where possible, with the remainder of the required energy split between petroleum products and methanol.

When converting to the average total power demand, I have based calculations on the assumption that the UK population will have risen to 70 million.

The relative significance of the respective energy sources is a matter of personal choice. The total energy figure is significantly higher than that applicable to the current position or the ultimate picture because of the variable efficiencies of the respective processes for converting one form of energy to another, and because we would not by this point have exploited all opportunities for energy usage reductions and efficiency improvements. For example, I have assumed that carbon capture (for use in methanol production) will reduce the energy efficiency of coal fired power stations from 33% to 25%.

Table 2, below, illustrates this scenario, and the bottom row of figures is carried over to the centre column in fig. 4.2. of the main paper.

3. Ultimate Energy Consumption

For this scenario I started with my estimates for 2050 energy consumption, including production of methanol-based fuels for all land-based "mobile" uses. This converts to an average power demand of 319 GW.

I then made certain assumptions regarding the likely utilisations of the respective sustainable energy sources (which have a total theoretical average output capacity of 400 GW), in order to arrive at the probable typical mix of contributions adding up to the 319 GW. My assumptions regarding respective utilisations attempted to take account of probable maintenance downtime requirements for each of the sources.

This scenario is illustrated in Table 3, and the figures appearing in the bottom row are carried over to the right hand column of fig. 4.2. in the main paper.

The total energy demand in this scenario is significantly lower than our current requirements, having fallen from the considerably higher total figure in the transient scenario. This is quite respectable in light of the assumed population increase of about 17%, and more so when one considers the assumed energy losses implicit in the proposed production of methanol-based fuels for all land-based "mobile" fuel requirements and the assumed degree of repatriation of our food and manufactured goods production to the UK.

Table 1. Derivation of Approximate Current Energy Consumption and Production

Usage Category	Total Energy (kWh/d/p)	Sources (DD's estimates): Oil	Gas	Coal	Electrical	Nuclear	Others	Imports*
Car usage	40	40						
Flying	30	18						12
Heating, cooling	37	4	29	2	2			
Lighting	4				4			
Powering gadgets	5				5			
Food production	15	2	1		2			10
"Stuff"	48	2	6		4			36
Transport	12	10						2
Defence	4	2			1			1
Sub-totals	195	78	36	2	18			61
Sub-totals minus imports	134	78	36	2	18			
Electricity generation:								
Gas: 7.5 @ 65% effy:			11.5					
Coal: 6.2 @ 33% effy:				18.8				
Nuclear: 2.9 @ n/a effy:						2.9		
Oil: 0.2 @ 50% effy:		0.4						
Others: 1.2							1.2	
Totals (kWh/d/p)	150.8	78.4	47.5	20.8		2.9	1.2	
Totals (billion kWh/d)	9.05	4.70	2.85	1.25		0.17	0.07	
Totals (average GW)	**377**	**196**	**119**	**52**		**7**	**3**	

Note *: Imports refer to all energy sources not generated or supplied within the UK.

Table 2. Derivation of Approximate Transient Energy Consumption and Production

Usage Category	Total Energy (kWh/d/p)	Sources (DD's estimates): Oil	Methanol	Gas	Coal	Electrical	Nuclear	O/S Wind	Tidal ct.	Others	Imports*
Car usage	30	12.5	12.5			5					
Flying	20	11									9
Surface transport	1					0.7					0.3
Heating, cooling	28	2		14		12					
Lighting	3.5					3.5					
Powering gadgets	5					5					
Food production	13.5	2.5		1.5		2					7
"Stuff"	42	1		4		12					25
Transport	10	6				2					2
Defence	4	2				1					1
Sub-totals	157	37	12.5	19.5		43.2					44.3
Sub-totals minus imports	112.2	37	12.5	19.5		43.2					
Methanol production:						25					
Electrical total:						68.2					
Elec. total inc. losses						71.6					
Electricity generation:											
Gas: 7.6 @ 65% effy:				11.7							
Coal: 5 @ 25% effy:					20.0						
Nuclear: 20 @ n/a effy:							20.0				
Off-shore wind: 25								25.0			
Tidal currents: 7									7.0		
Others: 7										7.0	
Totals (kWh/d/p)	147.2	37.0		31.2	20.0		20.0	25.0	7.0	7.0	
Totals (billion kWh/d)	10.3	2.59		2.18	1.40		1.40	1.75	0.49	0.49	
Totals (average GW)	**428**	**108**		**91**	**58**		**58**	**73**	**20**	**20**	

Note *: Imports refer to all energy sources not generated or supplied within the UK.

Table 3. Derivation of Approximate Ultimate Energy Consumption and Production

Usage Category	Total Energy (kWh/d/p)	Sources (DD's estimates): Oil	Methanol	Electrical	Nuclear	O/S Wind	Tidal ct.	Others	Imports*
Car usage	17		8	9					
Flying	8	4							4
Surface transport	2			1.5					0.5
Heating, cooling	18			18					
Lighting	2.5			2.5					
Powering gadgets	5			5					
Food production	12		4	4					4
"Stuff"	38			19					19
Transport	8.5	1	6.5						1
Defence	4	1.3	0.7	1					1
Sub-totals	115	6.3	19.2	60					29.5
Sub-totals minus imports	85.5	6.3	19.2	60					
Methanol production:				38.4					
Electrical total:				98.4					
Total req'd inc. losses		6.3		103.3					
Total req'd (billions kWh/d)		0.44		7.23					
Total req'd (av. GW)	319	18		301					
Total elec capacity (av. GW)	400				100	235	35	30	
Notional usage split (av. GW)	**319**	**18**			**90**	**156**	**30**	**25**	

Note *: Imports refer to all energy sources not generated or supplied within the UK.

PEAK OIL

FOSSIL FUELS DEPLETION

GLOBAL WARMING

Do the above concern you?

Are you alarmed by the climate change debate?

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Do you yearn for some proper figures?

Are you frightened there's no solution?

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Energy & Climate: Time We Took Out Insurance?

by David L.J. Dunbar