LESS IS MORE:

Energy Security After Oil

David Olivier with Andy Simmonds

AECB
the sustainable building association

Acknowledgements

We gratefully acknowledge comments and help with figures and sources, including from David Andrews, Stephen Andrews, Bill Bordass, Alan Clarke, Bob Everett, Nick Grant, Phil Jones, Bob Lowe, William Orchard, Richard Priestley, Mark Siddall, Fionn Stevenson, Gordon Taylor and David Toke. Such contributions are much appreciated. But any remaining errors are ours alone.

We acknowledge too the leading research, development and demonstration programs on energy efficiency and renewable energy funded by national or local governments since 1974, along with private sector work which was catalysed by this public sector enthusiasm and implicit support. These funders include inter alia many federal and local governments, especially in the USA, Canada, Sweden, Denmark, Switzerland, Germany, Austria, the Netherlands, Norway and Finland. These contributions continue to this day. Without them, one would not be so positive about the feasibility of a sustainable energy future.

We also thank those on the above list who took the time to review this report, especially Bob Lowe. They provided very useful comments indeed, which greatly helped to improve both the content and the presentation. In addition, we are extremely grateful to Will Anderson for his help in writing an executive summary which succinctly sums up a complex message.

David Olivier and Andy Simmonds, January 2012

Cover photograph:
Earth’s atmosphere viewed edge on from space.
Image courtesy of NASA

About the Authors

David Olivier is Principal of Energy Advisory Associates, a consultancy focusing on the application of energy efficiency and renewable energy technologies in buildings. Over the past 30 years he has assisted in the design of hundreds of low energy buildings including the Elizabeth Fry Building at the University of East Anglia, the headquarters of Disability Essex in Rochford and many dwellings for private clients. He has written extensively on energy efficiency and renewable energy in buildings and has taken a particular interest in advanced building practice in mainland Europe, Scandinavia and North America. His books include *Energy Efficiency and Renewables: Recent Experience on Mainland Europe* and *Energy Efficiency and Renewables: Recent North American Experience*.

Andrew Simmonds is a Partner in Simmonds.Mills Architects and part-time Chief Executive of AECB, The Sustainable Building Association. His architectural and building experience covers historic buildings, innovative and traditional materials and the development of energy efficiency products for the mass market. Simmonds.Mills Architects designs low-energy domestic and non-domestic projects to the AECB Silver, Passivhaus and EnerPHit energy standards. Andrew led the development of the AECB energy standards and initiated the AECB CarbonLite programme. He also led the AECB team supporting the Technology Strategy Board's 'Retrofit for the Future' competition, including developing the low energy buildings database, and was closely involved in setting up the Passivhaus Trust to bring to the mainstream the work of AECB CarbonLite.

LESS IS MORE owes a good deal to a series of three earlier reports which appeared after the 1970s' first and second oil crises. These studies were in part government-funded:

- *An Alternative Energy Scenario for the UK* [1]
- *A Low Energy Strategy for the UK* [2] and
- *Energy-Efficient Futures: Opening the Solar Option*. [3]

LIM is written in the context of other recent studies of the UK's energy future, which include:

- *Zero Carbon Britain 2030* [4]
- *Sustainable Energy Without the Hot Air* [5] and
- *Scenarios for 2050 - A Key Scene Setting Report*. [6]

Disclaimer

AECB Ltd. and the authors consider that the information and opinions given in this work are sound, but all parties must rely upon their own skill and judgment when making use of it. Neither AECB Ltd. nor the authors make any representation or warranty, expressed or implied, as to the accuracy or completeness of the information contained in this report, and they assume no responsibility for the accuracy or completeness of such information. Neither AECB Ltd. nor the authors assume any liability to anyone for any loss or damage arising out of the provision of this report.

Throughout this report, the copyright holders are acknowledged wherever possible in relation to individual pictures and charts, and AECB is grateful for their permission to use their material. Where no acknowledgement is made, a chart should be attributed to the authors. If any errors have been made, AECB apologises to those affected and would be glad to correct the mistake(s) in a subsequent edition.

Contents

Foreword

LESS IS MORE: Energy Security after Oil (LIM) comes at the end of an unprecedented 15 years in UK energy policy history. It began with the formal acceptance of the need for a climate change policy by the last Conservative Government in 1997 [7] and culminated with the Climate Change Act and the 4th Carbon Budget. *LIM* is a significant new contribution to the debate.

Thirty years ago, David Olivier was responsible for what was arguably the first detailed energy scenario building exercise aimed at decarbonising the UK economy. In the subsequent three decades, he has continued to work in energy, in the main helping to design individual building projects and writing reports for private clients, plus occasional books. Over this period, he has been responsible for some of the UK's most energy-efficient buildings.

Over this time, he has maintained a network of contact and collaboration with colleagues across the northern hemisphere. This gives him unrivalled familiarity with energy demand reduction and supply options, especially in Scandinavia, mainland Europe, Canada and the USA. These open up and clarify a broader spectrum of strategic options than those in UK technology and policy-making circles have considered to date. The fact that he works as a practitioner, outside academia, and brings a fresh set of insights to the field, adds significantly to the value of this report.

LIM offers an alternative to the emerging orthodoxy of large-scale electrification of heat and road transport as a way to achieve or beat the UK's 2050 CO_2 emissions target. This is based on more vigorous and systematic pursuit of energy efficiency throughout the economy; on technologies such as large-scale solar heat, piped to urban buildings; a road and air transport system synthesising liquid fuels in part from renewable electricity, supplementing the biofuel resource; a small electricity supply system, supplied largely by despatchable sources, assisting with network security; and the more vigorous pursuit of carbon dioxide (CO_2) sequestration options, particularly in the biosphere.

LIM contends that an electric future is more costly and could be slower to deliver significant CO_2 reductions than the alternatives. Vigorous pursuit of energy efficiency, plus biosequestration, plus more focus on UK energy uses and the characteristics of energy systems, sets the stage for significantly cheaper and more secure energy supply options. Less-electric futures appear to have the capacity to deliver CO_2 reductions both more cheaply and more quickly than more-electric. Cumulative emissions to 2050 are at least as important as emissions in the year 2050.

LIM highlights key areas for technology, product and supply chain development. They include piped heat, which is a mature technology in several of Britain's continental neighbours, and heats over 60% of Danish buildings, but remains uncommon in the UK. They include high-performance insulation systems that could significantly reduce losses in heat storage and distribution systems at all scales, along with renewable fuel production. Heat networks play a systematic role in the scenario, opening up access to large-scale solar, geothermal and waste heat resources at lower costs than new electricity sources and reducing the risk that the UK will be unable to keep the lights on.

LIM contains a critique of the dysfunctionality of UK energy markets. The authors note that water is supplied by vertically-integrated and regulated local monopolies, which have access to capital at near-public sector interest rates, especially if they are debt-funded. They pose the question of why such arrangements cannot be used again in the energy sector, paralleling as it happens the situation with some private US utilities and with utilities in Denmark.

LIM does not offer the prospect of an easy path to energy independence and decarbonisation. It makes it very clear that all options pose acute difficulties. But it warns policy-makers not to reject technologies just because they appear difficult without making sober comparisons with the reality of the other technologies under consideration.

Prof. Robert Lowe (pictured), Deputy Director
Prof. Tadj Oreszczyn, Director
Energy Institute, UCL

Executive Summary

Overview

In Britain, there is a broad political consensus that the threat of climate change is so great that a major transformation of our energy intensive, fossil-fuel-dependent economy is required. A new future must be planned for and built in which greenhouse gas emissions are radically reduced. The official target is for an 80% reduction by 2050. At the same time, energy security must be maintained, a goal that appears ever more challenging as international oil supplies peak, indigenous fossil fuel production declines, power stations close and energy prices rise.

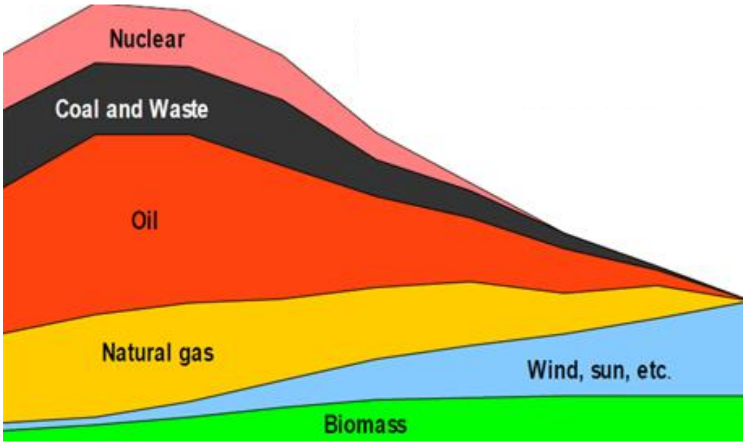
This political consensus is, however, fragile. The current economic crisis has raised fears that commitment to long-term change may be sacrificed in order to protect the perceived short-term competitiveness of the economy. It is therefore critical that the national vision of a low carbon future is sustained and strengthened. Without a properly planned and cost-effective strategy for delivering both decarbonisation and energy security, the economy will become ever more vulnerable to energy shocks that could have devastating consequences.

This report does not challenge the scientific or political consensus that we need to act. Members of the AECB have long been committed to a vision of a genuinely low carbon future for Britain. The report does, however, challenge the prevailing view in government about what this low-carbon future will look like and what we have to do to get there.

Given the scale of the change that we are collectively seeking to engineer, it is not surprising that real questions remain about what approach, or combination of approaches, we ought to pursue to deliver this change. The cost-effectiveness and real-world practicality of different options remain a matter of genuine debate. This report is a contribution to this debate. It describes a roadmap to a future of near-zero greenhouse gas emissions which integrates radical energy efficiency with a balanced approach to the use of renewable energy, paying particular attention to the need for energy storage as we move beyond the age of fossil fuels.

The title **LESS IS MORE** captures a view that the UK's energy security and economic well-being after oil depend on much more extensive investment in energy efficiency, in all its forms. It is the only future bulk energy option which appears to compete with fossil fuels.

The Goal



Vision: 100% Renewable Energy Supply in 2040 for the EU-27.
Source: International Network for Sustainable Energy,
Gl. Kirkevej 82, DK-8530 Hjortshøj, Denmark.
www.inforse.org.

The scientific evidence is clear. We must dramatically reduce greenhouse gas emissions if we are to avoid the worst effects of a warming world. Politically and economically, we must also prepare for a world in which fossil fuel supplies are likely to decline. In the absence of decisive action to address energy insecurity, this will inevitably lead to higher prices and rising fuel poverty.

Although the government’s target of an 80% reduction in greenhouse gas emissions by 2050 is one of the most ambitious in the world, it does not go far enough. This report proposes that:

- A target should be set for a 100% reduction in net emissions by 2050. Ideally, we should be removing more greenhouse gases from the atmosphere than we put in before 2050.
- Targets should be set for cumulative emissions to 2030 and to 2050. These are at least as important as emissions in the year 2050.
- These reductions should be achieved within UK borders, except for reasonable trade with other developed countries; e.g., in bio-energy. They should not depend on achieving savings in developing countries.

The roots of climate change lie in the industrial revolution that began in Britain in the 18th century. We therefore have a particular responsibility to demonstrate ambition in defining and pursuing an affordable way to mitigate global climate change.

Maximum Ambition, Minimum Risk

If we are to achieve a 100% cut in emissions by 2050, we cannot carry on tinkering at the edges. We have to embark upon a transformation of ways in which energy is produced, delivered and used. We have to rethink every part of the system. Yet this has to be done without damaging the economy through needlessly costly measures.

Such a radical rethink demands ambition and courage. But it also demands a sober consideration of all the options. There are many possible paths to a low carbon future, each with its risks and opportunities, its costs and benefits. It is the contention of this report that the government has set out on a path towards 2050 which is impressive in its ambition but carries too much risk and bears too great a cost.

The heart of the government's strategy is the 'decarbonisation' of electricity supply and extensive or total electrification of heating and transport. This will need a large increase in electricity generation capacity over the same period that we have to switch to renewable sources. It will take huge investment in new electricity supply, a major expansion of the national grid and, most challenging, the creation of new ways to store electrical energy in bulk at an economic cost.

Although energy efficiency is a significant component of current government strategy, it is not the primary focus. As usual in UK policy, the centralised levers of energy supply dominate the scene.

There are significant risks involved in a strategy focused on a vision of an 'electric Britain'. They include a substantial loss of energy storage, which is intrinsic to today's fossil fuel technologies; a potentially large increase in peak loads and associated network vulnerability; an over-dependence on future breakthroughs in technology; and escalating costs versus today's fuel supply systems. This policy path may be ambitious but it is fraught with risk. Would it not be better to invest our ambition in a path that sets out explicitly to minimise risk, contain costs and prioritise those solutions which we know work from convincing experience elsewhere?

This is the path set out in this report. It shares the ambition of government policy but it directs this ambition principally to the transformation of energy use through the systematic and intensive deployment of energy efficiency measures at every point along the supply chain from generation and conversion, through transmission to end use. **LESS IS MORE** because a significant decrease in national energy consumption across all sectors will reduce the problems of "decarbonising" energy supply and open the way to a more discriminating approach to the use of renewable energy technology, not just for electricity generation but for heating and the manufacture of road transport fuel. In this low-energy scenario, a more meaningful role is also possible for carbon dioxide biosequestration.

The path set out in this report is not an easy one. The focus on energy efficiency and a diversity of renewable energy supply and storage methods, along with an emphasis on biosequestration, add a diversity which the 'all-electric economy' seemingly avoids. There is, however, a good case that this alternative approach is a great deal more achievable. It focuses on proven, widely-used technologies. It targets low-cost technologies and it aims not to exacerbate the vulnerability of the power grid. Through its diversity, to a degree it spreads our risks. It combines maximum ambition with minimum risk.

Starting Points

A number of straightforward principles underlie the integrated approach to climate change and energy policy described in this report. They are as follows:

a) Pursue best buys first. We know a good deal about the cost-effectiveness of different measures in reducing carbon emissions. We should therefore act on this knowledge, in the interests of not damaging the UK economy.

b) Prioritise options which increase energy security and network stability. We should not take actions that increase the risk that the lights will go off, either because the energy is unavailable or because the network cannot cope.

c) Prioritise technologies which have an established track record, ideally in a mass market. We should not base long-term projections of carbon descent on technologies that are at a research phase or have not been fully demonstrated somewhere.

d) Model long-term impacts on energy/network security in detail before embarking on the transformation of the energy system. This is especially important for future scenarios dominated by electricity, which cannot be stored.

e) Base decisions on systematic greenhouse gas accounting. All the emissions - positive or negative - associated with any technology or measure, in the short term, as well as the long term, should be identified and included in a unified UK GHG balance sheet.

f) Climate change policy should be developed in the interests of all citizens and not allowed to impact disproportionately on low-income groups.

Radical Energy Efficiency

Every energy strategy produced by government acknowledges the role of energy efficiency in creating a low carbon economy. Yet the value and cost-effectiveness of energy efficiency has never been fully understood, acknowledged or translated into UK investment. While £ billions are spent subsidising energy supply, energy efficiency programmes are expected to be self-funding. The proposed Green Deal typifies this approach.

This approach may appeal to a cash-strapped government, but it appears blind to the concept of opportunity cost and the need to spend limited resources wisely, to make maximum GHG reductions. An analysis of the costs of a decarbonised energy supply, focussing on offshore wind, suggests a likely ten-fold rise in energy whole system cost compared to 2010 offshore oil supply. In contrast, it is possible that a future energy mix dominated by energy efficiency and supported by lower-cost renewables could be broadly competitive with today's fossil fuels, in terms of annual total cost-in-use.

Cheap energy efficiency measures are not just a free lunch, but a lunch that one is paid to eat. Given the cost-effectiveness of many energy efficiency measures, and the steadily rising cost of energy supply, energy efficiency remains as important an opportunity for energy policy as the discovery of a new series of giant oilfields, but without their global warming impact. Policy-makers should pursue energy efficiency in all its forms as seriously as geologists have explored the earth's crust for oil and natural gas deposits.

Unlike oil, the potential of energy efficiency cannot be exploited with one grand technological intervention. Energy efficiency consists of a wide range of technologies and delivering substantial savings involves investment in many different areas at a more local level. This makes the task more complex, seen from "the centre". But unlike exploitation of the oilfield, the benefits are permanent and widely-distributed. We have to look all across the energy supply chain and focus on the fine details of energy consumption, including those 'beyond the meter', where the energy efficiency resource is concentrated.

There is scope for radical improvements in energy efficiency in all sectors and for all uses. However, the high unit cost and carbon emissions associated with electricity make demand reduction particularly attractive. Measures to use electricity more efficiently, including lighting retrofits, appear much more profitable to the UK than building new 'low-carbon' generating plants or even running existing gas, coal, nuclear and offshore wind power stations.

The lower the UK's energy consumption, the more selective and critical we can be over supply-side investment. The more that demand is reduced, the more resilient the system as a whole becomes. The risks inherent in intermittent supplies are reduced and a flexible combination of low carbon energy sources becomes possible, some of which might not seem feasible or significant if the energy supply mix has to meet current loads.

Electricity: No Silver Bullet

Electricity is the most valuable of all energy carriers used today. As a high-grade form of energy, it can meet most energy demands, a fact that has made it attractive to policy-makers seeking to map out a mass transformation to a low carbon economy. Yet the manifest advantages of electricity to users disguise major difficulties in securing, delivering and paying for a reliable supply of it as we seek to move towards more variable energy sources.

Most of the electricity consumed in Britain today is generated from storable fuels, above all coal and natural gas. In fact, almost all Britain's energy supply is storable; 96% of our delivered energy to homes, offices, industry and power stations could be said to rely on stored chemical energy. But electricity itself is not storable on a significant scale. Matching changing electricity supply to changing demand is a core concern of the operators of the national grid, to whom a surplus of electricity is as unwelcome as a deficit. For these operators, a stable and predictable supply, meeting a reasonably level demand, is key to keeping the lights on.

As the energy mix for electricity generation shifts away from fossil fuels, the difficulty of achieving the demand-supply balance at any given time tends to increase. While some renewable sources can easily be turned on and off, others cannot. Wind and solar PV technology are the leading, and well-known, examples of 'variable' renewable energy.

In the face of a shift to a less dependable supply, there are ways of making the grid more robust, such as creating a 'smart' network which is responsive to the variability of supply. This is currently a key part of the government's program to transform the energy mix. But the success of such a strategy has not been demonstrated anywhere to date. Any potential improvement in resilience from such moves is quite likely to be offset by the drive to meet demand for heating and transport from electricity, especially during cold weather peaks.

Current policy direction appears to combine three different risks:

1 A switch to less storable energy supplies, which cannot be 'despatched' as and when we need them, creating a less stable and less resilient situation.

2 The addition of new weather-dependent, variable electrical loads such as space heating, which make demand less predictable day to day, weekday to weekend and month to month, and decrease the system load factor.

3 An overall increase in demand, which marginalises essential electricity uses and makes them vulnerable to any impacts on the network from these new and more variable loads.

‘Essential electricity uses’ have come to play a central role in modern society. They include lighting, most domestic appliances, commercial office equipment, pumps, fans and controls for heating and ventilation, and the internet, mobile telephones and other communications technologies. These uses do not need large quantities of electrical energy – only 12% of energy delivered to UK consumers in 2009 had to be in the form of electricity – but they do need a reliable supply. The electrification of heating and transport could put this supply at risk. If almost everything is driven by electricity, even the smartest networks will struggle to protect essential electricity users when extreme peaks in space heating in severely cold weather threaten to overwhelm the grid.

The alternative is to consciously reduce risks wherever possible. This can be achieved by reducing electricity consumption via radical energy efficiency, avoiding the electrification of heat and road transport and, in consequence, keeping electricity demand to a level that can be met by a more dependable range of renewable sources. The is more likely to deliver an electricity network in 2030 or 2050 that is greatly decarbonised but is as stable and secure as the network today.

The future set out in **LESS IS MORE** does not depend on any new nuclear or coal power stations. We will need greater investment in established but underexploited renewables such as tidal power lagoons, geothermal and biomethane CHP and the UK’s small amount of remaining hydro. There will also be a continuing role for intermittent resources such as wind, designed so that surplus electricity unwanted by the network is used to manufacture clean, synthetic, fuels, effectively ‘storing’ the surplus electricity, or used in large heat pumps to make hot water and store it in very large tanks for heat networks. These routes both produce forms of energy which can be stored affordably for long periods. Compared to current policy, we need increased emphasis on heat and fuels, to reflect their storability and their importance in the UK economy, with 88% of delivered energy being used for these purposes.

Piped Heat

As with electricity, the first step of a renewable heat strategy should be to significantly reduce demand through cost-effective reductions in heat loss. But given the range and important historic features of the country’s building stock, and the diminishing returns to insulation improvements, even in new construction, ‘designing out’ heat loads altogether is unrealistic. The supply of heat is unavoidably a key component of any low-carbon future.

If electricity is not the answer, given the impact on network security and possibly on energy supply security from migrating all heat supply to the national grid, what is? This report proposes a major role for piped heat, which is a mature technology in several of Britain's continental neighbours, heating over 60% of Danish buildings and 65% of its detached houses. Although the investment needed to migrate urban heat supply from gas networks to heat networks will be considerable, heat networks offer an adaptable, long-term solution to renewable heat supply, especially the “low-resource” ones now being emphasised in Denmark.

Local heat networks are a missing link in the UK energy jigsaw. Policy has focussed on micro-systems for individual buildings and on systems to supply national and international energy needs. City- or town-sized heat networks benefit from economies of scale and can deliver both heat and power from plant that is designed for optimal fuel efficiency. They are close to consumers but do not require homeowners to become involved in energy generation.

Even if heat demand is reduced, storage capacity to cope with the variability of demand has to be maintained. This is more viable on heat networks than on electricity networks. On heat networks, high demand can be met by stored fuel or, if heat is supplied by variable ambient sources of energy, by large insulated stores of hot water. These approaches offer a more secure long-term solution to the supply of heat in severe winter weather to urban buildings than electricity networks.

Heat networks can adapt and evolve over time to accept a wide range of energy inputs. These include:

- Large-scale solar heat. Solar collectors linked to heat networks; e.g., the one in Marstal, Denmark, appear economic against today’s fossil fuels and could be extended to provide heat through the year if sufficient storage is built in. Alternatively, in the short term, other means can be used to provide the peaks.
- Geothermal heat. Thirty years have elapsed since Southampton developed its heat network, but the UK still has no geothermal licensing system. Without this basic framework, it is very hard to see how this valuable resource can be fully developed.

- Biofuels. Biomethane from large anaerobic digestion plants has great potential if scaled up to town-sized combined heat and power plants. Other biofuels should probably only be considered if a full GHG balance sheet of their growth, harvesting and combustion demonstrates clear benefits over fossil fuels and over biomethane.
- Heat pumps, supplying large heat stores, driven by surplus electricity from wind turbines. Diversion of surplus wind energy into large heat stores on heat networks is expected to become a means to keep Denmark's electric grid stable as the country's windpower fraction rises from today's 20% towards 50%. Such stores can also be utilised for storage of renewables such as solar; see above.

The use of surplus intermittent renewable energy also has a potential role to play in making synthetic fuels for the transport sector. An expansion of wind power, especially off-shore, combined with reduced electricity consumption, would create opportunities to produce synthetic fuels from unwanted electricity surpluses and to complement the limited biofuel resource. This largely avoids the cost of electricity network reinforcement.

Biosequestration

Biosequestration is the removal of carbon dioxide from the atmosphere using biological methods. A tree or forest is one mechanism for biosequestration; farming in a manner that restores soil organic matter is another. This report suggests that the key role of biomass in climate change strategy may be not to maximise bio-energy production, i.e., by burning it, but rather to optimise CO_2 capture and storage.

At today's level of emissions, biosequestration within UK borders could only have a modest role to play in the UK's 2010 GHG balance sheet. Nonetheless, it is an important component of this balance sheet, or could be if this balance sheet were compiled. If Britain's emissions are to be reduced by 100% by 2050, biosequestration has a role to play. The unique role of farming and forestry may turn out to be its potential for CO_2 sequestration at modest costs.

Recommendations

If we are serious about tackling climate change, we must define targets that constrain current as well as future greenhouse gas emissions

- Greenhouse gas targets must be defined not only as future emission levels for target years, such as 2020, 2030 and 2050, but also as cumulative emissions up to these dates. A robust greenhouse gas balance sheet is needed to achieve this.
- As far as possible, measures to reduce GHG emissions in the UK should be implemented within UK borders. Possible exceptions to this rule include biosequestration, geo-engineering and trade in synfuels.
- UK greenhouse gas accounting must take account of CO_2 emissions created by international trade in manufactured goods.

Policy-makers must focus on the lowest cost options, even if they are unfamiliar.

- Rigorous investigation of the whole system costs and risks of all potential UK energy scenarios is needed. With the arguably excessive emphasis on “decarbonised electricity”, our analysis suggests that some of the lowest-cost and lowest-risk opportunities to replace fossil fuels have not received the attention they deserve.
- A comprehensive review is needed of current government incentives for renewable and ‘low carbon’ technologies. Technologies should be prioritised which are tried and tested, are economic versus fossil fuels, contribute to energy security after oil, reduce cumulative CO_2 emissions in the next two decades and do not place excessive demands on scarce technical skills which are unlikely to be available.
- A strategic shift is needed in UK energy policy. The full potential of energy efficiency has yet to be recognised by government. Energy policy must focus on enhanced energy productivity – negawatts – to squeeze more economic output out of increasingly constrained energy supplies.
- Investment to displace fossil fuels should focus squarely on energy efficiency, at least up to the point where the marginal cost of energy efficiency measures equals the marginal cost of new energy supply or other abatement measures, such as biosequestration or acceptable geo-engineering.
- The government should publish a marginal abatement cost curve for all the energy efficiency measures, CO_2 sequestration measures and renewable supply systems available to the UK. This enables a comparison of their relative merits and impacts on total UK energy consumption and net GHG emissions.

- All measures or technologies which are supported by public funds must be supported by adequately-resourced monitoring and reporting mechanisms. This is vital if net CO_2 emissions are to be reduced cost-effectively.

The full potential of energy efficiency must be exploited

- Energy efficiency measures that abate CO_2 emissions at negative or low cost should be identified and pursued with vigour in all sectors, as a matter of urgency. This needs the removal of avoidable institutional and market barriers which have been documented for some time.
- Measures to improve the efficiency of electricity use should be prioritised, given the high cost of electricity as an energy carrier. Current investment in electricity supply should, at the very least, be matched by investment in measures to improve the energy efficiency of electricity use.
- Government should mandate highly energy-efficient lighting, domestic electrical appliances and office equipment in order both to reduce consumption and to reduce the risk of overheating and the subsequent installation of active cooling systems. “The market” is not delivering and EU efforts are slow and inadequate.
- The EU energy labelling system should be overhauled to provide consumers with clear information about which electric and gas appliances have the highest energy efficiency and lowest energy consumption.

The dependence of energy security on storable fuels - chemical energy - must be recognised and addressed in strategic energy planning

- Policy-makers must give greater priority to energy storage in their plans for a ‘low carbon’ future. Whatever the future energy mix, energy storage is likely to be critical to security of supply.
- Alternatives to the ‘all-electric’ future must be explored with some urgency. This reflects the difficulty of storing electricity, the problems of meeting a varying demand for a non-storable energy vector from a range of variable ambient sources and the barriers to electrifying road transport.
- The alternative in this report – investment in piped heat, affordable building insulation/draughtproofing measures, major investment in the efficient use of electricity and extensive synfuel production – should be assessed in detail. It offers an approach to meeting heating and transport energy needs that is more practical, more cost-effective and above all *more secure* than the 100% electric pathway.

- The cost and visual impact of the planned investment in new electricity infrastructure should be compared to the cost of investment in infrastructure for the supply of renewable heat and synfuels, which can be cheaper to distribute and store.

We need to be smart with heat and fuels, not just electricity

- At a time of radical rethink in energy policy, we should not ignore golden opportunities just because they – or the infrastructure they need – are unfamiliar in the UK. The potential for piped heat in settlements of all kinds should be identified through heat mapping/planning, to make possible the exploitation of both waste heat, including heat produced by large-scale anaerobic digestion CHP plants, industry and cost-effective renewable heat such as large-scale solar thermal and deep geothermal.
- Biomass should be treated first and foremost as a means of sequestering carbon dioxide. Its secondary role is likely to be in producing modest amounts of clean low-CO_2 fuels, above all $CH_{4,}$ to complement other renewable sources in all sectors of the economy, not only the road transport sector.
- A geothermal licensing system should be introduced in order that the potential of geothermal heat in the UK can be fully exploited.
- Future investment in the supply of renewable electricity should focus on supplying essential electricity in a more energy-efficient manner. A scenario in which demand is radically reduced allows for a more discriminating combination of sources including tidal, hydro, geothermal CHP, bio-methane CHP and wind.
- More development work is needed to produce clean synthetic fuels using spilled electricity from windpower and other variable sources. However, it is being done commercially on a small scale in Germany and Iceland and the basic chemistry is well-established.
- Policy on renewable energy supply must never adversely affect the optimisation of energy efficiency. The two must be fully-integrated. This is true both for large infrastructure and for household-scale interventions, where the installation of renewable technology can not only divert resources from energy efficiency but physically limit the scope for future efficiency improvements.

The scale of the challenge demands that we explore every avenue and learn from success

- Strategic decisions about how the transformation of the energy system is to be funded should follow, not precede, assessment of which pathways are the most cost-effective and robust. If as we believe, “deregulated” utilities supplying mains energy services cannot deliver on energy efficiency in the short time we have available - just a decade or so - they should be re-regulated.

- Government should therefore reconstitute energy suppliers as integrated energy services companies (ESCOs) which supply energy services to a defined region on a long-term franchise. This would mean a return to one supplier, one tariff and price control by the regulator, as for mains water.
- The UK needs to learn from regions with hard-won experience in implementing energy efficiency in a coordinated manner. We recommend that the government studies *among other things* the following international good practice: (a) California's experience of least-cost electricity planning; (b) Denmark's approach of least-cost heat planning; (c) Switzerland's efforts to improve the energy efficiency of office electrical equipment.

Preface

AECB members work in the building research, design, construction, manufacturing, local authority, social housing and self-build sectors. They share an active interest in broad aspects of sustainability, with most fully involved in the detail of commissioning, planning or delivering low energy and low carbon buildings. A significant number of members are industry leaders focused on the efficient use of energy, the carbon sequestration potential of buildings or products and energy efficiency technologies generally.

Following the development of its CarbonLite programme and the recent setting up with industry partners of the Passivhaus Trust, the AECB has become increasingly aware of concerns within the membership and more widely over the lack of integration between UK climate change and energy policies and sustainable building initiatives. The lack of a coherent policy has led to government and industry initiatives which are not integrated, leading to perverse and/or ineffective outcomes. The inexorable decline in UK public funding for applied research in this field has also hindered the adoption of new technology by the mainstream construction industry.

For those individuals, businesses and clients who work in the building design and construction sectors, a confused business landscape needlessly increases costs, hampers effective operations and inhibits planning and development. The policy approach also seems to have had a less than substantial effect on greenhouse gas (GHG) emissions from the built environment - building energy use has increased since 1990. This has been ameliorated only by the so-called “dash for gas” and by the fall in the energy consumption of manufacturing industry, some of which closed or moved abroad. These two trends combined, turned a potential increase in UK CO_2 emissions into a slight decline.

LIM was commissioned by the AECB to explore the apparently underutilised and significant potential of energy efficiency for climate change mitigation and enhanced energy security. The AECB wanted to understand better the benefits of a demand reduction-led approach, delivered through well-integrated national energy efficiency measures, and how an improved understanding of the potential of energy efficiency might inform the current development of UK energy and climate change policy.

Unusually for UK energy scenarios, *LIM* has drawn on the detailed experience gained by practitioners who work mostly on improving the energy performance of small to medium-sized UK buildings. Especially in the case of the principal author, they maintain close contact with experts in other European countries which have progressed further towards implementing successful and large-scale solutions. Some of this overseas technological progress and analysis appears to be almost unknown in the UK, although much of it is translated into English

Chris Herring, Chair, AECB January 2012

1. Climate Change Policy

> "If global emissions of carbon dioxide continue to rise at the rate of the past decade, this research shows that there will be disastrous effects, including increasingly rapid sea level rise, increased frequency of droughts and floods, and increased stress on wildlife and plants due to rapidly shifting climate zones."
>
> James Hansen, NASA, 2007. [8]

Targets

The UK government aims to cut UK GHG emissions by 34% by 2020 and 80% by 2050, compared to 1990 emissions. It has enshrined this target in law. [9] Yet a German Parliamentary Commission proposed a 80% reduction target back in 1991. [10] 20 years on, even this ambitious pace of reduction appears as too little, too late. Climate scientists seem to have underestimated the pace of climate change, and there is concern that we may be entering a period of instability.

The climate scientist James Hansen, cited above, said in 2007 that to avoid dangerous climate change we need to return atmospheric CO_2 levels to 350 ppm or less. [11] The pre-industrial concentration was 290 ppm, the concentration now is 390 ppm and it is rising by 3 ppm per annum.

While a return to 350 ppm is an ambitious global target, it appears more prudent than "just" cutting developed country CO_2 emissions by 80%. The UK has contributed disproportionately to past CO_2 emissions, [12] and it was the first country in the world to industrialise, so it would be especially fitting and symbolic for it to take a lead in showing others how to solve the problem cost-effectively.

The UK's climate change strategy includes the possibility of investing in technologies abroad; e.g., in developing countries, to meet its national targets. To quote the government:

> "International emissions credits are a mechanism by which developed countries such as the UK can pay for emissions reductions to take place in developing countries, and count these against domestic targets. This relies on the fact that greenhouse gases have the same impact regardless of where in the world they are emitted, but abatement in developing countries can be cheaper than in developed countries."

The problem is that this amounts to treating the energy efficiency potential of developing countries, which in our view they should be exploiting on their own account, to meet their own GHG targets, as belonging to the UK. We think that UK initiatives would be more convincing if they aimed to meet all but minor aspects of a target within UK borders, and virtually 100% of it within other developed countries; e.g., the rest of Europe, North America, Japan and Australasia. Reasonable exceptions to achieving it all in the UK might include; e.g., bio-sequestration, geo-engineering and the scope for trade in bio or synfuels.

It is also important for future UK climate change targets to account for the CO_2 emissions represented by international trade in manufactured goods. Because they do not do so today, they do not give a full picture of the GHG emissions arising from different economic activities. [13] We have known of the discrepancy for some time, so it would be possible for government to resolve it.

Mitigation Measures

Choices

To reverse rising CO_2 levels, a very extensive combination of measures would need to be implemented. The bulk of them would probably be chosen from the list in Table 1. [14]

Category of Measure			
1		2	3
Energy-related technologies		***GHG sequestration***	***Geo-engineering***
Energy efficiency, including CHP and thermal cascading	Low-temperature heat	Reforestation	Change earth's albedo; e.g., use pale-coloured roofs, roads, car parks et al
		Biochar production, perhaps linked; e.g., to Fischer-Tropsch synfuel plants	
	High-temperature heat	Agroforestry techniques	
	Transport	Use of permanent grass and rotational grazing, not arable crops, to produce animal protein	
	Essential electricity	Direct drilling and reduced ploughing of arable land	Increase ocean absorption of CO_2 by fertilisation
Renew-able energy	Solar	Pre-combustion CCS on natural gas wells, geothermal wells and anaerobic digesters	
	Wind		
	Hydro	Post-combustion CCS, initially on wood- and coal-fired plants, later on other fuels	Artificially-accelerated weathering of silicate minerals
	Tidal		
	Geothermal	CCS on steelworks, cement and lime kilns and other industrial processes, and/or direct reduction of iron ore with H_2	
	Biomass		
	Wave	Use more CO_2 in plastics and other chemical production, including foam insulation	
Fossil fuels	Replace coal and oil by natural gas, consistent with falling total demand		Remove atmospheric CFCs
		Use more certified timber in insulation, furniture, finishes, claddings, civil engineering and construction	
		Engineered biomass "storage silos"	Screen out sunlight by injecting dust and/or aerosols into atmosphere
		Sequestration in carbonate rocks	
		Injection into active oil wells, allied to enhanced oil recovery	
	Phase out or forgo fuels with higher CO_2 emissions than coal	Geological sequestration in salt domes or ex-coal seams	
		Injection into ex-natural gas or oil wells	
		Artificial trees	Cloud modification
		Injection into aquifers	
		Deep ocean disposal of liquid CO_2	Mirrors in space

Table 1. List of Climate Change Abatement Measures.

NOTES:

1. The list includes a wide range of options but does not claim to be comprehensive.

2. It is not implied that all these measures would be used. Some may not be particularly wise or effective; e.g., some type 3 and even type 2 measures raise great concerns. See text.
3. The list excludes materials substitution measures; e.g., in the construction industry, which might help to reduce GHG emissions. See Appendix 5.

Energy Measures and GHG Sequestration

Most type 1 and 2 measures in Table 1 appear to be lower-risk than type 3. But some type 2 measures may need more development or assessment, or pilot-scale plants, before they can be deployed to best effect or can be considered commercially-proven. Examples include post-combustion CCS, biochar and the use of CO_2 from pre-combustion CCS; e.g., separated CO_2 from anaerobic digesters, to make synthetic fuels (synfuels). A few type 2 measures appear to be risky and might be foregone if other measures can deliver the desired end result. But a notable point in Table 1 is the diversity of the options to be considered, in addition to the energy measures to which this report is largely devoted.

Reforestation needs no fundamental development. Farmland and gardens have potential roles in CO_2 sequestration too, via a range of practices which raise stored organic matter, either in the soil or the standing biomass. There is a debate over the relative ability of permanent and temporary grassland, temperate broadleaf forest and other land uses, including intensively-farmed grade 1 horticultural land, to sequester more CO_2. [15] [16] This might be termed shallow sequestration, as opposed to deep sequestration in sites such as ex-oil and gas wells and aquifers.

We suggest the term biosequestration for measures which sequester CO_2 in the planet’s soil and/or standing biomass and do so permanently enough to contribute to climate change mitigation targets. Worldwide, biosequestration appears to have large potential benefits, set against the scale of anthropogenic GHG emissions. It appears more attractive in many ways than other measures put forward to sequester CO_2, including post-combustion CCS. Changes to farming or horticultural practices also need less capital investment than the extremely expensive energy-related investments which are going ahead. [17]

One study notes that worldwide farming practices which increase the soil’s organic matter content could raise crop yields, sequester up to 3 G tonnes/year and reduce atmospheric CO_2 concentrations by 50 ppm by 2100. [18] This is a striking set of benefits from relatively safe and proven technologies, some of which are also considered to be good farming practice; e.g., by most UK mixed farmers. A Royal Society review puts potential rates of CO_2 sequestration at up to

3-4 tonnes/ha.yr. in large-scale "industrial" farming. [19] If this could be achieved over large parts of the world's arable land and temporary pasture, it would add up to very large CO_2 sequestration rates. Even on the UK's limited farmland area, it appears that it could possibly add up to ten percent or more of current gross emissions, a welcome change from UK farming and forestry today, which is a small net source of GHG emissions. [20]

The CO_2 sequestration rate has been put at up to 50 tonnes/ha.yr in small-scale temperate horticulture, gardening and agroforestry, based on measurements since 1994 on a 0.8 ha research site in Devon. [21] It is uncertain how much of the UK land area could adopt such practices, because they can be more labour-intensive than commercial agriculture, but some moves in this direction could contribute significantly towards biodiversity targets and food security.

Suppose that a mechanism could be devised to pay growers and farmers say £50/tonne for emissions avoided and to police the system effectively; e.g., by random testing and large fines for infringement. Such high sequestration rates could possibly attract annual payments of £2,500/hectare to small-scale enterprises which achieve the higher rate listed above, or up to £150-200/ha to more normal farming operations. The payment for CO_2 sequestration services might approach or exceed the profit from the food output. [22]

Farmers in Australia and New Zealand have set up private initiatives to reward those who sequester more CO_2. [23] [24] They are careful to distinguish their activity from so-called "C offsetting". The two activities are totally different.

Some UK land may have limited scope to hold more organic matter; e.g. peat bogs already hold very high levels. The most likely targets for more CO_2 sequestration appear to be arable land, especially the lighter soils; orchards; temporary pasture and grassland which has been ploughed in the past. [25]

An issue needing study is the vulnerability of biosequestration, other than biochar, to climate change. A balance is likely to be reached between higher productivity of soils richer in organic matter, with potentially higher biomass and crop yields, and accelerated oxidation and loss of organic matter as soil temperatures rise. This may, however, be less of a concern in cold and temperate climates than in warmer ones, and less of a concern with perennial crops than with annual crops which receive regular cultivation.

Geo-Engineering

The borderline between GHG sequestration and geoengineering measures in the above table is indistinct. Some measures could be reclassified in future.

The measures usually classed as geoengineering appear to range from low-risk to very experimental. One safe and beneficial measure is to use pale-coloured roofs, roads, car parks and other paved areas. First studied in California many years ago, it keeps districts cooler in summer and yields large savings on electricity and medical bills; the cooling impact on the planet of a higher albedo is a bonus. [26] The energy efficiency expert Arthur H Rosenfeld put it this way:

> “Suppose over a period of 15 years, all eligible flat roofs in major cities from Chicago to Sydney were colored white, whether or not they are air-conditioned. That would offset the heating effect of 15 billion tons of CO_2. It's like turning off the entire world's emissions for four months or about 40% of the world's passenger cars for 15 years. This idea slows global warming, saves utility bills, and makes buildings and cities more comfortable in summer. I commend it to your attention.” [27]

Given the UK’s high population density, and the unusually high fraction of its land area which is “developed” by buildings, paths, roads, railways and car parks, the impact of such initiatives would be fairly significant in percentage terms. Using lighter-coloured roads, roofs and car parks is also a move of relative simplicity.

A fairly innocuous-looking step is accelerated weathering of silicate-rich rocks by quarrying and grinding them. Exposed to the air, crushed silicate minerals absorb atmospheric CO_2, speeding up a process which occurs anyway over geological timescales. Crushing the rocks needs 0.04 kWh of electricity per kg CO_2. [28] But if one could utilise them in civil engineering, landscaping or other works that are set to proceed anyway, the marginal energy consumption would be below 0.04 kWh/kg.

If one adopted the use of man-made sulphate or dust aerosols to block incoming solar radiation and mimic the impacts of volcanic activity as a short-term emergency measure, one would have to selectively revoke the Large Combustion Plants Directive; i.e., permit emissions at a height in the atmosphere that depresses global air temperatures, but continue to ban or restrict emissions which raise temperatures; e.g., low-level soot. The particle sizes are critical too. Artificial aerosols could be pretty risky if not applied carefully.

One of the riskiest-looking measures is to site clouds of miniature mirrors in space, to reduce the amount of solar radiation reaching the earth. This would do nothing to reduce atmospheric CO_2 levels. The temperature drop is likely to vary across different parts of the globe. International disagreement over its use seems likely. It also seems set to be expensive.

The United Nations (UN) Development Program has placed restrictions on several geo-engineering options, including ocean fertilisation. It has even banned the background research. That could be a big problem if we decide that we have to go well beyond energy-related measures and CO_2 sequestration. [29]

A GHG Balance Sheet

If some of the geo-engineering measures prove viable, we could add them to our portfolio, enabling a more cost-effective climate change strategy to be devised. But most scientists view the most drastic geo-engineering technologies as a means to combat a planetary emergency, not as a permanent adjustment. In other words, they help to buy time. Before including them, we need a long-term strategy in which net GHG flows into the atmosphere decline sharply over 40 years and cumulative GHG emissions are minimised.

The approach we prefer is to compile an annual GHG balance sheet in which gross GHG emissions are itemised and are clearly separated from GHG sequestration. In any particular year, net GHG emissions; i.e., the figure which matters, are the sum of:

- All GHG emission terms, comprising CO_2 and other substances.
  minus
- All GHG sequestration terms, mainly CO_2 and sometimes elemental C.

A company would use an analogous approach to forecast its cash flow. With some exceptions, the state of California, USA has presented its GHG emissions in this way for the period 1990 to 2008. [30] [31] The UK is moving in this direction too, but it needs to use a more consistent convention for bioenergy, avoiding perverse outcomes; see Chapter 4.

We must also consider cumulative net GHG emissions over a longer period. These are analogous to a company’s profit and loss account. The UK does not appear to have a target for cumulative emissions over the period to 2030, or 2050, but this is crucial. Targets should be drawn up as soon as possible.

In principle, combinations 1, 2 and 3 in Table 2 all conform to current UK policy. They give 80% lower net GHG emissions by 2050. One combination reduces gross GHG emissions by 80% and features no sequestration activity. Others reduce emissions less but sequester GHGs at a higher rate.

Combination	Gross GHG Emissions	GHG Sequestration	Change in GHG Emissions
	%	%	%
1	-50	30	-80
1	-60	20	-80
2	-70	10	-80
3	-80	0	-80

Table 2. Possible GHG Reductions by 2050 to Meet Current UK Policy.

NOTES:

1. Percentage cuts or sequestration rates relative to 1990 emissions.
2. Past targets took the form of cuts in total UK emissions which were broadly the same as cuts in emissions per capita. New projections are for UK population growth of 0.6%/yr, faster than in the last 50 years. [32] Emissions per capita would have to fall by more than 80%.
3. UK emissions per capita have fallen somewhat since 1990.

But combinations proposed as alternatives, each sufficing to cut net GHG emissions by 80%, could be implemented together. To achieve the negative net emissions which now appear necessary, and using a 110% reduction purely to illustrate the point, some possible routes might be as noted in Table 3.

zCombination	Gross GHG Emissions	GHG Sequestration	Change in Net GHG Emissions
	%	%	%
1	-80	30	-110
2	-90	20	-110
3	-95	15	-110
4	-100	10	-110

Table 3. Possible GHG Reductions by 2050 to Meet a Strengthened Climate Change Policy.

NOTE: Percentage cuts or sequestration rates are expressed relative to 1990 emissions, or 1995 emissions for certain GHGs.
Combinations 1-4 appear consistent with a 110% emissions reduction over the period 2011-50. Some experts consider that a 95% reduction in gross GHG emissions, with no sequestration, could suffice to reduce atmospheric CO_2 slowly, because the CO_2 sinks which are naturally present would slowly reduce the concentration back to 350 ppm. On the other hand, the warming momentum built up by two centuries of industrialisation, and by earlier deforestation, especially in the Old World, is very large. Stopping all emissions tomorrow would not necessarily halt this warming process. Other measures may be needed. This point would benefit from further input from climate scientists.

With 62 million people living on 241,000 km^2, the UK's scope for biosequestration is limited. If it can benefit from activity in more spacious developed countries, via EU or wider agreements, the scope for sequestration may increase. But if the UK is treated as the system boundary, the sequestration rate in combination 1 looks challenging. A viable strategy could need to be based predominantly on energy-related measures.

A recent UK study considers that sequestration of various kinds amounting to 10% of current emissions might be possible by 2030, at a cost of around £60/tonne. [33] The further potential by 2050 remains to be quantified. So combinations 2, 3 or 4, if not 1, might seem to be possibilities. The present UK rate of dwelling construction sequesters GHGs at a rate equal to 2% of current emissions. Clearly, even small terms count.

At the other end of the scale, reducing gross GHG emissions to zero by 2050, as in combination 4, also looks problematic. Eliminating C-based fuel consumption, and only using electricity and heat as energy vectors, with no fuel used to support heat or electricity networks, or only gases such as hydrogen, could give zero gross CO_2 emissions. Superficially, this combination may seem to be the answer.

But energy storage is a vital buffer between supply and demand, especially if the supply becomes intermittent. Storing this energy only in the form of heat or electricity could make a future energy system very costly and/or brittle. Chemical energy, like H_2, is cheaper to store and transport than hot water or electricity. [34] [35] But fuels with the H_2 stabilised by C atom(s), as in hydrocarbons, alcohols and ethers, are much easier and safer to handle. [36]

There is a potential trade-off between the utilisation of C-based renewable fuels in the UK energy system, to give it greater stability, resilience and lower capital costs, and added provision for C sequestration. The optimum mix of energy-related and CO_2 sequestration measures is not precisely known, because surprisingly little work has been done. But most published data suggests that CO_2 sequestration measures are likely to be more economical in £/tonne than the expensive renewable energy supply investments which are underway.

Regardless of the CO_2 emissions from our future energy supplies, most of them are set to be much more expensive than fossil fuels. So Chapter 2 sets out further issues which we must come to terms with.

2. Energy Economics - The Coming Age of Scarcity?

> "There is no substitution for energy in our economy. Every single economic product created requires first an expenditure of energy. The amount of human labor that oil and other fossil fuels have been able to replace or allocate to other pursuits is gargantuan. The average human can generate only about 0.6 kilowatt-hours per day from physical effort, which, based on median U.S. salaries, equates to more than $300 per kWh generated by human labor. Oil, even at $110 per barrel, costs us just 6 cents per kWh, or 500 times cheaper than human labor. This replacement of human effort by fossil fuels has been the single primary driver of economic riches of the past couple of generations. For all intents and purposes, on human time scales, oil in our lives is indistinguishable from magic."[37]
>
> Nate Hagens, ex-Editor, The Oildrum.

An Essential Input

Without energy, industrial society would grind to a halt. The present input of cheap, relatively high-grade energy in the form of fossil fuels has brought a more comfortable life to billions of people. People tend to forget that our standard of living is arguably much more related to the oil and natural gas flowing freely from the ground for the last 50-100 years than to our innate ingenuity, social organisation or economic or banking systems, which have been around for centuries, if not millennia.

Given the generally-accepted problems of climate change, we have to find an energy system which provides a viable alternative. A basic requirement for a future "sustainable" energy system is that it is "affordable" in the way that fossil fuels have been. If building, operating and maintaining a new system takes an excessive fraction of a nation's resources, the process becomes self-defeating. Investment in the energy sector could start to absorb the very wealth that it is meant to create, with similar or worse consequences than the 1970s "oil price shocks". These acted as a major tax rise on OECD economies. [38]

This chapter highlights the fact that most future energy supply technologies are very capital-intensive; i.e., expensive, compared to past fossil fuel systems. This trend explains some of the delay in replacing fossil fuels by other energy sources. The financial limitations are allied to basic physical ones. A technology's energy return on energy invested (EROEI) must be adequate; i.e., the energy "output" from the oil or natural gas field, wind turbine, anaerobic digester, solar collector, heat main, geothermal well, retrofit wall insulation, energy-efficient lamp or other technology must exceed the energy input by an adequate margin, taking account too of differences in energy quality; see Appendix 1.

The EROEI of oilfields, refineries and delivery systems appears to have fallen from 100 or more to 18 in the last 80 years. [39] Many future energy supply technologies seem to have even lower EROEIs than the large, accessible oil fields on which industrial society has been built. [40] This is a critical trend.

See Figure 1. As the EROEI of an energy supply technology declines, its net energy output falls precipitately, implying a major increase in the resources and activity needed to maintain and operate a society's energy supply system(s). As the EROEI falls linearly from 100 to 90, 80 and so on, the net energy yield in percent falls extremely slowly for a long time. But it drops noticeably as the EROEI reaches the range 10-15 and it plummets towards zero as the EROEI approaches one. At this point, there is no net energy output. Even at EROEI = 10, the overheads are much higher than they are at EROEI=100.

Reflecting its shape, this graph is often called "the energy cliff". For most of the last century, we have been living off fossil fuel supplies with high EROEIs, typified by the left hand side of Figure 1. In the future, we are likely to be considering energy supplies with EROEIs closer to 10 than 100, especially if the energy storage which is needed for security of supply is included in the calculation. [41]

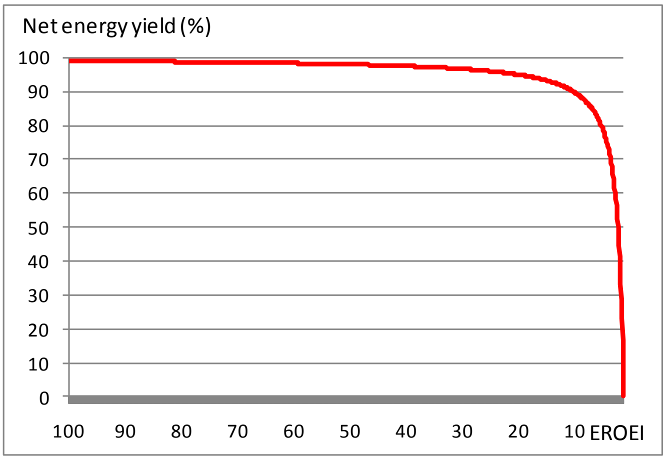


Figure 1. The energy cliff".

Concern has been expressed over EROEIs of as high as eight. Yet some technologies in use today may have EROEIs in the range 1.5-3.0. [42] Such systems, by themselves, seem incapable of operating industrial society. [43] But their inadequacy may be concealed and/or subsidised by higher-EROEI technologies which remain in use; e.g., existing large oilfields or "stranded" gasfields. There is a risk of reliance on low-EROEI technologies causing problems at a late stage, after large capital investments have been sunk and most high-EROEI resources have been used up.

Put another way, we could be well-advised to use the energy surplus from high-EROEI resources; i.e. starting now, and for the rest of the fossil fuel age, to help to build up the infrastructure for the lower-EROEI resources which we shall need in say 2050 or 2100. A delay could make the transition much more difficult. We may need virtually all the net energy output from future energy systems; i.e. those with an EROEI of nearer 10:1, to maintain the societies which we have built up, leaving less over to manage the resource demands of a relatively rapid transition from one set of energy sources to another. This potentially tricky situation has been called “the energy trap”. [44]

On a more positive note, many energy efficiency improvements which have not yet entered widespread use in the UK have quite high EROEIs. On our preliminary estimates, external solid wall insulation to the optimal thickness could sometimes have an EROEI of over 100:1. This appears as good as the world’s early oilfields.

In the difficult situation which we face, it appears necessary to analyse and publish the EROEIs for different options which are proposed to form part of a UK climate change strategy. This should supplement economic studies, because the two are inextricably linked. Ultimately, surplus energy equates to money. [45]

Peak Fossil Fuels

The UK has already been through a series of transitions to cheaper, more concentrated and/or more convenient energy sources. Coal steadily replaced wood in quantity in the 18th century. Its consumption grew rapidly all through the 19th century. The UK experienced its “peak coal” in 1913, followed by its peak oil in 1999 and peak gas in 2000.

Figure 2 shows the rates of UK coal, oil and conventional natural gas extraction over time in common units. If we continue burning them at today’s rates, growing amounts of these fuels would have to be imported, with adverse balance of payments implications. We already import 70% of our coal and 50% of our natural gas. Worldwide, oil is widely regarded as being the fossil fuel in scarcest supply, relative to rates of consumption.

Large reserves of shale gas have been found in recent years, offering to some observers the possibility of an easier "natural gas bridge" to renewable sources, as long as total fossil fuel consumption falls fast enough, and/or sequestration rises fast enough, to meet GHG targets. [46] Natural gas still emits GHGs though, albeit less than coal-fired combustion plants. [47] [48] So any contribution from gas would need to be accompanied by enough investment in energy efficiency and enough CO_2 sequestration to give falling net GHG emissions. Given the low cost of natural gas and most energy efficiency measures, though, and the apparently modest costs of many CO_2 sequestration measures, this combination has some economic merits over current policy. The exclusion of natural gas from UK policy is hard to follow, given that even in 2050 the "pathways" feature a role for oil. [49]

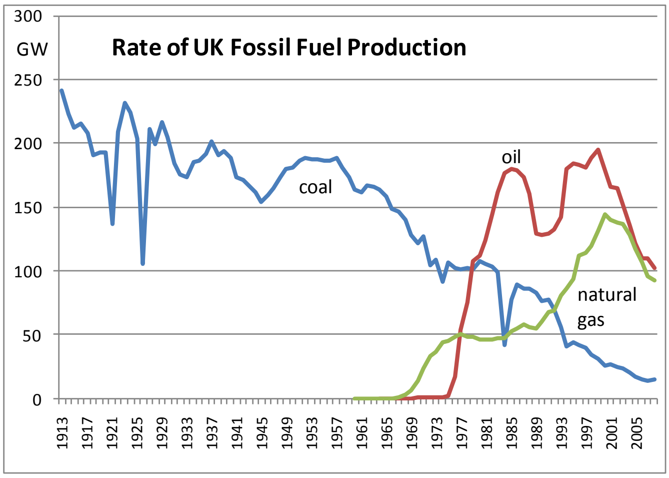


Figure 2. UK peak coal, oil and conventional natural gas production.

Sources: Dept. of Energy and Climate Change's (DECC's) *Digest of UK Energy Statistics* for coal and natural gas production. BP PLC's *Statistical Review of World Energy* for oil production. All converted to common units; i.e., GW.

NOTES:

1. Year-by-year data for the century before peak coal in 1913 is not available.
2. The above is conventional natural gas production and excludes shale gas, which is in commercial production in the USA but not in Europe.
3. The UK's rate of energy consumption is about 300 GW; i.e. primary energy production, minus exports, plus imports. In 2009, UK fossil fuel extraction equated to about 70% of UK energy consumption. This percentage is falling.

Similar charts have appeared at the global level. They can be summed up in Figure 3, showing the past and expected future development of world oil production. It was produced in 1956 by M King Hubbert, a geologist working for Shell USA. He correctly predicted that US peak oil would occur in 1970. There are disagreements over the date of the worldwide peak, which was delayed relative to Hubbert's forecast by the 1973 and 1979 oil crises, but there is much less doubt of its existence. [50] [51]

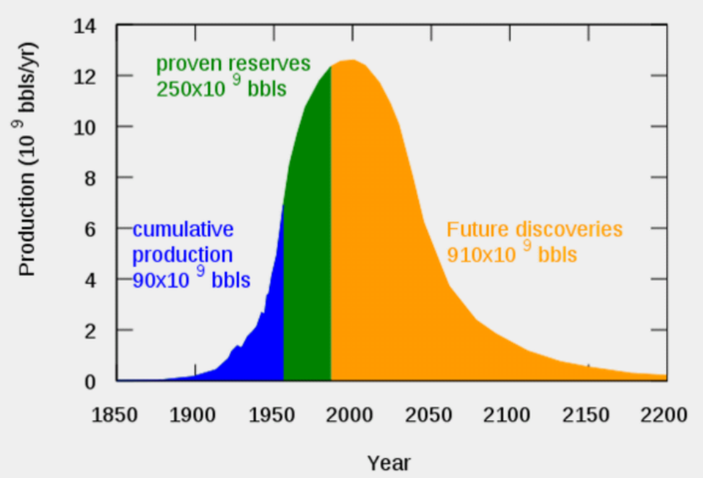


Figure 3. Schematic graph of peak oil. [52]
Source: Wikipedia.

Future Energy Supply

UK coal, oil and natural gas are all past their peak production, so the obvious question is: "What comes next"? As we attempt to move away from fossil fuels towards "sustainable energy", for climate change and resource depletion reasons, what will fuel industrial society. Will it be:

- Offshore or onshore wind
- Wave
- Tidal stream turbines, barrages, lagoons or other barrier systems
- Shallow geothermal heat
- Deep geothermal heat or electricity
- Concentrating solar power (CSP) for electricity
- CSP for industrial heat; i.e. low-pressure steam
- Lower-temperature solar thermal
- Solar PV

  and/or

- Nuclear fission in various forms?

There is not necessarily a straightforward answer to this question. But at current UK levels of energy efficiency, or after minor improvements, the answer seems to be: “None of the above”.

Writers routinely point out that the sun provides as much energy to the earth in an hour as humanity consumes in a year. Many also point to nuclear fission technologies which are in theory less limited than the use of uranium in burner reactors. In such terms, some of the above energy sources can seem almost “limitless”. But the prospects that they can achieve by themselves what oil and natural gas have done for the world economy look dismal, given the underlying economics.

Many renewable energy systems and related technologies under discussion are not fundamentally new but are more an updating and improvement of previous versions of the technology. [53] For instance:

- Greece and Rome required passive solar design of new buildings 2,000 years ago, to combat wood fuel shortages caused by deforestation
- Chaudes-Aigues, in central France, has had geothermal DH since the 14th century [54]
- Egypt had concentrated solar power (CSP) pumping systems in the 1890s
- Solar water heating was widespread in the 1890s in the southern USA
- Exeter’s sewage works generated bio-methane for the city’s street lighting in 1895
- For centuries, UK rivers were dammed almost continuously from source to sea and apparently exploited more of their hydropower potential than they do today. [55]

So why did fossil fuels take over, and why have renewables not replaced them faster since climate change became a pressing issue, starting in the late 1980s and early 1990s? In short, cost.

Whole System Costs

Rising Capital Intensity

It is useful to analyse the relative capital costs of different energy systems, including the plant and equipment needed to deliver energy to a consumer at a given rate. Since these whole system capital costs were first studied in the 1970s by strategic planners at Royal Dutch Shell, [56] followed by the Rocky Mountain Institute drawing attention to them, [57] the results have usually been expressed in units such as £ per delivered kilowatt (£/kW) or US$ per barrel/day.

These capital costs broadly reflect the resource intensity of different technologies and are crucial to their ability to supplant previous ones. To first order, an energy system which takes ten times more material and labour inputs per average unit output than another system costs ten times as much per kWh. One can apply the same methodology to energy efficiency technologies, producing costs in £ per saved kW, which can be compared to figures for various supply systems. [58]

For illustration only, we consider three energy supply technologies and two energy efficiency systems which save respectively heat and electricity:

- A fossil fuel supply technology - offshore oil
- A renewable energy technology supplying electricity - offshore wind
- A renewable energy technology supplying gaseous fuel - biomethane from waste materials
- An energy efficiency measure which saves heat - retrofit cavity wall insulation.
- An energy efficiency measure which saves electricity - an energy-efficient central heating pump.

The energy system costs are given in £ per average kW, not £/peak kW. Electricity supply systems have to be sized for the peak demand imposed on the network, not for the average demand, and their costs are usually quoted as £/peak kW. Fuel supply systems are more often costed on the basis of their average output in kW. We need a like-for-like comparison.

The oil system studied is an early example of the offshore oilfields which are increasingly being developed around the world. Earlier onshore oilfields cost less than this.

Offshore Oil

The Magnus oil platform in the northern North Sea, and the associated plant, cost £3.2 billion to build at today’s prices. [59] It supplies oil and natural gas to shore at an average rate of 5 GW; i.e., a specific cost of £640 per delivered kW. Refineries to distil crude oil into petrol, diesel, kerosene, HFO and other end products cost £350/kW. [60] The total so far is £990/ kW.

Depending on load density, the transport of oil between refineries, storage tanks and final users; e.g., filling stations, airports and domestic heating oil tanks, uses HGVs or pipelines.

Intermediate between ports, refineries and final users is an extensive pipeline network, carrying crude and refined products, with large and small fuel storage tanks widely dispersed throughout the system.

Most oil pipelines were built years ago. The replacement cost is the correct figure to use as an indicator of the capital intensity of fuel delivery systems versus electric ones. It is difficult to ascertain a typical figure. No UK sources could be found except for figures quoted by UK companies working on African pipelines. These suggest a replacement cost of £700 per m for a 1.3 GW pipeline. [61] *Pro rata*, a 200 km pipe, which is more typical in a small country like the UK, would cost £140 M to carry an average 1 GW, or £140/kW.

The published estimates from the USA, which consumes oil and natural gas at a mean rate of 2.0 TW, suggest a replacement cost of £500/m for a 1 GW pipeline. They put the replacement cost of the USA's entire oil and gas transmission pipeline system at £360 billion, [62] giving a specific cost of $(360\text{x}10^9)/(2\text{x}10^9)$ = £180/kW. Because gas pipes cost more than oil pipes, this composite figure somewhat overstates the downstream cost of oil supply systems and understates the cost of natural gas ones. The figure also excludes the low-pressure end of the gas distribution system.

Faced with a lack of UK figures, we tentatively use the US figure, giving an indicative cost for offshore oil systems of £990+180 = £1,170/average kW. The lower end of the distribution system, using HGVs, is estimated to have a capital cost of the order of £50/kW. On this basis, we assume a whole system cost close to £1,250/kW in making a basic comparison with renewable energy and energy efficiency. More detailed comparisons with the two technologies below, and with others, would be invaluable.

Offshore Wind

This is a system to satisfy the existing pattern of electricity demand, which has a 65% load factor. Figure 4 shows the 2005-06 load duration curve (LDC) in Great Britain, measured at the power plants.

Given the mismatch between wind supply and electricity demand, some fuel-fired plant, probably combined cycle gas turbines (CCGTs) or open cycle gas turbines (OCGTs), would be used to back up windpower. It is assumed that all wind energy produced is utilised immediately as electricity and none is spilled. This is characteristic of a limited system in which wind generates only a small fraction of electricity; e.g., up to 15%.

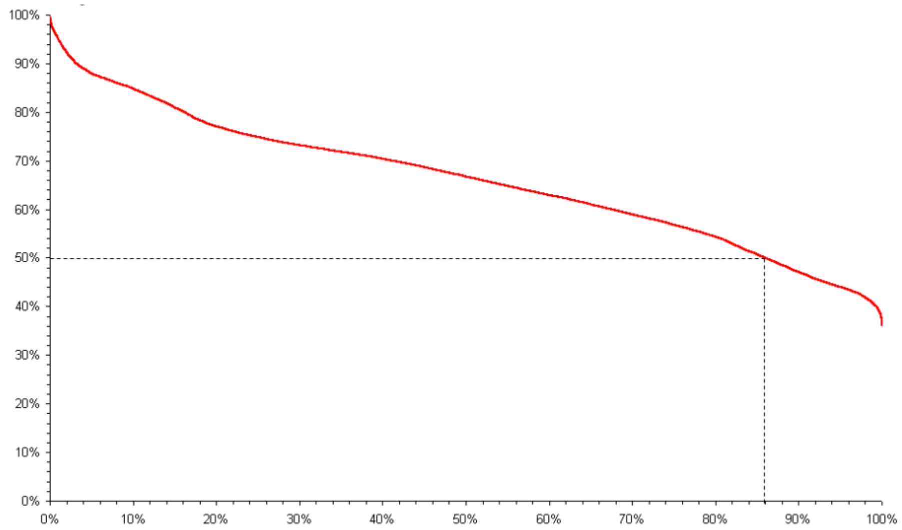


Figure 4. Electricity load duration curve, Great Britain, 2005-06. [63]
Source: National Grid PLC.

Since 2003, the UK cost has risen from £1,750 to £3,200 per installed kW(e), excluding part of the grid connection. This is apparently due to a combination of materials shortages and rising steel prices. [64] [65] [66] Bearing in mind the slightly lower costs achieved in Denmark, via a different bidding system, it is assumed that the increase is driven by temporary market conditions and would fall back in time, so that £2,000/installed kW pays for the turbines and full grid connection. [67] [68] If we assume that offshore sites achieve a capacity factor of 35%, the whole system then costs £2,000/0.35 = £5,710/kW as far as the grid connection point.

Also needed are costs of switchgear, pylons, cables, transformers and poles from the grid connection to final users. They are unpublished. It was estimated at privatisation 20 years ago that the replacement cost of the national grid, excluding the generating plants, exceeded £500 per installed kW(e); i.e., £880/kW(e) at 2010 prices. [69] If the electricity transmission and distribution (T&D) system operates at 65% capacity factor; i.e., with the wind output supported by the output of gas-fired plants, this contributes £1,350/ kW to the whole system cost. Assuming 7.5% T&D losses, the whole system cost so far becomes £(5,710+1,350)/0.925 = £7,630/kW.

The generating plant used to support windpower might include CCGTs and OCGTs, costing roughly £350 and £125 per installed kW(e) respectively. [70] If it is split 50/50% between them, at 65% system capacity factor and 7.5% distribution losses, it contributes £430/ kW to the whole system cost. The overall total is now £8,060/ kW.

If the system capacity factor were to fall; e.g., with electricity more widely-used for space and water heating, the whole system cost would rise. Conversely, if less electric space and water heating were used and the electricity supply system was confined more to its "essential uses", the LDC would be flatter, the whole system cost would fall and the system load factor might approach 70%.

This is not yet a 100% renewable energy system. It is around 15% renewable. It is supported by despatchable generating plant when the wind does not blow. This backup plant caters for the variable wind output by operating at lower load factors than if the wind turbines were not there. One should add a small term to the £8,060/kW to reflect the continuing use which is made of the natural gas and/or oil supply systems. [71] On the other hand, at low windpower penetrations, the wind turbines' capacity credit is similar to their average output. This saves on backup power station capacity and helps to counteract this extra cost. [72]

We have not assessed the further expenditure needed to take this system from 15% to 100% wind energy. Hopefully, others will simulate the UK electricity system over a long period, including periodic wind surpluses and deficits, and show how to add enough energy storage to reach an acceptable loss-of-load probability (LOLP). Given that UK policy is to "decarbonise" the electricity system by 2030 and keep it stable with high capacities of wind, nuclear and/or coal/CCS plant, we think that analyses of this are overdue for wind fractions above 20% and for periods of many years, reflecting the varying wind energy outputs from one year to another.

Biomethane from Wastes

The projected capital expenditure to meet Germany's 2030 biomethane target - a mean output of 11.4 GW - amounts to £1,100 per average kW. [73] This includes buffer storage and upgrading the raw gas to pipeline quality. It appears to exclude remote long-term gas storage in caverns, etc, and any pipe needed from the digester to the gas grid. The costing implies a fairly large digester, consistent with Danish or recent German practice. £180/kW is added for transmission and distribution, as for the previous oil figure, but if any of the gas is to be used in small-scale plant this would be an underestimate and a correction would be needed to cover the low-pressure gas distribution system,.

If energy crops were used, there would be a further element to add. But the capital intensity of fuel production from wastes is fairly low, compared to wind electricity production. The low specific cost also reflects the rather low temperatures and pressures involved.

Cavity Wall Insulation

We take a 80 m^2 semi-detached house in or near Manchester, with a near-average UK climate; i.e. on a population-weighted average basis. Calculations are carried out using the German Passivhaus Planning Package (PHPP).
The base case dwelling is assumed to have:

- 75 mm mineral fibre loft insulation, U = 0.57 W/m^2K
- Double-glazed PVC-framed windows and glazed doors, U = 2.8
- A solid concrete ground floor.
- Air leakage of 11 air changes per hour at 50 Pascals (ac/h @ Pa).
- An uninsulated cavity wall, U = 1.46
- A 95% efficient natural gas or oil condensing boiler.

Its cavity wall is as follows:

- No masonry returns, cavity trays or one-piece steel lintels
- Galvanised steel ties, which are assumed to raise the λ-value of the cavity insulation by 10%
- A clay brick outer leaf
- A medium-density block inner leaf
- A plasterboard finish.

As part of an energy efficiency upgrade, the walls are injected with 50 mm polyurethane (PU) foam, λ=0.025 W/mK [74], at a price of £15 per m^2 wall area [75] or £1,234 for the whole house. The wall's U-value falls from 1.46 to 0.43 W/m^{2}K and the building's air leakage falls by an assumed 3 ac/h @ 50 Pa, by blocking air movement through the wall into the rooms. In a well-heated house, the two phenomena combined save 9,200 kWh/yr of heat. With an assumed marginal boiler efficiency of 95%, the whole system cost for this gas-saving measure is:

£1,234 x 0.95 / (9,200 kWh/yr)
= £1,270 per average kW, say £1,300/kW.

This is an unusually high-specification form of cavity wall insulation (CWI) for the UK. Common forms of CWI; e.g., mineral fibre and EPS beads, cost less per unit wall area but are non-airtight, with a higher λ-value, making them less effective at reducing CO_2 emissions.

In this exercise, we have costed the more effective and costly CWI specification. It is impractical for the UK to continue fitting a low-performance technology from say 2011-21, change its policy in the early 2020s, return to millions of buildings in 2025-35, remove the old material from the walls and refill the cavities with higher-performance material.

Energy-Efficient Central Heating Pump

We take the results of a UK study in which an energy-efficient pump was added to a gas-fired condensing boiler installation in a 100 m^2 cavity-walled detached house, located 40 km from London. [76] We could not find a larger UK study, and it is possible that none have been made. In the installation studied, a pump costing a maximum of £129 in new systems would save 375 kWh/year, giving a whole system cost of £2,900/average kW.

Policy Implications

Figure 5 sums up the whole system costs, in line with the limited analysis so far. Two of the systems relate to fuel, one relates to saving heat and two relate to supplying or saving electricity. Note the limitations of such a study carefully. It is indicative only but illustrates the kind of work which should be conducted for energy supply and use throughout the UK economy.

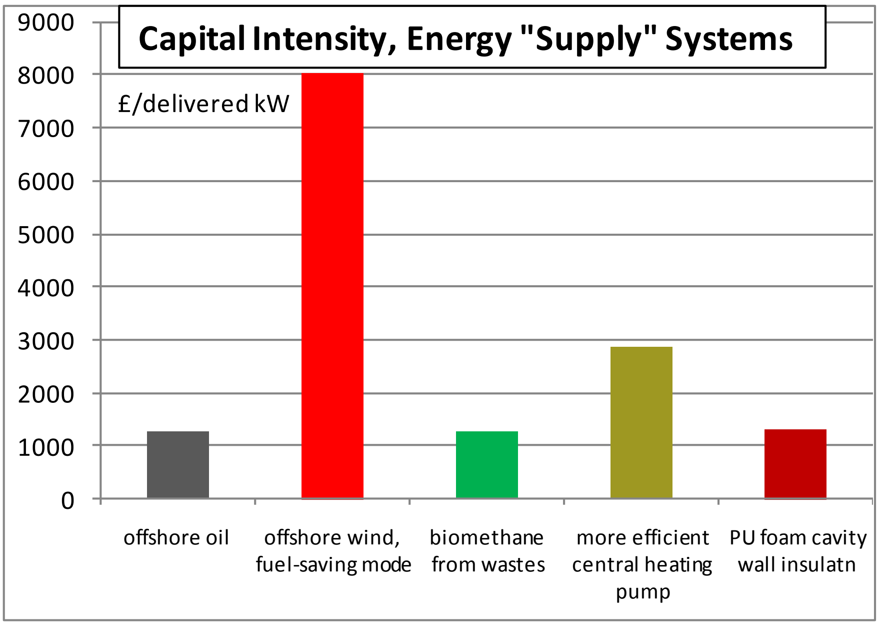


Figure 5. Energy whole system costs.
Preliminary analysis only.

The offshore oil supply system appears to cost roughly £1,250 to deliver energy at 1 kW to final users. This may be fairly representative of today's more costly fossil fuel supply measures. The insulation measure costs a similar amount to save fuel at this rate. Biomethane production from wastes appears broadly similar in cost. But while it is sustainable, it is a limited resource.

The wind electricity system costs around £8,000 to supply an average kW to final users. [77] This is for 15% wind. A system storing sufficient energy to supply near-100% wind electricity would cost more, especially if such an electricity supply system operates at a load factor below 65% and takes over the space and water heating load from natural gas and oil.

The more energy-efficient central heating pump "supplies" energy at around £2,900/kW, roughly one-third of the capital cost of the 15% wind system. It does not need backup plant or incur extra O&M costs.

These comparative resource costs remain poorly-explored. The message on rising capital intensity seemingly escapes the attention of many policy-makers, financiers, bankers, brokers, investors and politicians, not to mention consumers, to whom “green energy” has been understood to mean mainly renewable energy supply. Faced with the major cost increase associated with such systems as offshore wind electricity supply, we question the direction of UK climate change mitigation programs and suggest that more economically rational routes need to be explored and devised urgently.

Such costings begin to explain why other energy sources have not supplanted fossil fuels faster. The equipment needed to extract, process and distribute fossil fuels has been and is remarkably cheap versus that needed by most future energy supply technologies. On our current understanding, no technology is in prospect which lies “just around the corner” and offers the same combination of cheapness, convenience, storability, resulting security of supply, portability, energy density and simplicity as oil and natural gas. If renewables or nuclear energy did offer to play such a role, it is perhaps unlikely that the world’s oil majors would be drilling so intensively in harsh, hostile environments to bring oil, natural gas liquids and LNG to market. [78]

We submit that the nature of the coming energy transition differs radically from those which have generally occurred in the last millennium. This point has not yet been widely-understood or communicated to the general public.

A delegate’s account of the proceedings of the 2010 “peak oil summit”, which was held under Chatham House rules, includes these words:

> “A senior oil industry representative from a large company stated that 2004 was the ‘inflection point’ when global conventional oil production plateaued and oil stopped being cheap. The speaker affirmed that the supply flow is more important than reserves and that we know that $150[/barrel] oil ‘breaks the machine’ so that the global economy cannot function above that price. ‘It does not matter how much oil is left if we can’t afford it.’ ” [79]

This raises the possibility that, after peak fossil fuels, there may not be enough “affordable” energy supply for us to continue using energy on the same scale, with serious implications for the UK and world economy. One UK body states bluntly that we should plan for a forced decline in consumption, reflecting the high investment cost of future energy supply systems and the resource limits on the lower-cost renewables. [80] [81]

Electricity at 10 p/kWh is roughly equivalent to crude oil at $200/barrel; i.e., it is costlier than the threshold of $100-150/barrel which, on the above argument, “breaks the machine”. This adds to our concerns over the emphasis of UK energy policy on very costly options and the seeming lack of funds for more economic ones.

The Committee for Climate Change (CCC) has said that:

“Analysis by the CCC shows that decarbonising the power sector by the 2030s is the most cost-effective way of meeting the UK’s [CO_2] reduction targets”. [82]

We are unaware of any detailed studies of UK energy use that demonstrate this point. The CCC seems to have studied energy flows from a “top-down” supply perspective. It does not seem to have looked at the pattern of energy use downstream of energy meters or considered the adverse economics of replacing fuel by electricity.

As fossil fuel supplies run down, we think that the rising cost of energy supply is set to become a worldwide problem. But with falling supplies of indigenous fossil fuels, and a chronic balance of payments deficit, the UK must probably come to terms with it before most other countries. If the energy supply situation is set to become so constrained and pressing, the only significant option which we perceive to help transform the UK’s energy future is to begin far-reaching improvements in the efficiency with which we convert energy from one form to another and transform it into energy-related services.

A new strategic emphasis on demand reduction, and on more efficient energy conversion, would have potential economic benefits over a policy which stresses new supply:

- Energy efficiency in its various forms is usually cheaper to the UK than today’s world energy supply, in p/kWh
- Energy efficiency tends to be markedly cheaper than new non-fossil energy supply
- Energy efficiency improvements avoid the *marginal* cost of the more expensive new energy supply options; e.g., certain offshore renewables. These are higher than the average cost.

As such, it offers to reduce the total cost to the UK of energy-related services. This comprises the sum of the reduced energy bill and the capital expenditure on financing energy efficiency, both expressed in £ billions/year. There is growing evidence that current economic problems may be linked to the rising price of energy since the mid-2000s, plus the low efficiency with which it is used. These factors combined lead to high annual costs for the energy-related services concerned. On this basis, unless energy policy is rapidly re-formulated, to provide a more affordable way forward, the economic problems may continue.

Appendix 6 sums up reasons why we do not think that nuclear fission in its current state offers to play a very useful role in the coming energy transition. It strikes us as a costly distraction. We think that it is important to deploy scarce resources broadly as set out in this report, to maximise emissions reductions per £ spent and to minimise the risk that continued high expenditure on the energy sector could damage the UK economy.

3. Improved Energy Efficiency

The Resource

In the words of a US pioneer, Arthur Rosenfeld, the potential of energy efficiency is rather akin to discovering a new series of giant oilfields in our buildings, vehicles, factories, farms and even power stations. From these “resources”, we can “extract” fuel at relatively low prices. [83] Most of the resource available is cheaper than today’s world price of fossil fuels. It is certainly more permanent. It appears to be the only worldwide energy resource which is broadly competitive with cheap fossil fuels and does not cause climate change.

Would it run out? Perhaps, in the very distant future, the resource would become “depleted”. [84] But over the last 35 years, the underlying technology in many fields has advanced at least as fast as energy efficiency measures have been implemented. The typical potential for improvement in most fields is higher now than it was in 1980. [85]

The biggest obstacle to quantifying the resource is that energy efficiency has never been as fully-studied as energy supply. Developed country progress in this field peaked roughly in the period 1977-85, catalysed by two oil shocks in succession. 1973-82 was the last period of consistently high world energy prices. We could uncover many more opportunities, if we devoted more effort to the topic, and with more continuity.

More giant oil and gas fields have been discovered recently, mainly thanks to the intense rate of offshore exploration since prices began rising in around 2005. But on the long view, the pace of oil and natural gas discovery, including the giant fields which supply nearly 50% of global production, peaked in the late 1960s. [86] [87] If lavish application of energy efficiency is the most logical sequel to cheap fossil fuels, surely we need efforts to document its costs and performance which are on a par with the past exploration of the planet for petroleum deposits?

It would be particularly fruitful to investigate measures for the more efficient use of electricity. It is a more costly form of energy than heat or fuel, by a factor of 3-4 or more. None of the energy efficiency measures cited in this report would cost the UK more than about 3 p per kWh electricity saved; i.e., they would equate to selling a consumer electricity for less than 3 p/kWh. Most consumers already pay 8-13 p/kWh for their electricity and prices are forecast to rise further.

More efficient use of electricity would undercut the short-term avoided cost of operating existing power plants. The variable cost of fuel, operation and maintenance was given recently as 4 p/kWh for gas-fired plants, 2.5 p/kWh for coal or nuclear plants and 2.5 p/kWh too for offshore wind. [88] Electricity delivered to 230 V loads incurs 12.2% T&D losses. On that basis, even if the power station has already been built, the short-term avoided costs from reducing consumption in such buildings are respectively 4.6 p and 2.8 p per delivered kWh of electricity, depending on which source of electricity is displaced.

Reduced electricity consumption also saves on some use-of-system costs. These costs amount to 4-8 p per delivered kWh; i.e., a typical consumer pays 4-8 p more for a kWh of delivered electricity than it costs the utility to generate that electricity at the power plant. [89]

On grounds of economic rationality, we cannot see why the UK has a *de facto* policy to spend £20 billion/year on electricity supply up to 2020 but no policy to spend an equally serious sum on more efficient electricity use. It is surprising for a government and regulator to decree that £200 billion should be invested in energy supply in the next decade with no apparent major debate or assessment of alternatives.

Under the existing system of electricity and gas supply, private companies will have to borrow this money. They in turn will demand that consumers repay it on their electricity and/or gas bills, plus a commercial margin. A senior industry figure has stated that this scale of expenditure may not be financeable. [90]

Abating CO_2 Emissions at a Profit?

A valid way to approach the topic is to view energy efficiency technologies as CO_2 abatement measures and to evaluate the cost of different options in £ per tonne CO_2 equivalent. Several such analyses have been presented as marginal abatement cost curves (MACCs). In these charts, the cost of each measure in £/tonne is shown on the y-axis and successively more costly measures are plotted from left to right along the x-axis. This shows the saving from individual measures and the cumulative saving in tonnes/year.

A MACC was published for the USA, to the year 2030, by the Environmental Protection Agency. [91] In 2008, Siemens AG published a study for London to the year 2025. [92] In 2009, McKinsey and Co. published a worldwide analysis. See Figure 6.

A striking point of such analyses is that many energy efficiency measures abate CO_2 emissions at negative cost. Because these low- to medium-cost measures save energy which is worth more than the cost of the measure, the CO_2 is saved at a negative cost. As Amory Lovins of the Rocky Mountain Institute put it, this is not a free lunch; it is a lunch which one is paid to eat! Yet as Appendix 6 sets out, assessments of the social cost of CO_2 emissions, and the taxes on some forms of energy, are strongly positive, often up to £300/tonne.

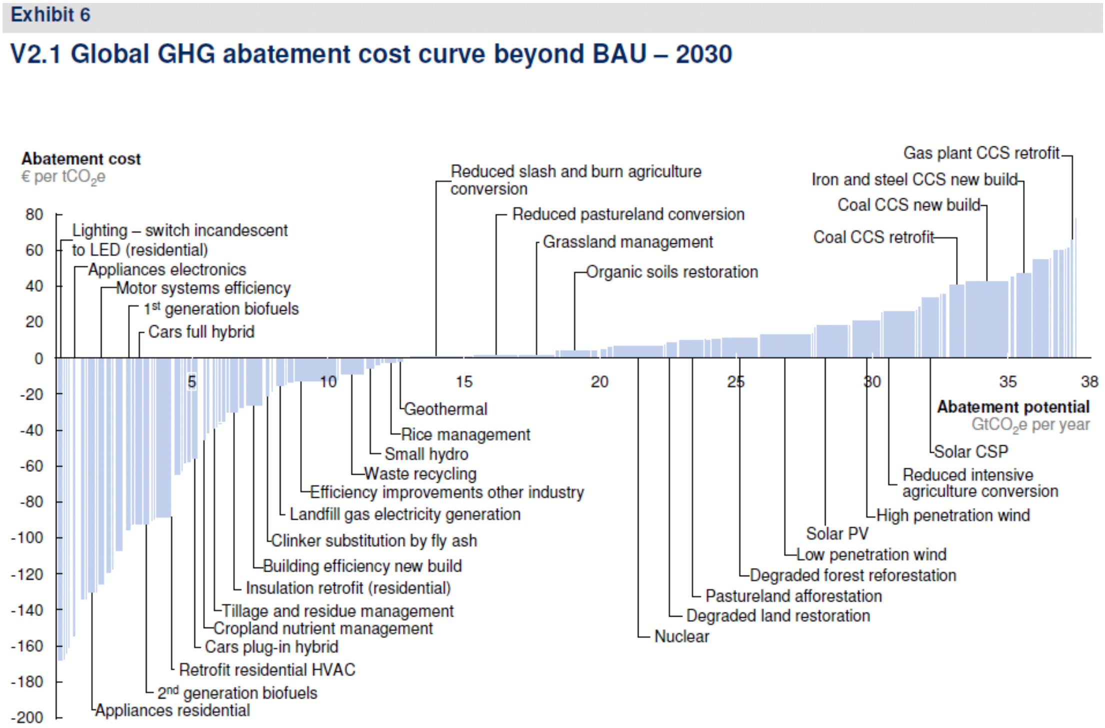


Figure 6. Worldwide Supply Curve of CO_2 Abatement Measures - Costs and Cumulative Savings. [93]
Source: McKinsey and Co., Inc.

There appears to be fairly wide agreement that the social cost is at least £40-50 tonne. The UK Climate Change Committee has suggested that a 80% reduction by 2050 needs investment in CO_2 abatement measures costing £250/tonne. [94]

Before confirming such a figure, the UK would benefit from studying the potential for enhanced energy efficiency throughout the economy, including the more economic option, in urban areas, of heat networks rather than electric heat pumps and replacement electricity networks. The message behind this report is that we have not yet exploited a range of measures which abate CO_2 emissions at negative or low costs; e.g., minus £200 to £50-150/tonne. In a functioning GHG abatement market, measures at minus £150/tonne would be implemented well before anyone would pay £1,000, even £150/tonne.

Figure 6 shows the format needed. But it is a worldwide scoping study and does not include national differences; e.g., in building construction methods. Figure 12 does take this into account, albeit just for one broad dwelling type, namely post-1960s cavity-walled low-rise housing. It would be a very good idea to produce a MACC for more of the resources available to the UK. The debate would benefit from this detailed, systematic, like-for-like study of available energy efficiency measures throughout the economy, alongside renewables and nuclear energy. Such a study should include CO_2 sequestration technologies.

If a large energy efficiency resource exists at negative abatement costs, which seems to be the case, policy-makers are working under a gross misconception. For instance, DECC has said of the Renewable Heat Incentive that its purpose is to induce consumers to move to more expensive energy technologies. We take a contrary view, that if government would act to remove the avoidable institutional and market barriers to "negawatts", [95] the parties who could profit massively from this resource would be freed up to exploit it. This would slow drastically the rise in average energy supply costs and help to meet or exceed the Stern Report's timely target that climate change could be tackled at a cost of no more than 1% of GDP. [96] Government should also adopt such an approach to encouraging the private sector to offer CO_2 sequestration services, including biosequestration.

This could offer to transform a situation in which utilities have been asked to spend up to £200 billion, mainly on electricity supply, and in which the government plans to subsidise other high-cost options by some £50 billion, all by 2020. [97] [98]This greatly increases the burden of energy expenditure on the UK economy and on consumers.

UK Energy Use

Almost any observer new to UK energy policy would conclude from the media discussions that most energy is supplied to consumers as electricity and that the energy problem centres on electricity. But we should all remember that energy is *not* the same as electricity. Confusing the terms means confusing the debate.

The Sankey diagram in Figure 7 shows the details of energy supply and demand for different sectors of the UK economy in 2009. Energy flows to final users were divided as follows:

- 38% in the form of natural gas - mostly for heating urban buildings, some for industrial process heating and a little for cooking.
- 42% in the form of oil - mostly for road, air and sea transport, a little for industrial process heating and for heating rural buildings.
- 18% in the form of electricity - mostly used in buildings, two-thirds of it for tasks where electricity is essential and one-third for providing forms of heating.
- 2% in the form of solid fuel, mostly coal. Most of it went to industry, small amounts to other sectors.

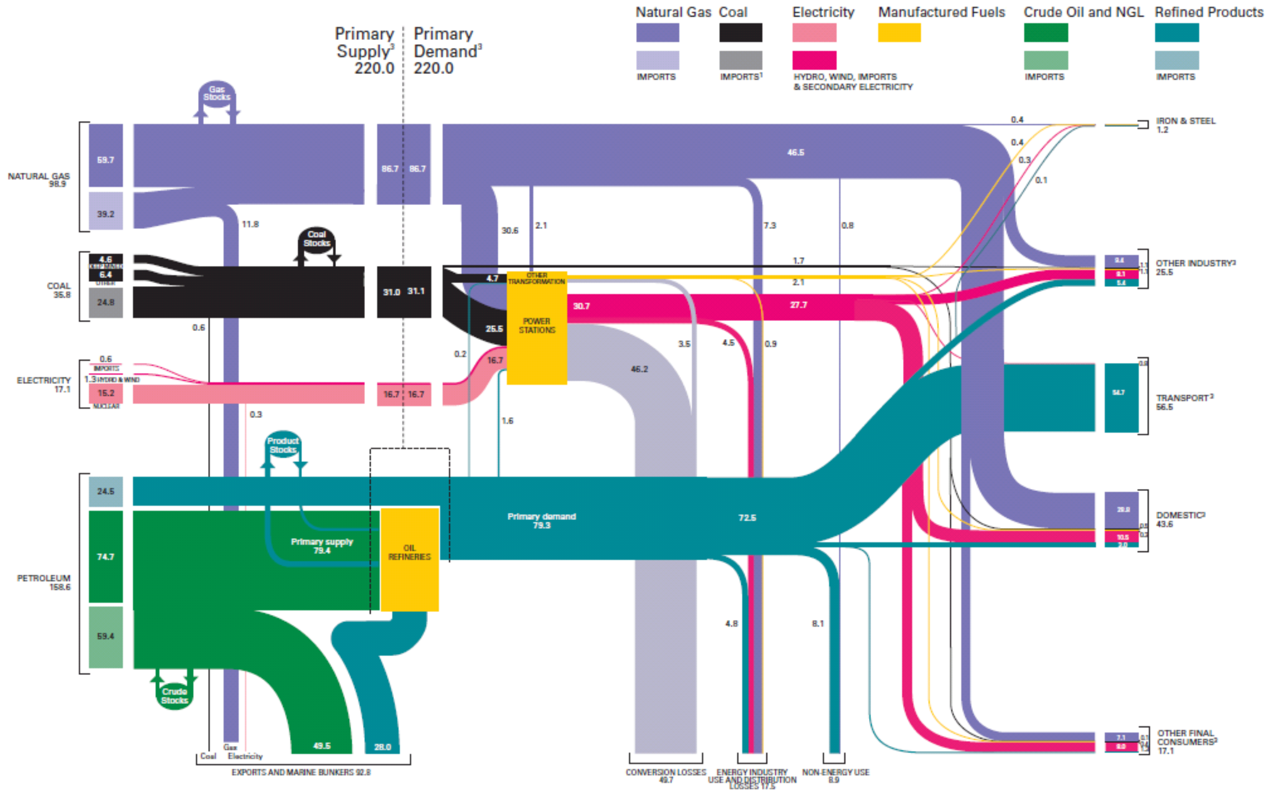


Figure 7. UK primary energy supply and energy consumption, 2009.

Source: DECC.

NOTES:

1. The chart excludes CHP plant. A small amount of fuel labelled as being delivered to buildings was actually converted to electricity and hot water in CHP plant - albeit sometimes within buildings - and delivered to consumers in these forms. It is estimated that 2-3% of UK buildings are heated by DH.
2. It excludes certain renewable energy sources; e.g., wood.
3. It excludes non-commercial energy flows; e.g., the passive solar gains which already contribute to UK space heating.

An estimated 93% of domestic space heating and 83% of water heating came from gas, oil and solid fuel. [99] Even so, a third of all the electricity was used for space and water heating and industrial process heating. Lesser amounts went on cooking and heat-consuming electrical appliances. Cheaper, less CO_2-intensive forms of energy could have been used in many cases. [100]

Figure 8 shows UK primary energy consumption and delivered energy in 2009 divided according to the type of energy needed. The two largest energy flows were to provide low-temperature heat and transport, followed distantly by higher-temperature heat and essential electricity; e.g., for lights, electronics, etc. Please note that the energy use for transport is the liquid fuel input, not the work output from the engine.

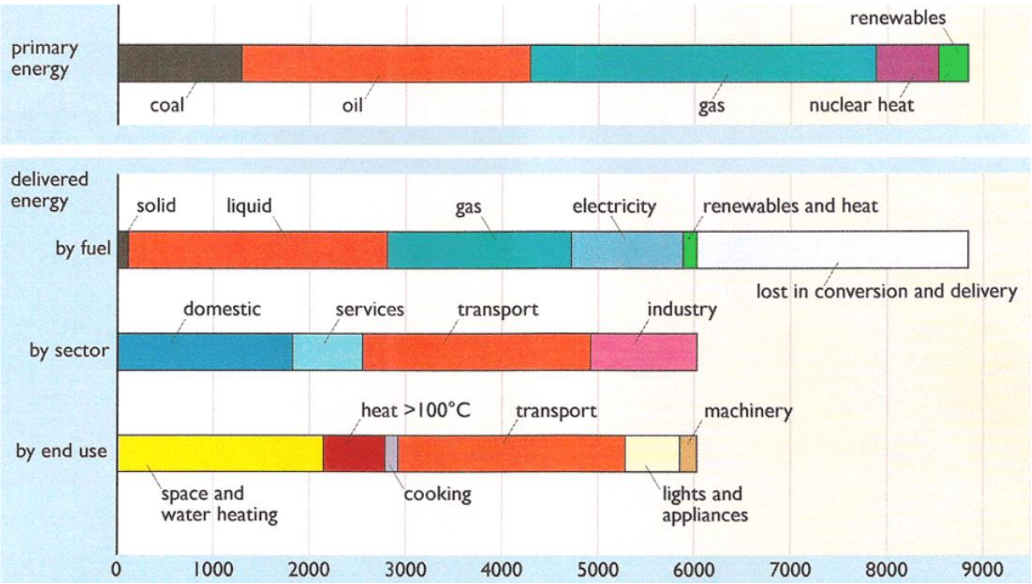


Figure 8. Breakdown of UK delivered energy in 2009 by energy quality needed, PJ/year. [101]
Source: Dr. R. C. Everett.

NOTES:

1. A significant amount of transport energy is used for space heating, lighting and cooling, not for traction.
2. Space cooling is classified above under the heading “lights and appliances”, but is a thermal use; i.e., chillers could use hot water from CHP plant, instead of electricity, via absorption-cycle heat pumps. Or they could just use a natural source of very cold water, where available.
3. Some electrical appliances need partly a heat input, not an electricity input for motive power; e.g., washing machines, clothes dryers and dishwashers.
4. If the chart was corrected for these effects, energy consumption for thermal purposes would rise and usage for motive power and essential electricity would fall slightly.

The basic classes of energy use within buildings can therefore be divided into:

1. Thermal uses - space and water heating and space cooling, plus more minor uses of heat
2. Cooking/catering
3. Lighting
4. Electrical appliances and equipment
5. HVAC fans, pumps and controls.

Uses 1-2, which account for 40-50% of delivered energy, involve provision of heat at low or moderate temperatures. Energy efficiency can here be improved in two entirely independent ways:

1. Reduce the *quantity* of energy consumed; e.g. insulate a wall to reduce a building's heat loss, insulate the walls of a domestic oven or an industrial furnace for the same reason.
2. Reduce the *quality* of energy used for the task; e.g., in a fossil or bio gas-fuelled situation, one could replace gas or electric resistance space and water heating by methods such as (a) piped heat from a gas-fired CHP plant, (b) electric heat pumps run off a similar gas-fired power station, (c) gas-fired heat pumps, (d) absorption-cycle heat pumps. See Appendix 1.

The percentage savings can be multiplied. If step 1 saves 75% of the energy consumption or CO_2 emissions for a particular task; e.g., space and water heating, and step 2(a) also saves 75%, then the GHG saving from applying step 1 and step 2(a) is:

$$100[1 - (1-0.75) \times (1-0.75)] = 94\%.$$

In today's conditions, a 75% reduction in gross CO_2 emissions does not seem to be enough. A 94% cut is more useful. To cut emissions from heating existing buildings over 90% solely by insulation, draughtproofing and new/modified windows needs high-cost measures and the timescale available for fitting these fabric measures may be shorter than the natural timescale of building repairs, improvement and replacement. It is more economical to attain such a large cut via two distinct approaches which complement each other.

In this regard, it is striking that no "pathways" issued by DECC explicitly feature a large role for piped heat in 2050, but one features "100% electric heating". [102] Appendix 2 sets out significant concerns over the practicality of this route. Among other problems, many buildings would probably need two heating systems, to limit peak demand in very cold weather and thereby protect "essential electricity" users.

Energy uses 3-5 above need electricity. The principal way forward is to dramatically reduce the quantity of electricity, by more efficient utilisation. Examples include:

- Replace domestic sector incandescent and halogen lamps by compact fluorescents and LEDs, replace many old fluorescent tubes by modern ones and use more efficient luminaires in either case, often saving up to 80%.
- Replace inefficient fluorescent lighting systems in non-domestic buildings by advanced T5 fluorescent systems and add controls, saving 75-80% or more.
- Replace inefficient central heating pumps by properly-sized and energy-efficient ones, saving 75-80% or maybe more.
- Replace existing refrigerators by best available technology, saving 75-85% now and perhaps 85-90% in the near future. [103]

Heating and Cooling

Space and Water Heating

New Buildings

Most of a building's energy is needed as low-temperature heat. As Figure 9 shows for a detached house, the heat consumption of a given size of building can be reduced more than a factor of ten by moving from a thermal standard characteristic of old, poorly-insulated and draughty UK buildings to higher standards. As a rule, these improvements feature:

- Thicker thermal insulation
- Better draughtproofing
- Improved fenestration.

Given the knowledge, and the skilled labour, new buildings can eventually reach the Passivhaus Standard or beyond, and existing buildings can move towards this level. But with the current UK availability of technical skills, this is a non-trivial task. There are diminishing returns, too. Government policy should acknowledge the reality on the ground and it should measure the energy performance of housing meeting recent Building Regulations.

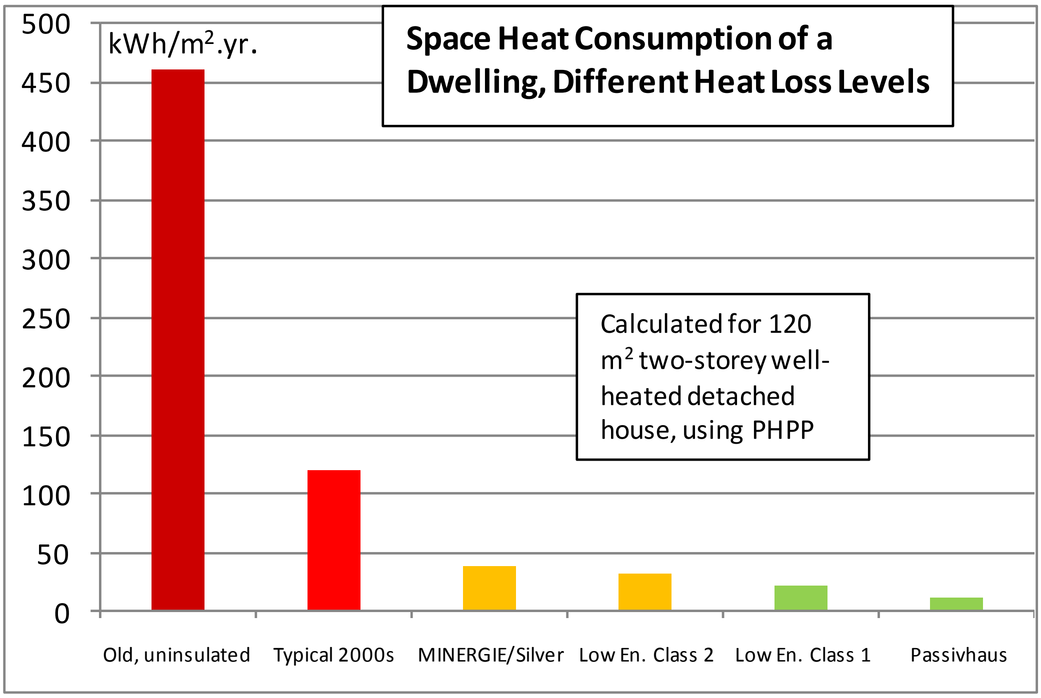


Figure 9. Decline in space heat consumption as insulation and airtightness levels improve.

NOTES:

1. The typical standard met by UK buildings in the 2000s was estimated by the principal author and input into a PHPP-2007 calculation.
2. MINERGIE is a Swiss government voluntary low energy standard, owned jointly by the 26 cantons.
3. Silver is a UK voluntary low energy standard developed by the AECB.
4. Low Energy Classes I and II are Danish voluntary standards, defined in relation to Building Regulations requirements.
5. Passivhaus is a voluntary standard developed in Germany by the Passivhaus Institut from 1987 onwards.

Disturbingly, some UK dwellings were being constructed in 2010 with cavity wall insulation of only 100 mm mineral fibre, even in areas not supplied by piped gas; i.e., where buildings rely on higher-cost, higher-CO_2 fuels. Denmark was using cavity walls with this U-value 33 years earlier. See Chapter 7. More wall insulation than 100 mm is clearly cost-effective to the UK and should be required by law. Building this way in 2010 is storing up trouble for the future.

Also hard to follow is why the government has not issued basic design guidance to alert the industry to low-cost improvements to thermal envelope design. This is costing everyone dear. [104]

Existing Buildings

It is relatively hard to reduce the existing building stock's heat consumption dramatically in the short to medium term. Some factors which delay improvements are common to most developed countries, but others are peculiar to the UK:

- Buildings outlast most other consumer goods. They sometimes last for 200-500 years or more. They may be re-roofed every 100 years or so; re-rendered if applicable every 50-100 years; good-quality wooden window frames may last 50-100 years; the sealed units therein may last 20-25 years and heating, ventilation and cooling systems may last 20-40 years, with lighting possibly replaced over shorter time cycles, like 10-15 years. Unless improvements to these components can be timed to coincide with a major refurbishment, they may be costly, slowing down the feasible rate of improvement.
- Internal temperatures in UK dwellings are much lower than in other northern European countries. Elderly, disabled and low-income people have legitimate aspirations for warmer homes. The 25,000 excess deaths in a normal UK winter are in part caused by living in a cold environment. In contrast to the mantra "turn down the thermostat", we should be improving buildings' thermal performance so that some people can turn *up* their thermostat for health and comfort reasons, giving conditions more akin to continental European buildings; i.e., nearer to 22°C than 17°C.
- Listed buildings, scheduled Ancient Monuments, Conservation Areas and other designated areas; e.g., Green Belts, National Parks and AONBs, may pose more hurdles to renovation. The UK has a very large stock of "heritage" buildings compared to most countries. This is directly relevant to our earnings from tourism.[105]
- An estimated 70% of UK dwellings have cavity masonry walls. [106] The rest are solid-walled, timber-frame, concrete or steel. Few other European countries have as high a percentage of cavity walls. [107]
- Cavity-walled structures are not "easy to treat". Rather, they can be problematic and complicated. As Chapter 2 set out, the government is arguably making a bad situation worse by funding the installation of sub-optimal wall insulation materials, which locks in relative energy inefficiency. But even if we adopt different insulants, we may have to accept lesser standards than externally-improved solid walls and no better than internally-insulated solid walls. [108]
- The solid ground floors typical of pre-1800 and post-1945 buildings are hard to insulate well, short of total reconstruction.

Technically, one of the easiest kinds of building to improve [109] appears to be a rectangular, unlisted 19th or early 20th century solid-walled building with these features:

- A suspended timber ground floor.
- A deep crawl space or basement, giving access to treat the ground floor from below without disturbing the floorboards or carpet.
- A pitched roof and windows which need replacement.
- External walls which need attention on the outside; e.g. re-pointing, re-painting, re-rendering.

One of the hardest buildings to improve beyond a limited point is arguably an “easy to treat” cavity-walled house or its non-domestic counterpart, having such features as:

- Masonry returns, cavity trays and steel “top hat” lintels across the cavity
- A plasterboard-on-dabs finish on the external walls
- A solid concrete ground floor
- Timber upper floors whose joists extend through the inner leaf to the cavity
- A roof in good condition, with impermeable felt
- External walls and windows in sound condition.

The second building type is much more common than the first.

Some retrospective improvements to building fabric insulation can be costly in £/tonne. The returns are often quite low compared to the improvement of consumer electrical goods, or office equipment, or processes and building services in industry and in non-domestic buildings. [110]

But as noted above, the energy quality needed for space and water heating is very low. If this heat is produced more appropriately; e.g., using the waste heat from a thermal power plant, the drain on resources can in theory be reduced 17-fold, where existing heating is from a condensing gas or oil boiler, and 33-fold, where it is electric resistance. See Appendix 1. The practical reduction from combined heat and power is less than 17 or 33-fold, but it is still high enough to complement the reduction from better insulation and airtightness. It also helps to offset the constraints on improving the fabric of existing buildings, especially those whose aesthetics and historic features we value.

To reach a sustainable end-point, at an affordable cost, we propose that the UK follow established practice in Denmark and emerging thinking in Germany. The supply of heat to cities or larger regions is coordinated on a larger scale than individual buildings. This is done in the interests of reduced CO_2 emissions and lower overall costs. See Appendix 2.

Space Cooling

Space cooling has developed into a major energy use in office buildings, hospitals and shops. Keeping cool has also become an issue for some private and social housing. But summers are remarkably cool in the south-eastern UK, compared to central Europe, and the rest of the UK and Ireland are even cooler. See Table 4.

Location		**Mean July Temperature**
Country	City	°C
UK	Aberdeen	14
	Aberystwyth	14.5
	Birmingham	15.5
	Plymouth	16
	Kew, London	17.5
Ireland	Dublin	15
France	Lyon	21
Germany	Würzburg	18
	Freiburg am Bresgau	20
Austria	Vienna	22
Switzerland	Geneva	19
	Lugano	21

Table 4. Mean midsummer temperatures across north-west and central Europe.

NOTE: The entry for Plymouth is for August which is its warmest month.

In theory, UK buildings which avoid excessive solar or internal heat gains need no cooling energy now or in 2050, assuming that summers warm by 2-3 K. The basis for this statement is the performance of German and Swiss offices to the Passivhaus, Low Energy, MINERGIE and MINERGIE-P Standards. Assuming adequate thermal capacity, they can be kept comfortable without active space cooling. [111]

Thermal simulations show no cooling load for standard high-mass dwellings in Lyon, France today, with reasonable external thermal insulation levels. [112] London's summers are unlikely to become that warm for 75-100 years. It would take a 6 K warming for summers in west Wales to become this warm.

The key means by which one can reduce or eliminate space cooling energy are:

- Reduce solar gains by temporary summer external shading
- In new buildings, use better orientation, preferably N-S or SSE-NNW, and high thermal capacity
- Procure energy-efficient electrical equipment and lighting, to reduce internal heat gains
- Minimise standing heat losses from space and water heating systems, via load compensation controls, etc, and by high insulation levels on all domestic hot water (DHW) pipes and tanks.

The first point needs more education of architects and clients. Voluntary programs would be better than forcing action on the industry via Building Regulations. Attempting to drive progress forward via Regulations sends people a message that the Regulations are recommended or even good practice. But as an official once said, the Regulations must set a standard which is achievable by the worst builders, on the worst sites, in the worst weather. Failure to meet this threshold is a criminal offence, so there is a problem in raising the Regulations too far, too fast. Doing so could bring the law into disrepute.

The second point needs education. It could be greatly assisted by Building Regulations which provide simple deemed-to-satisfy options, also by public authorities planning new housing developments better.

It is hard to overstate the case for mandatory government action on the third point. The EU tends to lag behind Australasia, North America and the Far East. [113]

The fourth point illustrates how one should implement a series of low-cost and surprisingly straightforward measures before devoting resources to expensive and complex ones. It is fundamentally simpler to change the boiler controls and insulate the DHW pipework than it is to design a central air conditioning system and retrofit a building.

If climate change-induced summer warming causes cooling to remain a major energy use, despite the above action, in very dense city centres the drain on energy resources can be reduced about three-fold by using a three- or four-pipe system and distributing chilled water, from seawater or river water chilling and/or absorption chillers at CHP plants, using their reject heat.

In less dense areas, piped heat at 70-80ºC can be used to operate absorption chillers in offices, hospitals, shops, etc. The likely COP is around 0.8, indicating a lower energy consumption than electrically-powered compression chillers so long as the system is using CHP or waste heat. [114] [115]

Essential Electricity

Energy for lighting, most domestic and office equipment, heating and ventilation pumps and fans must be in the form of electricity. But with aggressive promotion of energy efficiency, total consumption could still be reduced sharply, not left to grow as in a default situation.

Domestic Lights and Appliances

With an effort on more efficient electricity use, the domestic sector in 2050 could need around 2,000 kWh/year per household for “essential electricity”. [116] Considerably higher appliance ownership is assumed, more than offset by much-improved energy efficiency. [117]

The EU energy labels are not capturing the energy efficiency resource very well, especially not with “wet” appliances. [118] “Cold” appliance labels have been criticised too. Most models on sale are labelled A, A+ or A++ but some use three times more electricity than others. [119] Trying to cover such a wide range by only three energy labels; i.e., A, A+ and A++, which sound similar, is unhelpful to consumers. The forthcoming A+++ compounds the lack of clarity.

Rising consumption by TVs has hardly been tackled either. Yet a new and relatively inefficient wide-screen TV, using plasma, not LCD or LED technology, may consume more electricity than a refrigerator. Most households have several TVs. So do all hotels, student residences, nursing and care homes, hostels, prisons and other residential buildings.

At say, 30 M households in 2050, the potential electricity consumption with intensive implementation of energy efficiency, superimposed on increased appliance ownership, is around 7 GW or 60 TWh/year. This is 50% of today's domestic electricity consumption and 15% of today's total UK electricity consumption.

Non-Domestic Lighting

There is also electricity consumption by non-domestic buildings, industry and agriculture. Few studies of these sectors have been made in recent years, but we can illustrate the large potential for more efficient use of electricity.

One significant use is non-domestic lighting. It is especially topical with the concern over "keeping the lights on". In 2009, it consumed approximately 12% of UK electricity, or 4.4 GW, or 39 TWh/yr. [120] Fluorescent lighting in offices, schools, hospitals, shops, hotels, etc accounts for much of it. To quote the government:

> "The non-domestic lighting and appliances sector presents opportunities for relatively quick, significant reductions in demand." [121]

The media focus on the bans on larger incandescent lamps, which have been unpopular. [122] [123] But this could prove to be a diversion from savings which encounter less opposition and are easier and cheaper to implement. 90% of artificial light in Europe comes from fluorescent or other HID lamps. They are used for longer hours than domestic lighting and account for over 70% of lighting electricity. [124] At the least, non-domestic fluorescent lighting probably justifies the same priority as domestic incandescent lighting. [125]

Figure 10 shows the downward trend in the consumption of office-type fluorescent lighting systems from 1975 onwards *if* a system from then on had utilised best available technology. Consumption would have fallen by 82% in 35 years. Pre-1975 fluorescent lighting technology is still in use in some buildings, giving great scope for updating. Government documents do not seem to acknowledge the striking efficiency gap between the most and least efficient fluorescent fittings. [126]

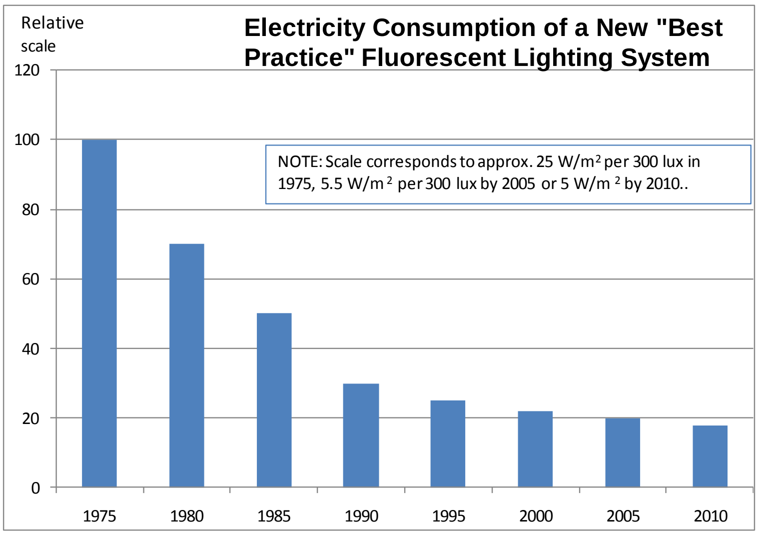


Figure 10. Rise in Fluorescent Lighting Energy Efficiency over Time.

NOTES:

1. 1975-2005 figures for best available technology from Fagerhult AB, Sweden, chart in 2008-09 catalogue.
2. 2010 estimate from data in their 2010-11 catalogue, compared to consumption of earlier years.

Little lighting fitted over the last 35 years has ever met “best practice” of that year. Many new installations and modernisations employed 15-20 year old technology. There should be a potential to reduce fluorescent lighting electricity consumption by at least 65-70% if we scrap the “power-guzzlers”. [127] [128]

Dimming controls to utilise daylight, or occupancy sensors, are an option too and could sometimes save 50-70% of the reduced electricity consumption. They are compulsory in new buildings but less common in existing ones. [129] If the new light fittings consume 65% less electricity, and controls save 70% of the electricity used by the new system, final consumption would occasionally be as low as 10% of the starting point.

Most retrofits of old lighting systems are very profitable, undercutting the cost of new power stations or the cost of running existing ones. Lighting contributes to the UK winter peak in demand at 17.30 h, seen in Figure 11. Lopping this peak is directly relevant to cutting the risk of supply interruptions in 2015-20. Lighting retrofits which would save the UK money, reduce CO_2 emissions *and* improve network security look to us like win-win-win investments.

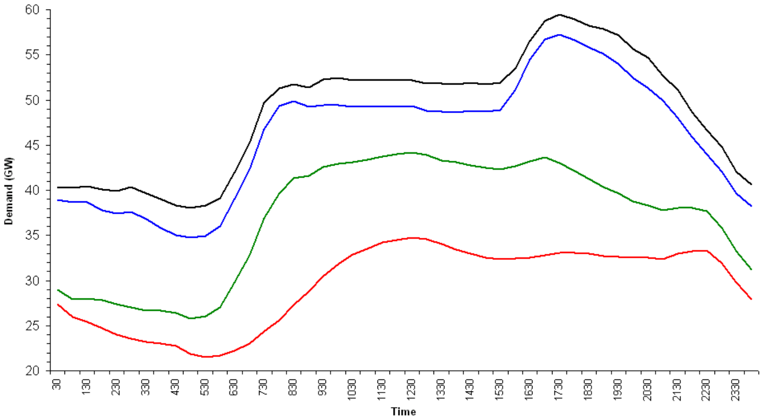


Figure 11. Great Britain hour-by-hour electricity demand on typical summer and winter days, 2005-06. [130]

Source: National Grid PLC.

NOTE: Red = summer weekend, green = summer weekday, blue = winter weekend, black = winter weekday.

Literature from the Carbon Trust, [131] [132] Energy Systems Trade Association members and others [133] can be used to calculate the cost of saved electricity, if new lighting systems are amortised over say 15 years at UK PLC interest rates. Generally, it ranges from minimal, if it is undertaken when old lighting is being scrapped anyway, and the marginal cost of a more efficient system is paid, up to about 3 p/kWh if an old system is replaced prematurely and no credit is given for installation work which would be needed anyway in 5-10 years' time.

But this technology displaces delivered electricity. It saves the T&D costs, as well as the operating costs of existing power stations. The electricity it saves at the consumer's meter usually costs 8-13 p/kWh. This is 3-4 times more than the measure has cost. CO_2 is saved at a negative cost.

In the electricity sector, we should really be assessing negawatts costing up to 8-13 p per kWh saved. At UK PLC real interest rates, the long-run marginal cost of delivered electricity from new non-fossil fuel power stations seems to be at least this high. So far, we have implemented few negawatts costing 2 p/kWh.

The Australian government has reviewed the typical costs of more energy-efficient lighting. [134] A South Australian government report states that electronic control gear on HID street lights reduces CO_2 emissions for £75/tonne. The circuitry would be utilised to dim the lamp 30% initially, and 15% in mid-life, giving a constant light output over its life as its efficacy slowly declines, rather than overlighting the task at the start. [135]

This profoundly "exotic" step abates CO_2 emissions more economically than most electricity supply technologies. It also offers to turn a country's street lighting into *de facto* spinning reserve, embedded within the distribution system. As with the potential use of dimmable electronic ballasts on larger fluorescent lamps in offices, schools, hotels, hospitals and factories, it would become feasible to dim the lights slightly in extreme power shortages, but still keep them on, perhaps at 50% of full power, perhaps less.

Most "lighting retrofit" products on the market constitute "cream-skimming". They exploit the cheapest of the energy efficiency resource, giving users a 25-40% electricity saving and a 100%/yr return on capital. But they forgo the full 70-90% potential saving from best available technology, because this gives cash-short businesses "only" a 40-50%/year return on investment. 40-50% is still roughly *ten* times the allowed return on capital of regulated utilities.

If the full measures are assessed, they are highly profitable to the UK compared to building new "low-CO_2" wind or nuclear generating plants or even running existing gas, coal, nuclear and offshore wind power stations. It would apparently cost less to rip out many UK office, hospital, school and shop lighting systems and put in state-of-the-art technology than to pay the reported cost of operating and maintaining offshore wind turbines or the fuel, operation and maintenance costs of existing coal, gas and nuclear power plants.

If "market forces" led to a stampede to "scrap that power-guzzling lighting", our high street shops, some supermarkets, hospitals, schools and offices would not be full of electricity-wasting pre-1980s lighting systems. [136] But they are. A revised climate change strategy should include a rigorous, least-cost approach to replacing obsolete lighting. To implement it, we recommend re-regulation of utilities to align their financial interests with those of electricity consumers and of UK PLC. See Chapter 6.

Electrical Office Equipment

Most office PCs and early data centres - the latter are the technology behind web searches, “cloud computing”, offsite backup services and video-on-demand TV - were designed with little thought to energy efficiency. “Market forces” are apparently not even implementing savings which would increase the cost of a new PC by £1 and save its owner £1/month on electricity. [137] There is a good case for government intervention, on the grounds that the market has failed. This could also be assisted in part by re-regulating electricity suppliers, as set out in Chapter 6. There would then be a large financial incentive for them to encourage investment in more energy-efficient systems.

Some other EU countries are collaborating to publish details of the most energy-efficient appliances. [138] Consumer information is available on most domestic and non-domestic electrical equipment, building on the lead taken by Switzerland, which pioneered this exercise in the late 1990s. [139] [140] What is conspicuously lacking so far is information in other countries and incentives to reward consumers who buy this technology and avoid utilities spending £ tens of billions on new power stations.

Catering

Commercial and domestic cooking equipment, using gas or electricity, can be made more energy-efficient. By reducing commercial kitchen temperatures, it would also improve working conditions.

Redesigned gas burners in restaurant kitchens can save 35-40% of the gas. Automatic on-off sensors can save a further 50%. [141] In combination, these measures could save 65-70%, where cooking is by natural gas or LPG. This technology could also be applied to domestic gas hobs, although on-off sensors in that sector would be unlikely to save as high a proportion.

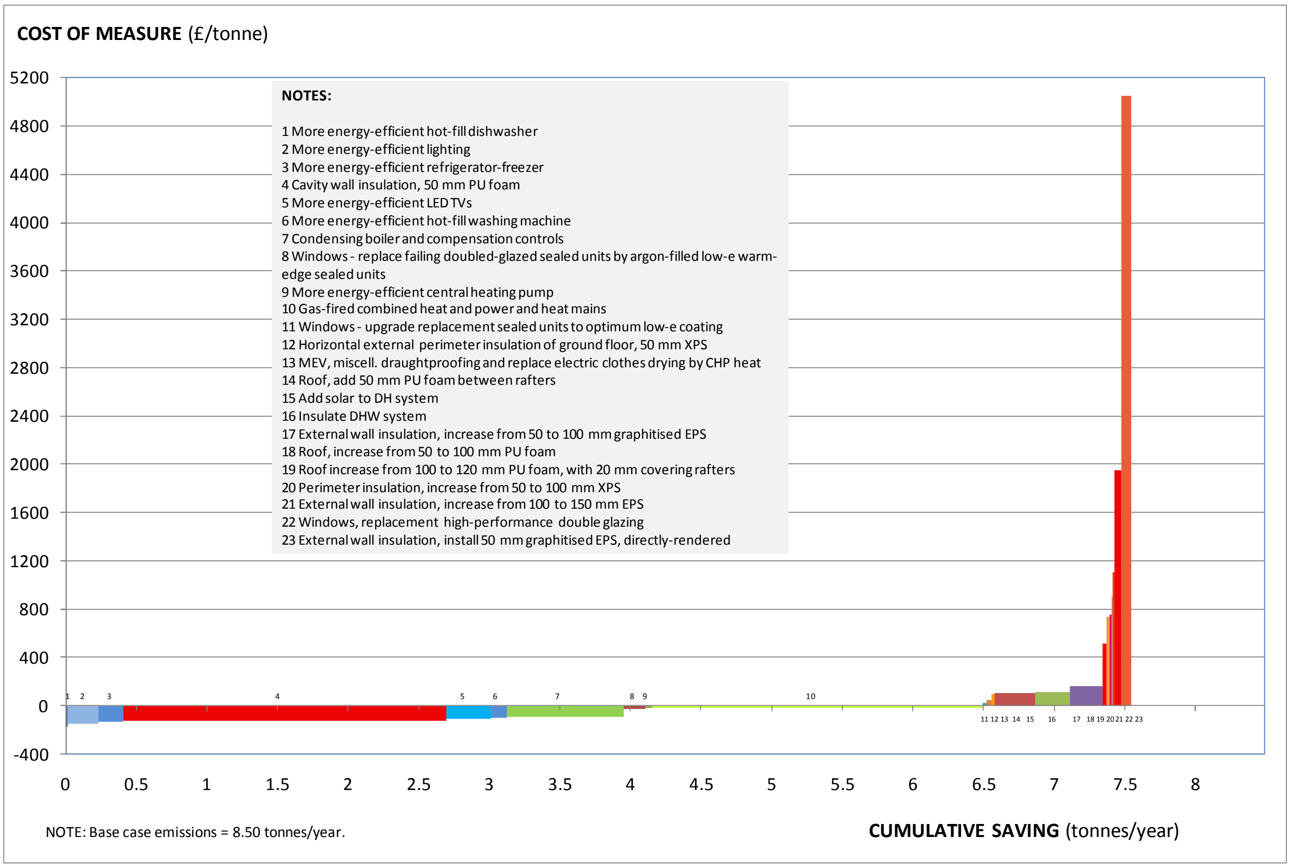
Domestic electric cooking emits more CO_2 than gas cooking. Shifts to gas should be encouraged to the same extent as other CO_2-saving measures. Where there is no alternative to electricity, as in blocks of flats, other options are available. They include replacement of solid or spiral-ring hobs by induction hobs and possibly replacing normal hotplates and ovens by plug-in appliances with internal elements; e.g., breadmakers, rice cookers and deep fryers.

Case Study - Dwellings in London

Figure 12 is based upon the marginal costs of the main CO_2 abatement measures analysed in late 2009 for some early 1970s cavity-walled London terraced and end-terraced houses. [142] The calculation here is repeated for a notional semi-detached house in a UK town or city.

The improvements are confined to proven technologies. It is quite possible that more measures would become available as time goes on, especially in making small electric appliances more energy-efficient. The existing dwelling has 75 mm mineral fibre loft insulation, a ten year-old, 75% efficient gas combination boiler to radiators, double-glazed PVC windows with failing sealed units, an uninsulated 50 mm cavity and air leakage of 11 ac/h at 50 Pa.

The UK may have 10-15 M broadly similar suburban and urban dwellings. They were mainly built from the 1930s to 2002-04. After that, under the 2002 Building Regulations Part L, filled cavities became standard and not the exception. Some of the cavities in older houses have already been retrospectively insulated, but this is a house where they have not.



NOTES:

1 More energy-efficient hot-fill dishwasher
2 More energy-efficient lighting
3 More energy-efficient refrigerator-freezer
4 Cavity wall insulation, 50 mm PU foam
5 More energy-efficient LED TVs
6 More energy-efficient hot-fill washing machine
7 Condensing boiler and compensation controls
8 Windows - replace failing doubled-glazed sealed units by argon-filled low-e warm-edge sealed units
9 More energy-efficient central heating pump
10 Gas-fired combined heat and power and heat mains
11 Windows - upgrade replacement sealed units to optimum low-e coating
12 Horizontal external perimeter insulation of ground floor, 50 mm XPS
13 MEV, miscell. draughtproofing and replace electric clothes drying by CHP heat
14 Roof, add 50 mm PU foam between rafters
15 Add solar to DH system
16 Insulate DHW system
17 External wall insulation, increase from 50 to 100 mm graphitised EPS
18 Roof, increase from 50 to 100 mm PU foam
19 Roof increase from 100 to 120 mm PU foam, with 20 mm covering rafters
20 Perimeter insulation, increase from 50 to 100 mm XPS
21 External wall insulation, increase from 100 to 150 mm EPS
22 Windows, replacement high-performance double glazing
23 External wall insulation, install 50 mm graphitised EPS, directly-rendered

NOTE: Base case emissions = 8.50 tonnes/year.

Figure 12. MACC for a 1970s Suburban Semi-Detached House.

NOTES:

1. To give the specific cost of CO_2-saving measures, the value of the energy saved was deducted.
2. Individual measures appear on the chart in order of ascending cost, left to right. The order of ascending costs was normally calculated by evaluating the saving of a measure as applied to the base case.
3. If one externally insulates a wall which is already insulated in the 50 mm cavity, the marginal cost of making the added insulation thicker is less than the cost of a basic thickness. So these measures appear on the chart in an unexpected order.
4. The interaction between measures is very complex. The above list should be regarded as preliminary only.
5. Adding an energy efficiency measure to a building sometimes reduces the cost-effectiveness of subsequent measures. More efficient use of electricity; e.g., improved central heating pumps, TVs or refrigerators, reduces internal heat gains. This increases heat consumption and improves the cost-effectiveness of insulation, draughtproofing or more efficient heating systems.
6. Heat-saving measures, or heat with a lower marginal cost, reduce the value of the internal heat gains from electrical appliances. A technology such as CHP improves the cost-effectiveness of subsequent electricity-saving measures, but reduces the cost-effectiveness of subsequent fabric insulation measures.
7. The chart excludes technologies that were not demonstrated or on the market as of mid-2010.

The different types of retrofit measure are shown in distinct colours:

- Lighting, electrical equipment, HVAC fans, pumps and controls - shades of blue
- Insulation and draughtproofing of the thermal envelope, including glazing - shades of red and orange
- Space and water heating “thermal” services, including heat mains - shades of green.

Nearly all the type 1, most of the type 2 and some of the type 3 measures have negative costs; i.e., they abate CO_2 emissions at a profit. The single two largest CO_2 savings, which each reduce emissions by roughly two tonnes per year in a well-heated house, are from:

- CWI with airtight materials
- Heat mains to distribute low-CO_2 heat from gas-fired CHP plant.

The shape of the MACC is perhaps more dramatic than usual. About 13 measures near the origin of the y-axis deliver large energy and CO_2 savings at negative or low costs. Ten measures on the right-hand side, mostly retrofit insulation and replacement windows, deliver small savings at fast-rising marginal costs, ranging from £100s to £1,000s/tonne.

Figure 12 relates to a house where a condensing gas boiler is fitted in the period before piped heat and CHP plant becomes available. If an area was connected to piped heat today, the MACC would differ in appearance from Figure 12, because a typical building would go straight from a non-condensing boiler to CHP, not to a condensing boiler and later from there to CHP.

A MACC for a solid-walled house or block of flats, or for the 15% of urban buildings which have electric heating, would be different again. However, in the absence of the resources to prepare these variants, Figure 12 is thought to be a representative case.

The most expensive measure in Figure 12 is external insulation of existing walls (EWI) after fitting high-performance CWI. The second most costly is prematurely replacing the windows by high-performance double-glazed ones.

Triple-glazed high-performance windows have been excluded from the analysis. They save no energy in this building, owing to the reduced passive solar gains.

GHG emissions would fall by about 75% before one needs to install measures with positive abatement costs. They would fall by nearly 80% before the marginal costs of the most expensive measures exceed £100/tonne.

The average cost of a package of measures can be obtained by summing the areas of all the measures below the y-axis and all those above it. It appears that a package of the first 16 measures would have a negative overall cost, although the more expensive measures within the package just exceed £100/tonne.

The best buys in Figure 12 fall into three basic categories:

- Improved energy efficiency of domestic electrical appliances, lighting and HVAC pumps, fans and controls.
- Basic fabric improvements, including CWI and roof insulation with airtight material, re-glazing windows whose PVC frames are still sound and specifying a low-emissivity coating on the new sealed units which improves the passive solar gains.

- Building services measures, including laying heat mains to utilise waste heat from power stations, condensing operation of gas-fired CHP plants, improved DHW tank and pipe insulation, heat traps, improved thermostatic controls.

Progressively less good buys include:

- Roof insulation beyond a point of rapidly-diminishing returns.
- Perimeter insulation of solid concrete ground floors, even if fitted while laying heat mains
- Replacement high-performance windows, especially if existing ones are in sound condition and airtight.
- EWI on cavity walls which have already been insulated, albeit poorly by today's standards.

Figure 13 below, taken from the 2009 project in London, sums up the projected result of applying measures which abate CO_2 emissions at negative and low cost. The suggested package delivers an 81% reduction in CO_2 emissions. Before the retrofit, about two-thirds of the dwelling's CO_2 emissions come from its gas space and water heating. After the retrofit, which includes a large range of energy-efficient appliances, and connection to a gas CHP plant, two-thirds of the CO_2 emissions would be from the consumption of electricity for lights and appliances, even though three-quarters of the energy delivered to the dwelling would be low-temperature heat.

The work delivers lower emissions than Passivhaus-certified new dwellings heated by an electric heat pump. The GHG emissions in column 4 are based on today's electricity emissions, in kg/kWh. That is, emissions are cut by 82% without depending on "electricity decarbonisation". With a small reduction in the electricity emissions coefficient, say by 25%, and with the buildings connected to a CCGT plant, rather than to a small gas engine, the CO_2 reduction would approach 90%.

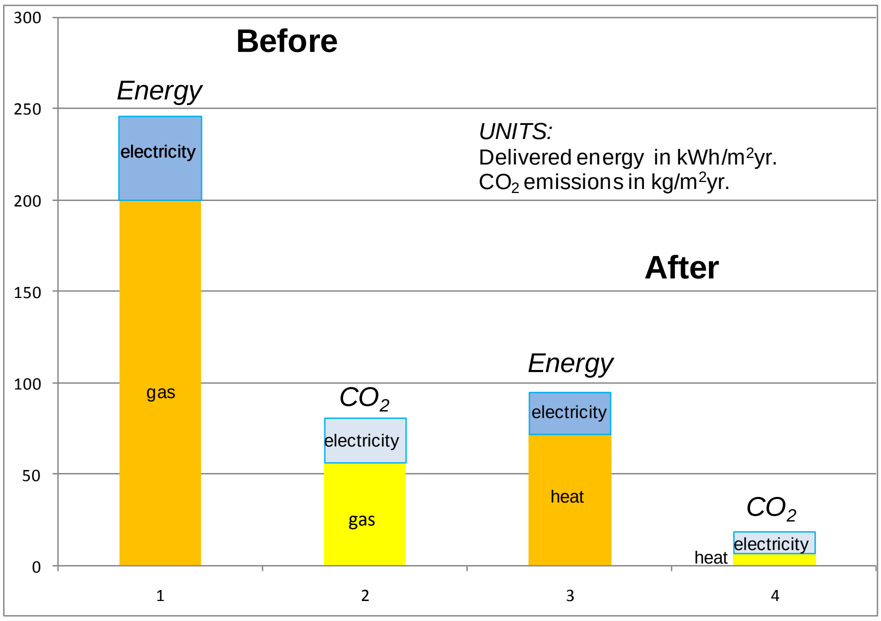


Figure 13. Results of Applying Negative- and Low-Cost CO_2 Abatement Measures to London Terraced Houses.

Buildings such as the rural solid-walled house in Appendix 3 would yield a differently-shaped MACC, from a somewhat different package of measures, and added in a different sequence. A rural cavity-walled house would show a lower cost in £/tonne for the external insulation of a filled cavity wall.

The costings in this report should be expanded, so that the full implications of the situation are clearer as we seek to move beyond fossil fuels. Figure 12 shows the format needed.

The Rebound Effect

In exploring the possibility of lavish spending on energy efficiency, we must refer to the rebound effect. This expresses the tendency for consumers who become more energy-efficient to spend some of the money which they save on energy elsewhere in the economy, or possibly on the same end use. See text box.

The rebound effect has occasionally been presented by proponents of energy supply investment as a reason why energy efficiency may not work; i.e. an implied argument against it. By contrast, it arguably provides a positive case for investment. It is a manifestation of the overall cost savings and the economic benefits of meeting more of our needs for energy services by energy efficiency, and less by energy supply. [143] [144] [145]

The Rebound Effect

Some economists claim that energy efficiency would not reduce energy consumption. They assert that consumers would spend the saving on energy on other goods and services, which could increase energy consumption elsewhere in the economy.

It is true that there are significant economic impacts from investing in typical energy efficiency measures. An obvious one is that, after investing in insulation and draughtproofing measures, most UK householders find that they can afford to keep their home warmer. Occupants usually choose to take some of the expected fuel saving as higher temperatures. They value the extra comfort more than the energy savings which are foregone.

UK policy needs to be modified to address this issue. But experienced energy modellers already allow for the effect. Added insulation measures should be costed, and optimised, on the basis that a building will be kept significantly warmer if its heating costs are reduced. As heat losses are reduced, temperatures finally stabilise at a point where heating costs are no longer a significant constraint on occupant behaviour. There is good evidence from Scandinavia and North America and from UK “ultra-low-energy homes” as to where the temperatures stabilise. Beyond this point, subsequent fuel savings are close to 100% of those expected.

We have read some arguments that energy efficiency has caused energy consumption to stabilise, but has never caused it to fall. This appears to be wrong. One example comes from Denmark. Insulating buildings better, and providing towns with lower-CO2 piped heat, did not increase energy consumption in kWh/m2yr or CO2 emissions for space heating. From 1973 to 2011, consumption and emissions slowly fell. California has stabilised its per capita electricity consumption since 1975 and hopes that it may start to decline within a few more years.

It is usually true that, if a consumer becomes better off as a result of energy efficiency, they will spend some of the value of the energy saved, minus the cost of financing the energy efficiency investment, elsewhere in the economy. However, the resulting spending on goods and services will tend to be in proportion to the average energy intensity of the UK economy. If we suppose that energy makes up, say, 8% of the price of average goods and services, the total energy consumed as a result of this extra economic activity would be somewhat below 9% of the estimated saving. That seems quite low compared to the direct energy and CO2 saving from the measure.

Ctd.

Energy efficiency reduces the marginal cost of the relevant energy-related service. One could argue that this would increase demand; e.g., that drastic improvements in car fuel efficiency - see Appendix 4 - would reduce the marginal cost of travel and lead to more driving. But looking decades into the future, the higher marginal cost of renewable transport fuel, versus fossil fuel, may offset the cost savings from energy efficiency. Capital repayments on a more energy-efficient motor vehicle would probably rise too by several £100/yr, reducing the funds for consumers to spend on other goods and services. It appears that the real cost of driving could be roughly constant if vehicles become much more fuel-efficient, vehicles become slightly more expensive to cater for fuel efficiency improvements and fuel becomes significantly more expensive.

Some arguments put forward for the rebound effect are perverse. Its proponents sometimes seem to be arguing that, because energy efficiency saves consumers money and makes them better-off it should not be undertaken, lest it should lead to a slight secondary increase in economic output and in energy usage! One might think that the UK’s present gloomy economic situation would make this impact decidedly welcome.

4. Energy Supply - Where From?

Introduction

This chapter deals with some of the main future options to supply energy. It sets out some principles which we should follow, to contribute towards affordable energy security after oil. 40 years is a very short timescale for major changes to a country's energy system and infrastructure. So we must focus on making maximum GHG reductions on minimum resources, while enhancing or maintaining energy security, and meeting other policy objectives. If we fail, it will be hard to secure a sustainable energy system even by 2050.

Despite drastic rises in energy efficiency helping to stretch the cleaner resources, such as natural gas, renewable energy supply will eventually need to take over from fossil fuels. But we shall need less energy, and a higher proportion can come from sources which are less variable, cheaper and/or more storable. The higher our total consumption, the more we are obliged to exploit expensive, variable resources. [146] The higher the fraction in the form of electricity, and the more irregular the demand and supply profiles, the more that we are forced to solve significant engineering problems related to network stability.

We have not attempted detailed graphs to show potential energy demand and supply in 2030 or 2050. It is clear that total supplies from "firm" or storable renewables, including solar thermal, geothermal, hydro, tidal and biofuels, are useful and significant, set against potential heat and electricity demands *after* applying strong energy efficiency measures. It is also clear that demand for storable liquid or gaseous fuels would be likely to exceed the contribution of indigenous bio-energy, but that synfuels could also be produced from variable sources of renewable electricity; e.g., peak wind outputs which would destabilise the electricity grid and cannot be used without expensive new transmission lines.

We suggest that the broad trend would resemble the Danish scenario for the EU-27 shown at the front of this report, or the "2 kW society" put forward by the Board of the Swiss Federal Institutes of Technology, which assumes a tripling of Swiss GDP by 2050. [147] However, the UK tidal range in the Severn estuary is the second highest of any site in the world, and its wind resource exceeds that of other EU member states, except for Ireland or Denmark. So the UK energy mix by 2050 could differ somewhat from the EU average.

"Sustainable" energy supply is discussed later below according to whether it is in the form of heat, fuel or electricity. Some conversion processes provide multiple outputs. CHP plant provides heat and electricity. Synfuel plants fed only by electrolytic H_2 and CO_2 might provide a liquid or gaseous fuel output, together with a smaller heat output for DH systems, if they are conveniently sited. Or if they are remote, to benefit from higher wind speeds, say off the west coast, they might provide fuel only and the low-grade heat might be used to help sequester CO_2. [148] Some plants fed by solid biomass could provide outputs of liquid fuel, electricity and low-grade heat. Such technologies are normally discussed once, with reference to one energy vector.

We include several technologies which are hardly acknowledged in official documents but which appear to give low abatement costs in £/tonne. One is large-scale solar thermal for space and water heating. We are very surprised to see this technology excluded from a CCC survey of renewables [149]. Another is synfuel production from unwanted electricity from variable sources. While expensive, it is a way to produce high-value storable energy, adding to our future security; to supplement the biofuel resource and to avoid grid reinforcement.

System Scale

The scales of renewable energy supply systems, and energy networks, span a wide range, from micro-systems on an individual building, via local and regional systems, to national, EU-wide or international networks. There has arguably been excessive emphasis on tiny and international systems. Moderately large systems may benefit from most of the engineering economies of scale and still be local to the consumers they supply.

UK policy since the 2003 Energy White Paper [150] has been dominated by the term “micro-generation”, implying at times a generator in each house. But few people appear to want a semi-autonomous building full of expensive “kit” to maintain. Surveys suggest that they place more value on security, convenience, affordable running costs, freedom from manual intervention and low maintenance.

Since the mid 20th century, the historical trend with heating systems particularly has been away from multiple small plant needing manual intervention, towards larger, professionally-maintained, automatic systems. In most European countries, oil quickly replaced solid fuel heating from the 1950s. Piped gas and piped heat later replaced individual oil boilers in most countries. Gas and electric cooking replaced solid fuel.

Engineering issues can favour larger installations than a single small building. Thermal electricity generation, electric heat pumps and insulated hot water tanks share strong economies of scale, in terms of their mechanical efficiency or cooling time constants. So do bio-refineries. These scale effects stem from physical fundamentals. They are hard to circumvent and have important practical impacts.

Scarcity of technical skills for installation, maintenance and safety inspections may also favour larger-scale systems. Consider a small city of 150,000 which is heated by a directly-connected, variable volume DH system, using heat sources such as CCGT plant. The network probably has fewer than ten moving parts; i.e. the turbine(s), variable-speed circulation pumps and various system controls. Buildings in the same city heated by individual gas boilers, electric or gas heat pumps have orders of magnitude more.

Energy Storage

The UK energy system today is supported by the ready availability of storable hydrocarbon fuels. They provide a large buffer between supply and demand. 82% of UK energy delivered to final consumers is in the form of storable energy vectors - solid, liquid and gaseous fuels and hot water. Over 80% of the energy supplied to power stations for electricity generation is also in the form of fossil and bio fuels. [151] In this sense, 96% of UK delivered energy could be said to rely on stored chemical energy. [152]

Whatever approach is taken to provide energy supply after oil, it must continue to provide adequate energy storage. Future energy systems are set to need a continued storable fuel input, for stability and security of supply.

On electricity supply systems, stored fuels burned in thermal power stations can compensate for changing supplies of wind or PV electricity, helping to provide a reliable supply to consumers. The UK has limited hydro capacity to perform this function. Electrical and mechanical or potential energy can only be stored at relatively high cost. Their use is often confined to diurnal storage. Here a store is used many hundreds of times a year and high capital costs can be repaid.

On heat networks, hot water itself can be stored for long periods, given a reasonable level of thermal insulation and a low surface-to-volume ratio. But a liquid fuel tank is more flexible still, less bulky and cheaper than a heat store. Heat networks use stored fuel to meet extreme demand peaks.

One route to improve energy security involves dispersing energy storage throughout a system, to act as a buffer against unexpected rises in demand, or short-term supply difficulties, or component failures. This happens with fuel and heat supply systems. But if batteries replace fuel tanks in the road transport system, the amount of local energy storage falls from about 300 to 2 kWh per vehicle, assuming that on average energy stores are half full. If electric heat pumps displace rural oil boilers, the amount of local stored energy falls from about 5,000 to 0 kWh.

Future Energy Vectors

In 2009, as Chapter 3 noted, 18 % of UK delivered energy was in the form of electricity and two-thirds of the electricity; i.e., 12% of delivered energy, went on electricity-specific tasks or on uses where electricity is usually advantageous; e.g., electric railways. Around 6% went on uses where electricity is optional, including space and water heating, cooking, industrial process heat, clothes drying, heating water in washing machines and dishwashers. Figures 14 and 15 indicate roughly where electricity was used in recent years. Please refer also to Figures 7 and 8.

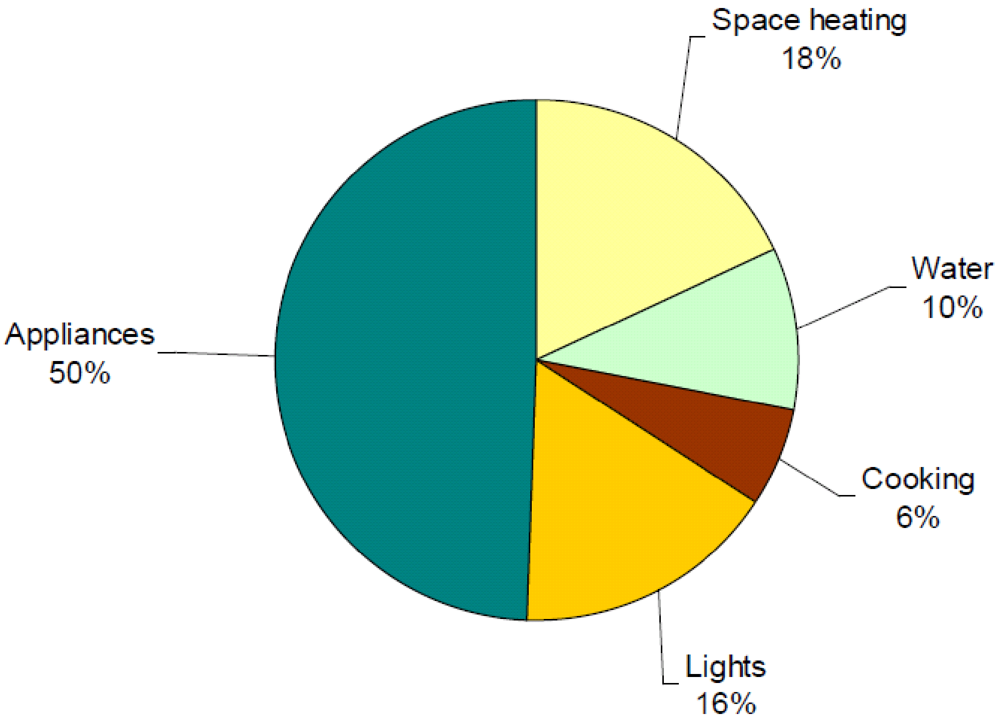


Figure 14. UK domestic electricity consumption in 2005.

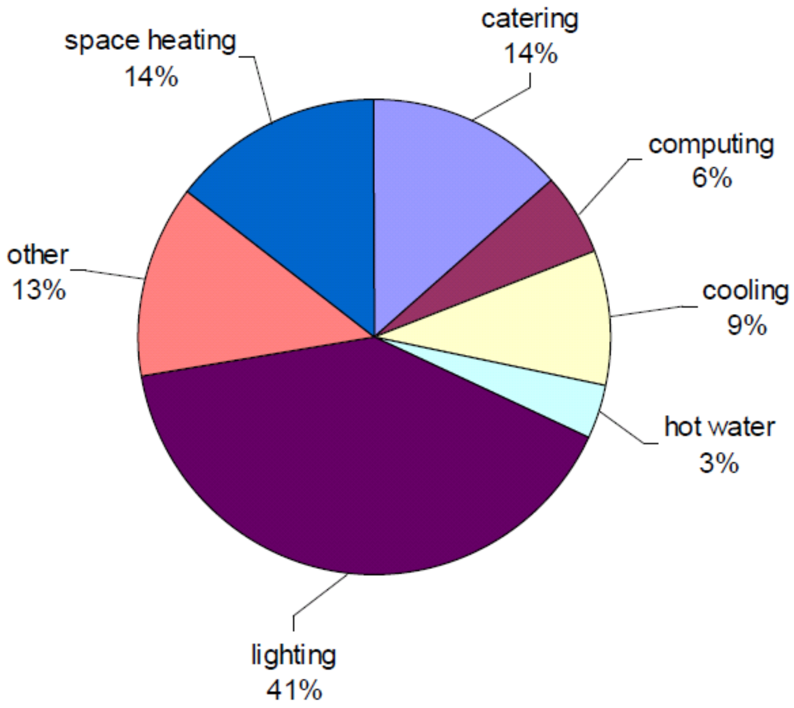


Figure 15. UK electricity consumption in non-domestic buildings in 2006.
Source: DECC. [153]

Although most of the fuels that generate it today are storable, electricity itself is not storable in bulk. Faults at one point on the system sometimes propagate. The grid's dependence on inter-regional transfers in the north-east USA and eastern Canada was identified as one factor behind the August 2003 blackout. [154] Besides electricity networks occasionally failing instantly, overhead wires are more vulnerable to accidental or deliberate damage than underground pipes or indeed wires. [155]

If electrification proceeds as the government plans, a challenge would be to keep stable a growing electricity supply system which meets high weather-sensitive loads and is supplied by variable sources. The government's goal is to "decarbonise" the system, so the goal is implicitly to be met without using fossil fuels in peaking CCGTs, OCGTs or steam turbines. [156]

Some renewable energy supporters suggest that a trans-European electrical grid would allow us to accommodate variable supplies more readily. East-west interconnections can certainly help despatchable electricity generating systems. With the time difference between groups of EU countries, their peak demand does not coincide with that of countries to the west or east, even if their daily load curves are identical, and usually the load curves are slightly different. Either way, capacity is in effect shared between countries.

Storage hydro in a country with surplus capacity can compensate for wind energy deficits in another. This comes at the cost of uprating the turbines and maybe reinforcing the grid, because the electricity would otherwise be used internally and not exchanged much with its neighbour.

But if adjacent countries generate their electricity from variable sources, excesses or deficits may coincide in time. The passage of a weather system over one country is correlated with its impact on adjacent countries; it often covers several countries at a time. [157] With an existing UK peak demand of 60 GW, the impact of one medium or large EU country aiming at near-100% wind electricity exceeds the ability of, say, 25 GW of Norwegian hydro to compensate for the peaks and troughs in wind output. Also Norway is unusual in having spare hydro capacity. Most European hydro is devoted to keeping the relevant country's grid stable.

Figure 16 shows the impact of windpower as modelled by Pöyry Ltd. for a hypothetical situation in winter 2030. The upper graph shows wind output in a one month period. As the lower graph shows, if all windpower is delivered into the electricity network, the residual electricity load over the 30 days ranges from 3 to 62 GW(e), a profile which appears only to be compatible with oil-, gas-fired or hydro plant. In summer, such wind output would be unusable as electricity.

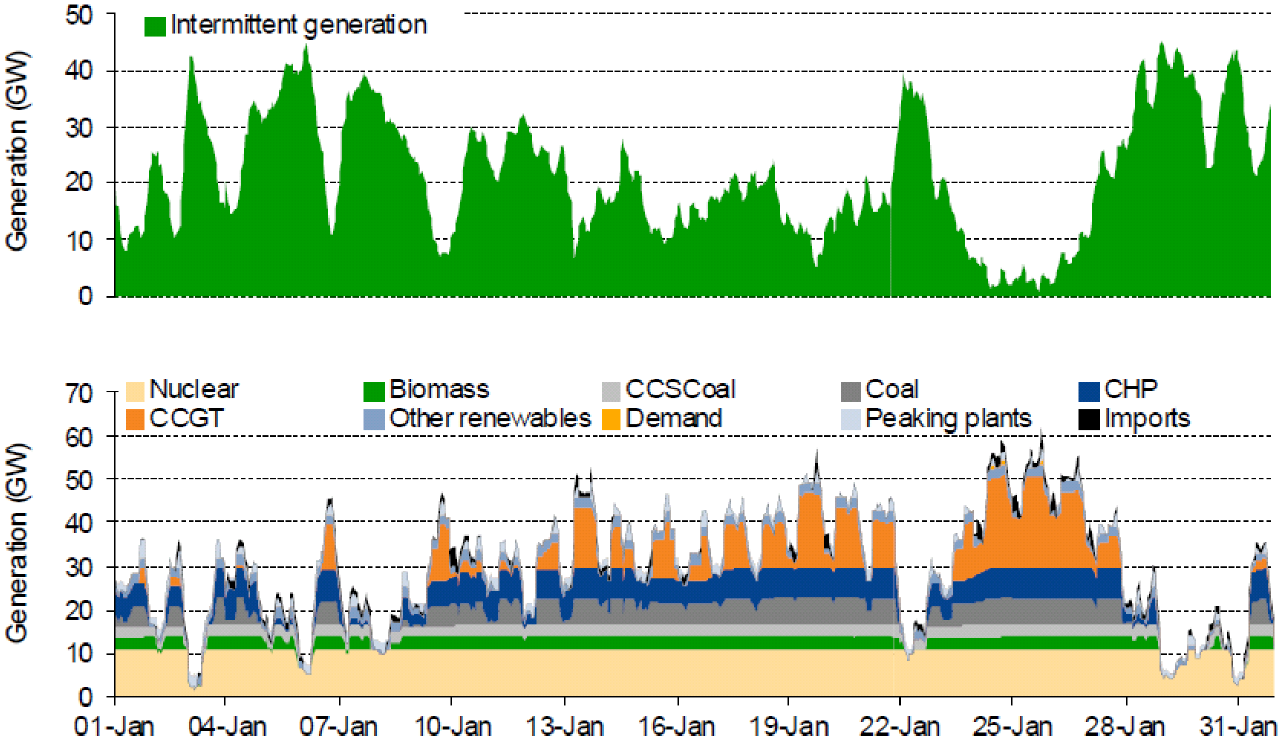


Figure 16. Predicted Residual Electricity Consumption in 2030 with 45 GW of Windpower. [158]
Source: Pöyry Ltd.

More relevant to today, Figure 17 shows a Swiss analysis of a theoretical wind turbine program spread around Great Britain and sized to provide 20% of electricity consumption in 2009. Cumulative wind output is compared to consumption. [159] The 20% wind contribution would have needed 3.8 TWh of electricity storage. The need for storage would grow at above 20% wind, and for analyses over a longer period, reflecting more mismatch between supply and consumption and wind energy fluctuations month to month and year to year. [160]

Can UK policy deliver a secure outcome? In its current form, which would deliver a growing proportion of energy as electricity, and depend on new methods to keep the system stable, we do not think so. The Institute for Integrated Economic Research (IIER) suggests that orthodox "sustainable energy investments" will not lead to workable end results. They are unconvincing and leave questions unanswered. [161]

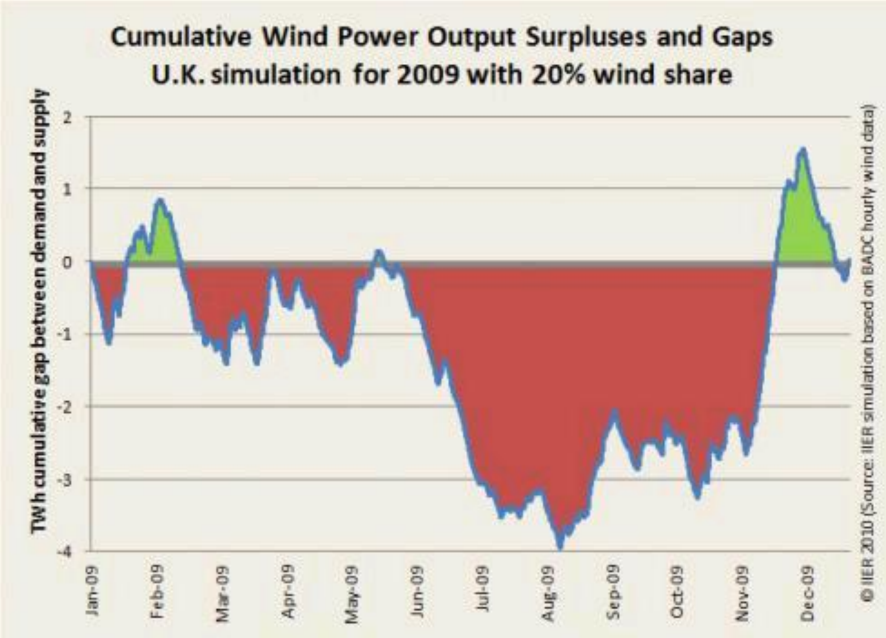


Figure 16. Correlation between UK Electricity Consumption and Month-by-Month Wind Energy Output, 2009. [162]

Source: International Institute for Integrated Economic Research, Switzerland.

Storing electricity or mechanical energy for a near-100% wind network, or even for 20% wind, would be too costly. The main storage option left is to produce electrolytic H_2 or CH_4. Chemical energy can be stored indefinitely, at low cost. CH_4 can be piped around in the gas network and burned in CCGTs, OCGTs or reciprocating engines to meet demand during wind energy deficits. [163] Or the CH_4 can be used for other purposes, like road transport. But the capital cost of a 100% wind system would be higher than that of a 15% wind system.

Ways Forward

The perceived need for large interconnections and/or a “smart grid” appears to be driven in large part by decisions and/or policies to provide a growing proportion of final energy as electricity and the need to keep the resulting network stable. The stability concerns are justified. [164] A cost-benefit analysis should be made of a modified policy of:

- Providing electricity only for essential uses; i.e. lighting, domestic appliances, office equipment, controls, etc
- Discouraging, not encouraging, electric heating.
- Providing most final demand in the form of storable energy vectors; i.e., heat and fuels.
- Accepting that year-to-year energy storage, albeit as renewable fuel, not fossil fuel, will play a major part in future security of supply.
- Using known technology; e.g., dimmable electronic ballasts, interruptible supplies to larger “cold” appliances and certain industries, to manage demand for essential electricity at times of shortages .

We should be comparing investment in interconnections or in developing a so-called “smart grid” to investing the same money in negawatts and/or in new generating plant which would produce firm renewable electricity supplies; e.g., hydro, geothermal, tidal, biofuel CHP. We should also cost investment in infrastructure for fuel and heat supply, to divert windpower which cannot be conveniently used by the electricity system but which could be stored long-term in bulk as other forms of energy.

By not electrifying heat and transport, the smaller network needed for “essential electricity”; i.e., some 12% of delivered energy, could be supplied by relatively high proportions of “despatchable” sources, whose availability is likely to be limited. This would help to provide essential electricity at an acceptable LOLP, post-fossil fuels.

We are concerned at the risk that adding space heating, a large weather-sensitive load, to the electricity system could cause cold weather peaks which would prejudice the security of supply of “essential electricity”. If we are to “keep the lights on”, which is a vital goal, it is unhelpful to confuse this with a separate, more debatable goal of moving towards an “all-electric economy”.

Therefore, our suggestion is to:

- Confine major strategic infrastructural investment primarily to heat mains
- Secondarily to synfuel production, for which most pipes and tanks already exist, only the plants are needed
- Avoid the electrification of heating and road transport.

In the context of falling electricity consumption, with energy efficiency improvements in lights, refrigerators, ICT, etc outpacing the addition of small new loads such as railways and trams, the case for large interconnections is unproven. We agree that a few 1-2 GW connections to the Netherlands or Belgium might be helpful and cost-effective and could help to meet the regular UK 17.30 h winter peak. But a smaller system for “essential electricity” would need fewer cross-Channel cables to keep the network stable, especially with consumption falling, and would differ radically in scale from a “smart or “super”-grid. We would term this markedly scaled-down ambition a “stable grid”.

Unless an application needs or strongly favours the use of electricity, which applied to some 12% of delivered energy in recent years, there should be a presumption in favour of supplying energy in the form of storable energy vectors; i.e., fuel or heat. Heat networks supported by hot water tanks and fuel tanks, and fuel supply systems supported by distributed storage tanks, are more resilient and do not fail instantly. Even if such networks are supplied by variable ambient energy sources, fuel or heat can be stored in sufficient quantities to provide a buffer between demand and supply.

To heat built-up areas, it appears less capital-intensive to move from piped gas to piped heat than to reinforced electric cables and heat pumps or resistance heating. In road transport, barring a breakthrough in battery system costs, it appears that it would be less capital-and materials-intensive to move to renewable fuels than to renewable electricity. The discussion of energy supplies below should be read in this light.

Heat Supply

Active Solar

Small active solar systems have difficulty in producing an acceptable rate of return to UK PLC; i.e. *Green Book* rates or above. If a small system on a gas-heated urban building costs £3,000 and supplies 60% of a DHW load of only 210 W or 1,800 kWh/yr; i.e., the residual load after high tank and pipe insulation, it takes 75 years to repay the capital cost. If it supplies 50%, it takes 90 years. If the cost drops to £2,000 in a larger market, and it provides 60% of DHW, it takes 50 years. The prospective life of a good solar system is closer to 30 years than 50 or 90 years.

This calculation assumes a marginal boiler efficiency of 95% and average household occupancy. It omits solar maintenance costs and electricity usage by the solar pump. The result partly reflects an assumption that the building has already implemented more cost-effective measures; e.g., added tank and pipe insulation and heat traps near the tank. Adding these measures reduces the DHW load, so that a given size of solar system supplies less heat.

As Appendix 5 explains for the industrial sector, energy efficiency measures that pay back in less than one year are widely blocked by businesses’ lack of investment capital. Subsidising measures with 50-90 year payback times, and 1-2%/yr real returns on capital, but failing to support measures in industry with a 100%/yr return, amounts to a striking policy distortion.

Active solar on single buildings has better economics versus fuels such as oil and LPG and it may become a more reasonable investment if the system size is increased so that it provides some of the space heating needed in late autumn and spring. Low-density buildings have fewer choices of low-CO_2 heat, too, and experience elsewhere in Europe shows that such solar systems would cost less in larger-scale production and use than they do in the UK. But such cost reductions only raise the return on rooftop solar to 1.5-3%/yr with natural gas - below the usual public sector cost of capital - or a more attractive 3-5%/yr with oil or LPG.

Table 5 shows the cost now in Denmark of a rooftop solar system large enough to provide a substantial part of the space and water heating to a detached house, along with its estimated future cost in larger-scale production.

System Details	**Cost**
Marginal cost	£
2010, fitted when no other work is undertaken; e.g., roof or heating system replacement.	5.000
2010, fitted when existing boiler is replaced or a house is changed from electric to water-borne heating.	3,900
2020-2030, estimated in larger-scale production.	2,800

Table 5. Cost of small rooftop solar systems, Denmark. [165]

NOTES:

1. System comprises 10 m^2 of high efficiency flat-plate collectors plus 0.5 m^3 of water storage.
2. Heat yield is 5,000 kWh/yr towards the space and water heating loads in a house of moderate to high heat demand, closer to 3,500 kWh/yr in a house of lower heat demand.
3. Operation and maintenance costs are 1%/yr of system capital cost.
4. An estimate would be desirable of the marginal cost of solar at a time when the roof is being replaced, but none was available.

If we wish to encourage economic use of direct solar energy, we should be prioritising technologies for which good economic cases can be made, such as:

- Passive solar heat in new construction, or in total refurbishments where one facade has a good solar exposure
- Larger-scale solar collector arrays for DH, which are about ten times more economic than small ones [166] [167] [168]
- Daylighting, especially in non-domestic buildings. Solar light displacing electricity is a higher value use of solar radiation than solar heat displacing oil or natural gas boilers, heat pumps or CHP systems.
- Small-scale solar where DH is not an option and the fuel displaced is LPG, oil or similar.

The UK lacks the means to distribute heat and exploit large-scale solar, suggesting a strategic need to invest in heat networks so that it can. Table 6 shows Danish estimates of the cost of the heat from medium and large solar arrays. Given a network to deliver heat to consumers, large solar arrays break even in Denmark today versus the ex-tax price of fossil fuel. This is not a claim that many renewables can make.

Size of Solar Collector Array		**Annual Heat Production**	**Cost of Heat**
m^2	MW	kWh	p/kWh, FOB
500	0.35	250,000	7.3
1.000	0.7	500,000	6.2
5,000	3.5	2,500,000	3.8
10,000	7	5,000,000	2.8
20,000	14	10,000,000	1.6

Table 6. Solar heat cost versus system size. [169]

NOTES:

1. Assumes that 1 m^2 is rated at 700 W and produces 500 kWh/yr at suitable temperatures for DH.
2. At UK PLC interest rates, heat costs might be somewhat lower.

Figures 15 and 16 show aerial and ground-based views of the 18,000 m^2 solar thermal array in Marstal, Denmark. It was built in 1996 and extended in 2002-03. Another 15,000 m^2 of collectors may soon be added.

Figure 15. Solar collectors of the Marstal DH system.

Figure 16. Sheep grazing between the solar collectors. [170]
Source: Marstal Fjernwärme AMBA.

Higher-temperature solar systems of the CSP type could have a UK role. In the “sunbelt”, industrial-scale systems now give 15-35%/yr returns on investment, where the fuel saved is oil. [171] CSP heat usually gives a higher return than CSP electricity, given the rather low efficiency of turbines fed by low-pressure steam. [172] Solar steam is now being used in sunny climates for enhanced oil recovery, suggesting that it may cost less than steam from oil-fired heat-only boilers. [173]

The energy yield from such systems is broadly in proportion to direct normal radiation, so the yield is destined to be three to four times lower in the UK than in the sub-tropics. But even if the return drops four-fold to 4-9%/yr, it is higher than on small roof-mounted solar thermal systems. The energy is higher-quality too. It could be more economic to turn such solar facilities into CHP plants and generate low-pressure industrial steam or pressurised hot water *and* electricity.

Geothermal

In terms of GW mean output, UK geothermal heat potential exceeds that for electricity. In the aquifer regions marked on Figure 17, 75ºC hot water could be available at 2 km depth.

Until recently, Southampton was the only UK well in use, with a mean output of 700 kW(t). A borehole has now been drilled in central Newcastle-upon-Tyne, which is outside the previously-recognised aquifer boundaries. Hot water at 80º C was found at 2 km depth. Three larger wells are in use in Danish towns or cities with similar geology to the Southampton basin. [174]

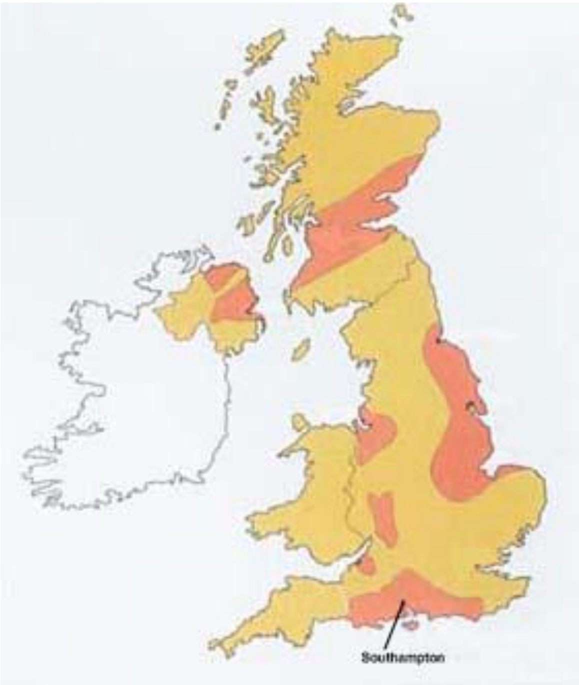


Figure 17. UK geothermal aquifers.

There are also deep geothermal resources, located in areas of higher temperature gradients and not usually associated with aquifers. They are not shown in Figure 17 but are discussed later below when dealing with electricity generation. The hotter water can be used in CHP or electricity-only plant.

30 years have elapsed since Southampton developed its heat network, but the UK still has no geothermal licensing system. Without this basic framework, it is very hard to see how this valuable resource can be fully developed.

Wind

There is scope for using spilled wind power to drive large heat pumps, using “custom” heat sources such as lakes, rivers, the sea and sewers, allied to large-scale heat storage on DH systems. Efficiencies can be higher for such large machines than for machines on the scale of a single house, due to scale effects.

These machines can be professionally-designed, -installed and -maintained, sidestepping the disappointing experience so far with small electric heat pumps and economising on scarce technical skills. Like any other factor of production, these will always be constrained to some extent. The challenge is for the UK to make best use of a scarce resource.

Significantly, heat stores need a low surface-to-volume ratio if they are to buffer the supply of intermittent renewables over a long timescale and assist with security of supply. This implies large insulated stores, logically linked to heat networks. Small insulated heat stores in buildings, linked to electricity networks, can stay warm for many hours, but they cannot give long enough cooling time constants to store energy over days, weeks, months or years. See the cooling curves in Appendix 2.

Diversion of surplus wind energy into large heat stores on heat networks is expected to become a means to help to stabilise Denmark’s electric grid as the windpower fraction rises from today’s 20%. The energy is no longer lost or sold to Norway at a low price; it is now stored and delivered later to heat consumers. The strategy needs investment in a heat distribution network, in countries which do not yet have one, but in return it avoids many costs otherwise incurred by heating electrically.

Fuel Supply

Biomass

In 2006, the European Environment Agency estimated the EU-27’s sustainable biofuel potential in 2030 to be up to 15% of EU energy consumption. [175] This equates to 400-460 GW or 3,500-4,000 TWh/year. This appears to be a large and useful component of future energy needs. If energy efficiency is deployed widely-enough to reduce total consumption, the percentage provided by biomass could exceed 15%, greatly assisting with security of supply and system stability.

Until recently, all biofuels have been treated as zero-CO_2 except for the fossil fuel used in harvesting, transporting and processing. Consistent with the balance sheet approach, outlined in Chapter 1, there is now a good case for accounting separately in a country's national GHG for:

- The CO_2 emitted by fuel combustion, ploughing arable land, etc.
  minus
- The CO_2 sequestered by growing biomass.
- Occasionally, other emissions avoided by producing fuel rather than leaving waste material to decay.

This approach signals more precisely the impact of using a particular fuel or sequestration method. [176] We wish to reach a situation of net sequestration.

Combustion and sequestration associated with bio-energy are always at best loosely-correlated. Burning a fuel in one location does not guarantee that equal amounts of GHGs are sequestered somewhere else. The degree of sequestration needed may not occur, or it may occur after the combustion, with the GHG emissions contributing to climate change for years while they are in the atmosphere and before they are removed again. [177]

Although biofuels are in theory sustainable, they should not be regarded as necessarily superior to fossil fuels in their impact, unless their use increases the ability of the biosphere to capture and sequester C, or reduce CH_4 or other GHG emissions. It only does so in a minority of cases. We suggest that direct emissions from biofuel and fossil fuel combustion be counted on the same basis. The biofuel would be a superior alternative where it can be shown that:

- Biospheric respiration leading to equivalent GHG emissions would have taken place on the same timescale as the combustion
  and
- There is no other practicable way to avoid such biospheric respiration.

With the need to offset the combustion emissions of biofuels by sequestration measures, their CO_2 balance is less good than formerly thought and assumed by many governments. Even if the EU-27 is able to produce up to 400 GW of biofuels "sustainably", some would be lower-CO_2 than others. For every tonne of CO_2 emitted in the combustion of some fuels, one would have to sequester over a tonne of CO_2 before the fuel could be considered "CO_2-negative".

An example of a favourable balance may be anaerobic digestion to convert garden, kitchen and restaurant waste, sewage, livestock manure and crop residues into clean fuel, fertiliser and soil conditioner. The fertiliser value of the digestate reduces fossil fuel usage to produce nitrogen fertiliser. The wastes emit less CH_4 and CO_2 to atmosphere. Energy use to manufacture herbicides falls, because digestion reduces the viability of any weed seeds contained in animal manure. [178] It seems to have fairly good public acceptance. [179]

But with the scale economies of any chemical engineering operation, large town-sized digesters look more advantageous to the UK than farm-sized ones. They benefit from:

- A lower output cost, allowing for extra transport energy of the feedstock. The digester soil conditioner output weighs less than the manure input, partly offsetting the transport energy of the raw materials.
- Higher waste to gas conversion efficiency, even after the smaller digesters are insulated to an economic level. Underinsulated ones can use over 10% of the gas output for heating.
- Higher CHP plant efficiency, if the gas is used this way.
- Proximity to pipes which could convey purified gas from digesters to larger, more efficient CHP plants [180] or to long-term gas storage to help stabilise the UK energy system.
- Proximity to large heat loads - more likely next to a town than on a farm.
  and/or
- The possibility of connecting large sites by pipeline to CCS facilities to bury the CO_2 separated from the CH_4 - or more likely, to synfuel plants to turn it into a low-emissions fuel.

CH_4 and similar biofuels may be more useful parts of the UK energy mix than C-rich solid biofuels, thanks to:

- The lower GHG (CO_2, NO_x, soot et al) emissions from burning gaseous fuels.
- The higher efficiency in use, including scope for condensing operation.
- The lower particle emissions of gas-fired combustion plants.
- The potential for pre-combustion CCS on digesters’ CO_2 output.
- The CO_2 emissions avoided by using the digestate in agriculture as a fertiliser and soil conditioner and producing less artificial fertiliser.
- The public health benefits of the lower PM-2.5 emissions.

Other biofuels with fairly low CO_2 emissions in their combustion include:

- DME, a possible replacement for LPG which can be produced from wood during paper-making.
- Ethanol, which is usable in diesel engines if a fuel improver is added.
- Methanol.
- Butanol, which is producible by fermentation, like ethanol.

If produced from low-temperature processes, with the residue composted or even digested, they offer potentially low- or zero-CO_2 fuels. But the synthesis of fuels other than methane tends to involve lower efficiency.

If biomass pyrolysis or gasification, plus Fischer-Tropsch conversion, ever makes sense, from a net GHG emissions viewpoint, it may be more useful as a route to fuels which cannot easily be made by other means; e.g., kerosene for aircraft. Such synfuel plants are around three times more capital-intensive than oil refineries, in £ per average kW. [181] It could be possible to produce biochar from the feedstock, so that all the H_2 goes into the hydrocarbon fuel output but some elemental C emerges in a suitable form for long-term sequestration. There are many permutations of fuel synthesis.

The fact that biomass sequesters CO_2 if it is grown and harvested, but not burned [182] is a key part of a UK climate change mitigation strategy. No other potential renewable energy source offers the easy possibility of a CO_2-negative outcome. The most useful role of biomass in a climate change strategy may be not to maximise bio-energy production but to optimise CO_2 capture and sequestration, producing modest amounts of clean low-CO_2 fuels to complement other renewable sources; i,e., with gaseous or liquid fuels given preference over solids, other factors being equal.

This point is rarely absorbed by biofuel advocates. They may cite a “sustainable” coppiced woodland as evidence that wood fuel is “CO_2-neutral”, implying that this is the best possible outcome. But a managed hardwood forest becomes “CO_2-negative” if it produces construction or joinery timber which are sequestered for centuries. One could also turn medium and small offcuts into floorboards and worktops respectively and turn the shavings and sawdust into insulation boards, or co-digest the fine material into CH_4, fertiliser and soil conditioner. Even if the lower-grade wood is to be used for energy, turning it into heat in small appliances, as per UK policy, is one of the least effective ways to reduce GHG emissions, given the low efficiency of the appliance and the GHG impacts of the soot, CH_4 and NO_x in the exhaust gases. [183]

As Chapter 2 showed, biosequestration should be able to outweigh modest residual emissions from bio and fossil fuels. In developing a climate change mitigation strategy, we need to do full annual GHG flows for decades into the future, both sources and sinks, rather as most organisations do cash flow forecasts. These net GHG flows must slowly become negative. Unless these forecasts account fully for all the impacts of bio-energy, perverse outcomes are likely.

The scenario which this report outlines would need CO_2 sequestration rates to rise and eventually exceed the gross CO_2 emissions from all C-based fuels used in the energy supply system, giving negative net GHG emissions by 2050, ideally earlier. Measures could comprise a mixture of bio- and geosequestration, perhaps mainly the former.

Wind

Wind can make a very useful contribution to most existing electricity supply systems as a fuel saver. But above about 15% of electrical energy, as we noted, controllability becomes a problem. One obvious option is to store spilled energy as fuel or heat, avoiding such problems. This implies a need for more coordination between fuel, heat and electricity supply in the future.

If storing appreciable amounts of energy as fuel is necessary, to give long-term security of supply, it is unclear why one would always reconvert the fuel to electricity. For road transport, fuel would usually be the preferred energy vector. See discussion of battery electric-vehicles (BEVs) in Appendix 4. Also, if fuel is being stored, thermal power stations would remain in use.

Overall, we need much more effort to produce convenient synthetic fuels. There may be breakthroughs in fields such as the direct photolysis of water. But for the time being, one would have to rely on processes such as electrolysis of water, using intermittent renewable electricity, and synthesis of such fuels as methanol, DME or CH_4.

An Icelandic company is producing methanol from electrolytic H_2 and CO_2 given off by the country's many geothermal vents. [184] Its pilot plant began operation in 2007. A small commercial plant producing fuel at a rate of roughly 3.5 MW or 30 GWh/yr opened in early 2011. The methanol is blended with petrol and sold at filling stations. The plant costs £1,500/average kW. [185] Larger ones would cost much less, as per normal chemical engineering rules.

A German car company shortly starts to synthesise CH_4 from surplus wind electricity, combining electrolytic H_2 with CO_2 from anaerobic digesters. The project is co-funded by partners from other German states. [186] The efficiency of converting H_2 to CH_4 via the Sabatier process is about 82%. Some waste heat is available for DH.

It remains to be determined which fuel is more advantageous - probably CH_4 for most applications - but fuel synthesis is broadly equivalent to Danish plans to use spilled windpower in its heat networks, via large heat pumps and hot water stores of 10,000 m^3 or more. Such approaches convert unwanted wind electricity to forms of energy which are more easily stored and represent the types of energy that industrial countries need in bulk; i.e., heat and fuel. They may also avoid expenditure on new electricity transmission lines.

Essential Electricity Supply

Tidal

The UK has one of the world's best tidal resources. Experts have put the potential output from lagoons, barrages, other enclosures and tidal streams - the last are the least well-developed technology - at up to 27 GW or 240 TWh/yr. [187] Deducting 7.5% T&D losses, this could deliver 25 GW or 220 TWh/yr of electricity to final users.

The exploitable resource from established technology could be below 25 GW. The potential of barriers on the seven main estuaries is "only" 6.2 GW or 54 TWh/yr. [188] [189] But if energy efficiency is implemented *en masse*, this potential tidal output appears to be on a par with domestic sector electricity consumption.

It is surprising that the government decided that Severn tidal was a less appropriate technology than wind or nuclear. [190] With life-cycle costing, it appears more cost-effective to the UK than nuclear or offshore wind. [191] [192]

If lagoons are located in relatively shallow water, they reduce civil engineering costs compared to damming an estuary and potentially reduce the environmental impact. Barrages or lagoons can if necessary be configured to load-follow or to provide pumped storage, making them more useful to a future electricity system than technologies that need support from fuel-fired plants, batteries or mechanical energy storage.

Hydro

Today's UK hydro output is 0.7 GW average or 6 TWh/yr. The bulk of the capacity was built 50-60 years ago by the North of Scotland Hydroelectric Board (NSHEB). Its unusual remit was to act commercially *and* deliver social benefits to the population by utilising the natural resources of the Highlands. The Scottish government's 2008 study [193] is in line with a NSHEB study 30 years earlier which found that hydro in the Highlands could be expanded to around 3.1 GW installed or 10.5 TWh/yr. [194] Not all of this capacity is environmentally-acceptable today. On the other hand, the NSHEB excluded schemes below a threshold of 14 MW(e).

About 50% of the UK's theoretical potential is in central and northern Scotland. [195] The rest is located in the Southern Uplands, the hilly countryside of northern England, Wales, the Marches and south-west England and on some large rivers in lowland England; e.g., the Thames and Trent.

A recent Environment Agency (EA) study gives a small hydro potential of 1.2 GW(e) in England and Wales, generating 0.5 GW or 3.7 TWh/yr electricity at existing weirs, with an average project size of 45 kW(e). [196] [197] About half is said to be at sites where hydro schemes could enable funding of fish ladders and litter filters, yielding net environmental benefits. The rest is more controversial and/or expensive, although 50% or more may be attainable. However, the EA excludes all high-head sites, which are more able to provide despatchable power, and it excludes low-head sites where civil works were removed in the past.

Other European countries exploit a larger percentage of their hydro potential than the UK and often generate power from very low-head schemes. [198] [199] Figure 18 shows a run-of-river power station on the River Neckar. Even the rather flat Netherlands generates 3.8 times more electricity from falling water than from solar PV. [200]

UK output could certainly be increased, [201] but the last 25 years' studies have used disparate assumptions. To our knowledge, no work has ever costed the resource comprehensively, from a UK PLC viewpoint. The only body to have had a comprehensive remit was the NSHEB, from 1944 to 1990, and its work was confined to the Scottish Highlands. The most consistent observation is that the assessed potential has slowly increased and that overseas progress with hydro has enhanced the prospects for low-head schemes. [202] [203]

Figure 18. Hydroelectric power plant on the River Neckar at Kiebingen, Germany. [204]
Courtesy: Energie Baden-Württemburg AG.

Returns on refurbished water mills can be quite high if the original civil works remain. Public support is good too compared to onshore wind. Perhaps total UK output might be able to reach a mean 1.7 GW, or 15 TWh/yr, by 2050, with 2.3 GW or 20 TWh/yr being an optimistic estimate. This is very little of today's consumption, but it could be 20-25% of a reduced domestic sector load, if energy efficiency is implemented and heating and road transport are not electrified.

Typical generation costs appear to be 6-12 p/kWh sent out at UK PLC interest rates, plus use of system costs and T&D losses. 9 p/kWh sent out is half as much as solar PV, though, assuming a low £3/W(p) installed PV system cost. Also the hydro output is more stable.

Storage hydro's most useful role is probably to load-follow and to provide system capacity rather than energy. The energy output varies from year to year, anyway, due to rainfall variations. It basically offers a means to help stabilise a grid which receives inputs from variable sources. The output of run-of-river plants is less useful than that from dams, but easier to accommodate than wind or PV.

The EROEI of hydro schemes can be very high, reflecting the fact that falling water is concentrated solar energy. [205] [206] In the past, tapping the local river for power was almost always favoured over going to the effort and cost of constructing a windmill.

Administrative barriers discourage marginal schemes going ahead, even if they would be profitable to the UK. The “red tape” in developing a small scheme is formidable. FIT also encourages site owners to use hydro on site for low-value purposes; e.g., resistance heating. The buyback price, in p/kWh, is lower than the price of domestic heating oil or LPG.

Take for instance a dam with a mean annual output of 8 kW, equating to say 90 ltr/s falling through 10 m. It could be used for two different purposes:

- To heat *15* extremely well-insulated dwellings, of near-Passivhaus level, assuming heat consumption of 4,700 kWh/yr.dwelling or 0.55 kW average
- To light *900* dwellings fitted with extremely energy-efficient lighting, assuming electricity consumption of 125 kWh/year. [207]

So, a hydro plant which can heat at most 15-20 small buildings could light all the dwellings in a small town, using state-of-the-art lamps and luminaires. There is major value to the UK in using other energy vectors for space and water heating and keeping a controllable supply of electricity for essential purposes, including literally “keeping the lights on”.

Geothermal CHP

The UK has some geothermal electricity potential, probably in association with CHP plant. Two plants are planned in Cornwall by 2012-13. The Redruth site would produce up to 55 MW(t) to heat buildings, although the resource would be used more effectively if the system operated at low flow and return temperatures; e.g., 60-80ºC flow and 15-30°C return. It would then have a higher electricity/heat ratio, reduced pumping costs within the well and a higher overall useful energy output.

The other regions of most interest seem to be parts of Devon, Derbyshire, Cumbria and north-east Scotland. Such sites could generate both heat and electricity, if there are built-up areas nearby to use the reject heat. Using output heat at near 200°C, such generating plants should be able to produce around 18% electricity, 75% hot water at 75°C for DH, the rest being lost.

DECC estimates that deep geothermal could generate 1-5 GW(e) from 2030 onwards, [208] implying up to 4 GW or 30-40 TWh/yr delivered electricity and 11-17 GW or 100-150 TWh/yr hot water. 3.4 GW or 30 TWh/yr is 50% of the potential domestic sector demand if electricity is used much more efficiently.

The usual financial incentives to private companies favour generating base load electricity, but geothermal could be more useful as peak or mid-merit order plant. Like tidal double lagoons, storage hydro and biofuel CHP, it can follow load, making it an asset in operating a grid which also receives irregular electricity inputs. The thermal reservoir is always full and the plant can operate flexibly, akin to plants running on stored fuel.

Bio-Methane CHP

The EU-27 potential for biomethane from existing manure streams, sewage, crop wastes, other waste streams, household and trade waste and energy crops on a nominal 1% of its land area has been put at 70 GW, or 600 TWh/yr of gas, or 1,200 kWh/yr.cap. [209] National Grid PLC estimates that at a “stretch” UK “bio-gas” production might be 18,432 Mm^3/yr by 2020 although its central estimate is one-third of this. [210] Part of this quoted figure is producer gas, however, not pipeline-quality methane. Some of the wetter woody biomass assumed by NG to be gasified might be more advantageously digested. This reflects the higher thermal efficiency of today’s technology, [211] the better GHG balance and the yield of premium fuel.

Germany, with 80 M people, produced 4 GW or 34 TWh/yr biomethane in recent years; i.e., a third of the way towards a 1,200 kW/yr.cap output. [212] Its targets are 6.9 GW or 60 TWh/yr in 2020 and 11.4 GW or 100 TWh/yr in 2030. [213] E.ON suggests that £12.5 billion of investment is needed to increase gas production to the 2030 level. [214] Figure 19 shows a German digester supplying purified methane into the gas grid.

Figure 19. A 7 MW anaerobic digester at Güterglück, Germany. [215]
Courtesy: RWE.

Royal Dutch Shell is about to build a floating offshore LNG production platform with a seemingly similar specific cost to these digesters, albeit 3,000 times larger. An £8.4 billion investment will produce 3.6 million tonnes/yr of LNG, 1.3 M tonnes/yr of condensate and 0.4 M tonnes/yr of LPG. This equates to £1,200 per average kW. [216] So with biomethane from wastes, perhaps the capital costs of renewable energy and fossil fuels are at last converging.

Denmark has accumulated more experience than any country with large digesters and is *en route* towards its estimated potential of 1.2 GW or 11 TWh/yr. Costs cited are £6M for a digester with an output of 5.8 MW, or £3.5M for a smaller 3.75 MW digester; i.e., around £1,000/average kW. [217] [218] This is lower than offshore wind and close to the offshore oil well cost cited in Chapter 3. But for non-waste feedstocks, which do not arrive free of charge or pay a fee to be disposed of, the cost of growing the crop must be added.

The Danish authorities report CH_4 leakage from digesters.[219] Spark-ignition engines sometimes used for gas CHP instead of dual fuel engines can emit unburned CH_4 in the exhaust. Because CH_4 is a strong GHG, these issues must be resolved. On the other hand, digesting waste materials reduces CH_4 and CO_2 emissions to atmosphere, so the net impact may still be favourable and it is possible that anaerobic digesters fed by wastes could abate CO_2 emissions at negative cost. If so, this would be unusually favourable for a renewable energy system.

Wind

The potential for wind electricity is well-known. It is less-realised that, with aggressive implementation of energy efficiency, a small inland English county might in theory obtain 20% of its electricity from ten large wind turbines. [220] While large individual wind turbines are very noticeable, ten in a county could perhaps be tolerated. The “capacity density”, in MW(e) per km^2, would be 75% less than Denmark had accommodated by the mid-2000s. [221]

As we have noted, wind would always be a very variable energy input to the UK. Beyond a contribution of 15-20% of electricity on the current system, it seems clear that one needs to store and/or spill windpower. Utilising most wind, especially the peaks, to supply energy to final users as storable fuel and heat, not to supply electricity, would help to sidestep these potential problems.

5. Building a New Energy Policy

> "I do not see the government's task as being to try to plan the future shape of energy production and consumption". Nigel Lawson, Secretary of State for Energy, announcing the privatisation and liberalisation of UK energy markets in 1982. [222]

Leading Question

In 1981, the House of Commons Select Committee on Energy said:

> "It remains quite extraordinary that the government still has no idea whether investing £1,300 M in a single nuclear plant is as cost-effective as spending a similar sum to promote energy [efficiency]". [223]
> *and*
> "... It is our considered opinion that there are many [energy] conservation measures which are so much more cost-effective than most energy supply investment that the caveats expressed by the Dept. of Energy appear mere quibbles". [224]

Governments have continued to sidestep this basic point ever since. In 2010-2011, opposite answers were received on whether a comprehensive study of energy efficiency costs versus energy supply costs has been made. Apparently none has been made. [225] Meanwhile, a recent Ministerial statement used these words:

> 'Energy efficiency is the most important and the best value for money consideration in terms of saving carbon.' [226]

This confused situation sums up the central problems with UK energy policy. They are:

- The low and falling priority given to energy efficiency in practice compared to theory. [227] [228]
  and
- Its poor integration with other aspects of policy.

Concern has been expressed over risks of electricity supply interruptions in 2015-20, owing to the forced closure of old nuclear, coal and oil generating plants. The nuclear ones are at the end of their design lives; the coal and oil ones cannot meet emissions standards. Rather as

Parliament put the above points to the government in 1981, we might raise other points today over the UK's ability to meet peak demand; i.e., to "keep the lights on":

- The UK is not systematically investing in the more efficient use of electricity. But it is building 14 GW of new gas-fired power stations. [229]
- None of these plants' waste heat is set to be used to heat the UK's urban buildings and displace natural gas and electric heating. [230]
- The government is subsidising electric heating, which raises peak demand. [231]
- The UK envisages a doubling or tripling of electricity consumption by 2050. Germany plans on a decline. It is surprising to see two EU member states of similar climate and population density adopt such opposing policies. [232]

Current Policy

Several different UK programs reward investment in "green energy". Table 7 lists the estimated cost of the external support, in £ per tonne CO_2 emissions avoided.

Most of the support is for energy efficiency or renewable energy. The battery-electric vehicle (BEV) subsidy and related concession on vehicle excise duty and energy taxes is a payment to switch from an oil/biofuel mix to electricity. The heat pump subsidy is mostly a payment to change from oil or natural gas to electricity.

We have completed the table to the best of our ability. The matter is complex, due to the existence of overlapping programs. In cases where we could not work out total support, it is labelled as unclear.

The estimates are of what the UK pays or plans to pay to reduce CO_2 emissions by one tonne. They are not necessarily the same as the cost of a technology in £/tonne to the UK at the discount rates in the *Green Book*.

Technology			**Technology Displaced**	**Support Program**	**Proposed / Actual Level of Support**	
					p/kWh heat or £ of grant	£/tonne CO_2 saved
Energy Supply, Including CHP						
Heat Generation						
Heat-only boilers	Wood	≤45 kW(t)	Oil cond. boiler	RHI	£950	∞
		45-500 kW(t)	Oil cond. boiler	RHI	6.5	∞
	Biomethane	≤45 kW(t)	Natural gas cond. boiler	RHI	5.5	Unclear
		45-200 kW(t)	Natural gas	RHI	5.5	Unclear
	Bioliquids	≤45 kW(t)	Oil	RHI	6.5	∞
		45-200 kW(t)	Oil	RHI	0.0	∞
	Bio-DME	All sizes	LPG	RHI	0.0	0
Electric heat pumps	Ground source	≤45 kW(t)	Oil	RHI	£1,250	660
		45-350 kW(t)	Oil	RHI	5.5	520
		>350 kW(t)	Natural gas	RHI	1.5	390
	Air source	≤45 kW(t)	LPG	RHI	£850	181
		≤45 kW(t)	Oil	RHI	£850	86
		45-350 kW(t)	Natural gas	RHI	2.0	8,700
Solar thermal, active		≤20 kW	Oil	RHI	18.0	600
		20-100 kW	Natural gas	RHI	17.0	780
		10 MW = 20,000 m^2	Natural gas	RHI	Unclear	Unclear
Passive solar					0.00	0
Electricity Generation						
Hydro		≤15 kW(e)	Existing generation mix	FIT	19.9	340
		15-100 kW(e)		FIT	17.8	300
		100-2,000 kW(e)		FIT	11.0	190
		≥2,000 kW(e)		FIT	4.5	80

Solar PV		≤4 kW(e), avge. of new and retrofit			FIT	35.4	670
		4-10 kW(e)			FIT	33	560
		10-100 kW(e)			FIT	28.7	490
		100-5,000 kW(e)			FIT	26.8	450
Wind		≤1.5 kW(e)			FIT	32.6	550
		1.5-15 kW(e)			FIT	25.5	430
		15-100 kW(e)			FIT	24.1	410
		100-500 kW(e)			FIT	18.8	320
		500-1,500 kW(e)			FIT	9.4	160
		1,500-5,000 kW(e)			FIT	4.5	80
Electricity-only plant		Biomethane			FIT	10	Unclear
CHP	District- or town-wide	Natural gas, recip. engine or CCGT			FIT	0	0
		Biomethane	≤500 kW(e)		FIT	11.5	Unclear
			>500 kW(e)		FIT	10	Unclear
		Wood			FIT	Unclear	Unclear
	Micro	Natural gas			FIT	10	∞
		LPG			FIT	10	∞
Energy Efficiency							
More Efficient Use of Heat							
Retrofit thermal improvements.	Pitched roofs	Add external insulation and air barrier during re-roofing				0.0	0
		Rafter level insulation; i.e., inside existing tiles				0.0	0
		Top-up loft insulation on attic floor				50%	22
	Solid external walls	EWI				0.0	0
		Internal insulation				0.0	0
	Cavity external walls	Non-airtight material; e.g., mineral fibre, EPS beads				50%	9
		Airtight materials; e.g. PU foam				0.00	0
	Flat roofs	Inverted roofs				0.00	0

		Warm roofs			0.00	0
	Suspended timber ground floors	Versions with internal, external and intermediate air barriers			0.00	0
	Solid concrete ground floors	External perimeter insulation			0.00	0
Glazing	Existing window frames in good condition and airtight	Replace failing sealed units by warm edge, argon-filled, low-e units			0.00	0
		Optimise new low-e coatings for orientation			0.00	0
	Existing windows in Conservation Areas and in listed buildings	Fit extra window internally to give 1+1 or 2+1 glazing			0.00	0
	Replacement windows	Marginal cost of higher-specification, lower U-value new windows			0.00	0
Draughtproofing work on services entries, etc					0.00	0
Improve new buildings to above Part L / F					0.00	0
More Efficient Electricity Use						
Domestic electrical appliances		A++ models, etc			0.00	0
Office electrical equipment		Ditto			0.00	0
Battery-electric vehicles					£/vehicle	
					5,000	370 to ∞

Table 7. UK support for “low-carbon” energy efficiency and energy supply technologies.

NOTES:

1. The cost in £/tonne is the proposed level of outside support divided by the CO_2 saving. It is not the resource cost of the measure to the UK.
2. To calculate the cost in £/tonne saved, we assume the same COPs as achieved in Switzerland; i.e, 3.3 for ground source heat pumps (GSHPs) and 2.75 for ASHPs. [233] We assume that the low COPs measured by EST are not repeated. [234] The UK notional limit of 2.9 for heat pumps looks less than the potential of well-installed small GSHPs but too high for small ASHPs. We have not allowed for the higher electricity emissions from the national grid in winter.

3. Proposed funding for ASHPs has changed radically since this table was first drafted in 2010. The above entry assumes that the £850 up-front subsidy is amortised over a ten year life at *Green Book* rates, in a dwelling with a heat load of 15,000 kWh/yr.
4. The level of biomethane support is unclear. Net GHG emissions differ between gas from wastes and gas from crops.
5. The technology replaced is assumed to be either a natural gas or oil condensing boiler, according to whether the grant recipient is urban or rural. For instance, a small GSHP is assumed to be used in a rural area. Costs in £/tonne would be less on buildings with solid fuel or electric resistance heating.
6. For PV and wind, the table is based on rates paid after year two.
7. Costs are labelled as infinite if CO_2 savings are zero; e.g., some 1 kW(e) gas-fired micro-CHP plants appear not to reduce emissions versus using a gas-fired condensing boiler for heat and using the national grid or a CCGT plant for electricity. [235] Where a technology may increase GHG emissions, the cost is also labelled as infinite; e.g., small wood-fired combustion plants emit more GHGs in kg/kWh than natural gas or oil and have lower fuel-to-heat conversion efficiency. [236]
8. Grant aid for CWI or loft insulation is assumed to be 50% for recipients receiving no means-tested benefits and no district council top-up aid. Resource costs of measures before grant aid are taken as £500 = £5/m^2 wall area for 50 mm blown mineral fibre CWI and £6/m^2 or £300 to top up loft insulation from 75 to 275 mm mineral fibre. Neither measure significantly affects building air leakage. The grant aid is amortised over 30 years at *Green Book* interest of 3.5%/yr. CWI and loft insulation save respectively 6,910 and 1,720 kWh/yr of heat. At an assumed 95% boiler efficiency, they save respectively 1.50 and 0.37 tonnes/year and £207/yr and £52/yr of natural gas, giving negative CO_2 abatement costs. This is not allowed for.
9. Support for BEVs is taken as £5,000 for a vehicle and battery system driven 15,000 km/yr. The sum is amortised over 20 years at *Green Book* interest rates, costing £352/yr. Other payments; e.g., waiving of vehicle excise duty, loss of fuel duty and VAT revenue and covert payments to internal combustion engine (ICE) car makers to make BEVs [237] are excluded. To calculate the abatement cost, it is assumed that a BEV using electricity at 21 kWh/100 km, including space heating, [238] replaces an ICE vehicle (ICEV) using petrol at 80 kWh/100 km. Respective CO_2 emissions are 1.28 and 2.24 tonnes/yr, a 0.96 tonnes/yr saving versus the vehicle stock. But the CO_2 saving turns into higher CO_2 emissions if the correct comparison is made and a new BEV is compared to a fuel-efficient new ICEV using 35 kWh/100 km and emitting 0.98 tonnes/yr. This negative saving from BEVs versus a new state-of-the-art ICEV is relevant if the UK wishes to reduce CO_2 emissions in the important period 2010-30, when marginal electricity emissions are very far from zero.

Table 7 reveals that:

- Large numbers of cost-effective "low-carbon" technologies receive(d) no government support.
- Support for a technology is weakly-related to the benefit which might accrue to the UK in tonnes/year or to its marginal abatement cost in £/tonne.
- The anomalous cut-offs in FIT encourage non-optimal investment. By reducing the capacity of a borderline hydro plant by 20%, one might earn 10-20% more revenue at the cost of 15% of the potential electricity output.
- The UK is devoting scarce resources to very expensive options. Some options in Table 7 may be too costly to form part of an affordable climate change mitigation program. [239]
- Some support offered makes climate change *worse*. The former LCBP and the planned RHI subsidise options with similar or higher GHG emissions versus a well-controlled oil- or gas-fired condensing boiler. [240] The cost in £/tonne saved is therefore very high. Even if air source heat pumps (ASHPs) avoid obvious design and installation pitfalls, if they run on winter electricity from today's national grid their emissions are similar to those of a condensing gas or LPG boiler.

The Renewable Heat Incentive (RHI) was to be funded by a surcharge on consumers. It seemed unsatisfactory to use consumers' money to abate CO_2 emissions at £500-1,000 or more per tonne, when it could be re-deployed to abate CO_2 emissions at negative or low costs, leaving consumers better-off. Resources are now to come from public funds. But taxpayers' money could also be spent more wisely. The estimated cumulative expenditure on the RHI is £36 billion by 2020. [241] We doubt that spending this sum on options which are mostly not cost-effective, and some of which may increase the UK's GHG emissions, is an appropriate use of scarce resources.

The draft Green Deal (GD) is at grave risk of not delivering. The "Golden Rule" is wrongly-defined. The maximum budget cited is insufficient for many dwellings, given the rough costings which we have carried out and which we report on in Appendix 3. Key technologies are excluded. Loans are set to be charged to the wrong bill. The likely interest rate exceeds utility borrowing costs or mortgage rates. The organisations charged with delivering it are experts on retailing, not on domestic energy use. We have not put any estimates in Table 7. We consider that the details need to change radically before the GD can be considered a promising way forward. [242]

The arrangement of interlocking programs and conflicting rules which has developed is incoherent, muddled and obstructs efforts to reach a sustainable energy system. Lay people tend to assume that government support for a technology signifies that it delivers cost-effective

CO_2 savings, or vice versa if there is no support. From Table 7, if anything the opposite is the case.

At some point, government may acknowledge that the support system lacks consistency and try to change it, only to note the same and to change it again, and again. This will consume scarce political capital, of the kind needed to drive through initiatives which would cut CO_2 emissions sharply and cheaply - in other words, like those put forward in this report. More effective would be to admit that all is not well and make a fresh start on an integrated program which helps to deliver what we want, by directing support to technologies which:

- Are economic versus others competing for the same market.
- Make clear contributions to a more secure future after oil.
- Reduce cumulative CO_2 emissions in the critical period 2010-30, not just by 2050.
- Do not need technological breakthroughs. [243]
- Do not place excessive demands on scarce technical skills.

Tempting Offers

If an energy policy-maker has a hypothetical £200 billion to devote to low- or zero-CO_2 options by 2020, or perhaps £236 billion, given the further projected cost of the RHI, how should he or she best spend it or encourage “the market” to spend it to maximise benefits to the UK? Figure 12 provides clues as to productive areas for investment in retrofitting the cavity-walled building stock in built-up areas.

We submit that a new policy is needed which pays heed to the types of energy needed and to practical energy economics. It would stress heavy investment in enhanced energy productivity - negawatts - to squeeze more economic output out of increasingly constrained energy supplies.

Techno-economic analysis shows that many energy efficiency measures have similar investment costs to the newer offshore oil and natural gas fields and better economics than wind or nuclear energy projects. Measures which save electricity are particularly economic versus new generating plants. The measures that save CO_2 on heating existing buildings tend to have lower or broadly similar costs to those that gas-heated consumers are paying today. They are significantly lower, for rural oil-heated buildings. They yield major social benefits, in the form of warmer homes and fuel bills which cease to be such a worry, even to those on quite low incomes.

In a market economy, investing in negawatts would not just reduce total UK energy expenditure but would help to keep down the price of fossil fuels. It is the marginal cost of other energy options, both efficiency improvements and renewable supply, and how well they are exploited, which set limits to the prices that petroleum-exporting countries can charge for natural gas and oil.

The cheaper energy efficiency measures have sometimes been compared to picking the low-hanging fruit from a tree. That is a tempting enough offer. But to the UK, the resource is arguably more on a par with used £20 and £50 notes which are lying on the pavement and have not yet been picked up because passers-by do not expect such a bonanza and have their minds on other topics anyway.

This picture of the opportunities available to UK PLC sums up an extraordinary degree of market failure. [244] The government has not regulated markets to the degree needed. It has increasingly treated "the market" as "master". [245] We pay several times over for the resulting misallocation of resources. First, we pay for the unnecessary energy consumption, which costs the UK more in p/kWh than equivalent energy efficiency would have cost. Second, we pay for the unnecessary CO_2 emissions and for the damage to the earth's climate.

A shift from energy supply to efficiency, which is what we need to achieve energy security after oil, will *not* happen under existing "market forces". These are distorted by the above factors and more, giving little room for a strategic sense of direction or vision. [246]

From time to time, one hears comments that energy efficiency has been tried in the UK and has not worked. A more valid response could be that energy supply was the central, if not the only issue, at the heart of government. Because energy efficiency was treated as peripheral, the associated initiatives were ineffective. We refer readers again to the "leading question" at the start of this chapter.

However, if policies are well-thought out, and backed by political will, they can clearly deliver. [247] Danish initiatives led to CO_2 emissions falling gently from 1990 to 2010, despite steady economic growth. UK emissions stayed more level, despite a "dash for gas". See Figures 20-21. It would be useful to correct these charts further for the impacts of CO_2 imported in consumer goods, the lower market share of natural gas in Denmark, its lack of a major "dash for gas" and the way that it counts biofuels, but it appears that Danish policies 1990-2009 may have had more impact.

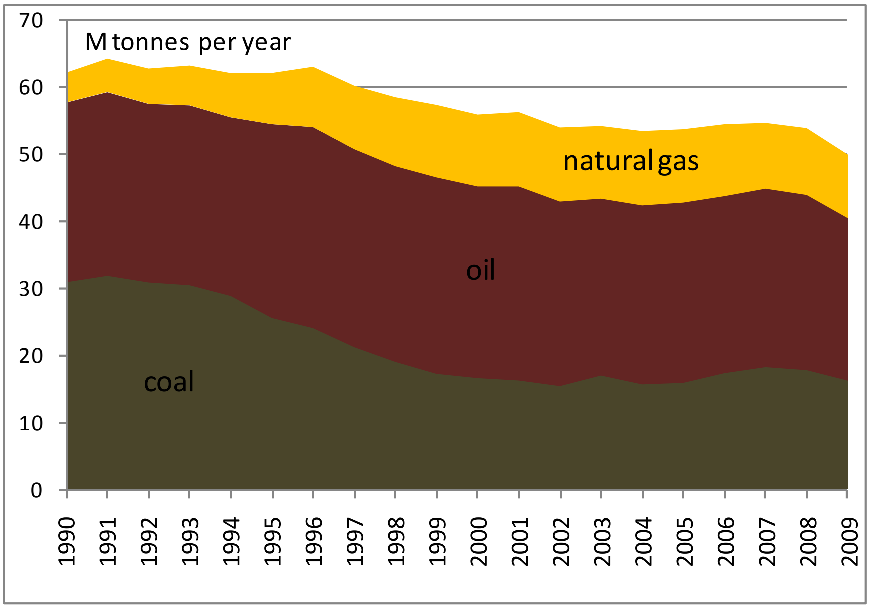


Figure 20. Danish CO_2 Emissions, 1990-2009. [248]

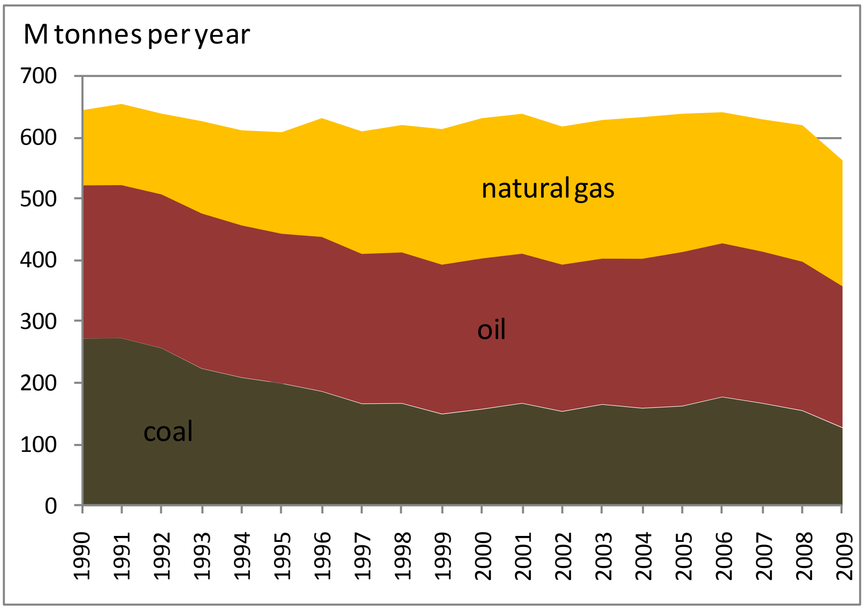


Figure 21. UK CO_2 Emissions, 1990-2009.

NOTES:

1. Figures 19 and 20 omit the CO_2 emissions from nuclear and renewable energy, including biofuels. They only show fossil fuel emissions.
2. It is likely that UK and Danish emissions/capita have followed roughly the same trend as total emissions.

A Policy Shift

Energy efficiency applied on a lavish scale makes a profit to UK PLC, versus energy supply at the margin. Much of it abates CO_2 emissions at negative or low cost. It would contribute to a more secure future after oil. But it does not prosper under current institutional structures.

To ease the transition away from fossil fuels, we need to displace them by investment in energy efficiency, including the use of reject heat. Investment needs to continue up to the point where the marginal cost of the most expensive energy efficiency measures on offer equals the marginal cost of new energy supply and/or other abatement measures; e.g., biosequestration and/or acceptably safe geoengineering. Social benefits need to be valued too. Some of them have a financial aspect, such as the savings on NHS and social services costs if fewer people suffer from the health effects of living in cold homes.

If government accepts the accuracy of the figures in this report - the sharply-rising cost of energy supply after fossil fuels, its adverse implications for the economy and the superior economics of energy efficiency - it has an implied duty to facilitate a strategic move away from increased supply, towards reduced consumption and towards the use of lower-grade energy for low-grade tasks, like heating buildings. In terms of the built environment, investment would need to take place in:

- The opaque fabric.
- The fenestration.
- Heating and ventilation services, including insulated pipes in built-up areas to utilise waste heat from power stations and industry and heat from large-scale renewables, plus well-insulated DHW tanks and pipes and improved controls.
- Lighting, both within buildings, external and street lighting and lighting of road and rail vehicles.
- Business and consumer electrical appliances therein, ranging from cookers, kettles, coffee-makers, doorbells, shaver sockets, [249] refrigerators and freezers to TVs, PCs, DVD players and other audio equipment, a plethora of office electrical equipment and the data centres on which the internet depends. Hot-fill washing machines and dishwashers and heat-driven clothes dryers can displace electricity by low-temperature heat, if EU rating systems are changed to signal CO_2 emissions correctly.
- Gas appliances; e.g., domestic cookers and commercial catering.

As this list suggests, the key to an affordable and sustainable energy future is *not* “high-level” academic research into “innovative” technologies, useful as they might be in the long term. The potential can be realised via lavish application of existing, proven and demonstrated technologies. Individually, some make only modest savings. Added up, the annual net savings to the UK would be £ tens of billions.

In industry and agriculture, investment in accelerated replacement of plant and equipment would be favoured, coupled with incentives to the workforce to identify new opportunities. [250] The returns on investment in these sectors can be much higher than on some domestic sector energy efficiency measures; e.g., retrofit fabric insulation. The industrial sector has been more active than the domestic sector since 2000, suggesting that early energy and CO_2 savings would be greater, with less time needed for programs to build up momentum.

In transport, investment would be needed in near-market R&D and stronger legislation and other initiatives would be needed to speed up the adoption of known technologies. The public sector should remove "restrictive practices" which block private sector innovation. [251] It could play a proactive role, by buying more fuel-efficient vehicles for government car fleets.

Renewables deserve equivalent support where they abate CO_2 emissions economically. Passive solar in new buildings [252] and large-scale solar thermal via heat mains to urban buildings come into this category. Biomethane appears very attractive. So do some hydro technologies and possibly tidal lagoons, especially if these are evaluated as a source of firm power and possibly pumped storage to help keep a future electricity network stable.

For consumption to stabilise and start to fall, energy efficiency cannot be treated as a minor adjunct to a planned energy supply program. It is a direct alternative to such a program. So resources must be transferred from the one activity to the other. If £250 billion is at stake over the next decade, we need assessments of the merits of investing such a serious sum in energy efficiency and/or waste heat utilisation, not in electricity supply and in heating systems with GHG emissions as high as their predecessors. It appears that a much lesser sum than £250 billion would suffice to connect the urban and suburban UK to heat networks, utilising mainly waste heat from power stations today and that plus other renewable heat later. [253]

Technologies should be assessed from a UK PLC viewpoint and rewarded on the basis of best buys first. Investment programs should be integrated with other measures which are scheduled to proceed anyway. New technologies should be compared to other new technologies, not to the technology currently in use. Thus:

- It costs less to pay the marginal cost of an energy-efficient appliance when a consumer needs a new TV, refrigerator or coffee-maker than to buy a new one and classify all the expenditure as energy efficiency investment. With short-lived consumer electrical goods, retrofit is seldom an option. Incentives towards the costs of new energy-efficient models are more useful, conditional on the old ones being scrapped and recycled.
- It costs less to insulate a building's roof to very high levels if it needs extensive refurbishment. It is very expensive to replace a roof structure or take off the tiles and battens and replace them just in order to retrofit insulation and an air barrier. [254]
- It costs less to externally-insulate solid walls if the render, paint or mortar needs attention
- It costs less to internally-insulate solid walls if a building is being totally refurbished, including re-plumbing, re-wiring and replacing built-in cupboards on external walls.
- Smaller-scale investment in CHP/piped heat - linkable to larger systems later - may be easier when a social landlord is replumbing and fitting new heating systems to its building stock.
- If a rural building has an obsolete oil boiler, the comparison is not between a new electric heat pump and an old boiler but between a heat pump and other technologies which might replace the old boiler; see Appendix 2.

Measures that are not widespread in the UK today need intervention to reduce the cost rapidly to that typical of a mature market. This does not occur at the desired speed under a *laissez faire* arrangement - a seemingly critical point, given that we wish to make massive GHG reductions within a short time period.

This dilemma was accepted by the US Department of Energy 30 years ago when it set up the Center for Building Science at Lawrence Berkeley National Laboratory, University of California. Its "intervention in the free market" accelerated the development and implementation of electronic ballasts for tubular fluorescent lamps, compact fluorescent lamps, low-e window glass and other energy efficiency technologies by decades. [255]

Having accepted this point, there is a well-established methodology to calculate the cost of conserved energy (CCE) in p/kWh, or the cost of avoided CO_2 emissions in £/tonne CO_2 equiv., for different energy efficiency or renewable energy technologies. It is set out *inter alia* in detail by the UK Treasury for projects in general [256] and by the German Passivhaus Institut for a specific technology. [257]

There is a correct procedure to follow too if an item is replaced early to fit in with the urgency of a national energy efficiency program; e.g., if a ten year old gas boiler with an expected 20 year life is scrapped prematurely when a household connects to piped heat; if a house is renovated in a location which is planned to connect to piped heat in five years' time; or if a roof needs replacing anyway in 20 years' time and the work is brought forward and combined with other thermal improvements; or an eight year-old refrigerator-freezer fit for another four years is scrapped and replaced by an A++ model, aided by a utility rebate. In these cases, avoided costs(s) should be discounted and included in the calculations.

As well as policies which are structured properly, and calculate £/tonne abatement costs correctly, we should reward people in ways which reflect known human nature. The incentive structures needed are painfully basic:

- Monetary rewards for what we want; i.e., payments for lower GHG emissions.
- Incentive structures which reward best buys first, worst buys last.
- Penalties for what we do not want; i.e., charges for higher GHG emissions.

Ideally, they are revenue-neutral, so that the penalties are used to fund the monetary rewards. Broadly, the more effectively the UK acts to remove market failures, the lower the rewards and penalties have to be to encourage the desired behaviour.

There must be long-term continuity in programs. Overseas experience is summed-up in Chapter 7. It often takes years for programs to build up momentum and start to deliver savings at the full rate. They may underperform initially and exceed targets later. Stop-start policies have less impact and may even demotivate people, causing needless cynicism.

Choices?

Arguments are sometimes heard that we must pursue "all options" in the energy policy field. But in a world of finite resources, an inescapable conclusion is that we cannot afford everyone's "sustainable energy" proposal(s). The UK attempts at this writing to close a current account deficit of £0.15 trillion/year. Constrained by sharply lower capital ratios, banks struggle to maintain lending to businesses. Credit conditions remain tight. [258]

To minimise costs and economic disruption, we should be concentrating limited expenditure on what saves most tonnes per £ spent, consistent with other policy objectives, varying from social harmony to EU air quality laws. We should not be adjusting a policy to suit certain industries and then writing rules designed to bring about economically irrational outcomes.

Especially in building thermal improvements, which are a very long-term enterprise, it is possible that we cannot undertake investment in series, in effect stepwise up the cost curve, because of lack of time. Arguably, such an exercise should have begun 30-35 years ago, when the UK last debated future energy supplies, costs and availability so vigorously. Given where we are, we just need to invest in parallel in the infrastructure and technologies that on balance we shall need in 2050.

But this is still not to say that we can afford everything. We must be highly critical and selective. Investment in excessively costly measures would damage the economy, which as we write is not in a particularly positive state.

An obvious reason not to do everything is that some options are mutually exclusive. Installing 30 GW(e) of windpower and just connecting it to the national grid not just produces too much electricity on some midsummer nights but conflicts with investment in more efficient use of electricity and early replacement of electric space, process or water heating by less CO_2-intensive systems. These steps would cut cumulative CO_2 emissions faster and cheaper in the critical period 2010-30 than windpower. Whether such windpower should be postponed, or turned into fuel or heat, remains to be determined.

Today's weekend summer night electricity consumption at the generating plants falls as low as 22 GW(e), or 20-21 GW(e) at consumers' meters. The national grid cannot accommodate 30 GW(e) of wind electricity, not even in a hypothetical situation where existing nuclear plants have closed and other plant on the system can all be switched off at times of high wind energy output. [259] Wind electricity supply at consumers' meters would exceed consumption by 7-8 GW(e).

More efficient use of electricity in refrigerators, fans, ICT, other office equipment, pumps, controls, various standby power, etc could soon reduce summer night demand to below the peak output of 20 GW(e) of wind farms. Options at this point might include:

- Turn off some wind farms and lose the income.
- Store the output as mechanical or electrical energy in compressed air or pumped storage plant or battery banks.
- Export surplus electricity. [260]

- Fit cold stores, space cooling systems and large commercial freezers with controls to shift load to the night hours, perhaps with ice storage, enabling some excess wind output to be utilised.
- More effectively for large wind surpluses, and at lower energy storage costs, divert the surplus to make heat via large heat pumps for use on heat networks or to make zero or negative-CO_2 synfuels via electrolysis for road transport.

Fitting small ASHPs or GSHPs or rooftop solar in urban areas conflicts with laying mains to supply a town from cheaper, lower-CO_2 heat, such as waste heat from CHP plant or industry, large solar collectors, geothermal in some areas and/or large heat pumps on DH systems to use spilled windpower. [261] The second option saves more CO_2 per £ spent. All the options are capital-intensive.

Although the UK gives grants for both options, combining electric resistance or heat pump water heating with solar panels on a building seems to make no economic sense. [262] A full solar contribution in summer, and a partial one in spring and autumn, hardly reduces the capital cost of the electricity supply system, especially if renewables and/or nuclear generation have largely replaced gas-fired plant. The system must still meet full winter peak demand.

Using small-scale active solar on rural buildings, the soundest heating system design philosophy is to back up the capital-intensive solar equipment by the sparing use of a low-CO_2 fuel, stored locally in a tank, for use to meet mid-winter peaks. Examples include LPG today and possibly bio-DME tomorrow, or similar synfuels.

The fuel distribution and storage system has a low capital cost, even if the fuel itself comes from a synthetic fuel plant. The arrangement does not destabilise energy networks by adding load at the time of electricity system peak.

In a finite world, life by definition always involves choices. The choices in the energy field just happen to be very difficult and very important ones. Perhaps the difficulty explains why some people who insist unhelpfully that “we must do everything” refuse to make them!

6. Financing Energy Efficiency in Buildings

Introduction

This section briefly discusses how we should finance energy efficiency and reduced CO_2 emissions in these areas of building energy use:

- "Essential electricity" for lights, appliances, etc
- Space and water heating.

Many suppliers of energy to buildings are delivering fuel mostly for space and water heating; i.e., (2). Electricity suppliers are mostly delivering energy for "essential electricity uses"; i.e., (1). They also provide some energy for (2).

Some energy suppliers have the characteristics of a natural monopoly. Others; e.g., those supplying liquid fuels by HGV to buildings for space heating, or to filling stations for road transport, do not. Some energy suppliers have access to low-cost capital which could enable them to finance heat-saving measures on consumers' premises and/or the supply of low-CO_2 heat via heat networks. Others seem to have less scope to assist with this work.

Energy Consumers

If we are to base our future on higher energy productivity, government must face up to some realities. Lay consumers do not understand the technicalities of energy policy and technology. It is arguably not their responsibility to understand it; that is one reason why societies educate professional scientists and engineers. But people who know less on these issues than the authors face major barriers and transaction costs in trying "to do the right thing", and a pitiful lack of impartial advice.

A picture of almost boundless opportunities could be an accurate assessment, viewed by those who formulate UK energy policy and are in a position to change the priorities. But it is naively simplistic to lay consumers, or community groups, who try to implement best practice; e.g., to buy energy-efficient A++-rated electrical equipment, to develop an anaerobic digester CHP plant to help heat a small town, or get a new house constructed to an assured energy performance standard. Even if they are fully aware of the possibilities, they face formidable transaction costs and/or institutional barriers.

These hurdles were identified so long ago that they could and should have been removed by now. They *have* been removed in many countries. For an individual or small business, the hurdles to accessing some technologies can be astounding, and the situation does not seem to have changed dramatically, as a few accounts from the late 1980s to the early 2000s indicate:

- An individual wanted an insulated external door, to make his 1960s semi-detached home in Yorkshire more energy-efficient. For affordability, he found that he had to import a mass-produced insulated and draughtproof external door from Canada, where they cost £100-200 each in DIY sheds. Similar UK products were five to ten times the price and were less well-insulated and draughtproof. The new door transformed their entrance hall from being the coldest room in the house to being among the warmest.
- A "green-minded" family resolved to source some light shades with high-quality aesthetics for use with compact fluorescent lamps. Unable to find anything in the UK, they ended up buying a car-load of products in Denmark during a business trip.
- A UK householder wanted to know if a new dishwasher could be connected to the hot pipe instead of the cold pipe, to save electricity and cut his CO_2 emissions. The English instructions warned that: "This must not be done". The householder persisted and asked the overseas manufacturer the same question in German by e-mail. A spokesperson replied "Yes, you may do this".

Only when consumers are able to get technologies installed without this trouble and effort, and without undue callbacks, will an energy efficiency program succeed. This argues for involvement by energy services companies (ESCOs), existing utilities, other energy companies with long experience and experts with a proven track record in a field, not retailers with no knowledge or experience of building energy use. It also argues for extensive training of building workers as applied *par excellence* by Canada in its R-2000 program. The success of a program, as other countries have shown, depends on both technical and marketing skills. Neither is sufficient by itself.

Energy Suppliers

Gas, Electricity and Heat

This section covers suppliers of mains energy services; i.e. piped gas, electricity and piped heat. Soon after privatisation of gas and electricity 20 years ago, the electricity regulator OFFER reviewed the possibility of following the US utilities which had been forced to invest in energy efficiency on consumer's premises when it cost less than new energy supply. See Chapter 9. But early UK experiments with investment by "regulated monopolies" in energy efficiency - called the Energy Efficiency Standards of Performance - did not develop further. Instead, the industry was "deregulated" in 1998-99, the regulators OFFER and in particular OFGAS disappeared and the possibility of least-cost planning slowly faded away. [263]

Today's deregulated gas and electricity suppliers make regular commitments to cut CO_2 emissions. There was once an Energy Efficiency Committment (EEC). [264] The EEC became the Carbon Emissions Reduction Target (CERT), which gave them more obligations. [265] With CERT came the Community Energy Saving Program, whose full relationship to CERT is unclear. There is discussion of giving them more powers and duties under an emerging "Green Deal", overseen by a new Office of Energy Efficiency (OEE). To replace CERT, an Energy Company Obligation (ECO) is on the way. [266] There are also means-tested or age-dependent grants, such as Warm Front, Warm Homes Discount, etc. There are the Energy Saving Trust and Carbon Trust, too. Their status is apparently called into question by the withdrawal of core public funding.

We are not denying energy supply companies' broad wish to improve energy efficiency, but we seriously question the effectiveness of the approach adopted. We note especially:

- The lack of legal/contractual targets; the savings appear to be aspirational.
- The confusing variety of overlapping programs and organisations.
- The many technologies excluded by UK policy; see Table 7.
- The lack of continuity, symbolised by programs' relatively short life.

Under the post-1999 arrangements, the six companies which supply over 99% of UK gas and electricity appear to operate under an actual conflict of interest. There is no apparent mechanism to reward utilities which invest £ billions in energy efficiency, as a positive alternative to new generating plant, and cut emissions accordingly.

Suppose that a hypothetical electricity supplier with sales of 4.6 GW or 40 TWh/yr spends £1.5 billion on more efficient use of electricity over ten years, reducing its sales to 3.4 GW or 30 TWh/yr and, as a bonus, closing two polluting coal-fired generating plants and cutting UK CO_2 emissions by a useful 10 M tonnes/year . If typical measures are amortised over a weighted average of ten years, at UK PLC interest rates, the cost of conserved electricity in this particular case would be 1.8 p/kWh and CO_2 emissions would be abated at minus £135/tonne; i.e. at a large profit to UK PLC.

To earn a return on its capital, this supplier will normally have to raise its unit price, because its capital base is now spread over lower unit sales. [267] But the main selling point for UK gas or electricity is a company's claim to charge less in p/kWh than others. [268] By spending £1.5 billion on energy efficiency, this company has ruined its market position. All UK consumers are free to switch tomorrow to a supplier which has invested nothing in negawatts and can offer a unit price say 1.0 p/kWh less. The supplier which "does the right thing" is now left with:

- Fewer customers.
- A £1.5 billion loan to repay from the revenue on its lower sales.

Under "liberalisation", if an electricity supplier invests so much in energy efficiency that sales fall, it could breach its legal duty to maximise shareholder value. Broadly, shareholders in a deregulated private energy company profit from the margin on each kWh sold, multiplied by total sales in kWh. They indirectly profit from higher CO_2 emissions.

There is also a prospect of resistance from companies which own the electricity and gas T&D systems, who may worry that this asset base could be devalued if consumption falls before networks which they have invested in are amortised. But given that these assets are regulated as natural monopolies, there should be ways to overcome such objections and to reward energy efficiency and declining sales instead of a situation of static sales or sales growth.

Utility Reform

Costs of capital are reduced if utilities operate in a regulated environment. This reflects the lower business risk. Consumers need lighting, warmth, hot water and cold food storage space. These are largely captive markets, especially the domestic sector, whose energy consumption has been noticeably stable from year to year, even through deep recessions. [269]

With their long-standing statutory powers, regulated private utilities can borrow money quite cheaply, especially if they are debt-financed. Welsh Water pays investors a real rate of 2.5 to 4%/year on its bonds. [270] This is very close to public sector interest rates. Private investors accept low returns because the water companies have been largely “de-risked”. [271]

Long-term thermal improvements to buildings and their services, including heat networks, would be financeable by regulated utilities at such interest rates at little or no cost to public funds. Consumers’ monthly bills would be less than, or broadly competitive with, what they pay today for gas heating of badly-insulated buildings. CO_2 emissions would fall. Social benefits would accrue, in the form of warmer homes and less condensation and mould growth.

The regulator can ask regulated monopoly utilities to achieve specific CO_2 or energy efficiency-related goals in their region. The utilities become *de facto* ESCOs. Via this route, the conflicting interests between electricity, gas and/or heat suppliers and consumers can be overcome, producing financial and environmental benefits to both energy suppliers and users. [272]

Under *laissez faire*, no means is readily visible to overcome the problem. It is especially hard to see how investment in infrastructure like heat mains can proceed under the existing framework. One concedes that ways around the problem could theoretically be found, but one suspects that they would be complex, take years to devise, reduce market transparency and yield unforeseen, paradoxical or perverse consequences. Transparency, which allows stakeholders to see and understand what is happening, and why, is essential to the transformation that we need in the UK energy system over the next 40 years.

The government’s continued attempts to force “deregulated” electricity and gas suppliers to meet a set of energy efficiency objectives face a major problem - that different parties’ financial interests are not aligned. Unless companies can undertake energy efficiency investment and make a return on it, reduced sales are not in their interests. The risk is that:

- Efforts will be half-hearted
- The minimum will be done to meet the letter of government directives
- Sales growth will continue, albeit markedly constrained by rising energy prices. [273]

Even the list of technologies is woefully short compared to lists which experts might compile if charged with making the steepest, fastest possible cuts in emissions. Table 7 merely outlines what such a list might include.

The government seems to be trying to return to *de facto* central planning of electricity generating plants, in a process called "electricity market reform". This threatens to give consumers the worst of both worlds. They remain supplied by privately-owned companies which, other facts being equal, have higher costs of capital and must charge higher bills. Yet privatisation was surely driven by a belief that in spite of higher costs of capital, privatised companies could behave more nimbly and innovatively than civil servants and nationalised industries had done before them, with consumers reaping the net benefits.

Our proposal is that mains energy suppliers be re-constituted as integrated ESCOs which supply energy to defined regions on a long-term franchise. They would be regulated to align the financial interests of the utilities, their consumers and UK PLC.

Regulation is not a new concept. UK privately-owned gas and electricity suppliers were regulated from privatisation in the late 1980s to "deregulation" in 1999. This was in turn the legacy of a nationalised electricity system which had featured:

- 12 regional electricity boards in England and Wales which distributed electricity and owned the distribution systems. In later years, some of them began to generate their own electricity; e.g., MEB's industrial CHP plants.
- The Central Electricity Generating Board which owned the transmission system and generated bulk electricity in England and Wales.
- Two vertically-integrated regional electricity boards in Scotland which generated and distributed electricity and owned their own transmission system.

All water suppliers in England and Wales are regulated as regional monopolies. There is one tariff per supplier, comprising a standing charge and a volume-related charge. Charges are set by the Regulated Capital Value, which is what regulated US electric and gas utilities call "the rate base"; [274] i.e., the capital sum on which a company earns a rate of return. If other utilities were reorganised this way, within broad constraints they could be allowed to decide how to deliver their statutory CO_2 target and not be given a "shopping list" of technologies by the government.

Utilities would supply electricity, piped gas and where applicable piped heat. They would be free to own their own power stations, outsource generation, and/or form subsidiary companies consistent with their legal duty; e.g., joint ventures with local authorities to supply piped heat in a city; joint ventures with other players, such as the oil majors. They would be responsible for providing loans for cost-effective retrofit insulation and draughtproofing, incentives for energy-efficient electrical equipment, lighting, fans, pumps, etc, industrial process energy efficiency investments and improvements in efficiency of mains-electric transport such as trains and trams.

They could finance heat mains in urban buildings and heat-saving investments on urban consumers' premises, either from their own resources, by issuing bonds, or with financial input from national or local government where this is deemed necessary; e.g., with consumers who are in fuel poverty. They could outsource design and development of specialist areas to known UK specialists if they wish; e.g., hydroelectric plants, anaerobic digester CHP plants. The remit would be to take an integrated view and to deliver on energy-related GHG emissions cuts and other franchise conditions.

They would be obliged to purchase energy from independent producers for electricity, gas or heat networks on the terms drawn up in the UK shortly before privatisation; i.e., more generous than now. They would also have to cooperate with neighbouring suppliers in specified respects and an independent body would be needed to manage access to the electricity and gas networks, helping to eliminate signs of UK regulatory failure such as "private wire". [275] [276]

We think that the UK could learn something from the regulation of privately-owned utilities in the USA. While utility regulation is devolved to state governments, if not to counties within the state, most gas and electricity suppliers operate under the following rules:

- Utilities must make submissions to the regulator to justify any price increase.
- In exchange for being awarded a long-term franchise, utilities must provide information requested by consumers or employees and cannot hide behind "commercial confidentiality".
- Public hearings are held at which documents and arguments are open to scrutiny and debate.
- Utilities must pass on cost reductions; e.g., lower wholesale prices, in the form of lower retail prices.
- Consumers can ask the regulator to investigate a utility's prices if they have cause to believe that it is making excess profits.
- Local government has the option to form a municipal utility at nominal cost when an investor-owned utility's franchise expires, usually every 25-50 years. The wayleaves, wires, etc are regarded as the intrinsic property of the public sector, not of the private sector. [277]

This contrasts with the rather opaque model of regulation as applied by OFWAT to the English and Welsh water companies [278] and by OFGEM to the electricity and gas transmission and distribution companies.

We tentatively suggest long franchises; e.g., 40-50 years, to reduce business risk and cost of capital, but subject to binding five-yearly targets for falling GHG emissions; i.e., up to or beyond 2050. Targets would be based on a presumption of lavish implementation of known and demonstrated technologies, including those which have not yet been widely-implemented. Bonuses would be offered for exceeding the targets; i.e., delivering CO_2 reductions ahead of schedule. This is a win-win situation as suppliers and consumers would both benefit from this.

It takes time and experience for programs to build up momentum. So early targets should be more modest than later ones, and 2015 targets should be non-binding, although there would be a sanction of good/poor publicity for meeting/missing them. Utilities which fail to meet later targets would have to re-bid for a franchise. If they fail to win the bidding process, full compensation would be due after an independent valuation of any assets which are to be taken over by the new incumbent. This same process should be applied to the change from the current incumbents to ESCOs.

Franchises should be open to for-profit and non-profit legal entities. Up to 2020, if for-profit franchisees meet targets, investors would be allowed to keep 10% of the net profit; i.e., over and above the regulated rate of return, versus the 2011 situation. Consumers would keep 90%. If franchisees exceed a five-yearly target, investors would retain 25% of the extra net profit, with 75% going to consumers.

The splits are a preliminary suggestion based in part on Californian experience with least-cost planning and on what level of “shared savings” induced serious investment in negawatts. 0% gave slow steady progress, but the results were not spectacular. By definition, if a supplier did not lose, but gained nothing, there was no motive to depart from the *status quo*. 15% led to a positive rush of enthusiasm; “money talks”.

The percentages should be kept under review by government and the regulator after 2020, based on different utilities’ performance. If any franchisees are “non-profits”, 100% of the saving from buying “negawatts instead of megawatts” would accrue to consumers, as it does in the USA or other countries with municipally-owned utilities or consumer-owned co-ops.

Many UK energy suppliers have a parent company based on the continent. So they are very familiar with retrofit solid wall insulation, DH, natural gas/biomethane CHP, renewable heat and electricity. E.ON AG, for instance, operates some DH systems in Denmark under contract to councils or consumer co-ops, has a Bavarian subsidiary which specialises in hydropower and has a biomethane division at its head office in Düsselforf.

Oil, LPG, Biofuels, etc

These non-mains energy suppliers; e.g. rural suppliers of LPG, kerosene, coal and sometimes nowadays compatible biofuels, are unregulated private companies. [279] They see their mission as fuel supply. Demand is implicitly somebody else's responsibility. Most of the fuel which they deliver to buildings is used for space and water heating. A little of the oil and several percent of the LPG is used for cooking.

These suppliers have no **incentive** to reduce consumption. It would cut their sales and profits. Their access to capital which could help to finance; e.g., near-Passivhaus retrofits on customers' premises may sometimes be little better than that of their customers. After all, their operations are very non-capital-intensive; that is the nature of liquid fuel distribution.

We think that public funding for investments in heat-saving measures in these buildings is essential, either directly or via a new institution such as a Green Investment Bank. Many improvements on oil-heated buildings save energy and CO_2 at reasonable costs, if loans are repaid over long periods at low, utility-type interest rates. Little or no subsidy is then needed compared to the rate at which the public sector borrows money, or the rate which some private utilities have recently paid. [280]

The economic argument looks as good as it does for enhanced Building Regulations in new construction. These are also implemented after evaluating the marginal costs of the improvements, at UK PLC interest rates.

Avoiding CO_2 emissions by insulating or draughtproofing these low-density buildings can be a *much* better investment in £/tonne to UK PLC than the same work on gas-heated urban buildings. External solid wall insulation gives a cost in £/tonne less than half as much - in favourable cases, a third as much - as the same insulation of a gas-heated house.

But the work might involve spending very large sums; e.g., a rural solid-walled detached house undergoing renovation at this time might benefit from a £30,000-plus loan to fund a large package of thermal improvements. The challenge is to structure the loan so that consumers' cash flow is improved from day one. We propose index-linked loans as a way forward. See Appendix 3.

More Efficient Use of Electricity

Under least-cost planning, with utilities allowed to recoup the cost of energy efficiency investment and make a fair return on capital, electricity prices in p/kWh could rise slightly, assuming that expenditure is added to the "rate base". But bills in £/year would fall sharply. Consumption is reduced by energy efficiency. The electricity displaced costs less than the electricity which would otherwise have needed to be supplied.

Virtually all consumers use electricity for lights and appliances, motors, controls, etc. Given the choice, which bill would a domestic consumer prefer out of the three alternatives shown in Figure 22:

- A 2010 electricity bill of £500/yr, at a mean unit price of 10 p per kWh
- A future electricity bill of £275/yr, after major efficiency improvements are implemented and the expenditure is repaid on all consumers' bills, at a mean unit price of 13.75 p/kWh *or*
- A future electricity bill of £600/yr, at a mean unit price of 12 p/kWh?

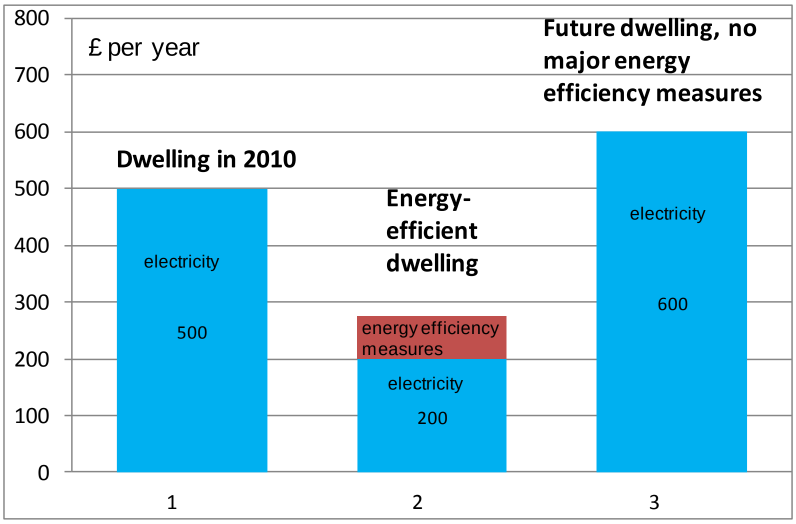


Figure 22. Potential Domestic Electricity Bill with and without Extensive Energy Efficiency Measures.

NOTES:

1. For illustration only. Dwelling with no electric heating but with high ownership of lights and appliances.
2. Details will vary between dwellings.
3. Excludes typical standing charges or the higher unit rate which applies to the first few hundred units consumed per quarter.

Case 1 is the dwelling in 2010 with high ownership of normal, energy-inefficient lights, appliances, pumps, fans, etc and consuming 5,000 kWh/yr. Case 2 is the same dwelling in say 2030 or 2040, with very energy-efficient lights and equipment, consuming 2,000 kWh/yr. Case 3 is the same dwelling then but without major energy efficiency investment and with a new supply mix including a higher proportion of more expensive plant. Hence the unit price rises to 12 p/kWh.

This is a cautious estimate of the consequences of substantially replacing fossil fuel electricity by offshore wind, CCS coal and/or nuclear as per current policy. This leads to a rise in generation costs and longer T&D distances, causing the price of delivered electricity to rise by 2 p/kWh.

The unit price in case 2 rises in order to repay utility expenditure on negawatts. With regulated electric utilities, the spending is assumed to be charged to the rate base, not to individual consumers. A working assumption is that the energy efficiency measures fitted to reduce consumption from 5,000 to 2,000 kWh/yr cost an average 2.5 p/kWh. Spread over the reduced consumption of 2,000 kWh/yr, this expenditure adds 3.75 p/kWh to unit prices, giving a new rate of 13.75 p/kWh. It is unlikely that case 2 would need a major fraction of electricity to come from offshore wind, CCS coal or nuclear plant, as Chapter 4 outlines. So the unit price is not assumed to rise from this cause, and it remains at 2010 levels.

We doubt that any consumers wish to pay £600/yr for the same electricity-related services for which they pay £500/yr today. Given a choice, we suspect that they would rather pay bill 2; i.e. just under £300/yr. If the industry is re-regulated, and the £275/yr is adjusted upwards to say £295/yr, to share savings between suppliers and customers, we doubt that anyone would turn the prospect down. Suppliers would profit more from investing in negawatts. [281] Consumers' and suppliers' financial interests would be aligned.

Space and Water Heating

Overall Approach

As Appendix 2 sets out, we advocate the zoning of heat supply methods between urban and low-density areas of the UK, to reduce overall consumer costs and to make the coming energy transition away from fossil fuels more affordable. It would also improve network security at times of peak heat demand. This is a matter of great concern in any move away from piped gas heating. Other objectives are to increase flexibility in choice of energy source and to continue to provide an adequate level of energy storage, which is vital as we move away from fossil fuels towards sources which do not come with inbuilt storage.

The boundary between zones needs to be defined after further analysis of UK settlement patterns and the potential of heat distribution today. However, Danish analyses of newer heat distribution technologies suggest that piped heat is a more economic method of space and water heating than electric heat pumps down to low suburban densities; e.g., detached bungalows on 1,000-1,500 m^2 plots. A threshold of 150 kWh/m.yr has been given in Denmark; i.e., above this, piped heat tends to be more viable. But for small, isolated groups of buildings, and/or at lower densities, GSHPs and the associated grid reinforcement may cost less than extending or building a piped heat system.

Given the poor thermal state of the UK building stock, work to bring it up to contemporary European standards is set to be costly, especially where there is no access to low-carbon heat infrastructure and CO_2 emissions must be cut via retrofit insulation, other fabric measures and changes to individual heating systems, possibly including solar. Some critical questions, to determine whether urban and rural consumers can afford to finance a package of CO_2-saving measures, include these:

- Real cost of capital
- Term of loan
- Conventional or index-linked repayments
- Legal security

  and
- Responsibility for repayments.

Answers to these points help to determine whether a package of measures will be attractive to a heat consumer and will be taken up. We suggest that the key to making measures affordable is a combination of:

- Regulated, low-risk utility-level returns on capital.
- Life-cycle costing.
- Index-linking, to improve consumer cash flow in the early years.
- Loans tied to buildings, not to owner-occupiers, lessees, landlords or tenants.
- A binding obligation to make repayments, as in the obligation to pay ground rent, service charges, etc on leasehold property. It is possible that missed payments could be rolled up and recouped with interest when a property is sold.

These principles can be applied separately to buildings in different areas, which may be suited to different types of heating system. To some extent, the above principles follow the proposed Green Deal, but they diverge from it in several major respects.

High-Density Buildings

We suggest that long-term borrowing at regulated utility costs of capital provides a means for the UK to finance the low- and medium-cost CO_2-saving measures of Figure 12 in built-up areas; i.e. the thermal measures. Retrofit insulation and lower-CO_2 piped heat are both part of an integrated solution in built-up areas of adequate density. They achieve greater savings in emissions than either step alone. The lower-CO_2 heat reduces the need for extremely high-cost CO_2 abatement measures.

We believe that progress needs, above all, government action to secure a level playing field, so that the supply of mains hot water is subject to the same legal and financing rules as traditional utilities. These undertakings are partly or wholly “de-risked”, depending on the extent to which they are regulated as natural monopolies.

In areas zoned for piped heat, there could be an obligation to connect on change of ownership, change of tenancy or in new or replacement buildings constructed in such areas. In our view, an obligation to connect in other circumstances should be avoided, unless heat is provided to the consumer by a non-profit entity, as it is in Denmark. Better approaches are campaigns to encourage consumers to connect when they replace an existing gas boiler [282] and substantial discounts to connect when a main is laid.

Low-Density Buildings

In Germany, consumers can borrow money from the state housing bank, or Kreditanstalt für Wiederaufbau, for Passivhaus-level retrofits, at low interest rates over 30 years. [283] [284] Similar loans for UK buildings in low-density areas could transform consumers' cash flow, providing room for a Green Investment Bank to provide a service which "the market" fails to provide.

We believe that such buildings need public sector loans, or another mechanism to generate public sector-level interest rates, to improve the fabric of these buildings and their space and water heating systems. Consumers do not have low-cost capital to finance it themselves. Rural fuel suppliers who supply heating fuel to such buildings do not have the means to finance it either. Financing it via electricity suppliers would create conflicts of interest and risk market abuse. Many such buildings are heated by oil or LPG, not by electricity.

At *Green Book* real interest rates, the repayments on a 30 year, index-linked loan of over £30,000 [285] for work to reduce a rural solid-walled dwelling's fuel bill by 95%, from some 8,000 to 400 litres/yr, could be lower than the first year energy saving. This is a case where the house needs its roof and windows replaced anyway. But without the attraction of long-term, low-interest loans, few consumers would ever contemplate such an ambitious project. In Appendix 3, we set out a typical package of measures and an illustrative cash flow for consumers who take out such a loan.

Social Policy

A large group of low- to middle-income households would need an input of public funds to cover part or all of the loan repayments. This is on social policy grounds. These are households which cannot afford to heat their home to a decent standard today. We can easily show that, in a modest-sized dwelling, a warm environment today would cost £1,000-3,000/yr or more using oil or electricity, and £600-1,200/yr with natural gas. Not all households have access to this level of disposable income, especially if they are on below-median earnings.

Some of these households cannot afford to pay the interest on a loan for CO_2-saving measures, even at "regulated asset"-type interest rates. However, it is likely that the majority of them could afford the cost of heating their home to a good standard after fitting CO_2-saving measures. In the case analysed in Appendix 3, the residual LPG bill after retrofitting a rural solid-walled detached house would be less than £200/yr.

This would slowly help to resolve “fuel poverty”. In the mid-2000s, this condition was said to affect 12% of UK householders, despite the low threshold the UK which uses to define fuel poverty, compared to the higher thermal comfort levels defined as acceptable on continental Europe. [286]

The proportion affected by fuel poverty varies from year to year as gas, electricity and oil prices fluctuate in relation to real after-tax incomes. Between 2008 and 2009, although the situation was meant to improve, the number of households affected rose from 4.5 to 5.5 M; i.e., 20% of households. [287] The conditions faced by some low-income households, and their inability to afford any heat, let alone thermal comfort, are distressing. [288] As this goes to press, 25% of households are said to be affected.

There is a marked impact on a further group of medium-income households. They may only spend 5-8% of their income, not 10% or more, on heat and light, but they still cannot afford to keep their dwelling as warm as they would wish to do. Influenced by the higher costs of heating, this “borderline fuel poverty” extends much further up the income scale in rural areas.

7. International Good and Best Practice

Examples

To move to a more secure energy system, we think that the UK needs to learn rapidly from regions with hard-won experience in implementing energy efficiency in a coordinated manner. We are in a serious situation and do not have time or money to waste on avoidable errors and reinventing inferior wheels. Below are examples of good practice in *inter alia* Denmark and California. They and other programs could be studied for invaluable lessons on what works and what does not.

Denmark has implemented least-cost heat planning from 1979 to date. It has accompanied it by a policy of high retail energy prices. They are sustained by a mixture of an energy tax, a CO_2 tax and full-rate VAT at 25%. [289] A significant consequence of these taxes is that there is a marked difference in heating bills between houses using individual gas boilers and houses heated by waste heat from power stations.

California has practised least-cost planning (LCP) for electricity and gas since the idea was first put forward in 1975. [290] The 1996 retail de-regulation of private gas and electricity companies interrupted the progress of LCP. In hindsight, this move is regarded as a serious error. [291] By the late 2000s, it had largely been reversed. The state's per capita electricity consumption is about the same as it was in 1975.

Denmark

> "We must not ... make ourselves [dependent] on purchasing oil and natural gas from a few and occasionally politically-unstable countries and regions."
>
> Anders Fogh Rasmussen, then Danish Prime Minister, 2007.

In 1973, before the first oil crisis, Denmark depended on imported oil for over 90% of its energy. 80% of its power stations were oil-fired. Most buildings in the countryside, villages, towns and suburbs were heated by oil boilers, although the city centres already had significant CHP and DH.

It resolved to replace oil by more secure alternatives; e.g., expanded DH systems fed by waste heat from power plants. From 1979, under a National Heat Plan, councils had a duty to prepare local heat plans which zoned their area to use one of three different categories of space and water heating:

- Zone 1 - piped heat including waste heat from oil- and coal-fired CHP plants, later from gas- and biomass-fired CHP plants, also now solar and geothermal and in future possibly large heat pumps using spilled windpower. [292]
- Zone 2 - piped gas from Denmark's North Sea fields, which were exploited from the early 1980s.
- Zone 3 - other systems; e.g., GSHPs, occasional ASHPs, LPG, oil and/or compatible biofuel condensing boilers, solid biofuel boilers including pellets and/or solar systems on individual house roofs..

Denmark terms the approaches in zones 1 and 2 "collective heating systems". Like electricity, piped gas and hot water depend on the functioning of a national or local energy supply network. Other systems, except for heat pumps, store the heating fuel at the consumer's premises. Table 8 shows the proportions of space and water heating supplied by the three different methods in 2010.

System		**Proportion of Space and Water Heating**
		%
1	Piped heat	62 [293]
2	Piped gas	16
3	Other systems	22

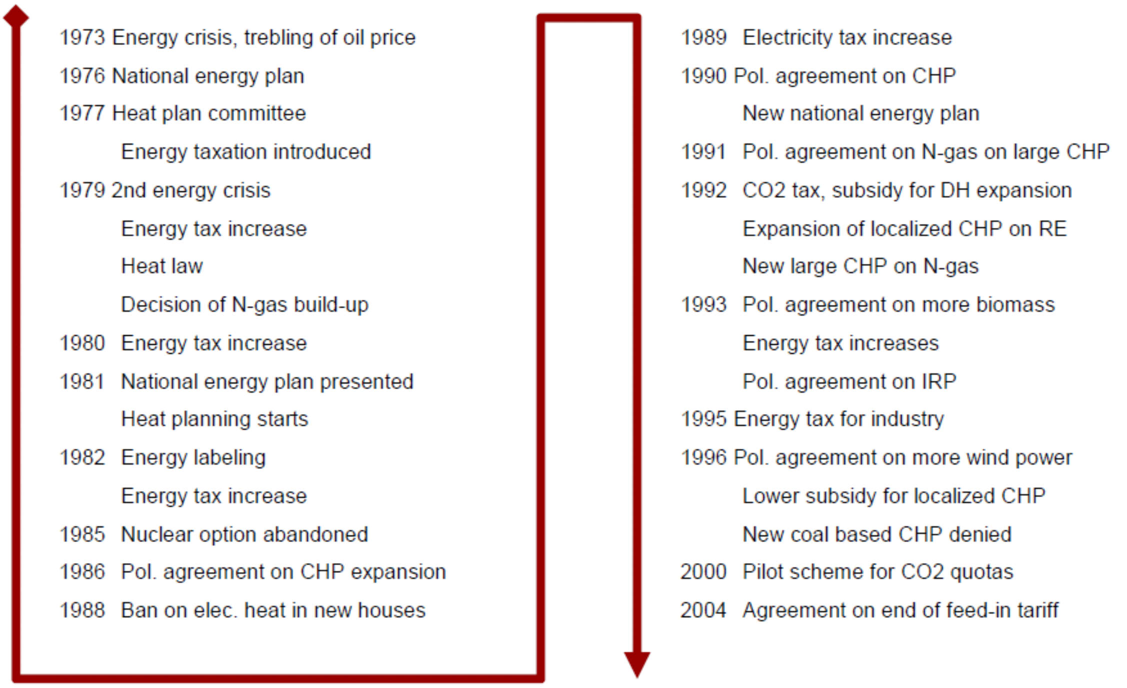
Table 8. Danish heat market 2010.

NOTES:
1. Percent DH estimated from Danish Board of District Heating (DBDH) publications.
2. Percent natural gas from Danish Gas Association.
3. Percent other systems calculated on a residual basis.

The Ministry of Climate Change and Energy had the task of coordinating the draft local plans to ensure that the final versions were compatible with each other and consistent with national policy. The later Heat Supply Act of 2000 states *inter alia*:

> "The objective of this Act is to promote the most economically-advantageous and environmentally-beneficial utilisation of energy for heating buildings and supplying them with hot water, while reducing the dependency of the Danish energy system on oil. …
> It is the duty of each local authority, in consultation with the supply companies and other interested parties, to prepare a plan for the supply of heat in the [district] …
> The Minister of Energy and Environment shall give an account of the more important measures planned in accordance with this Act to the Parliamentary Energy Committee …"

Its successor of May 2005 makes similar statements. The policy of least-cost heat planning has now been maintained, broadly unchanged, through 35 years, ten parliaments and four governments [294]. Table 9 lists the key events.



1973	Energy crisis, trebling of oil price
1976	National energy plan
1977	Heat plan committee
	Energy taxation introduced
1979	2nd energy crisis
	Energy tax increase
	Heat law
	Decision of N-gas build-up
1980	Energy tax increase
1981	National energy plan presented
	Heat planning starts
1982	Energy labeling
	Energy tax increase
1985	Nuclear option abandoned
1986	Pol. agreement on CHP expansion
1988	Ban on elec. heat in new houses
1989	Electricity tax increase
1990	Pol. agreement on CHP
	New national energy plan
1991	Pol. agreement on N-gas on large CHP
1992	CO2 tax, subsidy for DH expansion
	Expansion of localized CHP on RE
	New large CHP on N-gas
1993	Pol. agreement on more biomass
	Energy tax increases
	Pol. agreement on IRP
1995	Energy tax for industry
1996	Pol. agreement on more wind power
	Lower subsidy for localized CHP
	New coal based CHP denied
2000	Pilot scheme for CO2 quotas
2004	Agreement on end of feed-in tariff

Table 9. Danish heating and energy policy, main events from mid-1970s to mid-2000s. [295]

Denmark has five million people; i.e., the same number as Scotland or medium-sized English regions; e.g., the west Midlands or south-west England. Figure 23 shows the locations of the 600 main DH systems.

Many small- and medium-sized towns are supplied by gas or biomethane CHP. The largest CHP schemes are on the coast and are fired by coal and/or solid biofuels, delivered by sea. Some are fed by waste incineration. A few small sites have solid biofuel heat-only plants, sometimes supplemented by solar. Settlements as small as 30 buildings may be supplied by DH.

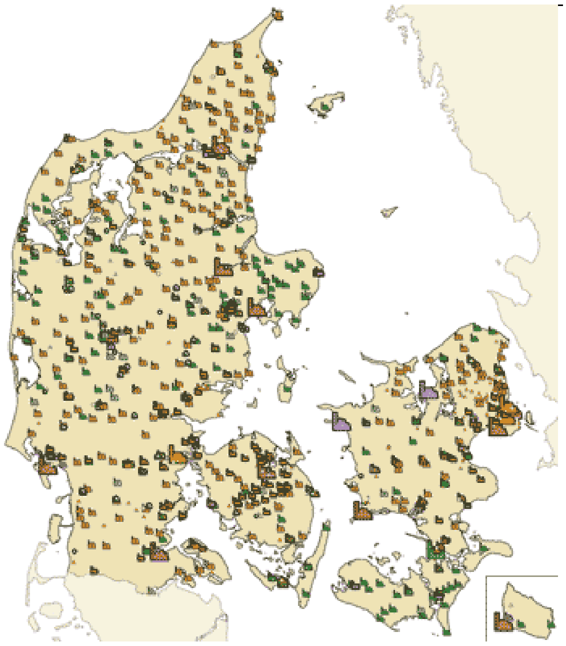


Figure 23. Map of Danish DH systems.
Source: DBDH, www.dbdh.dk.

Over 35 years, Denmark has steadily strengthened its Building Regulations to reduce buildings' need for heat. The efficient supply of low-carbon heat is one part of the picture; building owners and contractors are expected to "do their bit" too. The strategy combines both insulation and DH systems to deliver a least-cost result, although there is evidence of tension between the two.

The text box below shows the minimum standards in current Danish Building Regulations for a new dwelling, using a detached house as an example. It shows how the Low Energy Class I Standard is derived. The Regulations are quite tight compared to UK buildings, where it is now accepted that there is a marked thermal "performance gap", as standards which are required in theory do not seem to be met in practice. [296]

Figure 24 shows a new Danish cavity wall under construction in summer 1977. It has nearly as much thermal insulation as some new UK walls had in 2007; i.e., 75 mm mineral fibre, and it has less thermal bridging around the opening than a UK wall. By 2007, the maximum U-value listed in the Danish Regulations had fallen to 0.2 W/m^{2}K in walls, 0.15 W/m^{2}K in roofs and 1.5 W/m^{2}K in windows. [297]

As a result of this activity on CHP/DH and on insulation, heat consumption per unit floor area in kWh/m^{2}yr and CO_2 intensity in kg per kWh of heat have both fallen. CO_2 emissions per unit floor area, in kg/m^{2}yr, have fallen by 60% since 1975. Total emissions for space heating have also fallen, while thermal comfort standards have stayed level or improved. A winter indoor temperature of 22°C is usual.

Danish Building Standards in 2007

The Building Regulations

Maximum permitted energy use in a dwelling = (70 + 2,200/A) kWh/m^2.yr., where A = floor area.

Covers all space conditioning; i.e., heating, cooling and ventilation plus heating system pumps, fans and controls. Heat consumption counts directly towards this budget, on a 1:1 basis. Electricity consumption is multiplied by 2.5 to correct for the typical overall efficiency of the Danish electricity supply system compared to heat supply.

For a 120 m^2 detached house, energy budget = 70 + 2,200/120 = 88.3 kWh/m^2.yr.

Example: This budget could be met by sufficient insulation and draughtproofing to give a space and water heat consumption of 70 kWh/m^2.yr., plus a boiler fan, pump, ventilation equipment and all controls consuming electricity at 7.3 kWh/m^2.yr. This combination would give a total consumption of 70 + (7.2/0.4) = 88 kWh/m^2.yr.

Low-Energy Class I

Maximum permitted energy use = (35 + 1,100/A) kWh/m^2.yr.

For a 120 m^2 detached house, energy budget = 44.2 kWh/m^2.yr.

Example: This budget could just be met by enough insulation and draughtproofing to give a space and water heat consumption of 33 kWh/m^2.yr., plus a boiler fan, pump, ventilation equipment and all controls whose total electricity consumption is 4.5 kWh/m^2.yr. This combination would give a total consumption of 33 + (4.5/0.4) = 44.2 kWh/m^2.yr.

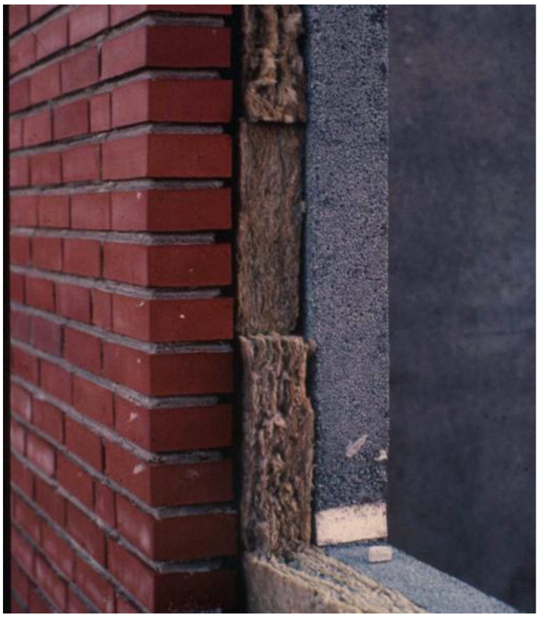


Figure 24. New cavity wall in Denmark in 1977.
Courtesy: Prof. R J Lowe.

Denmark regulates DH as a natural monopoly. Because of the adverse effects of competition in the supply of heat down an urban or suburban street, consumers in towns with DH are expected to use DH, not electricity or oil. This policy is maintained in the interests of reducing overall consumer costs. [298]

When Denmark discovered North Sea gas in the late 1970s, it laid gas pipes in some built-up areas which did not already have DH, to reduce oil dependence as fast as possible. Consumers in a town or suburb with piped gas are encouraged to use gas heating, not electricity or oil.

Under the zoning/integrated resource planning principle, councils which wish can make connection to piped heat compulsory in designated areas. Few have used the power in existing buildings, but new construction is obliged to connect if an area is zoned for piped heat or piped gas. [299] This obligation is increasingly academic, though, because most householders now voluntarily connect to DH soon after a heat main is laid in the street. Given the convenience and lower running costs, the connection raises a house's value by up to £8,000-10,000. [300]

As a *quid pro quo* for only having one heat provider in built-up areas, piped heat suppliers are constituted as non-profit bodies. Most are municipally- or cooperatively-owned and were built for environmental and/or energy security reasons.

Heat zoning raises questions over how compatible DH is with "deregulation", "choice" and "free markets". One could also ask: "How compatible is *laissez faire* with more efficient use of scarce fuel resources?" To the extent that UK policy has obstructed such initiatives and has depleted the North Sea of 75% of its oil and conventional natural gas in a generation, as Figure 2 showed, the answer could be: “Not very”. [301] The results of a consumer survey to ascertain if UK town-dwellers wish to spend more on heating their home in the interests of “choice and competition” would be interesting.

The Danish Building Regulations set reduced U-values and reduced need for heat *per se*. Current discussion may lead to new Regulations being amended, so that part of the sum budgeted for more insulation of new urban and suburban buildings is re-allocated to extending low-resource piped heat systems and the insulation increase is only implemented in lower-density areas. This abates CO_2 emissions more effectively for a given expenditure. Added insulation is coming up against diminishing returns. So far, in suburban districts, the provision of more resource-efficient piped heat systems is not. [302]

A number of features seem to sum up these Danish advanced “low-resource” heat networks:

- Low flow temperatures. A typical Danish “low” temperature is 65°C. The lowest in use is 52°C, in Lystrup. Traditional Danish DH systems, as built 30 years ago or more, operate at peak flow/return temperatures as high as 95/50°C, although 80/40°C is more typical.
- Return temperatures as low as 15°C when the incoming cold tap water is at 8-10° C
- Flexible PEX pipes if the system pressure permits, instead of steel or copper.
- Direct connection of radiators. This is already standard in Denmark. It gives lower costs, especially in suburbia, than the indirect connection and higher temperatures historically used in Sweden and Finland.
- Smaller pipes than in the past to reflect the lower peak heat losses, possibly 2x12 mm for detached house connections or small groups of low-energy row houses.
- Storage of DH water for DHW production, with the flow temperature reduced to 50-55°C.
- A DHW coil/heat exchanger on the consumer side with return temperatures as little as 5 K above the incoming cold water temperature.
- Pipes in suburbia laid below pavements or front gardens, not the roads, reducing excavation depths and reducing house connection lengths.
- Twin pipe, not two single pipes. To reduce heat losses further, oval pipes are preferred as soon as a manufacturer starts to produce them on a commercial scale.
- Good pipe insulation, including foil protection on the PU foam.

35% of Danish natural gas is used to heat buildings via heat-only boilers. Now that gas is running down, some of the gas networks are set to be replaced by heat networks, which are seen as more sustainable. In 2009, the Climate Change and Energy Ministry asked the district councils concerned to plan for a shift away from individual gas heating towards piped heat and/or other options. [303]

Denmark's "peak natural gas" occurred in 2004. See Figure 25. Its gas depletion curve appears to be about five years behind ours, which is shown in Figure 2. The Energy Ministry projects a 40% reduction in natural gas consumption between 2000 and 2030. If achieved, this should avoid very much dependence on imports.

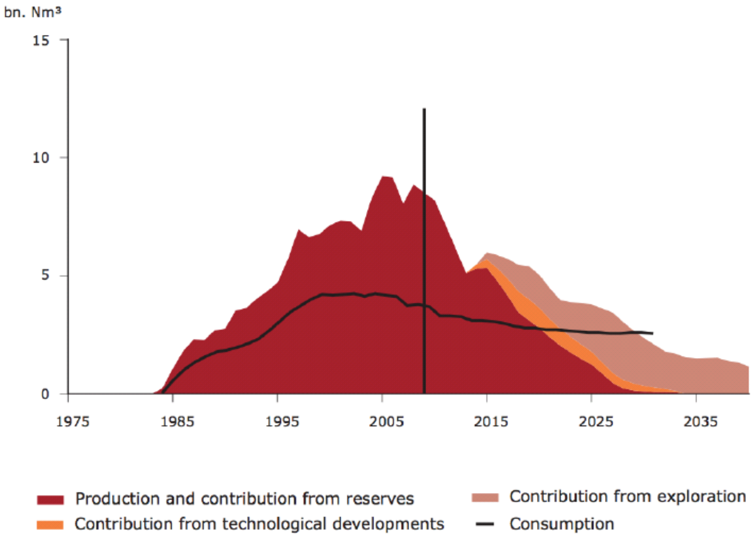


Figure 25. Danish peak gas and predicted rate of natural gas production. [304]
Source: Ministry of Climate Change and Energy.

In areas too far from heat networks, and/or not dense enough, the general preference is for GSHPs to replace natural gas. [305] [306] This implies that, as individual gas heating is phased out, Denmark's division of heat supply would change from three zones to two zones; i.e., a built-up zone 1 with heat networks and a dispersed zone 2 without them. Our suggestion is that the UK go from an uncoordinated arrangement, albeit with most of zone 1 heated by gas, and much of zone 2 heated by oil, to a similar system.

UK consumers are obliged to connect to mains drainage and possibly water if it is available in their street. They may not use private systems. The rationale behind this legislation was to ensure that building owners act in the wider public interest. We find it hard to see a great difference in principle between zoning drainage and zoning the heat supply, if the latter helps to provide the UK with relative energy security and other benefits in 2050.

The philosophy may also be spreading to Germany. A recent IEA report discusses optimal levels of retrofit insulation. It concludes that the costly measures featured in some Passivhaus retrofits could be avoidable in towns and cities where piped heat is provided. “Sub-Passivhaus” measures, and connection to CHP/DH systems, could lead to lower CO_2 emissions, at lower cost in £/tonne saved, than aiming at Passivhaus standard and heating by gas boilers or electric heat pumps. [307]

Reaching this end state needs both collective and individual action; i.e., by central and/or local government, as well as individuals and families. The IEA notes that:

> “A strategy to bypass these barriers is needed in the form of integrated energy planning for neighbourhoods [and/or] energy master plans for whole cities”.

The EU has recently issued a new draft Energy Efficiency Directive. [308] The new Directive is set to replace the existing Cogeneration Directive, which is felt to have been ineffective. It would require member states to prepare national plans for district heating and cooling and to incorporate this into local spatial plans.

California

> “[The] investor-owned utilities recently reported the results of their 2009 efficiency programs, which show a 10 percent increase in annual savings from a record-breaking 2006-08 program cycle, providing an estimated reduction in CO_2 emissions of more than 1.5 million tonnes for that year alone. These gains were driven by investments of about £420 million, or 2.5% of the utilities’ revenues, as energy efficiency continued to be the cheapest resource available, costing less than half as much [2.5 p per kWh] as supply-side alternatives. [309]

California has a population of 40 M and a similar GDP to the UK. Significant institutions include a State Energy Commission (CEC), dating from the 1970s, and an older Public Utilities Commission (PUC). The CEC sets state energy policy and commissions research. The PUC regulates investor-owned utilities, which supply 75-80% of the state’s electricity and most of its natural gas.

The state has 12 investor-owned and 31 publicly-owned electric utilities. See Figure 26. The PUC has no jurisdiction over consumer-owned cooperatives or municipal utilities; e.g., Los Angeles Water and Power or Sacramento Municipal Utility District. These utilities are regulated locally by boards of governors.

Figure 26. Service territories of Californian electric utilities. [310]

NOTE: The majority of investor-owned electric utilities also supply natural gas.

Soon after the 1973 energy crisis, some people in California recognised that energy efficiency was a strategic alternative to new energy supplies. The history of least-cost planning dates back to 1975, although efforts before about 1978 were experimental and very tentative. [311] They progressed more rapidly by the late 1980s. By the early 1990s, many programs had been fine-tuned and participants agreed what was working best and how to improve it further.

Many obvious but useful lessons were learned; e.g. best value was often achieved by subsidising energy-efficient refrigerators or lights at manufacturer or distributor level, not via rebates to retailers or consumers. A small sum of money; e.g., £25 per refrigerator, goes much further if it is contributed at this level than if it is offered as a rebate after further distributor, wholesale and retail mark-ups. It could reduce the final retail price of an energy-efficient device by, say, 95% rather than by 25%.

The first most important move in all the US states, including California, which induced investor-owned utilities to invest in energy efficiency, was to *decouple* their profits from their sales. This step ensures that, in principle, regulated utilities do not lose money from diversifying into energy efficiency. [312]

But if a regulator then goes further than “decoupling”, and allows utilities to keep some of the net profit from selling their customers negawatts, not megawatts - so-called “*shared savings*” - one can expect rapid investment. This happened in California at the peak of least-cost planning, in the early 1990s, when the rules were changed to allow shareholders to keep 15% of the net profits. The pressure towards energy efficiency became overwhelming, because more investment in negawatts now led directly to higher profits for shareholders.

In 1993, Pacific Gas and Electric Co. (PG&E), which supplies gas and electricity to central and northern California, disbanded its power station construction division and announced plans to build a “conservation power plant”. [313] It would be as effective as, but would cost less than, a fossil-fuelled one.

PG&E ran daylighting courses for practicing architects. In association with the Rocky Mountain Institute, it conducted the ACT^2 experiment, in which buildings on seven sites were retrofitted to reduce their electricity and/or gas usage by 45-75%. Many important issues arose, including the divergent perspectives held by different professions on how to assess the financial performance of energy efficiency investments. This created misunderstandings and difficulty in working together, but once resolved, offered to yield large energy and CO_2 savings. Workshops were held with M&E engineers and other professional groups and definite progress was being made.

By 1994, though, a strong US lobby had emerged for “deregulation”. There was strong pressure to allow large industrial consumers to opt out and buy electricity direct from “out-of-state” suppliers via the high-voltage wires owned by the regulated monopolies. From 1998, most US least-cost planning programs were scaled-back or terminated, the ACT^2 team was disbanded and in 2001 California experienced rapidly-fluctuating wholesale prices and serious disruption to its economy.

In hindsight, deregulation was perceived to have largely failed. [314] Strict regulation was reintroduced for investor-owned utilities in the 2000s, after an energy efficiency-based response to the electricity shortages of 2001. This emergency response included, *inter alia*, replacement of all the state’s incandescent traffic lights by LEDs. [315]

By the late 2000s, the priority given to energy efficiency had apparently returned to that of the early 1990s. [316] Per capita electricity consumption in 2009 was the same as in 1975 and the state hopes that it may start to decline within a few years. This seems to show the success of least-cost planning at its peak and the momentum towards energy efficiency which was built up in earlier years.

About 12 US states have imposed least-cost planning on their investor-owned utilities to a similar extent. [317] In 2008, the American Council for an Energy-Efficient Economy particularly commended the least-cost planning programs of ten other US states: Connecticut, Maine, Maryland, Massachusetts, Minnesota, New York, Oregon, Rhode Island, Vermont and Washington [318].

8. Lessons for Building Designers

Summary

The authors were asked to give some examples of lessons to be drawn for those involved in practical building design; e.g., architects, engineers and surveyors. This section tries to do so. It brings together several findings which are scattered throughout the report.

Some technology used to reduce the energy consumption of buildings, or their CO_2 emissions, is fully under designers' control. U-values, air leakage levels, fenestration, doors , ventilation and heating system controls and their usability, are within their remit. They can also incorporate technologies such as passive solar and daylighting as far as the site permits. There appear to be great misunderstandings, however, as to which of these can reduce CO_2 emissions most extensively and economically.

Some potential improvements to buildings' energy and CO_2 performance are outside designers' control and/or their usual remit. One is low-carbon heat infrastructure. Another is reducing the electricity consumption of and the heat gains from the electrical appliances, kitchen and office equipment.

Areas under Designers' Control

Fabric Insulation

As Table 7, Chapter 5 shows, there is no government help towards anyone who wishes to insulate new buildings beyond the minima in Part L of the Building Regulations. In many circumstances, going further is justified.

Although the Building Regulations have not always required all the measures which appear to make good sense to the UK, fabric insulation has been relatively well-studied over the years. Added thicknesses are subject to very diminishing returns. In the light of these limits, we appear to have made more progress with added thermal insulation than we have with reduced air leakage or refinements to fenestration design.

Fenestration and opaque doors

The present support system offers no help towards more use of passive solar or daylighting in new buildings, although they can be very cost-effective. Designers should stress to clients the value of these technologies in reducing CO_2 emissions.

Based on our analysis of the existing cavity-walled urban house, even if the existing windows and/or opaque doors need replacement there is no apparent energy benefit to fitting high-performance triple glazing instead of high-performance double. With triple, heat consumption goes *up*, not down. There are more passive solar gains through two panes of glass and one low-e coating than through three panes and two low-e coatings, which outweighs the penalty of the higher conduction losses. Also, frames to hold two panes of glass are less bulky and admit more solar gains. Given that passive solar is cheaper than most other renewables, it would be helpful for designers to become more familiar with the tradeoff between passive solar gains and heat losses, including Passivhaus-certified buildings.

The investigation of the rural house suggests that the shorter heating season after external insulation changes the situation and a potential CO_2 penalty from three-pane windows may turn into a small CO_2 saving. Further work would be useful. In an average UK climate, it is unwise for designers to invest in windows and doors beyond high-performance double pane unless they have confirmed that they save energy and reduce CO_2 emissions enough to justify the extra cost.

None of this refinement is apparent from the use of SAP or SBEM for buildings in the domestic and non-domestic sectors respectively. They are Building Regulations compliance tools, not design tools. We are concerned that the UK has confused the two processes. Designers are expected to reach a defined level of CO_2 emissions via the options in SAP or SBEM, but there is no facility for them to explore the issues in PHPP, which was calibrated with reference to the results of dynamic thermal simulations and can help to indicate the benefit or otherwise of using passive solar and varying the building’s thermal capacity.

Use of SAP as a design tool may lead to perverse outcomes which increase GHG emissions. Or more likely, its limitations may prevent useful options being explored.

Air Leakage

The standards that became mandatory in Sweden for new buildings in January 1978, namely ≤1-3 ac/h @ 50 Pa in buildings of varying geometry, are still rare in new UK construction. There is little evidence that improvements to new buildings abroad had a dramatic extra cost, unlike thicker thermal insulation, which does have a cost. Designers working at the level of individual building projects would probably be able to reach levels such as 1.5 ac/h @ 50 Pa in the near term, even though this is not yet a UK legal requirement. This would need a major change in current design education, which does not focus sufficiently on airtightness at present.

Heating Controls

There remain major gaps between UK standard heating controls and in other European countries. We seem to pay a price in higher CO_2 emissions. Based on measurements, some installers suggest that revised condensing boiler controls in small buildings could save 15-20% of the fuel typically consumed in UK practice. [319] This is a greater potential CO_2 saving than raising the roof, wall and ground floor insulation thicknesses by 50%, assuming that these are already 125-250 mm all round the building; i.e., opaque U-values around 0.2 W/m^{2}K.

There would probably be no overcost. The approach is conceptually simpler than UK-type time control. To say the least, it seems more economical to change from stop-start to load compensation controls before adding 20 m^3 of thermal insulation to the opaque fabric of a new semi-detached house. Or on a larger project, which has a full design team, this should be within the means of most M&E engineers.

Care needs to be taken with heating controls specified by designers to ensure that they are easy to use and understandable by the user. Various field trials show that users have a poor understanding of heating controls and control over them ([320]Pett and Guertler, 2004, [321]Shipworth et al, 2009, Stevenson and [322]Rijal, 2010, [323]Gill et al, 2010, [324]Coombe et al 2010) and that the addition of heating controls can actually *increase* energy use due to poor user understanding (Shipworth et al, 2009) .

Heat Sources

As Table 7 showed, the grants on offer for different heating systems are only weakly-related to a technology's intrinsic merits in reducing the UK's GHG emissions. But a designer's duty includes advising his or her client of a technology's intrinsic merits and its usability.

If a grant program is inconsistent, designing buildings around it leads to the adoption of ineffective or needlessly costly ways to reduce CO_2 emissions. If the client proceeds to implement lower-CO_2 measures, and foregoes the subsidy, he or she loses out financially. This places some designers in an awkward position. It may confuse clients too. Such a perverse situation arises because the support programs are so poorly thought-out and technically ill-informed.

In new buildings, designers should advise clients of the importance of choosing a space heating system which is flexible as to energy input. It mainly means technology able to utilise sources of low-grade heat; i.e. probably a radiator system or UFH. [325] A warm air system may need a peak water flow temperature of say 55-58ºC to deliver air at 50˚C. 55-58˚C appears too high for ASHPs, because of the penalty in cold weather COP, although it looks accessible to other systems including GSHPs and CHP.

In built-up areas, designers should make the radiators and other internals compatible with future connection to a piped heat system. Panel radiators should be slightly oversized compared to a 80/60ºC system. Controls should be designed to yield a very low return temperature, which implies weather compensation and not time controls. DHW heat exchangers should aim to give minimum return temperatures, using the cold incoming tap water in a counterflow heat exchange arrangement. This is common practice on the continent and almost unknown here.

In low-density areas, it would help to make the emitters, etc compatible with possible future connection to a GSHP. A low flow temperature then becomes even more important,, although not as low as needed by ASHPs.

The design changes which lead to a lower return temperature would raise the seasonal efficiency of natural gas or LPG condensing boilers today, from the mid 80s% to the mid or even high 90s%. This would not only reduce CO_2 emissions now but provide added flexibility for the future.

Whether a building is connected in future to piped heat, or to an electric heat pump, heat emitters with lower flow temperatures, lower return temperatures and DHW tanks with larger heat exchangers would clearly raise the system's energy efficiency. Modifying new heating systems which are installed now is likely to suit both these new methods of heating buildings, whichever is used in a particular building. This should be implemented by designers now in all buildings and should be referenced in legislation.

Ventilation

Most people welcome the concept of "heat recovery" on the ventilation air. The tacit assumption is that it is "a good thing". Heat is most often recovered by a balanced ventilation system with an air-to-air heat exchanger. But if the heating system has low CO_2 emissions; e.g., CHP, there may be little or no CO_2 benefit from using balanced MVHR in existing buildings, as opposed to the less costly option of continuous mechanical exhaust ventilation (MEV) which uses only a little more energy than MVHR. The energy consumed to operate the fan(s) is much higher-grade than the energy being recovered; i.e., it contains more exergy; see Appendix 1. It may be futile to consume 1 kWh of electricity to recover 1 kWh of heat.

The benefit of fitting MVHR rather than MEV is especially marginal in small urban buildings, with no chimneys, [326] heated by gas now and with potentially lower CO_2 emissions from a future heating system, like natural gas or biomethane CHP. If the air inlets used with MEV systems can cool the return water to a future CHP system, or to today's condensing boilers, which raises energy efficiency too. Best advice seems to be that designers should always calculate the specific fanpower of different ventilation systems and minimise the overall CO_2 emissions, bearing in mind possible future changes to the heat supply.

Whatever MV system is chosen, controls need to be specified by designers with care, to ensure that they are easy to use and understandable by users. Various field trials show that users have a poor understanding of MV controls (Stevenson and Rijal, 2010 [327], Gill et al, 2010 [328], Coombe et al [329]. Users may turn off ventilation systems altogether if they are poorly designed and installed which can result in poor indoor air quality (Crump et al, 2009)[330]. From experience, it cannot be assumed that newer controls will automatically be easier to use. This needs to be referenced in legislation and supported by field trials like those carried out in other countries.

Another possible move is from today's rural heating systems to a GSHP. There may be more of a case for choosing MVHR if the effective coefficient of performance (COP) of the MVHR system;

i.e. kWh of heat recovered per kWh electricity consumed, is higher than the COP of the heat pump.

Non-Domestic Lighting

There are no grants for non-domestic buildings to exceed the lighting system efficiency given in Part L2 of the Building Regulations. Yet it is likely to be an attractive investment. Good systems may be able to provide as much light and use 40-45% less electricity than the threshold in the 2006 Building Regulations. This was 50 lm/W including luminaire losses.

Since non-domestic buildings use more primary energy for lighting than heating, halving their lighting energy consumption would reduce CO_2 emissions more than completely eliminating their space heating energy demand. Attending to the lighting in this way is considerably easier.

It is unlikely that any buildings bar a handful meet best practice for energy-efficient lighting. Best available energy performance advanced by 10% between 2007 and 2010, so even what was advanced or best practice in 2007 was dated by 2010.

Surprisingly, a minimum lighting system efficiency was removed from Part L2 in 2010 on the grounds that this gave “extra flexibility”. In owner-occupied commercial buildings, or public buildings, designers have scope to specify the lighting to go well beyond these minima. They should advise their clients of the cost benefits of doing this, which appear to be significantly more favourable than raising insulation to Passivhaus levels.

Areas outside Designers’ Control

Low-Carbon Heat Infrastructure

Some of the potential for lower-energy, lower-CO_2 buildings is outside the control of designers or developers. It is more under the control of central or local government, which can choose to make low-CO_2 infrastructure available; e.g., heat mains. With the existing lack of powers as regards wayleaves, deemed planning consent, debt recovery, etc, hot water supply is a riskier venture for private companies than electricity, gas or cold water supply. It is unsurprising that investment is near-zero.

Some building developers have said privately that infrastructure is the responsibility of the public sector, not of the private sector. Accordingly, they say, government should “do its bit” to assist a developer which constructs buildings to higher thermal standards. We agree.

Where developers provide DH to new buildings, to meet UK regulations, there is a good case for familiarising themselves with advanced Danish DH practice and utilising this to the maximum extent. They should resist proposals to design and lay out the system according to standard UK practice. In buildings with low heat consumption, this will lead to high percent network losses. Good practice should be able to keep heat network losses no higher than electricity network losses in supplying LV loads; i.e., 12-13%.

Electrical Appliances and Office Equipment

Most designers have little or no control or responsibility over what their clients do to procure plug-in energy-efficient electrical equipment. Yet they are legally responsible for designing buildings to stay acceptably cool in summer. Internal temperatures are raised in this season by the pervasive use of inefficient electrical equipment, not just by sub-optimal building design; e.g., poor orientation, excessive glazing or lack of solar shading.

The consumption of this electrical equipment is largely controlled by large companies which mass-produce electrical goods and distribute and sell them worldwide. Their decisions influence; e.g., whether a 700 mm TV screen consumes 250 or 25 W(e), or whether an office ICT system with 20 PCs and a central hub consumes 100 or 5 W(e) in standby and 2 kW(e) or 100 W(e) during working hours.

Government can exert decisive influence, as happened in Switzerland. In the 1990s, the federal government persuaded manufacturers to produce more energy-efficient office and other equipment for the Swiss market. This was backed up by the prospect of legislation in the event of non-compliance. Or government can legislate. But in the absence of one of these actions, purchasers find it hard to get accurate information and most are far too busy running their business/other organisation to bother over seemingly small differences, or over any difference. Major progress has to come from government “doing its bit” and not abdicating its responsibility.

Pending that, the design community should formally ask government to act on the matter. A parallel example was the 1990s lobbying by the Chartered Institute of Building Services Engineers for mandatory airtightness standards on new non-domestic buildings. This followed several cases of new buildings which could not be kept warm with the space heating system provided by the design team. Mandatory airtightness standards became law on new UK offices, hospitals, schools, etc, many years before they became mandatory on housing.

9. Conclusions

1. Climate Change Policy

9.1 The UK probably needs to reduce net GHG emissions by over 100% by 2050. Before 2050, we should be starting to remove more GHGs from the atmosphere than we are putting in.

9.2 A comprehensive, *integrated* climate change and energy policy must be rapidly developed that combines a very wide range of *affordable* energy-related measures, CO_2 sequestration and the safer geo-engineering techniques. This would strengthen the UK economy and underpin current and future citizens' wellbeing.

9.3 It would be especially fitting for the UK, the first industrialised nation, to show other countries how to move from fossil fuels towards an affordable system which utilises *existing technologies* to provide energy security after fossil fuels and mitigate climate change. This would offer to position the UK as a leader and role model.

9.4 Climate change policy should be developed equitably, in the interests of all citizens, and not allowed to impact disproportionately on low-income groups. The situation should be regularly reassessed. Proposed policies should also set out the potential environmental and economic burden, if any, which they place on future UK generations.

9.5 Technologies to reduce the CO_2 intensity of an activity by 70% now are more beneficial than those which reduce its CO_2 intensity by say 10% now and 70% in 2030. Government should prioritise and support technologies delivering earlier, larger CO_2 reductions.

9.6 The most pertinent implications for the agricultural sector are not related directly to reducing energy consumption for heating, lighting, drying and traction. Such measures have much in common with improvements to the industrial, buildings and transport sectors. The unique role of farming and forestry may turn out to be its potential for CO_2 sequestration at modest costs.

9.7 Unsuccessful moves in energy and climate change policy, relative to the UK's international competitors, could set in motion a serious long-term decline in its fortunes.

9.8 Targets should be drawn up for maximum cumulative UK GHG emissions from 2011-30 and from 2030-50.

9.9 The government should assess the potential for the UK farming and forestry sector to provide CO_2 sequestration services whilst also achieving potential synergies; e.g., improvements in soil fertility via increased organic matter content.

2. Energy Economics - The Coming Age of Scarcity?

We must respond to climate change, as discussed in chapter 1, and we are increasingly concerned over fossil fuel shortages and security of energy supply. But it is *economics* above all which dictates that our energy future will be very different from the past. Future energy supply systems are much costlier than the fossil fuel systems that fuelled the development of industrial society.

A very limited analysis, using offshore wind in a fuel-saving mode to illustrate the point, suggests nearly *a ten-fold* rise in cost compared to 2010 fossil fuel supply. Policy-makers focussed on narrow aspects of the energy problem, typified by the phrase “green energy”, have not realised the significance of this point.

If building, operating and maintaining future “sustainable” energy systems takes an excessive fraction of a nation’s resources, the process becomes self-defeating. Investment in the energy sector starts to absorb the very wealth that it is meant to create. The consequences could be worse than the 1970s “oil price shocks”, which acted as a major tax rise on the UK economy.

The UK has to come to terms with the twin challenges of fossil fuel scarcity and rising energy supply costs sooner than some other countries. This reflects the combination of falling supplies of indigenous fossil fuels and its chronic balance of payments deficit.

The government needs to focus on the economic implications of current energy policy and to consider more affordable options. The only major one which appears to us to broadly compete with the cost of today’s fossil fuel is energy efficiency in its diverse forms, along with emphasis on *low-cost* renewables.

3. Improved Energy Efficiency

Energy efficiency appears as significant to policy as the discovery of a new series of giant oil or gas fields. The resource available is usually cheaper than today's world price of fossil fuels, and it would be much more permanent.

Energy policy-makers should treat the potential of energy efficiency in all its forms as seriously as they have treated the last 50-100 years' exploration of the earth's crust for oil and natural gas deposits.

It appears practicable to pursue such a policy at little or no extra cost versus the current fossil fuel-based energy system. There would be a saving to the UK versus the policy of shifting to electricity from renewables, fossil fuel CCS and/or nuclear fission.

The UK has not yet exploited energy efficiency measures which abate CO_2 emissions at negative or low costs; i.e., in a broad range of minus £150 to £50-150/tonne.

There is widespread confusion between *energy* in general and *electricity* in particular. Confusing the two terms means confusing the debate.

Measures to use electricity more efficiently, including lighting retrofits, seem very profitable to the UK compared to building new "low-CO_2" generating plants or even running existing gas, coal, nuclear and offshore wind power stations.

We do not follow why the UK has a *de facto* policy to spend over £20 billion/year on the electricity supply system up to 2020 but has no policy to spend a serious sum on the more efficient use of electricity.

The key to a more affordable energy future does not lie in "high-level" academic research on "innovative" technologies, useful as this work might be in the longer term. The potential which we identify can be realised via the lavish application of diverse *existing, proven* and *demonstrated* technologies.

The government should publish a marginal abatement cost curve (MACC) for the energy efficiency measures, CO_2 sequestration measures and renewable supply systems available to the UK, to indicate what the impacts would be on total UK energy consumption and on net GHG emissions. Technologies should be costed on the basis of mature market costings if possible; e.g., examples where our industrial competitors have already invested in these options.

The UK should cease public support for technologies which abate CO_2 emissions at costs such as £150, 300, 600 or 1,000/tonne, and upwards unless they have exceptional unrelated benefits. Scarce resources going into expensive technologies should be diverted into low-cost CO_2 abatement measures.

Public funding should be restored to applied research on the efficient use of energy in buildings; i.e., measurements of the real world energy performance of buildings as opposed to laboratory tests of building fabric elements and services. The UK all but terminated funding in the late 1990s. Compared to its industrial competitors, it lacks bodies which are charged with carrying out necessary work in this field and which the construction industry can rely on as impartial sources of information.

Energy research should be coordinated by a single institution which is adequately- and securely-funded and -staffed.

4. Energy Supply - Where From?

The lower the UK's energy consumption, the more selective and critical it can be over what supply it invests in. Significantly reduced energy consumption has benefits in the improved flexibility and resilience of future energy systems.

The UK's energy system is set to need a minimum storable fuel input to provide a buffer between energy supply and demand. The differences in storability between different energy vectors; i.e., heat, fuel and electricity, influence what strategic choices we should make as our energy system evolves from fossil fuels towards renewables.

12% of energy delivered to UK consumers in 2009 was for "essential electricity". The other 88% was used for tasks that needed energy in the form of heat and portable fuels.

By *not* electrifying heating and road transport as the amount of energy from renewables rises, the technical difficulties in operating future electricity networks are reduced if not avoided. The *higher the efficiency* of electricity use, and the *less* energy that is supplied in the form of electricity, the higher the proportion of electricity in 2030 or 2050 which can be supplied from despatchable sources. This offers to help significantly with network stability.

The government should put a figure to "essential electricity" consumption now, in 2030 and in 2050. This is to help define the electricity supply challenge more closely. It is essential to end the policy confusion between "keeping the lights on", a goal which one would agree with, and an "all-electric economy", an aim first put forward by the UK Atomic Energy Authority in the 1970s and which many would disagree with.

Recent UK policy has been dominated by the term "micro-generation", but few people appear to want a semi-autonomous building full of expensive "kit" to maintain. Surveys suggest that they place more value on security, convenience, affordable running costs, freedom from manual intervention and low maintenance costs. This is more easily-achieved using larger-scale systems which exploit the benefits of scale effects and economise on scarce technical skills.

More development work is needed to produce clean synthetic fuels, using spilled electricity from windpower and other variable sources. These fuels can supplement the limited biofuel resource *and* give us a renewable energy system with a similar security of supply to today's fossil fuel system.

We note the major role that piped hot water plays in built-up areas of some other European countries; e.g., Denmark, Finland, Sweden and Iceland. 50-90% of their buildings are connected to heat networks.

UK progress needs government action to ensure a level playing field so that the supply of hot water is subject to the same legal and financing rules as with traditional utilities. These are "de-risked", depending on the degree to which they are regulated as natural monopolies. Government help with technology transfer is also needed.

The key role of biomass in a climate change strategy may be not to maximise bio-energy production but to optimise CO_2 capture and sequestration, producing modest amounts of clean low-CO_2 fuels to complement other renewable sources.

30 years have elapsed since Southampton developed its heat network, but the UK still has no geothermal licensing system. Without this basic framework, it is very hard to see how this valuable resource can be fully developed.

5. Building a New Energy Policy

Many UK energy markets could be described as dysfunctional. So are government policies which consciously subsidise the least cost-effective options the most. Both failures lead to perverse outcomes. We need to formulate quickly a more joined-up approach which focuses rigorously on energy security after oil.

Examples of strategic thinking on energy include Churchill's 1910 move from a coal-fired to a diesel-powered navy; the Baldwin government's 1926 setting up of a national electrical grid to replace hundreds of incompatible small generating systems; the policy which the UK adopted out of necessity in World War Two and the Clean Air legislation in the 1950s and 1960s. The UK has arguably lacked strategic thinking since the government announced in 1982 that energy supply and demand would be left to "the market".

With the UK's precarious economic and environmental situation, it needs to develop a workable policy quickly. We applaud recent moves to develop new thinking on energy policy at DECC and we hope LIM contributes to the discussion.

A number of straightforward principles should underly an integrated climate change and energy policy. They include : (a) pursuing best buys first (b) giving preference to options which increase energy and/or network security and stability (c) supporting only packages of technologies which are compatible in an energy economics and engineering sense.

The Committee for Climate Change (CCC) has said that: “Analysis by the CCC shows that decarbonising the power sector by the 2030s is the most cost-effective way of meeting the UK’s [CO_2] reduction targets”. We are unaware of any detailed studies of energy flows through the UK economy that demonstrate this point.

The government should widen the CCC’s focus beyond its members’ existing knowledge and experience. This would imply a move from high-level research concentrated on electricity supply to a much wider range of demand-side expertise and to the production, storage and distribution of renewable heat and fuels.

Measures that are not widespread in the UK today need intervention to reduce the cost rapidly to that typical of a mature market. This does not occur at the desired speed under a *laissez faire* arrangement.

Interactions between climate mitigation/adaptation and energy security initiatives need to be better thought-through. Separate initiatives with different rules, including RHI, FIT, ECA, Green Deal et al, should be absorbed into a single program, as part of the development of an integrated and effective policy.

A greater degree of co-operation and flexibility is needed within government so that policy initiatives which are not delivering can be changed or abandoned without delay. This also implies more trials and test programs before large-scale roll-out.

Long-term continuity is essential. It takes years for support programs to build up momentum and start to deliver savings at the full rate. They may perform slowly initially and exceed targets later. Stop-start policies have less impact and may demotivate people, causing needless cynicism.

Support programs should be conditional on retrofit insulation thicknesses being optimised for high comfort standards, so that they do not become inadequate with time. There is a long-standing UK tendency to retrofit insulation thicknesses to buildings which in hindsight are regarded as uneconomically low, but block further improvements.

Support programs should not be allowed to physically compromise more important measures. Fitting solar panels on roofs before airtightness and insulation work has been undertaken may prejudice the implementation of this work - which has more impact on GHG emissions - or increase its cost.

It is crucial that public money is invested in measures that actually reduce net CO_2 emissions, rather than leaving them largely unchanged or even increased. So, all measures or technologies which are supported by public funds need to incorporate adequately-resourced monitoring, measuring, feedback and reporting mechanisms.

We have to make policy choices. A fundamental point is that we cannot spend the same money twice. Each £ billion spent on very expensive technologies starves more cost-effective technologies of funds and indirectly makes climate change worse. It is not sensible for UK PLC to invest in order of descending cost, going backwards; i.e. to promote high-cost, low-return measures as the main priority. But this is the *de facto* policy.

The missing piece of the jigsaw in the development of UK energy policy to date has been energy efficiency. The emphasis of this report is therefore that we should consider *the fine details* of energy consumption “beyond the meter”, where the energy efficiency resource is concentrated.

There are important potential synergies between patterns of UK energy use, heat networks, fuel storage and distribution systems, hot water storage, intermittent ambient energy supplies and electricity network stability.

Large-scale energy efficiency programs could lead to UK energy consumption falling, even as the economy grows, with the UK using progressively less energy but producing more economic output per unit of energy consumed. This could allow a growing proportion of energy to be obtained from renewables, at reasonable total costs.

In a market economy, investing in negawatts would not only reduce total expenditure on energy but would help to *keep down* the price of fossil fuels. It is the marginal cost of alternative energy options, both efficiency and supply, which set a limit to the prices of natural gas and oil.

From time to time, one hears comments that energy efficiency has been tried and has not worked. A valid response would be that it was never treated as central to policy and efforts were half-hearted. We need a fresh start, via a policy which gives it a central role.

Our remaining clean fossil fuels, especially natural gas and LPG, should be used as a ‘bridge’ to a renewable energy future, in the context of dramatic increases in energy efficiency and cuts in consumption.

The UK should take the proposed utility spending over the next decade, recently put at £200 billion, and reassess how/where such a large sum should be spent to reduce CO_2 emissions *most cost-effectively*.

Government should legislate to mandate much more energy-efficient domestic electric appliances and office equipment. Failure to do so is having a twin energy penalty: directly, by increasing equipment electricity consumption; and indirectly, by forcing the installation of electricity-consuming space cooling systems. *In extremis*, it should be prepared to move faster than EU legislation. EU progress is sluggish compared to that of Australasia, North America or the Far East.

More work is needed to produce clean synthetic fuels from wind and other sources of variable electricity. This both helps to supplement the limited biofuel resource *and* to give a renewable energy system with similar security of supply to today’s fossil fuel-based system. Indeed, given the reduced dependence on unstable regimes, the level of security might be superior.

In a finite world, we cannot afford to do everything. Some options are mutually exclusive.

6. Financing Energy Efficiency in Buildings

Chapter 6 makes clear the distinct and separate challenges for energy efficiency as related to the supply of energy for *heating* and to the supply of *essential electricity* for use in lighting, appliances, pumps, fans etc. This distinction is crucial to a clear and effective discussion.

For essential electricity, we suggest that the simplest and most effective way forward is to regulate electricity suppliers so that their financial interests are aligned with those of their customers; i.e., so that both parties profit from investment in the more efficient use of electricity. The present “deregulated” arrangement appears incompatible with bringing this about.

Attempts to impose targets on deregulated private companies so that they sell less energy may conflict with their legal duty to shareholders to sell more.

Mains energy suppliers should be re-constituted as integrated energy services companies (ESCOs) which supply energy to a defined region on a long-term franchise. They should be regulated so as to align their shareholders' financial interests, the interests of their consumers and the interests of UK PLC. It should be possible to finance thermal improvements to urban buildings via this route, both retrofit heat saving measures and supply of low-CO_2 or waste heat via heat mains.

Assistance towards the cost of thermally retrofitting rural buildings would need to involve public sector funding, possibly via a Green Investment Bank. Providing this via electricity suppliers would create a conflict of interest. Most rural buildings are not electrically-heated.

Space and Water Heating

Thermal improvements to large numbers of existing buildings are a long-term enterprise. They have modest returns, especially where the measures displace natural gas; i.e., today's cheapest heating fuel.

The same applies to infrastructural changes such as laying underground pipes to distribute waste heat that is otherwise thrown away by power stations or industry, or heat from solar, geothermal, etc. This type and scale of work also has returns which are reasonable to regulated monopolies, but not to higher-risk, small-scale enterprises.

"Thermal improvements" in built-up areas should include heat networks and low- to medium-cost improvements in insulation or draughtproofing.. The cost-effectiveness in £/tonne is similar. Loans to improve the *energy efficiency of space and water heating* via improved insulation, draught proofing and heat mains in built-up areas could be profitable to the UK if they were financed by low-risk, regulated utilities and repaid by consumers on their energy bills.

Such work also leads to various social benefits, including warmer homes, reduced fuel poverty and fewer deaths or cases of serious illness caused by living in cold homes. These are not apparent on the energy bills, although they would be credits on a UK PLC balance sheet and could be popular with the electorate.

To achieve high takeup, loans for such improvements would need to be legally tied to the property, not to the owner, tenant or lessee. This would also provide security to lenders. But an input from public funds would be needed for lower-income households, who can rarely afford to heat their homes today and cannot afford a loan to improve them either.

Progress on heat networks partly needs government to act to ensure a level playing field, so that they are subject to the same legal and financing rules as traditional utilities. These are partly or wholly “de-risked”, depending on the degree to which they are regulated as natural monopolies. It also needs help with technology transfer.

Efficiency of Electricity Use

Incentives to improve the *efficiency of electricity use* should be easier to set up and deliver results. In contrast to the use of heat in existing buildings, typical investment to use electricity more efficiently in lighting, appliances, office equipment, pumps, fans, controls, etc, usually gives financial returns over shorter timescales.

Many investments could be financed and repaid over shorter periods than loans to finance thermal improvements to existing buildings. Fast-moving technology, especially electronic equipment, also means that devices are paid for over short periods. The potential for improved efficiency is often changing faster than thermal improvements to buildings, which involve labour-intensive work which may not be done again for 50-100 years.

7. International Good and Best Practice

There are useful lessons from regions such as California on how to accelerate the deployment of energy efficiency by regulators aligning the financial interest of energy suppliers with the financial interest of energy consumers. One would hope that we could also learn from California’s adverse experience with retail deregulation.

The UK needs to learn rapidly from regions able to share hard-won experience in implementing energy efficiency in a *coordinated* manner. It should note examples of major policy errors and avoid repeating them. It does not have time to waste on avoidable errors and on reinventing inferior methods. Where possible, suggestions for new financial mechanisms and policies should be based on the most successful experience in other countries.

Successful experience from other regions provides useful examples of good practice, to be studied carefully for useful lessons on what works and what does not. This could be carried out through high-level study tours for civil servants and/or scientific advisers and/or commissioned expert reports for ministers.

We recommend that the government study in particular the following international good practice: (a) California's experience of least-cost electricity planning; (b) Denmark's approach of least-cost heat planning; (c) Switzerland's efforts to improve the energy efficiency of office electrical equipment. These are a few good examples out of dozens or even hundreds.

8. Lessons for Building Designers

Some technology used to reduce buildings' energy consumption or CO_2 emissions is fully under clients' and designers' control. Insulation levels in walls, roof, floors, windows and doors, air leakage levels associated with design and construction methods specified, and ventilation and heating system controls, are within their remit. Designers can also incorporate technologies such as passive solar and daylighting as far as the site permits.

Some important improvements to buildings' energy and CO_2 performance are not under designers' control. Yet ideally they would form part of any cost-effective low-energy design and decision-making process. These include low-carbon heat infrastructure and controlling the unwanted heat gains from electrical appliances and office equipment by making them more energy-efficient. There is a pressing need for government to "do its bit" to complement designers' existing efforts.

Appendix 1

The provision of energy to final users for space and water heating and for industrial process heating is particularly inefficient, compared to the use of oil in the transport sector or the use of fuels such as gas or coal for electricity generation. Pervasive misunderstanding is blocking effective debate in this area. Those responsible for energy policy, R&D, etc, should be encouraged to improve their technical understanding in this area.

To prepare for a future of increasingly constrained energy supplies, with energy resources becoming more costly relative to other goods and services, the quality of energy supplied to consumers should be matched more closely to the quality of the energy needed. Except in a few anomalous cases, this yields economic benefits.

Appendix 2

Strategies to heat the UK's buildings in the future, contributing to CO_2 cuts, keeping costs affordable and providing energy security after oil, could best be based on dividing the UK into zones, according to building density and the most economic and environmentally-beneficial measures to UK PLC. This is the policy in Denmark and parts of Germany and was proposed for other member states by a recent draft EU Directive.

We have doubts over the feasibility of mass electric heating as advocated by the government. Large increases in network and generating capacity would be needed to meet cold weather peaks. The system load factor would drop sharply. Unless all the concerns can be overcome, it may not offer as promising a route towards energy security after oil as was thought.

To heat the urban UK, we think that the lesser of the problems facing us is to seek to organise piped heat so that it works in the urban and suburban UK as well as it works in; e.g., Denmark. It clearly has difficulties, but *all* long-term options pose acute difficulties.

We are concerned that the government recently issued five "pathways" of which none included a large role for piped heat. One featured 100% electric heating.

Scarce UK technical skills should be devoted to ensuring that electric heat pumps in niche situations; e.g., rural buildings with no space for fuel storage, work with very good COPs, before seeking to use them in less favourable circumstances.

APPENDICES

1. Energy Policy and Thermodynamics

Introduction

This appendix is about the potential for saving energy by matching the *quality* of energy supplied to that needed. It is not about the scope for reducing the *quantity* of energy; e.g., using less heat by insulating and draughtproofing buildings. That is a much better-understood topic. Failure to understand both these topics and how they overlap can lead to mistaken initiatives being taken which increase and do not decrease CO_2 emissions.

The First and Second Laws

The first law of thermodynamics states that energy can be neither created nor destroyed. In practical processes, energy is not lost or consumed, but it is only transformed from one form to another.

The second law of thermodynamics states that, in real processes, energy is degraded from higher to lower quality; i.e., from more useful to less useful forms. This process is irreversible. To judge from the misinformation which surrounds the energy debate, this basic law of nature is unknown to many analysts and policy-makers.

Energy quality can be measured by a quantity called exergy, or available work. This reflects the fact that not all "energy" is of any practical use, and some forms are more useful than others [331] [332] [333]. The more exergy that a unit of energy contains, the more useful it is.

Chemical, mechanical and electrical energy are of very high quality. But the usefulness of thermal energy depends on its temperature relative to ambient. The higher its temperature above ambient, the higher its quality and the higher the efficiency of a heat engine which utilises this heat to generate mechanical power. The standard equation for the efficiency of such a heat engine is:

$$E = 1 - T_h/T_e$$

where: T_h = working temperature of the heat engine.
T_e = temperature of the environment to which it rejects heat.

Given the Second Law, it is misleading to portray heat at ambient temperature as renewable energy. Ambient temperatures at the earth's surface do reflect a balance between the incoming solar energy and outward heat losses into space. But if the ambient air or soil is all at 10°C, this heat has no ability to do work and contains zero exergy.

Table 10 lists some different forms of energy in descending order, from very high- to low-quality. It gives the exergy content of 1 kWh of energy in that form, using an external ambient temperature of 10°C as suited to England, Wales or other moderate European climates. A calculation for summer or winter ambient temperatures would give slightly different results.

Form of Energy		**Example**	**Temperature**	**Exergy Content**
			°C	kWh / kWh of energy
Very high-quality	Electricity		∞	1.00
	Mechanical work		∞	1.00
	Chemical energy	Natural gas fuel	∞	1.00
to	High-grade heat	Gas flame, cement kiln	1,800	0.86
		Diesel engine combustion chamber	2,200	0.89
Very low-quality	Medium-grade heat	Autoclave to cure calcium silicate blocks	200	0.40
	Low-grade heat	Hot water supplied to radiator	70	0.17
		Power station cooling water	28	0.06
	Heat at ambient temperature	Soil, lakes, rivers	10	0.00

Table 10. Examples of High- and Low-Quality Energy.

Misunderstandings

Most publications state that condensing gas- or oil-fired heat-only boilers are “very efficient”. Many senior officials of energy companies, government ministers, civil servants and lay people seem to believe this. [334] Over a year, a modulating natural gas- or LPG-fired boiler with the right controls might convert 10 kWh of fuel into 9.6 kWh of hot water, for use in a building’s space and water heating systems. [335] The other 0.4 kWh is lost via the balanced flue or out through the casing. Such a boiler would usually be quoted as having an efficiency of:

$$9.6 \times 100/10 = 96\%.$$

But the boiler has degraded a high-quality fuel, which in today’s equipment can reach a flame temperature of at least 1,800-2,000°C, into low-grade heat. [336] In terms of the Second Law, the boiler has a low, not a high, energy efficiency.

Then consider a 300 MW(e) CCGT generating plant which converts 1 kWh of gaseous fuel, via a flame temperature of 1,800°C, into 0.5 kWh of mechanical or electrical power, or a 500 kW(e) reciprocating engine which converts 1 kWh of gas into 0.4 kWh of mechanical power and 0.5 kWh of useful heat. The principal output of these machines is electricity, which is very high-grade energy. [337] Both of them have a much higher Second Law efficiency than the condensing boiler. Similarly, the heat engine in a car, HGV or ship is fairly efficient at producing mechanical work, another form of very high-grade energy. The usual efficiencies tend to be in the range 25-50% and are rising with development.

Scope for Improvement

The First Law efficiency means the efficiency of conversion before taking energy quality into account. The Second Law efficiency means the conversion efficiency after allowing for the degradation in energy quality. In 1975, the American Physical Society reported results broadly as in Table 11 on the Second Law efficiencies of different energy conversion processes in the US economy. [338] We have updated the list to include technologies in use today; e.g., CCGT power stations.

The fundamental task with space and water heating is to heat buildings and their hot tap water to comfortable temperatures. We can quantify the loss of efficiency by comparing the energy quality needed to that supplied.

The 95% or even 96% seasonal efficiency of a well-installed gas-fired condensing boiler, with good controls, suggests little remaining scope for improvement. But this so-called First Law efficiency does not take energy quality into account. The Second Law efficiency, which takes it into account, is 6%. This signals a theoretical 16-fold potential for improvement. The Second Law efficiency of 3% for electric resistance heating, which also incurs power station and T&D losses, signals a theoretical 33-fold scope for improvement.

Energy-Using Device			**First Law Efficiency**	**Second Law Efficiency**
			%	%
1	Gas-fired condensing boiler		95	6
2	Electric resistance heating from gas-fired CCGT power station, 48% seasonal efficiency, 92.5% T&D efficiency, delivered electricity = 45% of fuel input		100	3
3	Electric heat pump used for space heating, COP = 3, resistance water heating, COP = 1, weighted avge. COP = 2.5, delivered electricity as above		250	7
4	Car petrol engine, 50 kW		25	25
5	Lorry diesel engine, 500 kW	Current practice	42	42
		Advanced practice	55	55
6	Gas-fired CCGT power station, 300 MW(e), on full load		55	55
7	Coal- or wood-fired steam turbine power station, 500 MW(e)		40	40

Table 11. First and Second Law Efficiencies.

NOTES:

1. Devices 1, 2 & 3 - The temperatures needed are treated as a room temperature of 22°C and a temperature of 45°C for hot tap water. The ratio of space heat to water heat is assumed to be 3:1, giving a weighted average demand temperature of [(3 x 22) + (1 x 55)] / 4 = 121/4 = 30°C. The mean ambient temperature is treated as 10°C.
2. All devices - The input fuel is defined as having an exergy of 1 kWh per kWh; i.e. the exergy of the raw fuel is counted, not the resulting combustion chamber or steam temperature. Electricity has an exergy content of 1 kWh per kWh of energy.
3. Device 6 - Full-load efficiency. Part-load efficiency is lower.

Space and water heating, and low-temperature industrial process heating, use 45-50% of all UK delivered energy. The provision of this energy is inefficient precisely because the high quality of the energy supplied is so badly-matched to the low quality of energy needed. The more expensive that energy is set to become, relative to other goods and services, the more relevant this point becomes. It seems set to be very important indeed in a post-fossil fuel world.

In theory, a more efficient means to use a high-grade fuel such as natural gas or biomethane for heating is to burn it in a power station, generate electricity and either:

1. Pipe the rejected heat around and use it directly to heat buildings; i.e., as in a CHP plant *and/or*
2. Use the electricity to drive heat pumps in individual buildings.

A CHP plant uses the heat rejected by a heat engine to heat buildings and supply their hot tap water. An electric heat pump uses electricity, generated by a heat engine or by a source of mechanical energy, to pump heat from ambient up to the temperature needed for space or water heating. In theory, the two processes are equivalent and have equal potential to save fuel. [339] In practice, for several reasons, upgrading the reject heat from a large heat engine and using it to heat buildings usually consumes less fuel and emits less CO_2 than operating small electric heat pumps off the same heat engine. See text box.

CHP and Electric Heat Pumps

To date, practical electric heat pumps have given rather disappointing fuel or CO_2 savings compared even to well-controlled condensing boilers. This underperformance appears to reflect mainly design or installation errors, which could be corrected, given more input of skilled labour.

Another factor is size. A small machine; e.g., a 2 kW(e) heat pump heating a detached house, is fundamentally unable to attain as high an efficiency as a large machine; e.g., a 200 MW(e) turbine in a town-sized CHP station, or indeed a very large heat pump, such as 20 MW(e). Such scale effects are familiar to engineers.

Another issue is that individual electric heat pumps in buildings must pump up heat from relatively low temperatures. The evaporator coil is usually either located in the outside air or buried in the soil. In severe weather, on inland sites, these media may be at respectively -15 and +8°C. One relatively well-performing ASHP has a COP of 1.81 at -15°C, 3.10 at 7°C and 3.75 at +20°C to produce hot water at 50°C, excluding part load losses.

To heat buildings, a heat engine; e.g. a gas-fired CCGT, need only upgrade the cooling water from a normal 25-35ºC to a useful temperature of say 70-80°C, sacrificing some electricity in the process. CHP plants have fewer heat exchangers, especially if the network is directly-connected. Heat pumps need heat exchangers between the different working fluids. Each heat exchanger gives rise to a temperature drop, reducing the efficiency of the whole system relative to the theoretical maximum.

Heat pump suppliers sometimes quote the COP for heating a building in mild weather with low-temperature water. The COP for supplying DHW, or heating the building in midwinter, at an ambient temperature of -5 or -10°C, is lower. At a cost, the COPs of many heat pumps could apparently be raised by reverting to the larger heat exchangers used in the past. This point would be well worth assessing. However, other large improvements in the COPs of small heat pumps are likely to be limited by thermodynamics and by manufacturing costs.

Large heat pumps on DH systems could have important roles in the future. Larger machines are fundamentally more efficient than small ones and can be professionally-designed, -installed and -maintained. Large-scale, long-term heat storage is practicable, enabling surplus windpower to be stored until needed. With deeply-buried coils, and good design and installation, well-designed smaller GSHPs can have good midwinter COPs too, as long as the evaporator coil is not undersized and the deep soil is conductive enough. This usually needs a site survey.

At a minimum, small but viable CHP schemes tend to use 500 kWe gas-fired engines. Diesel engines of this size are also a possibility and have very high conversion efficiencies. Larger CHP schemes may use gas-fired 100-300 MWe CCGT power stations, or coal- or wood-fired steam turbines.

If CHP uses gas-fired CCGT plants, or solid fuel-fired steam turbines, practical COPs can be in the range 10-13; i.e., one obtains 10-13 kWh of hot water for 1 kWh of electricity sacrificed. This assumes that the design flow and return temperatures are 75/25ºC, with three-stage heating. The theoretical COP for these operating conditions is 17-18. The COP would be higher for the pioneering DH systems being built in Denmark, which utilise temperatures as low as 55-15°C.

Given its higher COP, CHP emits significantly less CO_2 than small electric heat pumps if they operate on a grid with the same mix of generating plant. The electric grid can be partly “decarbonised”, which is already a UK objective. There have been statements that using CHP and heat networks would increase the UK’s overall CO_2 emissions in future; e.g., 2030. This seems to assume that a future electricity system would operate on virtually 100% non-thermal generating plant; i.e., wind, tidal, wave, hydro. With present or foreseeable technology, we consider this outcome to be impracticable and probably uneconomic.

As we pointed out earlier, the expense of electricity storage means that even this kind of electricity system is only likely to give security of supply by using large-scale fuel storage. Fuel implies thermal generating plants; i.e., heat engines or fuel cells. These in turn imply reject heat, with an opportunity to utilise it in urban buildings at lower resource costs than using the electricity to operate small heat pumps. Even if totally unforeseen breakthroughs occur, which could keep an electricity network stable without fuel-fired plants, there are still numerous resources which can be utilised in heat networks, but cannot be utilised in electricity networks. Examples include geothermal wells, solar collectors, industrial waste heat and biomethane CHP.

The COP of monitored heat pumps in UK private houses in 1948 was 3.0. [340] A 1977 UK government report used ASHP COPs of 3.5 average and 2.75 at the time of system peak. [341] A Swiss 2004 survey showed seasonal COPs of 2.75 for ASHPs and 3.3 for GSHPs. [342] A more recent German survey showed mean GSHP COPs of 3.7. [343] The last figure was based on using UFH, not radiators, so it looks attainable in new construction but not on retrofit. It seems fair to say that COPs have not made a major breakthrough.

A 2008 EST survey showed mean UK COPs of 1.9 for ASHPs and 2.4 for GSHPs. [344] These COPs included provision of DHW in some, but not all, systems. They included any electric resistance backup heat. They apparently included the heat losses from the DHW tank and pipes, an unusual convention which would tend to reduce the COPs. The highest GSHP COP of 3.2 was similar to the mean COP reported in Switzerland but the spread was high.

It was suggested that the EST findings reflect user habits. But this implies a not unusual attempt to blame building users for design and/or installation failings! For decades, many design teams have delivered buildings of low energy consumption by largely allowing for known user behaviour; e.g., peoples' preferred indoor temperatures, their normal hot water consumption and their tendency to leave lights on unless prompted. [345] It appears that many different factors contributed to the low COPs.

2. Heating UK Buildings

Introduction

Below is a brief discussion of means to heat UK buildings in the future. Consistent with emerging Danish practice, we notionally divide the UK into two zones for space and water heating. We assume that different approaches would be taken in the two areas, which are divided as follows:

- Zone 1 - built-up areas, generally with a piped gas supply and feasible for heat distribution.
- Zone 2 - dispersed, low-density areas, generally with no gas supply and not feasible for heat distribution.

About 87% of the UK appears to have a piped gas supply, but the dividing line is not precise. In our view, zone 2 is likely to expand from 13% if more detailed work is done. Gas pipes were laid in some areas which would be uneconomic if they were re-assessed today by National Grid PLC and which might not suit heat networks either.

Figure 27 shows a clear example of zone 1, Figure 28 an example of zone 2. The low-density detached houses in Figure 29, 1 km from a large village, provide an apparent example of zone 2. The area has natural gas, but it may be too dispersed for heat mains. There may be appreciable numbers of such areas. Conversely, some villages and towns have no gas pipes but appear to be dense enough for heat mains.

Figure 27. Example of zone 1.

Figure 28. Example of zone 2.

Figure 29. Apparent example of zone 2.

Source for Figures 27-29: Google maps and streetview.

In zone 1, we assume that fuels delivered by HGV are unacceptable on environmental grounds and that a mains energy supply would be used for heating; i.e., either piped gas, piped heat or electricity. Table 12 sums up what we see as the characteristics of the principal options for zone 1:

- Retrofit insulation and airtightness.
- Send gas from increasingly renewable sources through the pipes, to heat-only boilers or conceivably to other systems such as gas heat pumps or fuel cell CHP.
- Send electricity from increasingly renewable sources through the wires, for use in resistance heating or heat pumps.
- Send hot water from increasingly renewable sources, and from waste heat, through insulated pipes to consumers' radiators.

Energy Vector		**1**	**2**		**3**
		Piped Gas	**Electricity**		**Piped Heat**
			Air Source Heat Pumps	*Grd. Source Heat Pumps*	
Infrastructure cost		Pipes usually very low, generation plant high, electrolysers fairly high	Very high	High	High to very high
Equipment cost in building		Moderate	High	Very high	Moderate to low
Energy storage to match supply to demand		Straightforward	Difficult	Difficult	Fairly easy
Network security at peak		Good	Poor	Poor	Good
Security of energy supply		Good	Good	Good	Good
Reinforce existing network?		No	Yes	Yes	Not applicable
Need new network?		No	No	No	Yes
Feasibility	City centres	Yes	Probably	No	Yes
	Typical built-up area, 15-25 dw/ha	Yes	Yes	Possibly	Yes
	Outer suburbia, 4-8 dw/ha	Yes	Yes	Yes	Probably
Modify existing radiator systems?		No	Yes, or fit UFH	Enlarge	Slightly enlarge
Energy flexibility		Low	Moderate	Moderate	Good
CO_2 emissions per unit of heat, kg/kWh	Now	0.22	0.21	0.18	0.08
	2030	0.09	0.075	0.06	0.03

Table 12. Options for Heating Zone 1.

NOTES:

1. The infrastructure cost given refers to underground electrical cables, to give a level playing field versus hot water, gas or oil pipes, which are expected to go underground for aesthetic and security reasons.
2. Existing gas pipes carry less energy if fed with H_2 or a CH_4-H_2 mix than with pure CH_4. The infrastructure cost is on the basis of no replacement pipes.
3. GSHPs are unviable in areas of attached buildings and narrow plots. There is no access for mechanical digging equipment, there may be too little ground space to bury an evaporator coil and there is a risk of causing a nuisance by cooling neighbours' gardens.
4. Heat distribution in low-density suburbia; e.g., 5 dwellings/ha, was ruled out in the past. With current UK practice; e.g. system temperatures of 95/60ºC, costs and losses become excessive. With best Danish practice, the threshold for heat consumption per unit length of main falls sharply from ≥700 kWh/yr.m to ≥150 kWh/yr.m. This lower threshold could be met by most UK suburbia, even after significant retrofit insulation.
5. Using piped heat, radiators would not need to be enlarged much. Moderate reductions in heat loss could offset the use of a lower return temperature than on individual heating systems; e.g., 80/30°C instead of 80/60°C. A supply temperature of 75°C would be close to that of existing individual heating systems.
6. Energy flexibility means the ability of the infrastructure to accept inputs from different renewable energy sources. It is least for a gas network, whose fuel specification must suit existing appliances and pipe materials; intermediate for electricity, which can accept any very high-grade energy; and highest for heat networks, which can accept any low-grade energy too.
7. Network security refers to severe weather when heating power may be two to three times more than on a normal winter day. Only applicable to electricity, piped gas and piped heat, not to systems using stored fuel.
8. Plant mix for piped heat now is assumed to be 48% CCGT, 49% gas reciprocating engine CHP, 3% oil or LPG reserve/backup boilers, the rest of the peaking plant being displaced by heat storage and the gas engine CHP systems, which can also provide grid balancing services on peak days.
9. 2030 plant mix is assumed for illustrative purposes only to be:
   (a) piped gas - 40% fossil CH_4; 60% other CO_2-neutral gases, possibly a mix of biomethane from wastes and electrolytic H_2
   (b) electricity - 5% coal, 25% gas CCGT, 5% plain gas turbine, 65% renewables and/or nuclear
   (c) piped heat - 15% reciprocating engine gas CHP, 25% CCGT CHP, the gas being 20% biomethane from wastes and 80% natural gas; 50% solar, geothermal or spilled wind electricity; 8% industrial waste heat. After use of heat storage, and some use of reciprocating engine CHP for peaking, it is assumed that a residual 3% comes from

backup/reserve boilers, operating on liquid fossil or biofuel. Its emissions are counted as 0.25 kg/kWh.

In zone 2, we assume that the only mains energy service is electricity. Buildings not using this for heating would use fuels delivered by HGV and/or active solar on the building for space or water heating. Table 13 summarises the characteristics of some technologies which appear worth considering for zone 2, namely:

- Retrofit insulation and airtightness
- Electricity from increasingly renewable sources, via high-COP GSHPs.
- Gaseous or liquid bio/synfuels increasingly replace oil and LPG in condensing boilers, supplemented heavily by active solar
- Solid biofuels, in non-condensing boilers, with or without solar as above.

Technology		**1**	**2**	**3**	**4**	**5**	**6**
		Electric Heat Pump		**Condensing Boiler plus Active Solar**			
		Air Source	*Ground Source*	*LPG*	*Oil*	*Compatible Biofuel*	*Synthetic Fuel*
Infrastructure cost		Very high	High	Not applicable			
Equipment cost in building		High, ~£5-7k.	Very high, ~£8-10 k	High, ~£6-7k			
Energy storage to match supply to demand		Very difficult	Difficult	Cheap and easy			
Network security at peak		Poor	Poor	Not applicable			
Security of energy supply		Good	Good	Similar to natural gas	Problematic	Good	Very good
Reinforce existing network?		Yes	Yes	No			
Modify existing radiator systems?		Major	Enlarge	Moderate/minimal changes			
CO_2 emissions per unit of heat, kg/kWh	Now	0.22	0.59	0.21	0.18	0.08	-
	2030	0.09	0.20	0.075	0.06	0.03	0.00

Table 13. Options for heating zone 2.

NOTES:

1. The infrastructure cost per building is higher than in built-up areas, because of the greater length of line. Although electricity is supplied to buildings anyway for lighting and appliances, there is an added cost to reinforce cables and transformers to carry a diversified peak demand of say 3-5 kW(e) instead of 1 kW(e) for a small building.
2. ASHPs may need UFH to improve their COP at the time of system peak, when they are pumping heat up to the heat emitter temperature from air at say -10°C. There may not be space for radiators five times larger than normal ones sized for 80/60°C. To avoid this, they could use a reserve heating system. But it may be more attractive to use a reserve fuel to back up an active solar system, giving faster “decarbonisation”.
3. Estimated mature market costs for heat pumps.

Relative CO_2 Emissions

Figure 30 shows the relative CO_2 emissions of different space and water heating methods. Typical practice today might be equated to an old gas boiler in zone 1 and to an old oil boiler in zone 2.

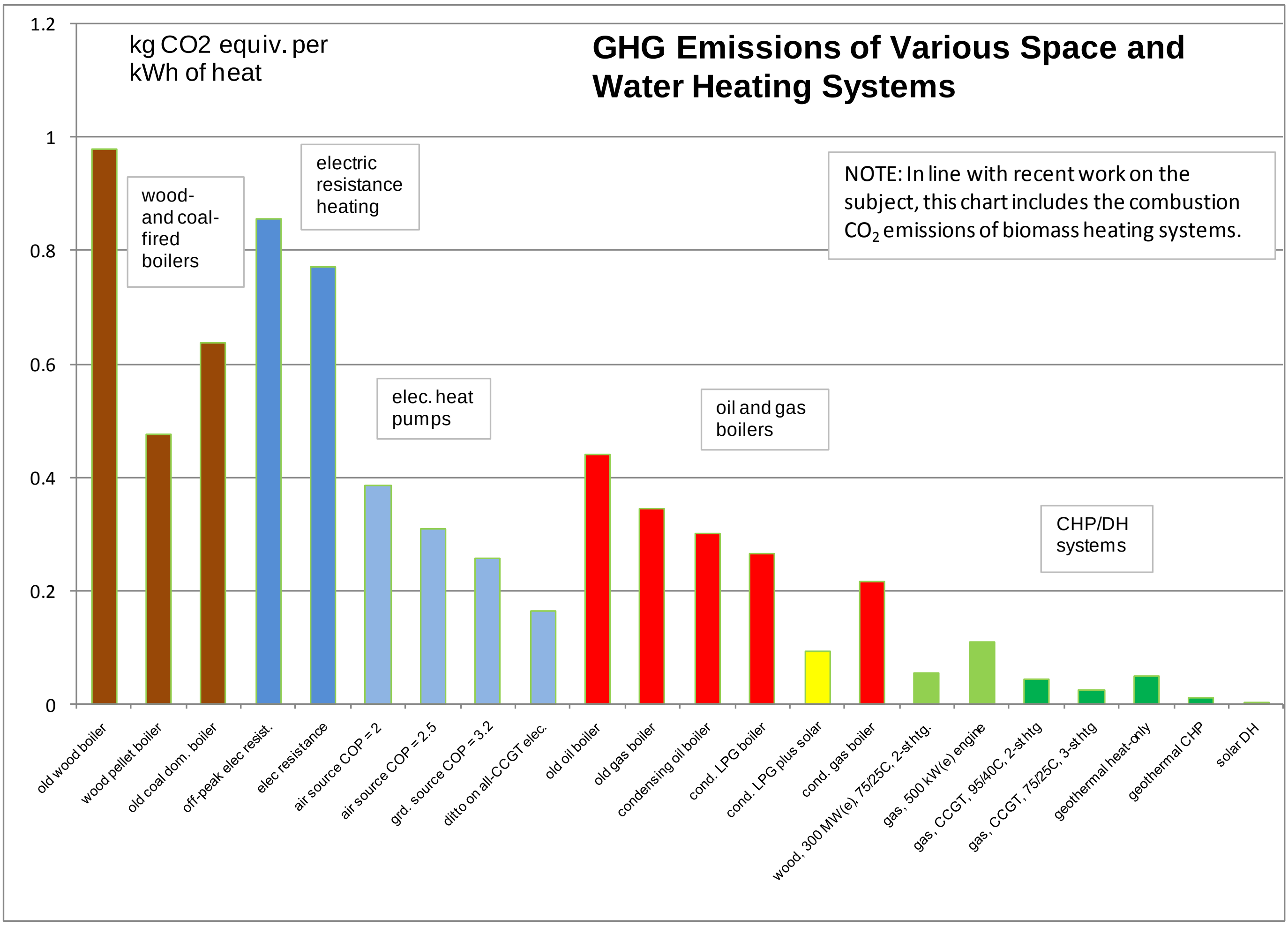


Figure 30. Relative CO_2 *Emissions.*

NOTES:

1. The solar and geothermal figures include rough estimates of the GHGs emitted in making the plant and equipment and emissions of trace GHGs during use.
2. The figures for older wood-burning technologies include the impact of trace GHGs such as CH_4 in the exhaust, along with the CO_2. [346] [347] [348]
3. The electric heating figures assume that electricity used for this purpose is weighted towards the months December to March inclusive and emits 0.75 kg/kWh, not the annual average of 0.61 kg/kWh for 400/230 V loads. There are arguments for using lower figures but there is a case too for using the figure for the marginal coal-fired plant retained on the system as a result of incremental increases in consumption, with emissions of about 0.92 kg/kWh.

There is a 30-fold range in CO_2 intensity between heating systems. “Worst practice”, offering the most scope for emission reductions, would be electric resistance heating in zone 1 and solid-fuelled open fires and older wood heating systems in zone 2.

“Best practice” in zone 1, with the lowest CO_2 emissions, would be various town-scale gas CHP systems and use of the same infrastructure to distribute renewable sources of bulk heat. A mix of technologies would reduce CO_2 emissions by 85% versus today’s practice, represented by an old gas boiler. This entails heating system changes and excludes the impact of reductions in building heat loss via insulation, draughtproofing, etc.

A low-CO_2 system illustrating “best practice” for zone 2 could be an LPG-fired condensing boiler backing up a large active solar system. It emits 75% less CO_2 than today’s average rural heating system, represented by an old oil boiler. This too reflects heating system changes only and excludes the impact of reduced building heat loss.

A GSHP, powered by an all-CCGT generating system, emits 60% less than today’s average rural heating system. Operating on the existing generating system, it reduces emissions by 40%. It reduces emissions 15-20% compared to a new oil condensing boiler and by 0-5% compared to a new LPG condensing boiler.

Condensing boilers and solar save CO_2 now. Rural GSHPs emit more CO_2 than this in the 20-30 years until electricity is “decarbonised”. A wiser strategy may be to install LPG/solar systems now, clearly in conjunction with demand reductions to reduce consumption from 1,000s to 100s of litres/yr. [349] Systems can readily be changed over to GSHPs in 15-20 years’ time if they are by then the most attractive alternative, or they could change to a renewable fuel backing up the solar system. GSHPs need lower-temperature heat emitters than systems using a stored fuel at the time of peak demand, but the increase in radiator area would be more limited than with ASHPs.

There are also low-density buildings with no space for fuel storage, the existing system being electric resistance. In these buildings, the CO_2 savings today from GSHPs are 70%, assuming a COP of 3.3. The UK’s scarce technical skills should be devoted to ensuring that heat pumps in these niche situations work with good COPs.

Zone 1

Electricity

Electric Heating Generally

Figure 9 had a LDC for electricity consumption in Great Britain. [350] The majority of it today is used for lighting, appliances, fans, pumps, etc, giving about a 65% load factor. 93% of domestic space heating comes from gas, oil, LPG, coal and wood. [351]

The LDC for space and water heating differs from this. The peak winter demand for space and water heating in low-heat loss buildings is six to seven times higher than the mean annual heat demand; i.e. the likely load factor is around 15-20%. This gives a challenging load pattern for the electricity system.

Figure 31 shows the calculated space heating LDC for a new 145 m^2 bungalow in Denmark meeting its Low Energy Class I Standard. It corresponds to half the heat consumption allowed by its 2005 Building Regulations, although slightly short of the Passivhaus Standard. The plan is for all new buildings after 2015 to meet this standard. [352] [353]

Space heat consumption is 31 kWh/m^2yr. Peak space heating demand is 3.4 kW(t) at -7ºC. The space heating load factor is 15%. For 3,000 hours/year, there is no space heat demand, only a steady hot water load of 0.2 kW or a winter peak of say 0.3 kW, assuming that storage has spread the DHW load uniformly over the 24 hours.

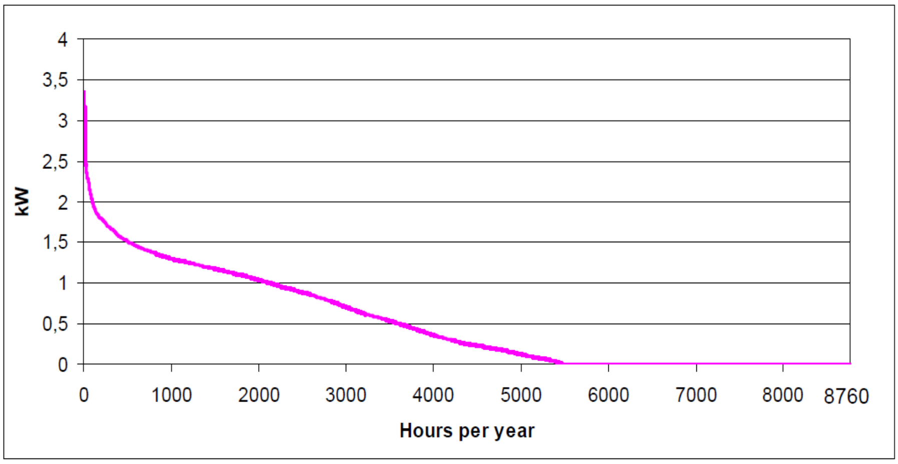


Figure 31. Load duration curve, space heating, new Danish detached house.

NOTE: Excludes DHW load. It would average about 0.2 kW, but with variations according to varying cold water temperatures. Network losses are also excluded.

This graph was derived from hourly weather data. The authors note that if the building can spread the space heating load uniformly over 24 hours; e.g., a heavy mass building, with UFH, the peak falls from 3.4 to 3.2 kW, which raises the load factor from 15% to 16%. A minority of buildings can do this.

All space and water heating LDCs have the same basic shape as Figure 31. [354] They can become peakier as building heat losses are reduced. The load to the right-hand side disappears, because in southern England a low-heat loss building has a negligible space heating load from about May to October inclusive. The load to the left falls but does *not* disappear.

For some years, commentators have suggested that heat storage on the consumer's premises; e.g., insulated DHW tanks, removes the extreme peak on this chart. But to radically change the shape of the LDC, the DHW tanks would have to retain heat for six months; e.g., summer to winter. At this small volume, they can only retain it for about 24 hours. See later discussion of piped heat.

Heating systems are sized to meet a building's peak demand on a "design day" - not the coldest possible day, but pretty close to it. But with resistance heating, electricity companies would have to invest in seldom-used generating plant and network capacity to meet the peak on the left of Figure 30.

Resistance Heating

Given the diversity on the appliance, lighting [355] and similar loads, existing LV transformers are rated at under 1.0 kW(e) per dwelling. Similarly for transformers to other buildings. But there is little diversity on the space and water heating load, because cold weather affects all buildings. With mass electric space and water heating, the capacity of the national grid would have to be upgraded.

The electricity network does not benefit from the storage which is available in the gas network. The peak would tend to exceed the 8 January 2010 peak of 199 GW in natural gas consumption. [356] As well as reinforcing the local LV network, some replacement transmission towers rated for higher voltages than today might be needed.

If the building stock is radically-insulated, cutting peak space heat demand from today's typical 7 kW(t) per dwelling to say 3 kW(t), the capacity of the 230 V transformers would need to rise from 1 to 4 kW(e) per dwelling, to cover domestic space and water heating and the existing

1kW(e) for appliances and lights. It gives a potential domestic load of 150 GW(e) at the power plants for 26 M dwellings, assuming 15% peak T&D losses to these loads. [357]

If buildings are only improved enough to offset the continuing rise in thermal comfort, capacity would need to rise to nearer 8 kW(e) per dwelling. The potential domestic sector load is then 260 GW(e). There would also be a further load from non-domestic buildings.

After paying for work to reduce peak loads to 3 kW(t), a very preliminary calculation of the offshore wind generator and other plant costs needed to heat dwellings in built-up areas, assumed to be 80% of the UK, by electric resistance heating, comes to £200-300 billion. This includes wind turbines, electrolysers and CCGTs to ensure security of supply. It excludes the marginal costs of grid reinforcement, uprated transformers, gas storage or the continuing use of the gas transmission system for the stored energy.

Heat Pumps

Peak demand with heat pumps would be lower than with resistance heating, in proportion to the peak COP. With best current technology, this is perhaps likely to be 1.8-2.0 for ASHPs and 2.8-3.0 for GSHPs. The load factor of vertical coil GSHPs might be as high as that of electric resistance heating, although if they use variable flow temperatures the COP is likely to be lower in cold weather.

Larger dwellings with heat pumps may need a three-phase electricity supply. Today's starting current if a heat pump motor is rated above 3.5 kW(e) has been too high for many single-phase supplies, limiting ASHP and GSHP peak heat loads to respectively 5-6 and 9-10 kW(t) on a single-phase supply. But this hurdle is being overcome by soft-start technology.

In the past, some heat pump refrigerants had a significant GWP. This concern is disappearing as more advanced machines move to refrigerants like CO_2. For fitness-for-purpose in displacing oil and LPG condensing boilers, heat pumps arguably need to be launched which can do all the following:

- Supply the whole DHW load at a seasonal COP of say 3.0
- Supply radiator heating systems at a seasonal COP of say, 3.5, without needing unduly large emitters
- Use refrigerants with zero GWP
- Operate on a single-phase supply *and*

- Meet all peaks on extremely cold days, with no resistance heat backup, at a COP of say 2.5-3.0.

This specification is not yet standard, making most heat pumps less than a full substitute for gas, oil or piped heat from CHP plant. There is a risk of consumers being misled if they are unaware of the limitations; e.g., that most heat pumps do not provide DHW and that existing radiators are not usually large enough for the low temperatures needed by ASHPs, unless the building heat loss is reduced.

There is a divergence of interest between electricity suppliers and electric heating users. Suppliers want consumers to install equipment that avoids peaks in demand. Consumers want low running costs, but also minimum capital cost. Systems whose design is driven by lowest first cost tend to transfer costs onto the electricity supplier, giving more severe demand peaks.

For example, an ASHP may be sized by a consumer to meet the space heating load at a mean daily ambient temperature of 0ºC, to give an “economic installation”. Because its COP falls at lower temperatures, when it must pump up heat from colder ambient air to hotter radiators, and because any supplementary electric resistance heating has a lower COP than the heat pump, the LDC imposed on the electricity system becomes peakier than in shown in Figure 31.

Figure 32 shows schematically the possible LDC of a small low heat loss building in southern England for space and water heating. The heat pump provides all heat down to a daily mean of 0°C. Supplementary resistance heating is automatically turned on below that, visibly steepening the gradient of the LDC at below 600 hours/year.

The house has an assumed balance point temperature of 13.5°C, with a specific heat loss of 153 W/K. Historic ambient temperature records for Croydon in the mid 20th century were used to derive the chart. It is not definitive and is purely intended to illustrate the impact of falling COP and electric resistance backup. [358] Continuous heating is assumed. The overall space plus water heating COP of a relatively advanced ASHP [359] is taken as:

- 3.75 at +20°C
- 3.1 at +7°C
- 1.8 at -15°C

with linear interpolation between these figures and with linear extrapolation above 20°C.

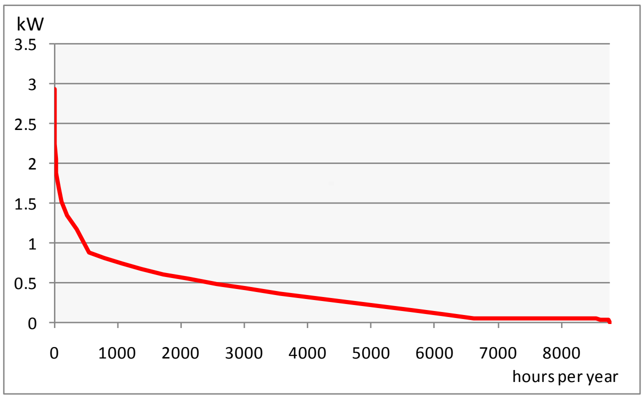


Figure 32. Schematic load duration curve, space and water heating, UK well-insulated house with ASHP and top-up electric resistance heating.
Approximate calculation, using simplified method.

The LDC shows a strikingly irregular demand for electricity and a troublesome peak for the national grid to meet. The building would give rise to a mean daily electricity demand for space and water heating at the meter as follows:

- 0.48 kW(e) at the UK average heating season temperature of 6°C.
- 0.88 kW(e) at 0°C.
- 2.94 kW(e) at -10°C.

If percentage T&D losses in the network rise at low outside temperatures, owing to the I^2R term, this could accentuate the peak.

Discussion

We think that the overall challenge in moving from gas to electricity for space and water heating has been understated. To provide a high standard of service, one must address variations in heat demand and the high cost of bulk electricity storage. This rules out long-term storage of electricity in the way that hot water and gaseous fuel can be stored.

Most privatised electricity suppliers are probably more interested in supplying baseload electricity. They then earn more from their generating plant. There is no baseload demand for space heating in very well-insulated buildings; see Figures 31 and 32. It is uncertain that the current payment structure provides an incentive to invest in rarely-used plant. [360] [361]

Modern ASHPs would reduce the peak load, compared to resistance heating. But they would reduce the mild weather load even more, creating a peakier load profile, especially if some top-up resistance heat is used. The load factor for the individual building featured in Figure 32 is around 16%.

If a UK-wide peak corresponding to around 40 million such peak loads, equating to all dwellings plus non-domestic buildings could not be met reliably and economically, there are two alternatives. Either UK buildings would need to be forced to fit reserve heating systems, or we would have to accept load-shedding.

Load-shedding would be socially unacceptable and would threaten the security of supply of “essential electricity”; see discussion at end of this chapter. It can be ruled out. Reserve heating systems would be needed. But is mass electric heating a good idea, if most buildings would need reserve heating systems; i.e. two systems?

Many buildings in Norway have electric space heating, and consumers are exposed to the varying market price. In a cold spell in winter 2002-03, the grid could not meet demand, even after spot prices rose sharply and large buildings on interruptible tariffs switched from electricity to stored oil, their usual reserve system. The consequences of the subsequent load-shedding in small buildings were unpleasant. [362]

This debacle occurred on a despatchable hydro-powered electricity system after the peak from smaller buildings exceeded system capacity. [363] Countries without despatchable renewable generating plant which seek to heat electrically would be not just trying to keep demand below system capacity, as Norway was doing, but trying to match a time-varying supply to a time-varying consumption. [364]

Today’s monitoring of small electric heat pumps seems to give broadly similar results to their performance in the last two periods of enthusiasm, which were the late 1940s/early1950s and late 1970s/early 1980s. [365] [366] The valuable innovations on motors and compressors do not altogether negate the poor cold weather performance. [367]

30 years ago, the nationalised Electricity Council (EC) suggested that, if ASHPs became widely-used, it would be a good idea for building owners to back them up by a stored fuel; e.g., an oil-fired system. [368] After field trials, the EC ceased ASHP work at its Cheshire research centre.

Piped Gas

70% of UK non-domestic space heating, 93% of domestic space heating, and somewhat lesser proportions of these buildings' water heating, comes from natural gas. Although the building stock may become better-insulated and -draughtproofed, sending exclusively fossil CH_4 down the pipes does not appear a long-term option. Various estimates suggest that biomethane, one of the more attractive biofuels, might supply up to 10% of present EU energy consumption by 2030. But there seem to be higher demands on bio-CH_4, in a future of constrained energy supplies, than burning it in heat-only boilers.

If today's pattern of gas heating is to continue, one possibility is that we would have to make electrolytic H_2 from interruptible renewable electricity. The H_2 would be stored seasonally and transported to buildings in winter. The gas in the pipes would change over from CH_4 to H_2 or to a CH_4-H_2 mixture.

Before North Sea gas, a carbon monoxide-H_2 mixture was piped to buildings. So H_2 in the pipes is not a new concept. It would certainly need a lot of electrolysers. They cost £200/kW(e), and O&M is 2-3%/yr of capital cost. Development and mass production of solid oxide models might increase this efficiency to 90% by 2020-30, albeit at higher capital cost. [369]

Buildings' peak heat demand would have to be reduced over 2.5-fold before existing pipes could convey a less energy-dense gas at a sufficient rate. After paying for this work, a very preliminary calculation of offshore wind generator and electrolyser costs to heat built-up areas comes to a few £100 billion, excluding any new pipes or gas stores and omitting the issues in the next paragraph.

Today's electrolysers are up to 82% efficient from electricity to H_2, plus waste heat which could be used for DH. This modest efficiency outweighs gas's lower distribution losses compared to electricity. So more energy would have to be generated at source than with electric heating. [370] But unlike electricity, gas is storable. Overall, a gas heating scenario needs less peak generating capacity and avoids the need to reinforce the urban electricity network. Any new pipes needed would also be underground.

There are more risks of leakage from the pipes and storage with H_2 than there are with CH_4. The serious risk of embrittlement in the transmission system must be tackled too. Given the need for urgent action, such factors greatly strengthen the case for producing CH_4 and not H_2. [371] Some people

But this arguably sets out an alternative to a straw man. Even if gas heating for built-up areas may present fewer technical and operational problems than mass electric heating, and fewer concerns over network security, is either approach desirable? The electric scenario seems rather brittle, costly and unproven. The gas scenario of continuing to burn fuel in heat-only boilers would be a waste of high-grade and high-cost energy, although it would deal well with the issue of network security. Mention of waste of high-grade energy brings us on to the third possibility.

Piped Heat

In 2009, the UK rejected more heat from gas-fired power stations than the amount of natural gas which it consumed to heat buildings. [372] Using this heat would have eliminated 98% of gas deliveries to buildings. The other 2% of the gas was used for cooking. It would also have eliminated the roughly 15% of electricity consumption that appears to be used for urban heating.

Other relatively clean sources of heat, apart from natural gas CHP, might include:

- Biomethane CHP
- Large solar collectors
- Surplus windpower, used via large heat pumps, with heat stored until needed
- Geothermal heat-only or CHP plant
- Industrial waste heat.

CHP/DH is an easier substitute for gas or oil than electric heat pumps where the building density is high enough. The flow temperature is closer to that of existing boilers, the same system can provide the DHW and there is less disruption to the building owner or tenant

The major disadvantage identified by many with piped heat is arguably not the technical and economic issues, which have been largely proven and overcome on the continent, as in Denmark, but the claim that digging up the streets to lay pipes would be too disruptive. It is only fair to point out that existing utilities regularly dig up the streets to lay services or repair or replace old ones, but the main difference is one of intensity. Digging of trenches by existing utilities is an ongoing, lower-level process. Connection of a city to piped heat usually takes place more intensively, and over a shorter time.

A large fraction of the low-pressure gas distribution system would probably have to be replaced between now and 2050 if piped gas in some form is to be retained for urban heating. If electric heating develops as the government envisages, distribution cables would need to be dug up and replaced by heavier-duty ones and LV transformers would need to be replaced. There seems to be no long-term urban heat supply option that does *not* involve digging holes, so the main question is what will go in the holes. Figure 33 shows a high-capacity heat transmission pipe being laid in central Copenhagen.

Figure 33. Large heat main being laid in Copenhagen. [373]
Source: Danish Board of District Heating, www.dbdh.dk.

There are institutional issues too. Areas which develop piped heat would need a new utility to sell hot water. Or an existing gas, electricity or water supplier would have to take on a new role. Or in our suggested way forward, suppliers of mains energy services would be re-regulated and integrated to become regional energy service companies (ESCOs). See Chapter 8.

In the UK, a company partly owned by local government, or working under contract to it, has often been used to distribute heat; e.g. Southampton. [374] A council-owned limited company is the usual approach abroad, although some councils outsource DH operations and management to an ESCO.

Given the low surface-to-volume ratios, long-term heat storage is practical on DH systems. This is important in a future which is likely to feature irregular inputs of ambient energy. Such heat storage is impracticable on small systems.

Figure 34 depicts the theoretical cooling curves of two hot water tanks whose volume differs by four orders of magnitude. Both are insulated by 150 mm PU foam, assumed λ = 0.025 W/mK, with no other heat losses. They initially contain water at a uniform 80ºC and they are situated in surroundings at 10ºC. If 75°C is the minimum temperature needed, the large 1,000 m^3 store would remain usable after three months. The small store, the size of a DHW cylinder, would become too cold after 16 hours. It cannot store heat over longer timescales and it is too small to provide well-stratified storage.

Heat stores are widely used on Danish CHP plants to decouple heat and electricity demands and to improve security of heat supply. The top of the tank contains the flow water, the base contains the return water and a roughly 1 m thick boundary layer forms between the two zones. [375] Odense built a 73,000 m^3 heat store in 2003, amounting to 1 m^3 of water storage per household in the city. Such stores are mainly useful for diurnal and weekly storage and for smoothing-out relatively short-term variations in demand.

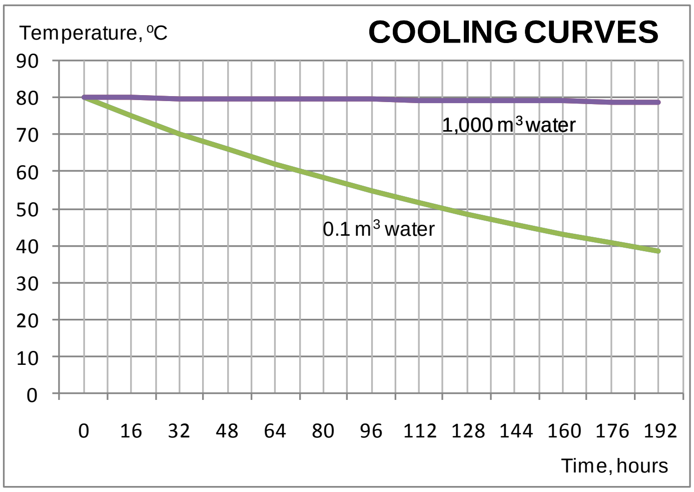


Figure 34. Rate of Cooling of Large and Small Well-Insulated Hot Water Tanks.

Danish development effort is now concentrated more on seasonal heat storage, which needs lower-cost and therefore different approaches from cylindrical steel tanks. Excavated pits in soil have an average cost of around £25-30/m^3 and a marginal cost of £15-18/m^3. [376] Swedish rock caverns have similar costs. [377]

To maximise long-term flexibility, DH systems should definitely be designed for lower supply and return temperatures. [378] Lower flow temperatures reduce CO_2 emissions and make it easier to replace fossil CHP by custom local heat sources; e.g., solar, geothermal, heat pumps run off spilled windpower. Lower return temperatures also reduce CO_2 emissions and cut piping and pumping costs. The capacity of a heat store increases by 40% if it cycles between 80 and 25°C, not between 80 and 40°C. So a lower temperature reduces heat storage costs by almost 40%.

As Figure 30 shows, CO_2 emissions for heat from a CCGT with three-stage heating and system temperatures of 75/25ºC are significantly lower than for two-stage heating and temperatures of 90/40ºC. Emissions are 80% lower for this CCGT reject heat than for GSHPs fed by a CCGT generating system.

Danish DH systems which supply suburban buildings of low heat consumption differ radically in design parameters from the UK. Unlike the UK, which treats DH as a option for "hard-to-heat" high-density buildings, Denmark treats it as an option for any built-up area. It is important to demonstrate and deploy advanced systems here, to avoid restricting the DH potential. [379]

Work to reduce costs to Danish levels and transfer appropriate technology should be publicly-funded, on the basis that past UK work by the gas and especially electricity industries was so treated. This development of heat networks contributes to strategic national security in 2050, secures a level playing field and amends a situation which unintentionally blocks significant development of a technology.

The differing legal position of water, gas, electricity, drainage and telecommunications suppliers, who have more legal powers than heat suppliers to lay pipes on private land, [380] [381] recover debts, etc, remains a barrier. It does not seem to have changed since the Marshall Committee reported on piped heat to government and proposed that some schemes go ahead. [382] A recent report to the government put matters thus:

> "In consequence, should government decide to intervene to support the development of stand-alone renewable heat in built-up areas, it would be inconsistent not to do for the DH options. A further implication of this is that stand-alone renewable heat technologies may be best suited for off-gas grid locations and areas of less-dense housing, where heat mains costs start to rise substantially." [383]

Some recent reports to the UK government discuss heat networks in detail. But they do not address the tacit UK policy of favouring the incumbents by applying "venture capital" discount rates to heat networks and "regulated asset" rates to gas or electricity networks. Nor do they address the two-fold installed cost difference between the UK and mature markets, nor the sale of the UK utilities to the private sector at below replacement cost, reducing the price of gas and electricity.

Much Danish DH supplies what the UK would term "less-dense housing". Figure 35 shows a street scene in a Danish town of 20,000 which was retrofitted with piped heat in the early 1990s. Of countries with appreciable DH; e.g., Sweden, Denmark, Finland, Iceland, Germany and Austria, the Danish experience appears the most relevant to us, because its settlement pattern is relatively similar to the UK's. 70% of its dwellings are low-rise houses, not flats.

To the extent that we are short of practical or engineering design skills, we should hire them in from the continent. A more mature market exists there, heat mains cost less, [384] [385] the cost model used is more precise than the UK's, [386] [387] representing more practical experience, and consultancies are familiar with design of advanced DH systems.

We consulted a few Danish experts and their general view is that progress is largely a matter of long-term infrastructure planning, with the public sector taking a key role. With normal regular maintenance, heat mains laid now could still be in use in 100 years' time, a period far outlasting most heat sources. It is also necessary to have closer integration of heat and electricity supply.

We refer the first point in particular to the government. In our view, no other UK institution can take responsibility for such long-term strategic planning. Thus only the Baldwin government could have decided in 1926 to build a national electricity grid, a decision which took over 50 years to bring to fruition and was paid for largely from public funds. The resulting network now supports entirely new services such as social networking, mobile telephones, cloud computing, offsite data backup services and the internet generally. [388]

The second point could be addressed by our utility reforms. They would move matters closer to the more coordinated way in which the electricity industry operated before retail deregulation

Figure 35. Road in Kalundborg, Denmark supplied by DH.
Source: Google streetview.

NOTE: The detached houses in the street were built in the late 1970s. The town was connected to piped heat over a short period in the late 1980s and early 1990s.

Network Security

Measures to meet design weather peaks, or meet demand in the event of the main CHP plant malfunctioning, are fairly standard on DH systems. They usually involve a mixture of reserve boilers, heat storage and the facility to raise the pumping rate and/or supply temperature in extremely cold weather.

In extremis, using stored fuel to briefly raise the flow temperature by 10-20 K, a DH system operating at 75°C in normal winter weather could cope with the below-design spells that the UK experienced in the last two winters. Because the plant and equipment is installed, owned and managed by the heat supplier, there is less disparity of interest between suppliers and users over network security than there is with electric heating. The heat source need not necessarily be heat-only boilers. Reciprocating engines can be used to meet peak heat and electricity loads and sending out hot water in extreme cold spells at say 90°C does not reduce their electricity generation efficiency.

With the concern over the UK's growing dependence on gas imports, energy security could be enhanced early on if decentralised modular CHP engines, with backup fuel stores, were located at LV transformers. In normal times, this plant would be supplied by gas, but it would switch to stored fuel in gas grid emergencies like those of March 2006, January 2010, et al. It could also heat and light an area in the event of electricity or gas grid failure.

If distributed DH pumps have battery backup, and buildings are directly-connected, with mechanical heating controls, everyone in the district concerned will still have heat and electricity even if the national gas and/or electric grids temporarily fail, leaving only the local CHP plant and reserve boiler(s) operating on the stored fuel. This provides a degree of resilience and security lacking in today's gas and electricity networks. The UK imports 60% of the fossil fuel for its heat, and 70% of the fossil fuel for its electricity, so the issue should be taken seriously.

CHP plants can operate on interruptible gas; individual boilers cannot. Piped heat would provide a means to improve network security at peak periods, providing a surrogate for the UK's low and inadequate level of gas storage. Danish natural gas comes from its own North Sea fields, but the gas suppliers provide six months' of onshore gas storage as a safeguard against the risk of any pipeline problems. The UK is further along its gas depletion curve than Denmark, and is more import-dependent, but has three weeks' gas storage.

Zone 2

The Heat Load

About 13% of the UK population lives in areas without a natural gas supply. Heating these low-density buildings costs much more, in £/yr.m^2 floor area, than heating urban buildings. [389] The fuel costs more than natural gas. Buildings are often detached, with more exposed area than attached houses or flats. Some are high above sea level, with mean air temperatures 2-2.5 K below the nominal figure for the same region. [390] Rural areas are more exposed, raising heat consumption by up to 25-30% compared to a sheltered urban location.

The combination of costlier heat, more detached buildings, more severe exposure and greater elevation leads to markedly higher heating costs. Fuel bills of £1,500-4,000/yr are not uncommon in well-heated detached dwellings; i.e., they consume 20,000-45,000 kWh/yr of heat or 25,000-65,000 kWh/yr of oil or LPG.

The Options

With the cost of future heat supply options, and the urgent need to reduce CO_2 emissions *and* oil dependence, the clear way forward seems to be very large improvements in insulation and draughtproofing. These options already compete with the marginal cost of heat in these dwellings. Correctly-controlled condensing boilers also yield large energy and CO_2 savings compared to current heating systems, which also include a mixture of older oil boilers, LPG boilers, electric heating and inefficient solid-fuelled stoves and fires. The options we perceive as most worthwhile include:

- Drastic improvements in insulation and airtightness, possibly Passivhaus, especially where building elements need major maintenance or renewal, making this work economic.
- Large active solar systems, providing much of the water heat and part of the space heat, backed up by LPG or bio-DME condensing boilers.
- Ditto, condensing boilers burning oil and/or compatible biofuel.

- Ditto, backed up by synfuels.
- GSHPs, subject to soil survey.

There is also the option of burning solid biofuels, alone or to back up solar as in options 2-4. However, the condensing appliance in options 2 or 3 typically:

- Costs £5k less than an equivalent pellet boiler
- Needs no "heat leak" radiator
- Has a more compact fuel tank, by a factor of 5-10.
- Is more thermally-efficient, especially option 2, to meet the residual load in a building which obtains most of its spring and summer heat from solar
- Lower servicing and maintenance costs, as per condensing LPG boilers
- Emits 10-100 times less particle pollution than a wood-fired chip or pellet boiler. PM-2.5s seem to cause more harm to public health than either road traffic accidents, passive smoking or obesity. [391] [392] A sound policy would be to continue to reduce them as fast as possible, not to subsidise technologies which emit more PM-2.5s.

Option 2 is particularly suited to low heat loads. The basic boiler is the same as for natural gas; i.e., it has a low thermal capacity, which benefits efficiency at low heat loads. Modulating burners are available. With the right controls, efficiencies in the mid 90s% are readily achieved. Overall, on both cost and public health grounds, there appear to be good grounds for utilising any solid biofuel in large combustion plants and not trying to reverse the decline in small-scale solid fuel use.

If fossil fuel backs up the system and solar provides 60% of annual heat, options 2 & 3 emit 0.12-0.14 kg per kWh of CO_2. 0.12 kg/kWh is 67% lower than a 75% efficient oil boiler. If heat consumption is reduced by 70%, which seems possible in many cases with sub-Passivhaus measures, all implementable before 2030, the total GHG reduction in providing the building's space and water heating would be a very satisfactory

$$100\mathrm{x}(1-[(1-0.7)\mathrm{x}(1-0.7)]) = 91\%.$$

Option 4 above has zero emissions. However, the fuel would cost more than the cheaper biofuel resources.

Options 2-4 obviate the need to reinforce rural wires to carry higher peak electric loads. Option 5 could need some reinforcement, even if a building is retrofitted to near-Passivhaus standard and the peak COP is 2.5. However, more efficient use of electricity for lights, appliances, pumps, fans and controls and a switch away from existing electric resistance heating might avoid this, as long as not all rural buildings use heat pumps.

A recent report suggests that average electricity CO_2 emissions may be around 0.43 kg/kWh in 2025. [393] If T&D losses are the same as today, emissions would be 0.41 kg/kWh for electricity delivered to railways or large factories and 0.45 kg/kWh supplied to 400/230 V loads; e.g., small buildings. Overall, we can see little evidence that option 5 would emit less CO_2 than options 2 or 3 for several more decades. We feel that it is undesirable for UK policy to reward actions which could lead to higher CO_2 emissions in the important period 2010-30.

For network security at peak, and for the higher overall seasonal COPs, GSHPs are favoured over ASHPs. As for piped heat, public sector support would be justified for work which aims to reduce GSHP installed costs to the level of mature markets, especially vertical boreholes as used widely in Sweden. These give higher midwinter COPs than horizontal evaporator coils, because the deep ground temperature is higher. They also fit onto smaller plots. We see no scope for securing these strategic advantages without government initiatives analogous to those which we propose for piped heat. We also note that many of the changes to heating system design being proposed for heat pumps would be nearly equally beneficial to CHP systems. It would be beneficial to coordinate the work associated with the two technologies.

Network Security

Of the rural options listed, only the GSHP presents network security issues. The other systems use stored fuel. But even buildings using a stored fuel lose their heat supply if the electricity goes off. To cater for a rise in the contribution from intermittent sources of electricity, it would be prudent to provide all new or refurbished buildings as a matter of course with a small uninterruptible power supply, so that they have power during supply interruptions. The only exception would be buildings which are on piped heat and are supplied at peak by a local CHP station.

This transforms the reliability of essential electricity in small rural buildings, providing potentially enough for lights, appliances, fans and pumps and mechanical ventilation if applicable. It also avoids the need to fit a woodstove and chimney, with the attendant heat losses and GHG pollution. This is an increasingly common response today to the risk of rural power cuts.

Difficulties and Options

Overall, we are concerned over proposals to move *en masse* from gas to electricity to heat UK buildings. In particular, we are struck by the implication of the demand peaks from typically variable UK weather, the contrast in demand between summer and winter in well-insulated buildings and the impacts which extreme peak electric heating demands could have on consumers of “essential electricity” for lights and appliances.

There are differences between piped gas, electricity and hot water as regards network security. The approaches which piped gas and piped heat can use to meet severe peaks are more varied and flexible than those available to electricity networks.

Under extreme conditions, gas networks can withdraw energy from underground caverns and local gasholders and store energy diurnally in the supply pipes, via “line packing”. Heat networks can withdraw hot water from stores previously charged by the CHP plant, raise the pumping rate and can even use stored fuel to briefly raise the flow temperature.

It has not yet been shown that the “electric solution” can reconcile these issues satisfactorily:

- Varying demand for heating, month to month and season to season.
- Varying supply of wind energy, ditto.
- Falling COP of heat pumps at low ambient temperatures.
- Increases in network capacity and installed generating plant to meet the most extreme peak. This plant could stand idle for 8,000-8,700 hours per year.

Nor has it been shown that the investment cost of an electric infrastructure would compete with that of heat networks in towns and synfuels in the countryside for those buildings which today use stored fuels. Unless it can be established that an electric system can overcome these issues, it may not offer as promising a route towards energy security after oil as has been thought.

It is prudent to consider how an enlarged electrical grid would have coped in winters 2009-10 or 2010-11, had space and water heating already transferred from fossil fuel to electricity. The very low ambient temperatures in central England in December 2010 are not conducive to high ASHP COPs. See Figure 36.

Assuming an advanced ASHP, the COP of a system replacing a boiler and supplying all space and water heating, with a temperature of 50-60°C in the radiators and the DHW system, could fall to

1.5-1.8. [394] [395] If the ASHP meets the whole peak, this implies a demand 55-67% as great as resistance heating on inland sites.

There has recently been a drop in solar activity to levels below those of the 20th century and closer to the 19th century figures. If it continues, it may lead to a higher probability of cold winters in coming years, offsetting some or all of the apparent warming in the late 20th century. [396]

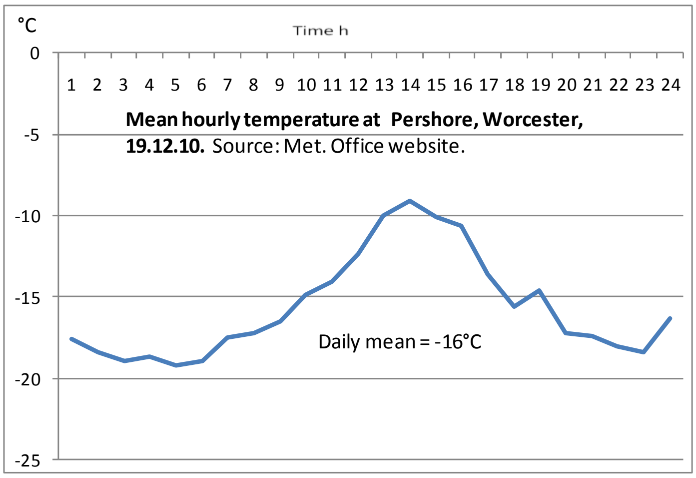


Figure 36. Hourly air temperatures at Pershore, Worcester on 19 December 2010. [397]

Given the costs of energy supply systems which deliver energy in the form of electricity, the combined capital investment in:

- Heat pumps
- Enlarged radiators or UFH
- Renewable generating capacity
- Backup power station capacity
- Grid reinforcement

would be considerable. It is important to compare it to the cost of other options for heating the built-up UK, *inter alia* piped heat and piped gas.

Radiators for an ASHP operating at peak flow/return water temperatures of 50/25 or 45/25°C would cost more than radiators operating at 75/25°C. The last combination may be reasonable for DH systems installed now. [398] UFH costs more than oversized radiators. It is disruptive and is best fitted if/when a building is unoccupied and undergoes total refurbishment.

In built-up areas, the sum of the investment costs needed to heat electrically is potentially higher than the cost of laying heat mains. The fact that such expenditure would be more widely-divided than expenditure on heat networks does *not* mean that it is lower.

Over time, the electricity network has become essential, to a point that it could be said to underpin “society as we know it”. The services which it now supplies are highly-valued, and need not consume much electricity, but they need a reliable supply, except for larger lighting installations, where it could be profitable to install technologies that make some of the load interruptible. They include above all:

- The internet and social networking.
- “Cloud computing”.
- ATMs.
- Electronic tills.
- Underground railways. [399]
- Mobile telephones.
- Heating controls and circulation pumps to operate central heating systems.
- Medical equipment in acute hospitals.
- Lighting.

Altogether, it may be unwise to add loads which might make the supply of essential electricity less secure. Added loads might be manageable if they are small versus other peak demands on the grid in 2030 or 2050. Thus a million or two rural dwellings, or 3-6%, retrofitted to near-Passivhaus standards, with GSHPs, might impose a coincident peak demand of 2-4 GW(e), which is probably not such a problem, especially if this load could roughly coincide with the electricity output of CHP plants burning stored fuel.

We also note the prospective year-to-year variations in both energy demand and energy supply, if the electricity comes from variable renewables such as wind. Realistically, in our view, such a renewable electricity system would need fuel-fired power stations, burning natural gas now and stored electrolytic H_2 or CH_4 in future. If wind energy is stored as fuel, the use of thermal generating plant to reconvert to electricity is inevitable and it might be sensible to use the waste heat from such plants to heat buildings in towns, not electricity.

We are also concerned over the investment which could be needed to allow gas heating to continue. Capital costs could exceed those of laying heat mains to built-up areas. Recurrent costs would almost certainly be higher. Given the concerns over using H_2 in the existing transmission pipes, the fuel seems more likely to be CH_4. But in built-up areas, even synthetic gas may have attractions over electricity.

The dilemma we face is that, without piped heat, it is quite hard to see how the urban UK can be heated in 2050 while reconciling a wide variety of different issues. These include:

- Climate change
- Network stability and security at peak
- Affordable running costs in a range of buildings, with varying heat demands
- A desire to supply 100% renewable energy by or before 2050
- A desire to maximise the flexibility on energy inputs to the network.

Overall, we think that the lesser of the problems facing us is to seek to organise piped heat where possible so that it works in the urban and suburban UK as it works on the continent; e.g., in Denmark. It clearly has difficulties, but *all* long-term options pose acute difficulties. There is also a profound opportunity to leapfrog Danish practice of 30 years ago, when their typical system was installed, and emulate good or best Danish practice now, the kind being used in their more advanced or demonstration projects.

Even with the best performance, such as a seasonal COP of 3.5, small electric heat pumps appear more useful in areas which are beyond the reach of heat mains. There might be merit in operating CHP plants to produce heat for urban areas and electricity whose output is partly used in rural GSHPs. These loads peak at the same time.

3. Financing Thermal Improvements - Existing Buildings

Summary

This section gives two examples of how extensive measures in existing dwellings could be financed. Both examples concern well-heated dwellings. One is in zone 1 and one in zone 2.

The examples given are fairly comprehensive retrofits. The analysis is from a UK PLC viewpoint. This chapter also summarises the assumptions behind the MACC in Figure 12.

The costings assume that measures are financed by long-term loans, at *Green Book* real interest rates. They come from utilities where possible or from quasi-government bodies such as a Green Investment Bank in circumstances where there is no other source of "de-risked" finance; e.g., buildings off the gas network which are heated by LPG, oil or other stored fuels.

Where appropriate, costs used for measures assume a mature market. For measures that are not yet applied widely in the UK, such as heat networks, these may be below figures quoted now. It is assumed that, where necessary, pump-priming is provided to reduce the costs of technologies to mature market levels; e.g., what they cost now in markets elsewhere in Europe where demand is higher.

The measures are economic to UK PLC in less well-heated dwellings, if the householders value the social benefits of the resulting extra comfort more than the fuel savings which they forego. This is usually the case. A warmer home would sometimes improve the occupants' health and reduce NHS costs.

All support programs for packages of measures should be conditional on insulation thicknesses being optimised for high comfort standards, so that they do not become inadequate with time. There is a long-standing UK tendency to retrofit insulation to buildings whose thickness in hindsight soon appears much too low; e.g., 25-75 mm mineral fibre EWI, 50 mm internal insulation bridged by battens. Even the wall insulation thickness added to the rural house here is a preliminary optimisation and should be confirmed by reference to the long-run marginal cost of renewable synthetic fuels.

Measures paid for now should not be allowed to physically compromise future measures which reduce emissions by larger amounts. For example, fitting solar panels on roofs before airtightness and insulation work has been either designed or carried out potentially prejudices its future implementation and increases its cost.

Low-Density Buildings

We take a solid-walled, rural, oil-heated 126 m^2 detached dwelling. Figure 37 shows what might be an example. It is in an exposed, windy location, with typical UK temperatures; e.g., east Midlands, coastal north-west England. It is unlisted, with a suspended timber ground floor above an unheated basement in half the house and a deep crawlspace in the other half.

The floorboards are in sound condition. The single-glazed wood windows and aluminium-framed double-glazed windows are respectively 110 and 35 years old and are both to be replaced. The former are at the end of their life. The latter suffer severe condensation on the frames in cold weather.

Figure 37. Rural solid-walled detached house.

The plastered external solid brick walls, which are 330 mm thick downstairs and 215 mm thick upstairs, are already rendered on the windward facade. It needs no re-rendering or re-pointing in the foreseeable future, so there is no credit for costs saved here. [400] It is acceptable to render all four sides, though, so EWI is chosen, using 225 mm graphitised EPS.

75 mm mineral fibre insulation was added between the rafters in a past loft conversion, with a 50 mm airspace and impermeable felt. The tiles, nails, battens and dormers need replacement,

but the rest of the roof structure is sound. The starting air leakage is 12.5 ac/h @ 50 Pa, which would be fairly typical of a building with suspended ground floor, plastered solid walls but still with some single-glazed windows. The final assumed value is 1 ac/h @ 50 Pa, based on work on similar pre-1900 detached houses. [401]

A 20 year old oil boiler and DHW tank, burning 8,000 litres/yr, are replaced by an active solar system with 10 m^2 high efficiency flat-plate collectors and 0.5 m^3 of water storage, yielding just over 3,000 kWh/yr of heat in a house of low heat loss. It is backed up in cold and/or cloudy weather by a LPG condensing boiler, burning 400 litres/yr. The fuel is changed from oil because of the somewhat improved supply situation, the lower CO_2 emissions and the improved control attainable on gas-fired appliances.

Table 14 summarises the measures added and the fuel consumption and costs before and after.

Measure	**Cost**	
Fabric	£/m^2	£
New roof tiles, battens and breather membrane replace old tiles, battens and impermeable felt. At same time, add 150 mm PIR foam and air-vapour barrier outside rafters, using stainless steel fixings into plywood sheathing and further 50 mm mineral fibre between rafters.	40	3,008
External solid wall insulation, 225 mm graphitised EPS or 150 mm phenolic foam.	85	13,430
Replacement windows, marginal cost to move from U=1.6 to 0.85.	150	3,240
Miscellaneous draughtproofing in other areas; e.g. services entries. Lump sum allowance.		1,500
Suspended ground floor, 100 mm mineral fibre between joists, airtight but vapour-permeable membrane below joists and 75 mm PIR foam outside membrane.	30	1,806
Sub-total.		22,984
Services		
New cylinder and pipes, marginal cost to reduce standing losses from 150 to 40 W using 150 mm PU foam on tank and 25 mm foil-faced phenolic foam equiv. on main pipes, heat trap(s) near tank and marginal cost of higher-efficiency modulating condensing boiler.		250
New radiators, capital cost saving from slightly smaller system, capacity cut from 16 kW(t), sized for 80/60°C and costing an assumed £1,120, to 3 kW(t) sized for 60/40°C and costing £420. No saving assumed on piping.		-700
MVHR system.		4,000
Solar system of 10 m^2 and 0.5 m^3, providing 80% of water heating and 40% of space heating on annual basis.		3,900
Sub-total.		7,450

Total net cost of retrofit.			30,434
Energy consumption			
Before			
Peak heat demand.			17.5 kW
Heat consumption.	Space heat.	57,60	kWh/yr
		457	kWh/m^{2}yr
	DHW	2,700	kWh/yr
		22	kWh/m^{2}yr
	Total	60,300	kWh/yr
		479	kWh/m^{2}yr
Seasonal boiler efficiency.		75	%
Fuel consumption, kerosene.		80,400	kWh/yr
		8,040	ltr/yr
		3,619	£
After			
Peak heat demand.	Space heating.	1.7	kW
	Water heating.	1.5	kW
	Total.	3.1	kW
Heat consumption.	Space heating.	32	kWh/m^{2}yr
		4,000	kWh/yr
	Water heating.	17	kWh/m^{2}yr
		2,100	kWh/yr
	Total.	59	kWh/m^{2}yr
		6,100	kWh/yr
Heat consumption from boiler, net of solar contribution, (0.2 x 2,100) + (0.6 x 4,000).		2,820	kWh/yr
Seasonal boiler efficiency.		95	%
Fuel consumption, LPG.		2,960	kWh/yr
		405	ltr/yr.
		160	£

Table 14. Measures Fitted to Low-Density Building and Resulting Energy Consumption.

NOTES:

1. Peak heat demand includes a nominal 1.5 kW for DHW.
2. Peak space heat demand is as calculated by PHPP.
3. The marginal cost for a new boiler is small because condensing boilers are compulsory in new installations. A nominal £100 is added for a modular model with a large enough heat exchanger to give 95% seasonal efficiency using load compensation controls, plus £150 for

improved insulation on DHW tank and pipes. It is not considered that load compensation and a few TRVs would cost any more than the UK practice of complex “programmable” time controls and possibly TRVs on all radiators.

4. Today’s solar system cost is from Danish sources, in a case where the heating system is replaced at the same time. [402] The estimated cost in 2015-2030 is 20-25% lower. No attempt has been made to optimise the solar system size versus the price of the backup fuel or versus the levels of insulation.

If, as is likely, the owners of such a house are already economising, by heating to a temperature nearer 16°C, first year repayments on a £30,400, 30 year loan at a nominal 6%/yr interest rate are £2,211, or more than the oil bill. Consumers will be unmotivated to change. Only if the house is very well-heated are the first year fuel savings from a near-Passivhaus retrofit higher than the loan repayments; i.e., £3,459.

On the whole, the incentive to invest such a large sum may appear weak, although oil prices will probably continue to rise at least at the inflation rate, making such a loan a good deal in the long term. [403] Consumers are especially reluctant to borrow if a loan is repayable when a house is sold, since there is very little evidence that heating bills affect a building’s value. We see no way to change this in the short or medium term, as UK housing shortages and planning restrictions tend to create a near-permanent seller’s market.

But there are ways to make large, long-term loans more attractive to consumers *and* to lenders. Suppose that the loan is legally attached to the building, not to the owner-occupier, landlord or lessee, providing more security; that the real interest rate is *raised* to 3.5%/yr and that the loan is made index-linked. Total fuel plus interest payments are then £1,855 in year 1, rising to £1,929 in year 2, etc.

With index linking, first year loan repayments are strikingly less than the first year fuel saving. The repayments would remain lower than the fuel saving unless real oil prices fall. If they do, the package would still save CO_2 at low costs, except in the event of truly unprecedented price falls; e.g. oil returning to $25-30/barrel.

In short, by re-structuring the financial package, we would achieve the following:

- An improved cash flow to consumers in the early years.
- A higher real return on capital to lenders.
- Greater security to lenders.

The first point improves potential takeup. The second reduces or eliminates any need for subsidy. The third reduces the interest rate at which investors would be prepared to lend money.

With index-linking, the monthly payment stays the same in real terms for 30 years compared to other goods and services, giving relative certainty to building owners. The fuel bill under normal occupancy conditions drops from £3,619/yr to £160/yr at 2010 prices. Although this remains variable and weather-sensitive, £160/yr is 0.6% of median household income. For the well-heated house, Table 15 shows the annual payments for a conventional loan at a nominal 6%/yr and for an index-linked loan at a real 3.5%/yr, both over a 30 year term.

Table 15. Hypothetical Cash Flow, Rural Detached House Initially Heated by Oil. £ sterling, nominal.

Year	**Business as Usual**	**Conventional Loan** Nominal 6%/yr, Real 2%/yr				**Index-Linked Loan** Real 3.5%/yr			
	Fuel	*Loan Repayment*	*Solar System Operation & Maintenance*	*Fuel*	*Total*	*Loan Repayment*	*Solar O&M*	*Fuel*	*Total*
	£/yr	£/yr	£/yr	£/yr	£/yr	£/yr	£/yr	£/yr	£/yr
1	***3,619***	2,211	39	160	***2,410***	1,656	39	160	***1,855***
2	***3,764***	2,211	41	166	***2,418***	1,722	41	166	***1,929***
3	***3,915***	2,211	42	173	***2,426***	1,791	42	173	***2,006***
4	***4,071***	2,211	44	180	***2,435***	1,863	44	180	***2,087***
5	***4,234***	2,211	46	187	***2,444***	1,937	46	187	***2,170***
6	***4,404***	2,211	47	195	***2,453***	2,015	47	195	***2,257***
7	***4,580***	2,211	49	202	***2,463***	2,095	49	202	***2,347***
8	***4,763***	2,211	51	211	***2,473***	2,179	51	211	***2,441***
9	***4,953***	2,211	53	219	***2,483***	2,266	53	219	***2,539***
10	***5,152***	2,211	56	228	***2,494***	2,357	56	228	***2,640***
11	***5,358***	2,211	58	237	***2,506***	2,451	58	237	***2,746***
12	***5,572***	2,211	60	246	***2,517***	2,549	60	246	***2,856***
13	***5,795***	2,211	62	256	***2,530***	2,651	62	256	***2,970***
14	***6,027***	2,211	65	266	***2,542***	2,757	65	266	***3,089***
15	***6,268***	2,211	68	277	***2,556***	2,868	68	277	***3,212***
16	***6,518***	2,211	70	288	***2,569***	2,982	70	288	***3,341***
17	***6,779***	2,211	73	300	***2,584***	3,102	73	300	***3,474***
18	***7,050***	2,211	76	312	***2,599***	3,226	76	312	***3,613***
19	***7,332***	2,211	79	324	***2,614***	3,355	79	324	***3,758***
20	***7,626***	2,211	82	337	***2,630***	3,489	82	337	***3,908***
21	***7,931***	2,211	85	351	***2,647***	3,628	85	351	***4,065***
22	***8,248***	2,211	89	365	***2,665***	3,774	89	365	***4,227***
23	***8,578***	2,211	92	379	***2,683***	3,925	92	379	***4,396***
24	***8,921***	2,211	96	394	***2,702***	4,082	96	394	***4,572***
25	***9,278***	2,211	100	410	***2,721***	4,245	100	410	***4,755***
26	***9,649***	2,211	104	427	***2,742***	4,415	104	427	***4,945***
27	***10,035***	2,211	108	444	***2,763***	4,591	108	444	***5,143***
28	***10,436***	2,211	112	461	***2,785***	4,775	112	461	***5,349***
29	***10,853***	2,211	117	480	***2,808***	4,966	117	480	***5,563***
30	***11,288***	2,211	122	499	***2,832***	5,164	122	499	***5,785***

NOTES:

1. A £30,434 loan is taken out for the marginal cost of a near-Passivhaus retrofit, plus heating system replacement comprising condensing LPG boiler and active solar, fitted at the time of other major refurbishment of the roof, windows and plumbing. The weighted average real interest rate is assumed to be 3.5%/yr and the loan term is 30 years. Some measures in the package will last longer than 30 years, but new window sealed units and mechanical services may not.
2. The base case oil bill would be £2,039/yr at an average whole house temperature in the heating season of 16°C, as opposed to £3,619/yr at 21°C.
3. Cash flow figures in nominal £ for future years assume 4%/year inflation.
4. Boiler servicing/safety inspection costs are assumed to be unchanged for LPG relative to oil, so such costs are not shown.
5. It is assumed that reduced demand for fuel has no impact on the price of fuel and that fuel rises in price from mid-2010 at the general inflation rate.
6. Figures in bold italics represent the total annual cost in all three cases - business-as-usual, conventional loan and index-linked loan.
7. For energy security, and CO_2 cuts, LPG is preferred to oil. Emissions per unit of heat in kg/kWh are 15% lower for propane than kerosene, taking account of the higher efficiency of LPG condensing boilers. The fuel's price has been 1 p/kWh higher than oil in recent years, so the measure costs around £240/tonne CO_2 saved, although this premium is somewhat debatable. System capital costs are assumed to be the same for both fuels.

If the house is well-heated, it appears to need no public sector subsidy, whatever form the loan takes, as long as it is provided on regulated utility-type terms. In the index-linked case, the outgoings fall by some 49% from £3,619 per year to £1,860/yr. With a conventional loan, the outgoings in year one falls by 33%.

If the house is heated to a rather low standard, an index-linked loan seems to need no subsidy. The occupants' cash flow is improved, and they would be more comfortable. The package saves CO_2 at negative cost. If it was broken down in more detail, condensing boiler and controls and basic solid wall insulation would save fuel for negative costs, whilst some subsequent measures; e.g., marginal increases in the wall insulation to very high levels, would be costly. Please refer to Figure 12.

If consumers were paid to reduce CO_2 emissions, or if fuel carried a CO_2 tax, this would enhance the value of undertaking the work, versus the *status quo*. We have not optimised the package in detail so that the marginal cost of the most costly measure matches the desired social cost of CO_2 emissions. We consider that it includes most of the available low-cost measures. The wall insulation added, 225 mm EPS, is roughly optimal for the marginal cost of LPG heat, assuming that the house is well-heated.

Circumstances will differ between dwellings. Most are not about to be extensively refurbished but could implement this work in phases. Given, however, that EWI in particular reduces heat consumption by about 50%, with a 12%/yr real return on investment against the fuels available in rural areas, it appears profitable to fit this now even if no other refurbishment is planned, followed later by work in other areas.

A strategy is needed for the low-density building stock, including rules on loan eligibility in different circumstances; e.g. where a house is to be partly retrofitted now and partly in stages later; e.g., floor now, walls and roof in 5 years' time and replacement windows in 20 years time. We need to combine energy/climate change and social policy to finance loans where existing buildings are not even moderately well-heated; e.g., homes in which the low-income and perhaps elderly occupants can afford neither a £3,000/yr oil bill, nor the repayments on a large long-term loan. These homes may be typified by one or two warm rooms, with the rest of the house left largely unheated.

Higher-Density Buildings

We consider a district typified by semi-detached houses, such as the one in Figure 38. They are cavity-walled, 80 m^2, built in the 1970s, with a solid ground floor. They have a fairly low-pitch roof and trussed rafters; i.e., no prospect of a loft conversion. The frames of the PVC replacement double glazing are typically in good condition but some sealed units are failing and it is likely that these could be replaced over time. There is 75 mm mineral fibre insulation on the attic floor, a zone which is quite full of electrical wiring and could not be made airtight without disruptive rebuilding. The tiled roof is in good condition and in no need of renovation. The party wall has two parallel leaves of masonry touching each other, as opposed to the empty cavity used in more recent years.

The 50 mm cavity in the external wall is uninsulated. The Building Regulations of that time could be met by the R-value of the lightweight block inner leaf alone. The dwelling's starting air leakage is 11 ac/h @ 50 Pa. It has a 75% efficient gas boiler.

Figure 38. Cavity-walled semi-detached houses.
Source: Google streetview.

The scale of expenditure on the rural house is not financeable on an urban house on a *pro rata* basis; i.e., in line with its smaller floorspace. Any more than the simpler measures starts to abate CO_2 at high costs in £/tonne. The pattern of sharply rising costs is seen in Figure 12. However, it is possible to reduce emissions 80% by combining the simplest and most cost-effective heat-saving measures with a change from individual natural gas heating towards a lower-CO_2 alternative, at an estimated mature market cost of less than £10,000 per dwelling.

We assume that a typical house in the area is given cavity wall and roof insulation at rafter level with airtight materials; modern PVC windows are re-glazed with warm-edge argon-filled low-emissivity double-glazed sealed units as the old SUs fail; mechanical exhaust-only ventilation (MEV) is fitted for good air quality as air leakage falls and minor extra draughtproofing is carried out to reduce air leakage to a maximum value of 3 ac/h @ 50 Pa, with the average property reaching 2 ac/h @ 50 Pa. The district is connected to piped heat from a modular condensing 500 kW(e) gas-fired reciprocating engine CHP plant, costing £600/kW(e) including backup boiler(s), fuel store and grid connection, versus £350 kW(e) for a CCGT. [404] [405] [406] The extra capital expenditure and O&M costs are charged to heat sales.

The roof insulation added is 100 mm PU foam between the rafters and 20 mm inside them. The judgement is that in a typical house the levels fitted would be partway between the optima for individual gas heating and piped heat. Inevitably, many dwellings will be heated by gas boilers for some time to come. On the walls, whether the heat is from a condensing boiler or gas CHP, the most economic measure appears to be to insulate the cavity with 50 mm of injected PU foam.

The CHP engine is assumed to consume interruptible gas at 2 p/kWh [407] and to have maintenance costs of 0.9 p/kWh(e), as opposed to 0.25 p/kWh(e) for the CCGT which it is assumed would otherwise be used. [408] Assumed electrical and thermal efficiencies are 50%/35% for CCGTs and 38%/50% for reciprocating engines.

Under today's charges for the use of the UK electricity system, the benefit due to reciprocating engines located near consumers at substations and available to provide grid balancing services is very hard to value, although a credit is due. So this calculation overestimates the costs which should be charged to heat consumers, but pending a fuller calculation it should be a useful contribution to the debate.

After ten years, the network is connected up to a gas-fired CCGT plant. The reciprocating engine would be moved on and reused elsewhere, probably initially to set up another network and later for mid-merit, peaking or standby duty on larger networks.

The local heat network is assumed to cost £5,000 per dwelling at this density. We assume that the UK has granted heat suppliers equal statutory legal powers to other utilities and has become as familiar with the technology as with gas pipes and electricity cables, easing the path to such development. In Denmark, retrofitting heat mains in suburbia costs £6,000-6,500 per dwelling on 1,200 m^2 plots roughly 25-30 m wide by 40-45 m deep. It costs less on smaller, UK-size plots, but not *pro rata* because there are also some fixed costs; e.g., valves, meters, etc.

The network to link these local networks up later to a CCGT is assumed to cost a further £1,000/dwelling, including transmission pipe and interconnections between the local networks. Alterations to the CCGT to extract hot water for DH are assumed to cost 25% of its original cost, or £90/kW(e). This is charged to heat sales.

In small settlements, connection to a CCGT might never happen. On the other hand, a small town heat network would cost slightly less if no future expansion is planned or catered for. Narrower pipes, with lower working pressures, can be used.

Table 16 sets out capital repayments on the basis that the heat main and retrofit insulation are financed by index-linked loans, with life-cycle costing, at *Green Book* rates. The step changes in annual payments reflect the capital expenditure on connection to a CCGT. In reality, such variations would be evened out in heat tariffs. If desired, this could be shown in the table as a uniform levelised cost.

These measures slightly improve householder cash flow versus the *status quo*. Annual costs fall by 20-25%, assuming a fully-heated house. Replacing individual gas heating by piped heat raises future energy flexibility.

As with the last example, if householders were paid for CO_2 emissions avoided, or if the fuel carried a CO_2 tax, there would be more financial incentive to undertake the retrofit. The main measures which reduce annual costs are the initial 50 mm of PU foam roof insulation, the wall insulation and upgrading the replacement sealed double glazing units. The shift to gas CHP gives a modest saving in running costs but a much higher saving in CO_2 emissions. CO_2 emissions for space and water heating fall by about 60% with a reciprocating engine and 85% with a CCGT, relative to a condensing boiler.

Year	Business-as-Usual					Index-Linked Loan for CO_2-Saving Measures							
	Gas Fuel	Pump and Fan Elec.	Boiler		Total	Insulation, Draught-proofing et al	Heat Mains, Meter, Valves, etc			Power Station Costs	Fuel Cost	Pump-ing Elec.	Total
			Repayments	*Servicing*		*Loan Repayments*		*O&M*	*Inspcn.*				
	£	£	£	£	£	£	£	£		£	£	£	£
1	877	66	141	75	***1159***	224	323	59	50	132	106	9	***904***
2	912	68	146	78	***1204***	233	336	62	52	137	111	9	***940***
3	948	71	152	81	***1252***	243	349	64	54	143	115	10	***978***
4	986	74	158	84	***1302***	252	363	67	56	148	120	10	***1017***
5	1026	77	165	88	***1356***	263	378	69	58	154	125	11	***1058***
6	1067	80	171	91	***1409***	273	393	72	61	161	130	11	***1100***
7	1109	83	178	95	***1465***	284	409	75	63	167	135	11	***1144***
8	1154	87	185	99	***1525***	295	425	78	66	174	140	12	***1190***
9	1200	90	193	103	***1586***	307	442	81	68	181	146	12	***1237***
10	1248	94	200	107	***1649***	319	460	84	71	188	152	13	***1287***
11	1298	97	208	111	***1714***	332	570	105	74	195	56	13	***1346***
12	1350	101	217	115	***1783***	345	593	109	77	203	59	14	***1400***
13	1404	105	225	120	***1854***	359	616	113	80	211	61	14	***1456***
14	1460	109	234	125	***1928***	374	641	118	83	220	63	15	***1514***
15	1518	114	244	130	***2006***	389	667	123	87	229	66	16	***1574***
16	1579	118	254	135	***2086***	404	693	127	90	238	69	16	***1637***
17	1642	123	264	140	***2169***	420	721	133	94	247	71	17	***1703***
18	1708	128	274	146	***2256***	437	750	138	97	257	74	18	***1771***
19	1776	133	285	152	***2346***	455	780	143	101	267	77	18	***1842***
20	1847	139	297	158	***2441***	473	811	149	105	278	80	19	***1916***
21	1921	144	309	164	***2538***	492	844	155	110	289	83	20	***1992***
22	1998	150	321	171	***2640***	511	877	161	114	301	87	21	***2072***
23	2078	156	334	178	***2746***	532	912	168	118	313	90	21	***2155***
24	2161	162	347	185	***2855***	553	949	174	123	325	94	22	***2241***
25	2247	169	361	192	***2969***	575	987	181	128	338	98	23	***2331***
26	2337	175	375	200	***3087***	598	1026	189	133	352	102	24	***2424***
27	2431	182	390	208	***3211***	622	1067	196	139	366	106	25	***2521***
28	2528	190	406	216	***3340***	647	1110	204	144	381	110	26	***2622***
29	2629	197	422	225	***3473***	673	1154	212	150	396	114	27	***2727***
30	2734	205	439	234	***3612***	700	1201	221	156	412	119	28	***2836***

Table 16. Hypothetical Cash Flow, Suburban Semi-Detached House. £ sterling, nominal.

NOTES:

1. Investments are amortised at *Green Book* rates over lifespans of 30 years for underground buried heat mains and a weighted 30 year average for the package of fabric insulation, re-glazing windows and internal building services. Reasonable lifetimes for individual elements might, however, be 60 years for roof insulation and underground heat mains, 100 years for wall insulation, 20 years for sealed units and existing window frames, 50 years for new wood window frames, 20 years for internal services.
2. Gas boiler servicing and safety inspection is assumed to cost a nominal £75/yr, rising with inflation.
3. Heat mains are assumed to cost 1%/yr of their initial capital cost in operation and maintenance.
4. House internals and connections for directly-connected DH systems are assumed to be inspected every other year, at a resulting cost of £50/yr, rising with inflation.
5. Pumping electricity consumption for DH is assumed to be 1.0% of heat consumption. This is more typical of very large schemes than small ones using reciprocating engines, which use around 0.3%.
6. Electricity consumption by pump(s) and fan(s) of individual gas boiler systems is taken as 3% of heat consumption. Typically, a system supplying a heat load of 15,000 kWh/yr would use 500 kWh(e)/yr. [409]
7. The potential heat load in the street is assumed to be connected linearly over a 10 year period. This involves capital repayments on pipes which are laid but not fully-utilised. This has been absorbed within the capital charges on the heat main, which are assumed to be inflated by 3.5%/yr interest for five years.
8. Cost of electricity sent out from a CCGT = [(2/0.5) + 0.25] = 4.25 p/kWh, fuel and maintenance only.
9. Ditto from a reciprocating engine = [(2.0/0.38) + 0.90] = 6.2 p/kWh(e). The extra capital cost of £250/kW(e), at an assumed 30% load factor, raises costs by 0.5 p/kWh(e), giving 6.7 p/kWh(e).
10. This extra cost is loaded onto heat sales, giving a cost for heat sent out of (6.7-4.25) x 0.38/0.52 = 1.8 p/kWh (t).
11. The fuel costs of the delivered heat from reciprocating engine CHP are as follows. Engine output = electricity 38%, heat 50%. CCGT output = 50%. Lost electricity = 12%.
12. CO_2 intensity of CHP heat sent out = (0.206x0.12)/(0.5x0.5) = 0.099 kg/kWh.
13. Assumed heat distribution losses = 12%.
14. CO_2 intensity of CHP heat delivered = 0.099/0.88 = 0.112 kg/kWh.
15. Fuel cost for reserve/standby/peaking condensing boilers is as follows.
16. Assume boiler efficiency = 90%, backup fuel = bulk LPG at 4.5 p/kWh.

Overall CO_2 intensity of heat delivered = 0.25/(0.88x0.9) = 0.316 kg/kWh.

17. Weighted average CO_2 intensity of delivered heat = (0.97x0.112)+(0.03x0.316) = 0.118 kg/kWh.

18. CO_2 intensity of delivered heat from CCGT CHP is 0.024/0.88 = 0.028 kg/kWh. See Figure 29. Weighted average, using reserve boilers for 3% of delivered heat and reciprocating engines for 12% of it = (0.85x0.028) + (0.12x0.112) + (0.03x0.316) = 0.047 kg/kWh.

Table 17 summarises the measures added and the fuel consumption and costs before and after.

Measure		**Resource Cost**	
		£ per m^2	£
Fabric			
Roof insulation, 120 mm PU foam between and inside rafters and on gable end.		28	1,338
CWI, 50 mm injected PU foam		15	1,277
Re-glazing to replace failed sealed units, marginal cost		9	135
Miscellaneous draughtproofing in areas not covered by wall and roof insulation; e.g., soil vent pipe, drains. Lump sum allowance.			500
Sub-total			**3,250**
Services			
New cylinder, marginal cost			150
Continuous MEV			1,000
Heat mains			5,000
Sub-total			**6,150**
Total			**9,400**
Energy consumption			
Before			
Peak heat demand		10	kW
Heat consumption	Space heat	23,300	kWh/yr
		291	kWh/m^{2}yr
	DHW	2,280	kWh/yr
		28	kWh/m^{2}yr
	Total	25,580	kWh/yr
		319	kWh/m^{2}yr
After			
Peak heat demand		4	kW
Heat consumption	Space heat	9,430	kWh/yr
		118	kWh/m^{2}yr
	DHW	1,420	kWh/yr
		18	kWh/m^{2}yr
	Total	10,850	kWh/yr
		136	kWh/m^{2}yr

Table 17. Measures Fitted to Suburban Semi-Detached House and Resulting Energy Consumption.

NOTE: Heat mains cost in Table 17 is for local network only, before linkage to a more remote CCGT.

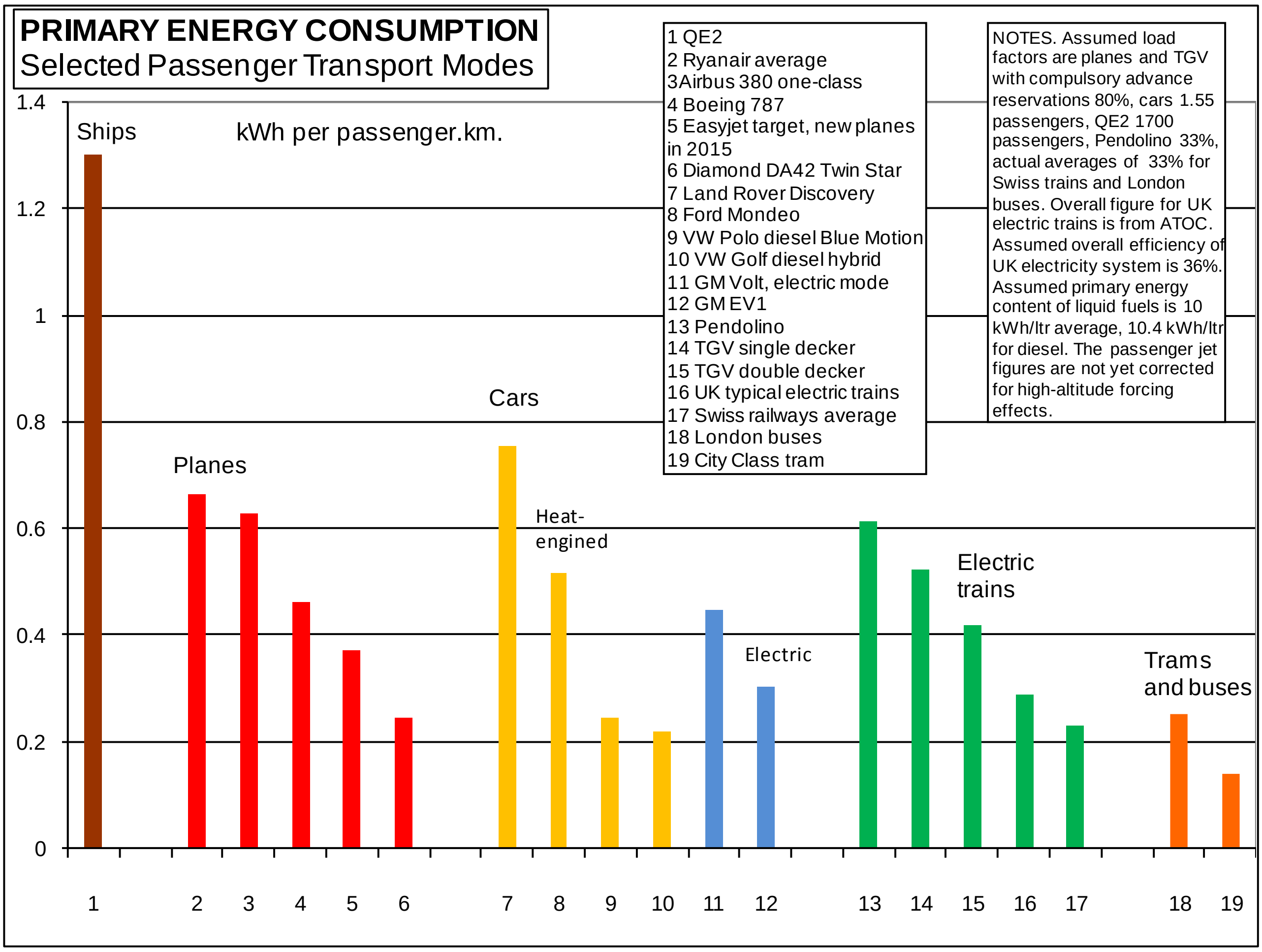
4. Transport Sector

Priorities

The bulk of the sector's energy is accounted for by road, air and international shipping. Road in turn is mostly split between cars and light vans and HGVs. Rail, bus, tram and motorcycle energy usage is low compared to use by these other modes.

As Figure 39 shows, some common assumptions on energy intensity are counter-intuitive. There is more variation within modes than between modes. A fairly reliable rule is that luxury and/or high-speed travel uses more energy than more modest modes of travel.

Trains can run on mains electricity, not on liquid fuels, thereby needing no batteries. But the primary energy use of heavy and fast electric trains is approaching that of newer planes, measured in kWh/passenger.km. The power to overcome air resistance increases roughly as the cube of the train's speed. Energy consumption for this purpose rises approximately as the speed squared.



PRIMARY ENERGY CONSUMPTION
Selected Passenger Transport Modes

NOTES. Assumed load factors are planes and TGV with compulsory advance reservations 80%, cars 1.55 passengers, QE2 1700 passengers, Pendolino 33%, actual averages of 33% for Swiss trains and London buses. Overall figure for UK electric trains is from ATOC. Assumed overall efficiency of UK electricity system is 36%. Assumed primary energy content of liquid fuels is 10 kWh/ltr average, 10.4 kWh/ltr for diesel. The passenger jet figures are not yet corrected for high-altitude forcing effects.

Figure 39. Primary Energy Consumption of Various Passenger Transport Modes. [410]

NOTES:

1. Figures for some electric cars, trams and trains may exclude space heating. Published figures are often ambiguous. Car figures usually exclude lighting and cooling. Figures for air and sea transport appear to include on-board “building services”.

Trains and Buses

In principle, most UK rail and urban bus travel could be electrified. Unlike road vehicles, which need batteries to operate successfully on electricity, mains-electric trains or buses weigh less than the liquid-fuelled versions and cost less to buy and maintain. According to the Dept. of Transport, the reliability and maintenance cost savings can make investment in the overhead wires self-financing to the UK. [411]

Energy efficiency measures can reduce a tram’s electricity consumption by some 75% from 4 to 1 kWh/vehicle.km, as in Table 19, although the doors are opened so often that winter space heating is likely to take another 0.5 kWh/vehicle.km, even with reversible heat pumps. [412] It is more a case of being aware of the potential, and the public sector being open-minded to new bidders, than of lavish spending.

Based on the stated payback periods, the measures appear cheaper than renewable electricity. We suspect that similar potential exists on new electric trains, if the subject is studied closely and if rewards are offered by utilities, commensurate to the saving on new power stations or operating existing ones.

Cars and Light Vans

Electric/Hydrogen/Other Fuels

Via tax and grant arrangements, the UK government at present offers a *de facto* £19k per vehicle subsidy to electric cars. [413] There is a lobby for H_2-fuelled cars too. But for several reasons, it could be hard for either technology to contribute to urgent climate change targets.

The most easily-electrified cars are those with reduced functionality and which make short trips. These are the journeys that one might think could most easily be made by tram, trolley bus, cycling or on foot.

Private cars are in use for about 300 hours/year, or 3% of the time, discouraging the use of capital-intensive plant and equipment. But batteries and motors displacing an ICE and fuel tank increase the cost of a new vehicle, reduce its range and increase its cost-in-use. The new combination is only favoured if a vehicle is used intensively enough to repay the battery cost, but always on short journeys, and if renewable electricity is so much cheaper than renewable fuel that the saving more than pays for the battery costs.

From a consumer's viewpoint, a BEV may sometimes appear cheaper to run if government continues to maintain the very high taxation level on ICEVs and the very high subsidy on BEVs. However, although this policy distorts the market, it does not affect the relative resource costs of the two options to UK PLC.

BEV prices today are kept down to £25,000-30,000, versus £15,000-18,000 for an ICEV, mainly by redesigning for a shorter range and lower payload. [414] But the monthly payments for the batteries and electricity are still over three times higher than the 2010 monthly ex-tax fuel costs of a ICEV. [415]

Battery systems to give a UK car and light van fleet a more generous range of 400 km could cost of the order of £1.5 trillion today and £400 billion at predicted 2030 battery prices. [416] The rest of an electric infrastructure would cost more than liquid fuels distribution. The overall resource demands of lithium-ion (Li-ion) batteries could be a concern. [417]

An issue for BEVs in cool climates is the lack of engine waste heat. The heat from power generation, which is used to warm ICEVs from autumn to spring and demist the screen, is not available, because it has been discharged elsewhere. Few BEVs could be adequately-heated by waste heat from the motor, although it would be a good idea to pursue this option, along with reversible heat pumps and insulated bodywork. It may be useful for mains-electric vehicles too.

Electric resistance heating reduces the range. [418] The heating load is time-dependent, not distance-dependent, giving a risk of running out in winter traffic congestion. One BEV manufacturer suggests pre-heating the car interior from a building's 230V AC electricity supply before setting off. [419]

Yet we are faced by many difficult issues:

- The urgent need to cut oil consumption, for clear geopolitical reasons
- The limited size of the biofuel resource
- The non-zero GHG emissions from most biofuels
- The value of storable fuels throughout the economy,

We conclude that we should deploy an option which was ignored or sidelined in the past - the synthesis of fuels such as CH_3OH or CH_4 [420] from electrolytic H_2 and air-captured CO_2, for use in efficient ICEVs. Or instead of air capture, some synfuel plants could be supplied with pure CO_2 from custom sources such as natural gas or biomethane separation plants, geothermal vents, steelworks and cement kilns. This would use spilled wind electricity which the national grid cannot easily use, supplementing the biofuel resource, which cannot be assumed to be sufficient.

Fuel cells could be used in vehicles instead of ICEs, if they became an economic option. This has not happened to date.

The reason for our coming to this view is that none of the post-oil options for road, sea and air transport appear attractive. Given the urgency, and lower investment costs, perhaps it is overdue for us to be pragmatic and realistic and, instead of pursuing breakthroughs, to pursue the “least worst” option.

The most obvious disadvantage of ICEVs and synfuels is that the pre-tax cost of renewable fuel would exceed that of fossil petrol and diesel. But the synfuel used by an ICEV would cost less than the electricity used by a BEV along with the annual repayments on its battery bank. [421] Figure 40 illustrates this schematically for today’s oil and electricity prices and for a case where synfuels, costed at UK PLC interests rates, are twice the ex-tax cost of oil. Both the BEV and ICEV are energy-efficient designs, relatively close to the 2010 state-of-the-art, although the BEV has a range of 200 km and a reduced payload of 300 kg, as with the Nissan Leaf.

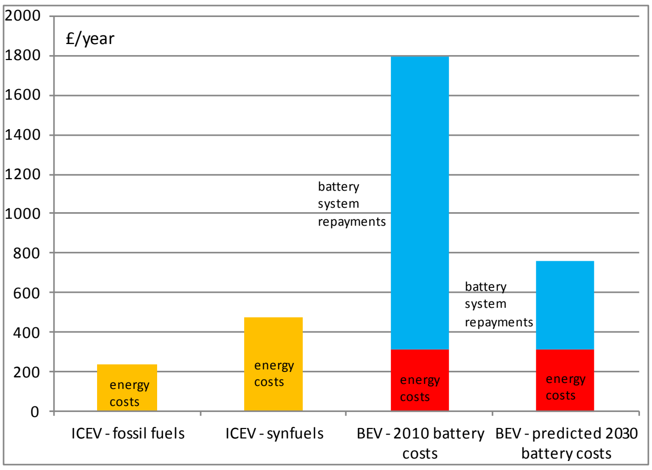


Figure 40. Annual energy costs and battery repayments for an ICEV and a BEV.

The “efficiency” from:

> Interruptible electricity → synfuel → storage → HGV → filling station → fuel tank → ICE → motive power

is set to be lower than that from:

> Interruptible electricity → storage → T&D losses → battery charging → storage and self-discharge → motive power plus ancillary losses of heat pump or resistance heating.

But the lighter ICEV needs less traction power, costs less and has features that users value; e.g., range and ability to refill the tank while on the move. [422] If much wind electricity has been stored as fuel, *inter alia* to keep the electricity network stable, the option exists of using stored fuel for transport, possibly delivering CH_4 via the gas network, and not reconverting it to electricity.

Battery system costs in 2010 are probably around £600/kWh, although it is hard to narrow down the exact figure and so Figure 40 has assumed £500/kWh. [423] The extra wind generation, electrolysers and synfuel capacity for the wind-methanol route, keeping today’s liquid fuel tanks and distribution systems, or conceivably stored methane, looks less costly than the battery banks, grid reinforcement and balancing costs for the wind-electric route. If 2030 battery price forecasts of £150/kWh [424] are borne out, the wind-synfuel route remains lower in cost for average and indeed for most vehicle usage patterns. With the high cost of batteries versus fuel tanks, an overall “energy economics” view leads to somewhat different conclusions than an “efficiency” view.

Even if synfuels could relieve us of a need to write-off filling station and fuel distribution infrastructure and invest large sums in electrification, experts suggest that a full transition from

94% fossil motor fuel to synfuels or synfuel-biofuel mixtures could *still* take 30 years. [425] So there is no time to lose. We need to look at all the options, informed by the actual status of technologies *now*, and their future potential, without relying on speculative breakthroughs. [426]

In the short term, "feebates" [427] to energy-efficient ICEVs would help lead to deep cuts in CO_2 emissions and in oil imports. Fuel efficiency measures would also help to keep running costs at reasonable levels after a move to synfuels. It is easiest to introduce them via mandatory EU fuel economy standards, with limits to the fleet average in g/km or kg/100 km. This should provisionally drop by say 20% every five years, with legal limits for 2020 and 2025, not just 2013, being published now. Given the low usage hours of private cars, such legislation should be subject to regular assessments to verify that measures introduced are cost-effective against long-run marginal fuel supply.

The g/km limits should apply equally to ICEVs and BEVs, to give a like-for-like comparison and to be technology-neutral. [428] The UK policy of taxing vehicles using renewable fuels and subsidising BEVs using renewable electricity, possibly from the same energy source, is bizarre and risks leading to perverse outcomes, with resulting waste of resources. Renewable liquid transport fuel is currently taxed on a par with fossil diesel or petrol. The position on biomethane and natural gas is less clear.

Ratings should use EU average CO_2 emissions for electricity. [429] Better would be to use emissions at the margin, to reflect the fact that higher consumption in a country leads to retention of more existing coal-fired plants. Electricity is traded across borders, tending to equalise average emissions between; e.g., the low national figures in France, Sweden, Norway and Switzerland and the high figures in Denmark, Germany, Poland, Greece and the UK, but also tending to set marginal emissions at the level of the "worst" plants in the EU, especially if consumption is static or rising, as these plants then stay in use longer.

For the same reasons, ICEV emissions ratings should use marginal CO_2 emissions for the fossil fuel remaining in the fuel mix. This figure may rise as we exploit more difficult offshore oilfields.

The g/km figure should include heating, lighting and cooling. It should be based on emissions under realistic driving conditions. This is not so today for BEVs or ICEv. [430] If legal standards are governed by a test protocol which does not predict real world performance, we could miss CO_2 reduction targets by tens of percent. [431] The US EPA has developed test protocols for use at different ambient temperatures. The EU could use similar methods to address the issue.

Lighting accounts for about 3% of road vehicle fuel consumption. So in future, it should be included in quoted fuel consumption. This gives an incentive for; e.g., a rapid changeover from halogens to LEDs. Vehicle cooling should be included. So should any vehicle space heating which does not come from engine waste heat. Given climatic differences, the correction for heating and cooling should vary between member states. It may be possible to divide the EU into its three basic climate zones; i.e., cold, moderate and warm, as is often done for space heating.

The quoted CO_2 emissions of any biofuels contained in EU motor fuel should include the fuel's combustion emissions. There is no guarantee today that any C-based fuel sold is CO_2-neutral. As was discussed earlier, with all but a few biofuels, there is the alternative of using biomass to sequester CO_2 and not burning it. The "national GHG accounts" are much clearer if we quote emissions and sequestration terms separately. This helps to avoid accidental or deliberate double-counting. [432]

Best Practice - Cars

For ICEVs on sale in 2010, the best performance is 35 kWh/100 km, 3.4 litres /100 km or 89 g/km. It is achieved by a sub-compact diesel hatchback. [433]

Today's "compact" cars may have 100 kW engines and top speeds of over 200 km/hr. However, an energy-efficient car can cruise at legal motorway and dual carriageway speeds of 100-120 km/hr on a 20 kW engine; i.e., only 20% of the normal engine size. [434] If society accepts speed limiters on cars, to match those on HGVs and buses, engines can be made smaller and lighter, structural weight can be eliminated and lighter tyres and suspensions can be used, saving on vehicle weight and fuel. As a rule, halving a car's engine size would only reduce its top speed by about 20%.

Aluminium bodywork can also be used, as in some "high-end" production cars, "premium" sports cars and the pioneering Audi A2 1.2 TDI, which consumed 3.0 litres/100 km *in 1999*. See Figure 41.

The estimated cost of using lighter materials *en masse* is of the order of £900 per vehicle. [435] Starting from one of today's very efficient vehicles, this appears to save fuel at 7 p/kWh, if the premium is amortised over 20 years at 15,000 km/yr, assuming no scrap value for the aluminium. The resulting marginal abatement cost is £250/tonne.

7 p/kWh barely competes with the ex-tax price of fuel, even in 2011. Aluminium's high scrap value may marginally reduce the cost. New cars are driven for more than 15,000 km/yr, though, so the CO_2 savings are weighted towards the early years of the car's life. The entire lightweight materials area may need government intervention to accelerate market development. As long as lightweight materials remain a niche area, the repair cost of non-steel car bodywork appears to remain too high. It is seen as "specialist", not standard.

It appears possible that such efficiency improvements undercut the cost of synfuels, but not the cost of fossil fuels. If so, there is a good case for supporting them before supporting either synfuels or BEVs.

Figure 41. The Audi A2 1.2 TDI, as manufactured from 1999 to 2005. Emissions = 81 g/km. Source: Wikipedia.

We estimate that this and other changes; e.g., continuing diesel engine improvements, could fairly easily deliver "sub-compact" cars by 2020-2030 which consume 20 kWh per 100 km, as long as the market is encouraged by feebates and by government procurement exercises to drive improvements forward. [436] This would correspond to actual emissions of around 56 g/km, assuming that the fuel is oil-derived.

This figure is beyond the 2013 EU legislation of 130 g/km or approximately 49 kWh/100 km and the EU target of 95 g/km or 35 kWh/100 km in 2020. Yet it is only 30% beyond the performance of the Audi A2 1.2 litre diesel, which was developed 20 years ago.

With lean burn engines, which were temporarily abandoned in favour of catalysts, petrol cars should be able to achieve near to 2010 diesel car fuel economy. [437] Today's diesels offer scope for a further 30% fuel saving. Car diesel engines have seen less development to date than car petrol engines or electric motors, so more potential remains. The first diesel passenger car was only launched in 1976, whereas electric and petrol cars were both in use 100 years ago.

While European and Japanese cars have become more streamlined in recent years, many pickup trucks, large vans and SUVs have rectilinear shapes and drag coefficients of 0.40 or more. The need to streamline these vehicles better should be obvious.

We think that the urgency of the situation, both fuel security and GHG emissions, demands government co-funding of R,D&D or for government to use its fleet buying power proactively; e.g. to write a demanding specification and agree in advance to buy a minimum number of vehicles from the competition winner, in a similar exercise to the US Golden Carrot refrigerator competition. [438]

This would start to reduce CO_2 emissions reliably in 2015 or 2020, not speculatively in 2030, and send a signal to the rest of the car and light van market that the UK government is "doing its bit" to reduce oil dependence. We suggest a requirement of 80 g/km or 0.29 kWh/km for mid-size cars delivered in 2015 and 60 g/km or 0.22 kWh/km in 2020, falling thereafter at around 25% per five years if the government organises regular competitions.

HGVs, Air Travel and Shipping

HGVs

HGVs and vans carry food, clothing and many other essential goods. Many vans are used on work which is essential to the smooth functioning of the economy; e.g. construction. Undoubtedly, some heavy freight could switch to electric rail, with the help of sufficiently consistent and constructive government policies, but it needs long-term strategic planning, such as raising loading gauges across the rail network. [439]

The discussion here includes both rigid vehicles and articulated tractor-trailer combinations. The potential for enhanced energy efficiency approaches that of cars and vans. The rate of return on a given investment is enhanced compared to cars, because the load factor of HGVs is much higher. Most of them are driven for 100,000-150,000 km/yr, or 6-15 times as far as a car. But there would be more emphasis on reduced drag, which has been implemented hardly at all on HGVs, and less on reduced weight, which may save much less. [440]

Influenced by legislation, new European HGVs are almost brick-shaped. The drag coefficient (DC) may have risen over time. It is close to 0.8, or about three times higher than that of new cars and five times higher than the estimated minimum for cars. [441] DCs can, however, be reduced as low as 0.25 by smoothing the front end of the cab, redesigning wing mirrors or using cameras, smoothing the base of the trailer, using gaskets to create smoother joints between tractors and trailers and slightly changing the shape of trailers. [442]

Other options include hybrid engines, albeit most beneficially on HGVs with stop-start useage patterns, saving 5-40%; turbocharging; smart cruise control; on-off controls like those now widespread on cars; bottoming cycles, raising diesel engine efficiency from 40-45% to 55-60%.; lower rolling resistance tyres and/or wide singles, saving 3-8%; and automated tyre inflation systems, saving 5-15%.

Multiplying together the measures, a US analysis in 2008 puts forward a cost-effective saving of 64%, in kWh/tonne.km. [443] This excludes savings from hybrid drive, diesel engine bottoming cycles and auxiliary power units, which could raise the cumulative saving to 75-80%. But a few savings suggested for North America; e.g., long double trailers, might be resisted here except on motorways, reducing the saving back to about 65%. Such long HGVs appear to be banned in the UK and Germany but allowed in the Netherlands and Sweden.

In a joint Canadian/US analysis, the rates of return on most measures at 2007 ex-tax fuel prices were from 20-50%/yr. Assuming the same cost to implement the technology in Europe, such measures are more profitable to UK PLC than buying oil. The rate of return was 1.5 times higher in 2010 than in summer 2007.

In the past decade, some UK companies have implemented easy options; e.g., the use of modern ICT technology to optimise routes and minimise empty running of vehicles, saving up to 7%. Other options are rarely heard of in the HGV industry. Yet the UK has the highest diesel prices in the EU, allegedly causing the HGV industry great concern. Rising prices are not being followed up by major redesign of new HGVs, suggesting market failure.

Several UK government studies have revealed large potential savings. As an IEA workshop noted, the technologies are widely-discussed, but action to implement them is all but invisible. [444] Japan has some minimum HGV fuel economy standards. The USA is introducing them. [445] Neither the EU nor member states seem to have such detailed plans yet. EU HGV legislation can limit the scope for aerodynamic drag reduction; US legislation is more relaxed.

Air Travel

Planes can achieve large improvements via more specialist means, but it needs intensive R,D&D to be implemented and measures to help/press airlines to adopt innovations faster. Changing the shape of passenger planes towards integrated bodywork and wings, so-called “flying wings” or other changes in shape; further drag reduction via active processes; composites and raised turbine efficiency via prop-fans and/or turbo-props are all valid ways forward to save fuel, and urgently need work. A reasonable target including the operational improvements below would be 70-80% less fuel per passenger.km by 2050, or for new planes entering service by 2035-40. [446] [447]

Known operational improvements include more integrated air traffic control, especially in Europe, where it could save 8-10%, as the system is particularly un-integrated; continuing efforts to raise load factors, especially on full-service airlines; continuous descent trajectories, saving 10% on short-haul flights; permitting more planes to use direct routes over oceans and towing planes to/from the takeoff and landing points instead of taxiing at part load. The last seemingly small step can save 1-2% of the fuel consumed on an entire flight.

Some of these methods have been known for over 70 years. Indeed, reviews of these strategies regularly appeared in the 20th century scientific press at times of high fuel prices, only to be quietly forgotten as fuel prices fell back. [448]

Rises in aircraft fuel efficiency slowed, if not stalled, for the two decades after oil prices fell in the early 1980s. [449] This is in large part because of airlines’ poor cash flow. [450] There has been more improvement in the fuel efficiency of small piston-engined aircraft than there has in jets. [451]

Even if fuel prices now stay high indefinitely, and do not fluctuate - at this writing, fuel makes up over 30% of some airlines’ costs - “market forces” are unlikely to fund the work fast enough. The world’s “jet aircraft industry” is a *de facto* duopoly, further reducing the incentive to improve fuel efficiency.

Developing a new plane can cost £8 billion and take 15 years. On the other hand, a large jet burns a billion litres or 10 TWh of kerosene over a 30 year life. This was worth £4 billion in 2010, or £5.5 billion as this goes to press. Viewed this way, the lifetime saving from improving the fuel efficiency of a fleet of several hundred planes could far exceed the development costs.

The US government's funding of major engine research when fuel prices rose in the 1970s points to what is possible. The fact that airlines lost interest when fuel prices fell back in 1982 indicates the conflict between societal interests and private companies' short-termism. [452] In hindsight, some airlines might wish that their predecessors *had* commercialised the US government work and that jets today used 30-40% less fuel than they actually do.

Some operational changes; e.g., more long-haul refuelling stops on overland flights, reduce a plane's fuel weight at take-off. This could reduce fuel consumption on trips over 5,000-6,000 km, with longer trips being divided into stages. [453] This amounts to a tradeoff between labour costs, fuel costs, landing fees and indeed payload. To save maximum fuel, the strategy would involve optimising aircraft for medium range. These planes weigh considerably less per seat than long-range aircraft. The saving on long-haul flights could be 25-30%.

About 60% of plane travel, measured in passenger.km, is classified as long-haul. The optimum stage is about 4,000 km. This is shorter than some non-stop flights today.

Short-range aircraft use nearly twice as much fuel in kWh/passenger.km on a 300 km flight as on a 700 km flight. This seems to provide a strong incentive to run the railways so that trains over such short distances provide an attractive and affordable alternative to planes, both in the UK and on mainland Europe.

Other speculative modifications have also been suggested, including hybrid engines. [454] Fuller use of tailwinds and of the jet stream are longer-term possibilities.

UK policy on fuel taxation is unclear. Air passenger duty (APD) was intended to substitute for a kerosene tax, but it appears to act as a revenue raiser, not as an instrument of environmental policy. It is inconsistent between destination countries. It depends on the location of a country's capital city, not on the destination city. It is not charged on light aircraft or on private jets. The tax gives no incentive to improve aircraft fuel efficiency, increase the plane's load factor or reoptimise long journeys to contain a refuelling stop. It risks becoming a form of double taxation when the EU emissions trading scheme is introduced in 2012.

APD is unhelpful too if it reduces airlines' cash flow and their ability to prematurely replace 20-30 year-old "gas guzzlers" by new, fuel-efficient planes. Scrappage schemes to ground gas-guzzlers and "recycle" them to prevent their resale for air freight would be more effective, as airlines have suggested, so far to no effect. [455] Also effective would be mandatory fuel efficiency standards on *all* new planes, accelerated depreciation allowances on this expenditure, feebates as for cars, more R,D&D expenditure and, pending wider international agreement, direct taxation of at least the kerosene used on domestic and intra-EEA flights. Such taxation is imposed in Norway, Japan and parts of the USA. [456]

Shipping

Shipping energy use is a global problem, and has been seen as such. But 40% of the UK's food is imported, so this is also a UK problem, and it is important to take steps which improve security. Shipping line owners have begun to discuss CO_2 emissions more keenly since the start of the economic downturn. [457]

New ships can be designed to use roughly 50% less fuel by increasing the vessel size and reducing front end drag. Optimising speed for today's fuel costs, and other factors, can cut fuel use in kWh/tonne.km by 75%, given the sharply reduced resistance to motion from even a small speed decrease. [458] Dual propellors can reduce fuel consumption and CO_2 emissions up to 20%. Operating with less ballast if possible can reduce drag. Bottoming cycles are an option, raising diesel engine efficiency from the mid-40s% to the high 50s%.

These savings are multiplicative. Introducing one reduces the absolute saving from subsequent measures. But unlike cars, and like planes, ships operate at high load factor, so it is easier for "exotic" fuel efficiency measures to give good returns on investment. Also little action has been taken versus other modes of transport, apparently because shipping was considered to be outside any one country's control.

Much the same as we could scrap old planes to improve the fuel efficiency of air travel, premature scrappage could help to raise the fuel efficiency of international shipping more quickly. This is an initiative which individual countries could take, to set a good example, before international agreements are reached. Since the fuel-saving options are abundant and well-developed, and would sometimes save CO_2 at negative cost, this move is easier to implement quickly in ships than it is in planes.

Where it is possible to use dual fuel engines, and/or partly change fuel from diesel to LNG, this reduces CO_2 emissions by 20-25%. Other advantages of supplementing oil by natural gas are that gas is more abundant and emits less soot, a pollutant which is implicated in the accelerating pace of Arctic warming. [459]

Liquid Fuel Demand

30 M cars and light vans driving say 15,000 km/year at 20 kWh/100 km need 10 GW or 90 TWh/yr of synthetic liquid fuel. Air travel, HGVs and international shipping need further amounts. At 2010 activity levels, these three sub-sectors would need GW or TWh/yr, assuming the same efficiency improvement.

This appears manageable, but the prospect is of liquid fuels becoming more expensive than today, if companies want the same margins as on oil and if governments want the same tax revenue. If liquid-fuelled travel falls, because some trips transfer to modes such as walking, cycling, short-range electric motorcycles, trams, trolley buses or trains, matters might be eased.

Using known load factors for variable electricity sources on prime sites, and electrolyser and fuel synthesis efficiencies, one could evaluate the demand for generating capacity. Synfuel production could utilise remote electricity sources without strong grid connections; the fuel can be moved by tanker or pipeline. Similar calculations can be made for air travel, shipping and the sector of the bus fleet that cannot be replaced by trams or trolleys, taking into account the UK biofuel resource.

Even if synfuels for ICEs cost as much as delivered electricity, in pence per kWh, the total cost of vehicle ownership could remain lower than BEVs. ICEs need no deep-cycle batteries, whose repayment costs exceed the cost of the energy consumed for traction and may exceed the loan repayments on the vehicle. Recent estimates suggest delivered renewable fuel could cost slightly less in p/kWh than renewable electricity. Although one must pay for the fuel conversion plants, and for their less than 100% conversion efficiency, the subsequent fuel storage and distribution costs less than electricity storage and distribution. If some wind energy cannot be used by the electricity system without expensive reinforcement, or is surplus to consumption, the input to synfuel plants would be less costly than firm electricity.

This route towards sustainable transport energy would sidestep the need to reinforce the electric grid so much and reduce the engineering difficulty of managing a network supplied by variable sources and meeting more weather-sensitive demands than today. With lights and equipment made more energy-efficient, the existing electricity network would have spare capacity for extra uses like a more electrified rail network, trams and trolleys replacing some diesel urban buses, some rural GSHPs and “niche markets” like electric motorcycles. [460]

The existing liquid fuels distribution infrastructure could continue to be used, with fuel composition moving from 6% to 100% renewables as more non-fossil fuels are mixed with fossil petrol and diesel. The government could continue to receive its road fuel duty, vehicle excise duty and fuel VAT revenue of £45 billion/yr. It loses this revenue with BEVs. They and the electricity which they consume are exempt from these charges and there is no easy way to tax electricity used by motor vehicles. [461]

With the future pre-tax price of motor fuel higher than pre-tax petrol and diesel now, running costs could provide an incentive to use liquid-fuelled vehicles only where other modes are impracticable. But the historical UK trend has been for real public transport fares to rise faster than real motoring costs. Any trend towards higher motoring and HGV running costs would need to be accompanied by government policies to make the alternatives more attractive; e.g., to make passenger rail travel as punctual and inexpensive per km as in most other European countries, reopen some branch lines to trams or light rail, move more road freight onto rail, install trams offered to the public sector at no up-front cost by private sector bidders [462] and make walking and cycling safer and more attractive for short trips.

5. Industrial Sector

Priorities

The industrial sector ranges from basic materials processing activities, such as iron and steel, cement and chemicals through to light industry such as food and drink, textiles and engineering. UK manufacturing industry has declined in importance over the last 30 years, and so has its energy use. But we now import more embodied energy and CO_2 in manufactured goods from developing countries; e.g., India, China, Vietnam, the Philippines and Indonesia. [463]

Some of these overseas factories may be less energy-efficient than their predecessors in developed countries. Chinese factories make more extensive use of coal than UK industries, which use mainly oil and natural gas. Global CO_2 emissions will have risen sharply, if the net transfer was from moderately-efficient natural gas usage to less-efficient coal usage.

Some developed countries; e.g., Canada, Australia, Norway, Sweden and Finland, retain extensive heavy industry; e.g., processing of ores into metals, paper-making. These countries have higher per capita energy use than countries which have “exported” their industrial sector.

Lower Limits

In existing industries, the energy used to extract a metal; e.g., steel, aluminium, copper, zinc, nickel, molybdenum or magnesium from its ore is usually near to the lower thermodynamic limit. The basic chemicals industry also faces lower limits to energy use. The cement and lime industries, likewise, are up against lower limits to energy use and CO_2 emissions, because their production involves the decomposition of calcium carbonate into calcium oxide and CO_2, plus other minor reactions in cement kilns.

In many industries, the main opportunity for saving process energy may be reuse, recycling and designing “consumer durables” for a longer life. This gives us the same standard of living with a lower material throughput. [464] As an example, refrigerators which are designed to last 20-25 years in normal household use are as acceptable to users as others which only last eight to ten years. There is a gain in convenience from needing to buy a new refrigerator less often and a health gain from the reduced risks of food spoilage if fewer appliances fail without warning.

In another case, washing machines now only last an average of seven years in normal household use before a component fails and needs repair or replacement. The verdict then may be that the machine should be scrapped and replaced because the spare part(s) and/or labour would cost too much. [465] By contrast, two brands on the market are designed to withstand domestic use for an average of 20-25 years before needing repairs. Both are economically repairable if/when a component does fail.

It is hard to see who benefits from reducing the lifespan of domestic appliances by 70-75% and making them impracticable to repair. The manufacturing energy saved is arguably becoming more significant than small savings in operating energy. The energy saved when the steel in an old machine is recycled is less than the energy which is consumed to manufacture a new machine.

Compared to many other “heavy” industries, for logistical and transport cost reasons, the bulk building materials industry continues to produce a high fraction of its output in the UK. Improvements to these industries would help to cut UK CO_2 emissions.

Reducing the cement industry’s emissions by consuming less concrete is not easy. The UK already consumes 50% less concrete per capita than countries in central and southern Europe, due to its widespread use of clay brick and steel-frame construction. But these two methods are distinctly more energy- and CO_2-intensive than concrete. [466] So they do not help to cut CO_2 emissions.

Also, high thermal capacity helps to utilise passive solar heating and passive cooling and cut the use of energy for space heating and cooling. This issue makes it less attractive to replace solid building structures by lightweight framed ones. [467] Overall, it appears that energy usage and CO_2 emissions could generally be reduced if wood, concrete and calcium silicate replaced some of the UK’s extensive use of clay brick and steel frame.

The most effective way to radically reduce the cement industry’s CO_2 emissions - indeed, to eliminate it - seems to be to accelerate sharply the use of concretes which sequester CO_2 instead of emitting it. At least two such products have been developed. [468] One is now in commercial use in the USA.

Other approaches worth considering are to apply CCS to cement and lime production. Further options are to replace concrete blocks and precast concrete panels by materials such as calcium silicate blocks and panels. Calcium silicate is slightly less energy-intensive than mass concrete and is manufactured using low-pressure steam. This steam can come from solar or CHP plant, instead of the product being fired at over 1,000°C which needs combustion of high-grade fuel or electric resistance heat.

Large-scale iron & steel production can be almost totally “decarbonised”. Examples are via pre-combustion CCS on fossil/bio-fuels, and subsequent direct reduction with the H_2, or direct use of electrolytic H_2. [469] The latter seems more favourable as emissions are close to zero.

Together, the concrete, iron and steel and clay brick industries account for most of the CO_2 emissions in producing structural building materials. Ready substitutes are available for fired clay bricks,; e.g., calcium silicate and concrete bricks.

Some industries have no fundamental lower limit to process energy use, or only a very weak one. Examples include food and drink, paper, textiles and parts of the chemical industry. Here, the redesign of processes can offer large savings.

Building Services

The less energy-intensive industries consume more energy for space heating, lighting and electrical office equipment than they consume in processes. Here the scope is much the same as in other non-domestic buildings.

International Case Studies

An international collaborative study, led by the Centre for the Analysis and Demonstration of Developed Energy Technologies (CADDET), produced several hundred industrial energy efficiency case studies from the USA, Canada, the UK, the Netherlands, Australia, Sweden, Finland and elsewhere. [470] It was an invaluable collaboration, and one of the most detailed such exercises ever carried out in the developed world.

A 25-50% energy saving was common from the technology featured in each case study. The highest saving reported from a single technology was 90%. Most of the investments had payback times between 2-3 months and 2-3 years. About 5% were outside this range. Of these, a few paid back instantly and one or two took 5-6 years. The measures taking 5-6 years; i.e., giving “only” 17-20%/yr real returns, were only installed by large companies which had lower borrowing costs and were confident enough of their future to take on “long-term” initiatives.

Combined Heat and Power

The energy quality needed for low-temperature industrial process heating; e.g., laundries, autoclaves, dryers, many chemical reactions, is low. If processes need heat at low temperatures, 50-200°C, this heat can be provided by reject heat from CHP plant instead of by burning fuel.

Referring to Chapter 6, it is more plausible to imagine that utilities reorganised as ESCOs could undertake this work, and sell a company heat, than it is to believe that private companies will develop more CHP plant under the current system. Today, an industrialist takes all/most of the risk and struggles to produce a system with a three or five year payback time. Under ESCO involvement, risks can be spread over different companies and could typically be amortised over much longer than three to five years.

Demands for low-grade heat are particularly common in the food and drink, textiles, chemicals and engineering industries. When burning clean fuels, such as natural gas and LPG, the exhaust gases may sometimes be used directly for purposes such as drying, not indirectly.

There are thought to be only 10,000 industrial heat-only boilers, as opposed to roughly 20M domestic boilers. Assuming a replacement cost of £100,000, a fuel price of 2 p/kWh and an efficiency improvement from 70% to 90%, premature replacement gives a 3-5 year payback time. The design life is 20-30 years. This return exceeds those typically available in domestic or non-domestic buildings.

Heat Recovery

There are limits to heat recovery. Many gases leaving a high-temperature furnace are dusty or contaminated, so heat recovery systems of the type used in HVAC applications can become blocked by debris. Given these limitations, the next possibility is thermal cascading, as outlined below.

Thermal Cascading

In principle, it is possible to re-use the heat from one high-temperature process in another process and eliminate the energy use for the secondary process. Basic thermodynamics states that energy is degraded with time, not consumed. Consequently, an energy-intensive industry which processes materials at a high temperature will have a corresponding amount of waste heat, which must be disposed of in some way.

If heat cannot be recovered, as above, a first priority is to use the waste heat within the factory for another process that needs lower-temperature heat, preferably in lesser quantities. For instance, waste heat from a kiln or furnace can sometimes be used to dry raw incoming goods, particularly in furnaces burning natural gas or LPG, which have clean exhaust gases.

There is no limit to the number of times that this heat can be cascaded, so long as the heat discharged from one process is at a high enough temperature for the next process. The potential saving is considerable in a factory which has a sequence of, say, four or five processes. It is non-existent in a factory with only one fundamental process.

Failing that, another possibility is to sell the heat to a company nearby which needs lower-grade energy. A collaboration of this kind involving five factories was reported from Denmark in the early 1990s. The five industries all gained on their “bottom line” and would not have cooperated otherwise. [471]

If factories become more energy-efficient internally, reject heat from the lowest-temperature process can sometimes be sold on to local DH systems at an adequate temperature, such as 70-80°C, and utilised to heat local buildings. Part of Gothenburg, Sweden is heated by waste heat from local industry. In cases where only a little of the input is used today, it would sometimes be possible to rearrange matters. An example has been given of a Swedish glass factory. Currently, 7% of its energy input emerges at the other end as hot water which is sold to a local DH system. But with more demand, or with heat taken and stored for later, about 40% could be utilised this way. [472]

Barriers

As we have long known, the greatest obstacle to investment in industrial energy efficiency is that industrialists and energy suppliers apply different discount rates. Also, many companies prefer to invest in their mainstream business activities, even if it gives a lower return than investment in reducing their overheads.

The end result is that many companies are only interested in energy efficiency if it pays back within one or two years. But energy suppliers have been known to invest in technologies which pay back over 30-40 years. Aided by UK public subsidy, energy supply technologies with 90-100 year payback times are going ahead; e.g., roof-mounted solar thermal systems displacing heat from natural gas condensing boilers, micro-scale wind turbines displacing grid electricity.

Companies' attitudes reflect their short time horizon. Many business owners do not know if their company will still be trading in ten years' time, although statistically most established businesses will still be there. Even if a premises changes hands, some assets are usable by a new owner or tenant, especially the fabric and services and non-specialist plant and equipment.

The disparity between energy users and suppliers indicates market failure. If investment capital were diverted from energy supply with payback times of 10-25 years to industrial energy efficiency improvements with payback times of three or five years, or longer, UK PLC's costs would be lower and manufacturing industry would be more competitive. [473] But because individual directors have such short time horizons, they are unable to take the long view.

Poor communication within large companies is another problem. Practical knowledge of manufacturing processes tends to be concentrated among groups of junior employees, but dissemination of useful findings to a company's other sites depends on higher management decisions. Some profitable units have been closed without management appreciating the huge energy efficiency savings which had been uncovered on the "shop floor". High levels of avoidable waste might not look good in company reports either, so the potential may be reported to managers less than observers would expect. [474]

Poor or non-existent internal communication may be more common in large companies. But one doubts that the problem is fundamentally different in smaller companies.

6. Social Costs and CO2 Taxes

A key question in climate change policy is the social cost of CO_2 emissions to the UK. There is disagreement on this figure, which in theory sets the appropriate level of a CO_2 tax. Most countries have a CO_2 tax ranging from zero to a few £10s/tonne. Sweden charges £90/tonne.

Some countries tax all energy at a high level, though, via a combination of energy taxes, CO_2 taxes and VAT. Although it is rarely confined to a direct CO_2 tax, the impact on energy prices is broadly similar. Denmark for instance has the equivalent of a £200/tonne CO_2 tax on domestic electricity, piped gas and oil. Electricity consumers pay about 26p/kWh, well above the ex-tax price of 10 p/kWh which they would pay otherwise. Natural gas costs them over 6 p/kWh, also well above the ex-tax figure of about 3 p/kWh.

The UK duty and the 5% VAT on domestic or commercial heating oil equate to an appreciable tax of around £50/tonne CO_2. But natural gas, LPG, electricity and solid fuel only carry 5% VAT. This equates to a tax of £5-10/tonne.

All EU countries charge very high taxes and duties on motor fuel. The UK has the equivalent of a £280/tonne tax on petrol and diesel; i.e., this is the combined effect of the duty and the VAT. Renewable fuels are taxed in broadly the same way. Indeed, 6% of the fuel at the pumps already is renewable. LPG used as motor fuel, however, pays duty of only 15.3 p/litre or 2.2 p/kWh. VAT brings the total tax on LPG to the equivalent of £120/tonne, less than half that on renewable fuel.

It is hard to see much consistency in the situation. It would be logical at least for the UK to harmonise domestic energy taxation upwards to the level on oil, so that energy vectors are taxed equally, and to harmonise road fuel taxation on for instance diesel, petrol and LPG, possibly by raising LPG and reducing diesel and bio-energy taxes, so that renewable energy is not more highly-taxed than fossil LPG.

7. Nuclear Energy

Some readers might expect a report on the UK's energy future to centre on nuclear power. We believe that the polarised arguments over its merits continue to divert readers from the key arguments. These are how to get from a fossil fuel-dependent energy system to a post-fossil fuel system which is affordable to the UK.

A 1976 report from the Royal Commission on Environmental Pollution, headed by Sir Brian, later Lord Flowers, recommended that there should be "no commitment to a major nuclear power program" until the waste disposal problem had been solved. [475] "Solved" in our view means that a permanent method is developed to place the material beyond reach in perpetuity, relieving our descendants from any further obligation to intervene to keep it safe.

35 years later, such disposal methods remain unproven. Continuing to store material on the surface, where it consumes electricity for cooling, is not sustainable. The risk that this intervention and energy consumption might have to continue for 50-100 years or longer after the last reactor has closed raises fundamental questions over the EROEI of nuclear energy. Is the cumulative EROEI high enough to sustain industrial societies? If the intervention has to continue for centuries, will our descendants be in a position to manage the problem?

Past reactor safety studies in the USA, Sweden and Germany established that a maximum credible accident could exceed the magnitudes of the Chernobyl or Fukushima events. [476] If this happened in a small country, most of the population might have to be evacuated. [477] Generating and reprocessing plants may also be at risk from terrorist attack. In 2003, the Japanese Nuclear Commission said that the probability of a fatal release was one in a million in any one year. But a major release occurred eight years later from events which the Commission had not anticipated. While very high tsunamis occur on the east coast of Japan, the historical records did not inform the design of the plants that were constructed there. [478] [479]

Unlike fossil fuel plants, nuclear plants do not "fail safe" in a loss of coolant situation. The nuclear industry has not managed to insure itself against such high-consequence, low-probability events. Above a point, taxpayers would have to meet any additional claims. If they could not afford to pay the claims, those affected would receive no compensation. To say the least, this arrangement does not seem very even-handed versus other energy industries, which have to insure themselves.

A German study stated that a severe European nuclear accident would lead to damages claims of £5 trillion. If the German insurance industry provided cover to the country's nuclear operators, up to this liability limit, the premiums needed would increase the cost of nuclear electricity by 45 pence per kWh or more. [480] The study suggests that this makes the industry un-insurable.

Nuclear plants' failure to pay for their own insurance amounts to a subsidy. It is not the only one. [481] Outside support continues for waste disposal, whose eventual cost is unknown. After 55 years of "commercial operation", beginning at Calder Hall in 1956, it is surprising that the industry still needs so much help. Like many past nuclear power stations, the latest nuclear projects seem set to be finished late and considerably over budget. [482]

Chapter 2 compared the economics of UK offshore oil supply, an offshore wind electricity system, also for biomethane production and two energy efficiency measures. In our view, if the quantifiable figures were added up, nuclear would give broadly similar costs in £/delivered kW to a mix of onshore and offshore wind. Both are very expensive relative to fossil fuels, or apparently compared to typical energy efficiency measures or to biomethane. Energy whole system costs are of the order of £10,000 per delivered kW, maybe more including grid balancing and energy storage costs. Given the unquantified subsidies, however, one might ask whether quoted nuclear costs are very meaningful.

The continued operation of fission power stations makes it difficult to pursue nuclear disarmament. This is a legal requirement placed on all countries by the UN Non-Proliferation Treaty, including the major nuclear weapons states. The links between weapons and "civilian" reactors are uncomfortably close, as we see to our cost in a few states which acquired nuclear weapons via what they called the "peaceful use of atomic energy".

For 50-60 years, the nuclear industry was at the heart of government and made repeated arguments to raise the nuclear output. In 1973, the Central Electricity Generating Board told the government that it wanted to build 32 US PWRs. In 1976, the Atomic Energy Authority said that the UK would need about 80 nuclear generating plants by 2000 and 300 by 2025. [483] In 1979, the new Prime Minister announced a plan to build ten PWRs within a decade. In 2008, the new Prime Minister announced that "nuclear had a role to play" and implied that he wanted to build ten nuclear power plants.

The first three plans were not fulfilled. The outcome of the fourth announcement remains to be seen. It has led to discussion of replacing existing and closed UK nuclear plants by new ones on the same sites and a debate on whether support to operators of such plants constitutes a "subsidy". The government "opposes subsidies", but supports the *de facto* insurance and waste disposal subsidies. It supports in other ways private companies who wish to build new nuclear plants. The implication is that the rules are distinctly different for nuclear than for other energy options.

If large EPRs proceed, the national grid would need more spinning reserve. This would cost electricity consumers an extra £160 M/year, which may equate to 0.4-0.5 p per kWh of nuclear electricity. [484] If this cost is not charged to the large nuclear plants, but is spread uniformly over all generating plants, it amounts to another subsidy for very large generating plants. Fossil fuel plants are often not built at this size precisely because of the diseconomies of scale, including the extra spinning reserve.

At its 1998 peak, nuclear generated 26% of UK electricity. It made up *4.4% of delivered energy*. Its contribution in 2010 was 16% of electricity or *3% of delivered energy*. After 55 years' of major efforts, funded by taxpayers, 3-4% of delivered energy does not appear as a great success, and is more akin to a costly distraction. Other options abate GHG emissions at lower costs and without posing such unique risks, so this report is devoted to them.

8. UK Institutions

In the 2000s, a large number of bodies have been set up to advise and support the government in the energy and climate change field. Examples are:

- The Committee on Climate Change (CCC) www.theccc.org.uk
- The UK Energy Research Centre, http://www.ukerc.ac.uk/support/tiki-index.php

A number of other bodies do relevant research:

- Supergen, a collection of consortia http://www.rcukenergy.org.uk/what-were-funding/supergen.html
- The MARKAL team http://www.ucl.ac.uk/energy/research/research-homepage-banners-2-col/Outline_impact_case_study_-_MARKAL_060211.pdf
- The Oxford Institute for Energy Studies, producing mainly an economic perspective on energy markets http://www.oxfordenergy.org/
- The UCL Energy Institute, with an emphasis largely on buildings, energy demand and overall systems http://www.ucl.ac.uk/energy/

Several further bodies provide funding for this work:

- The Energy Programme of the Engineering and Physical Sciences Research Council http://www.epsrc.ac.uk/plans/pra/Pages/energy.aspx
- The Energy Research Partnership – a strategic forum attempting to pull together all the main funding bodies, government and industry - http://www.energyresearchpartnership.org.uk/tiki-index.php
- The Technology Strategy Board
- The Energy Technologies Institute.

In addition, many energy experts work in the private sector, ranging from small specialist practices to larger energy and engineering consulting firms. Several of these larger consulting firms have done work to help inform UK climate change policy. Examples which particularly come to mind include AECOM & Pöyry Energy. However, the majority of these experts are only weakly-linked to the energy research community in academic institutions.

In recent times, the UK has not had the equivalents of, say, Denmark’s Technological Institute and Building Research Institute, Canada’s National Research Council, Sweden’s Building Research Institute, Germany’s roughly 60 Fraunhofer Institutes or the USA’s Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, Oak Ridge, Sandia and other National Laboratories. These institutes do publicly-funded or co-funded work which is intermediate between academia and the private sector and often leads to technologies entering commercial use within a few years. It is of little use for the UK to have successful technology emerging from laboratory experiments if it is not in a position to bring it into practical use, and little use if the UK directs limited support from government bodies to “innovative”; i,e,, complicated and expensive, technologies.

A 2005-06 House of Lords report revealed the very limited UK resources for applied research in the buildings field, and the disparate responsibilities for it, compared to other developed countries. [485] The situation was summarised by the CEO of BRE Ltd. in evidence to the Science and Technology Committee:

> “[The construction industry is] regulated, leant upon, involved with, 13 departments across government now. There is no focal point at all... We are now really the only country in Europe - with 21 equivalents across Europe - and there are equivalents in Canada, Australia, New Zealand or wherever - we are the only country in the world where there is no coordination of … applied research … working with the construction industry to the industry.” [486]

The IEA has also suggested that the UK could considerably improve its coordination of technology research, development, demonstration and deployment (R,D,D&D). [487]

9. Units, Abbreviations, Conventions, Conversion Factors and Glossary

Unit of Energy

The unit of energy used in this report is nearly always the kilowatt-hour (kWh) or multiples of it, such as the gigawatt-hour (1 GWh = 10^6 kWh) or terawatt-hour (1 TWh = 10^9 kWh). Occasionally, tables are reproduced which use other units, or else we must convert data from the original units. For example:

- One barrel of oil = 1,640 kWh.
- One tonne of coal = 28 GJ = 7,780 kWh.
- 3.6 petajoules (1 PJ = 10^{15} J) = 1 TWh.
- 3.6 exajoules (1 EJ = 10^{18} J) = 1,000 TWh.
- 1 M tonnes oil equivalent = 41.7 PJ = 11.6 TWh.

Unit of Power

The unit used for the rate of producing or using energy; i.e., power, is the watt (W) or multiples of it. These multiples include the kilowatt (kW), megawatt (1 MW = 10^3 kW), gigawatt (1 GW = 10^6 kW) and terawatt (1 TW = 10^9 kW).

While the UK uses a multiplicity of units for rates of energy consumption; e.g., TWh/yr for electricity, billion m^3/yr of natural gas, barrels of oil/day and M tonnes of oil/yr, the SI units are a strikingly simple alternative and help illustrate the output of different energy systems, such as oil and electric ones, in common units. Système International or SI is an abbreviation, from the French, for the ‘International System of Units’, the modern form of the metric system. SI is the world’s most widely used system of measurement for everyday commerce and science. Some examples of energy flows in these disparate units, converted to SI, are:

- One kWh per day = 41.7 W.
- One barrel of oil per day = 67.2 kW.
- One million barrels of oil per year = 187 MW.

- 10 TWh per year = 1.14 GW.
- One billion m^3 per year of natural gas = 1.22 GW.
- 1 M tonnes oil per year = 1.32 GW.
- 1,000 TWh per year = 114 GW.
- 10,000 TWh per year = 1.14 TW.

Higher and Lower Calorific Values

Where energy is in the form of chemical fuels, quantities of energy quoted refer to the higher calorific value (HCV). This value includes the latent heat of condensation of the water vapour in the exhaust gases. This portion of the energy content was lost in the past, but it is recoverable nowadays in such devices as condensing gas-fired boilers or condensing gas-fired combined heat and power (CHP) stations.

The UK uses HCVs for oil- and gas-fired heat-only boilers and coal-fired power stations and uses lower calorific values (LCVs) for gas-fired power stations. LCVs prevail too with imported wood pellet boilers from mainland Europe. This ambiguity, and the differing conventions between countries, lead to pervasive errors throughout the energy literature, often ±10%.

There is about a 10% discrepancy between the HCV and the LCV of natural gas; i.e., methane (CH_4); a 7% difference between the HCV and LCV of liquefied petroleum gas (LPG), which is mostly propane (C_3H_8); and a 18% difference between the HCV and LCV of hydrogen (H_2). Scientifically, the HCV is the correct value to use.

Financial Calculations

This report does the financial calculations for different options from the viewpoint of the UK, not of a private individual or small business. Energy and climate change are a prime example of a collective problem, not an individual problem. So doing the calculations this way seems to be the most appropriate methodology.

The report sometimes uses the term “UK PLC”. This represents a national perspective on the problem, as a country’s government should take. The thermal requirements in the UK’s Building Regulations are set this way.

The normal after-inflation interest rate used in these calculations is 3.5%/yr, as set out in the UK Treasury's *Green Book* for evaluating different options. [488] This rate is usually presented as a typical public sector borrowing rate. [489]

The costs in this report are quoted in £ sterling at 2010 money values. They utilise exchange rates of $(US) 1.50, Euros 1.20, $(Aus.) 2.00, D.Kr. 10.00 and S.Kr. 10.00 to £ 1 sterling.

The energy prices assumed in this report were typical of the UK in summer/autumn 2010. Unless otherwise stated, they are:

- Natural gas 3 p/kWh
- Kerosene, petrol or diesel 4.5 p/kWh
- LPG; i.e., propane, 5.5 p/kWh
- Electricity 10 p/kWh.

The prices quoted in this report exclude taxes and other transfer payments. Heating oil and motor fuel prices to the consumer include both excise duty and VAT at varying rates. Other fuel prices include VAT. The above costs exclude these charges.

To convert figures from the 1990s or 2000s to 2010 money values, the report uses a mean inflation rate of 3%/year. To convert from 1983 to 2010 money values, it uses a multiplier of 2.5. Where original costs were in a foreign currency, the inflation adjustment was made at this rate before doing the currency conversion.

Unless otherwise specified, the costs quoted in the report exclude taxes, duties, subsidies and grants. These are transfer payments within a country or region and do not reflect the inherent resource cost of a measure.

CO_2 Emissions Coefficients

The CO_2 emissions coefficients assumed for different energy vectors delivered to a UK consumer are:

- Natural gas 0.206 kg/kWh
- LPG 0.25 kg/kWh
- Heating oil 0.28 kg/kWh
- Electricity, average supplied to low-voltage (LV) loads 0.62 kg/kWh. [490]

General Terms, Abbreviations and Acronyms

The term “biomass” refers to a variety of raw biological materials. Biofuels, or sometimes “bio-energy”, refers to energy vectors obtained from biological materials. Such fuels can be solid, liquid or gaseous. Examples include wood pellets, bio-butanol, bio-dimethyl ether (bio-DME) and bio-methane.

Reference to “heating” in this report usually means space and water heating combined. In a majority of UK buildings, the two services are already provided by one system, namely a gas- or oil-fired boiler so it is fairly logical to deal with them together.

When we use the term “energy efficiency”, we are referring to all its forms. These include the utilisation of reject heat or reduced losses in transport of energy around the UK to final consumers. For instance, at a cost, we could modify electricity networks to reduce their transmission and distribution losses, with this extra cost being amortised over the lifespan of the measures. As the report outlines, new and existing heat networks could also be redesigned to reduce their distribution losses.

In our view, if one wants to mean solely the more efficient utilisation of energy by final consumers, excluding other energy conversion plants and the energy infrastructure itself, one should use a different term from “energy efficiency”, such as “end use efficiency”. This would make the debate clearer.

The energy policy field is full of abbreviations and acronyms. Normally, the meaning of these is set out the first time that they occur in the text and the abbreviation is used by itself thereafter.

Some terms that may benefit from clarification, perhaps because they are new and/or because of their common misuse, are these:

Despatchable - The term normally refers to electricity generating plants which are flexible in operation and can be readily turned on and off to meet the varying demand, perhaps with a few hours’ notice or even with just 10-20 seconds’ notice.

Geothermal energy - heat energy originating deep below the earth’s surface, where it is generated by the radioactive decay of elements naturally present in the earth’s crust, mantle and core; e.g., uranium, thorium, and potassium-40. Geothermal energy differs from ground source heat pumps.

Air and ground source heat pumps - These use respectively the ambient air and the ground as the heat source. From here, heat is pumped up to the temperature needed in the building; e.g., for hot water or for central heating. Or heat can be pumped out of a building to cool it in summer.

Heat pumps can be compression- or absorption-cycle, and powered by any sufficiently high-grade energy source, including oil, gas or very hot water, although electric compression-cycle heat pumps are the main ones already used in the UK for cooling and now being considered for use for heating. None of these heat pumps have anything to do with geothermal energy.

Spilled wind power - a wind energy output which exceeds the instantaneous demand for electricity, or exceeds the net demand for electricity after operating other plant on the network which must also run.

LPG - liquefied petroleum gas, a mixture of mainly propane and butane. Rather more of it comes from natural gas fields than from oil fields.

DHW - domestic hot water, as opposed to the process hot water used widely in sectors such as industry and agriculture. The term is often used even in non-domestic buildings like hospitals, offices, hotels and schools.

Biomethane - pipeline-quality methane gas from biological sources; e.g., anaerobic digestion. To produce almost pure methane, the CO_2 co-produced in anaerobic digestion, and other trace gases like H_2S, are separated from the raw “biogas”. Unlike “biogas”, which needs modified equipment, biomethane can be piped around the gas network and used in the same combustion plants as natural gas; e.g., standard CCGT power stations and reciprocating engine CHP plants.

References

[1] Todd, R, et al, *An Alternative Energy Scenario for the UK*. CAT, Machynlleth (1977).

[2] Leach, G, et al, *A Low Energy Strategy for the UK*. ISBN 0-905927-20-6. IIED, London (1979).

W

[3] Olivier, D, et al, *Energy-Efficient Futures: Opening the Solar Option*. ISBN 0-946281-02-5. Earth Resources Research Ltd., London (1983).

[4] Kemp, M, ed., *Zero Carbon Britain 2030*. ISBN 978-1-902175-61-4. CAT, Machynlleth (2010).

[5] Mackay, D, *Sustainable Energy Without the Hot Air*. ISBN 0-954-45293-3. UIT Cambridge Ltd. (2009).

[6] *Scenarios for 2050 - A Key Scene Setting Report*. UKERC Energy 2050 Project. http://www.ukerc.ac.uk/support/tiki-index.php?page=Energy+2050+Overview.

[7] *Climate Change and its Impacts: a Global Perspective. Some Recent Results from the UK Research Programme*. Dept. of the Environment, Transport and the Regions & Meteorological Office (1997).

[8] http://www.nasa.gov/vision/earth/environment/danger_point.html

[9] A valid concern is that this target may be adjusted when the obstacles to achieving it via current policy are appreciated. One would hope that at this point the policy and not the target changes. The target if anything needs to be strengthened.

[10] Anon, *Protecting the Earth: A Status Report with Recommendations for a New Energy Policy*. Enquete-Kommission on Preventative Measures to Protect the Earth's Atmosphere, Volumes 1-3. ISBN 3-924521-71-9. German Bundestag, ed. 1991).

[11] http://dsc.discovery.com/news/2008/06/27/climate-change-warming.html

[12] Along with a small group of industrial countries; i.e., the USA, Germany, Luxembourg and the Czech Republic. The World Resources Institute www.wri.org has published a comprehensive table of countries' cumulative CO_2 emissions from 1900-2004.

[13] http://www.bbc.co.uk/news/science-environment-13187156 (April 2011).

[14] http://royalsociety.org/Geoengineering-the-climate/

[15] Measurements suggest that permanent species-rich grassland sequesters more C in the soil than forest, but clearly less C in the standing biomass. Whether intermediate landscapes, such as "wood pasture", or orchards under permanent grass, can sequester more in the combination of the soil and the standing biomass does not yet appear to be known.

[16] Smaje, C, "Land Use Options for Sustainable Farming", *Agroforestry News*, vol. 18, no. 3, pp. 10-17 (May 2010.)

[17] http://www.farmingfutures.org.uk/sites/default/files/casestudy/pdf/Case%20Study%201%20-%20Bullock.pdf

[18] Hansen, J, et al, "Target Atmospheric CO_2: Where Should Humanity Aim?", *Open Atmospheric Science Journal*, no. 2, pp. 217-231 (2008). See also http://ec.europa.eu/environment/integration/research/newsalert/pdf/212na4.pdf

[19] http://rstb.royalsocietypublishing.org/content/363/1492/815.full

[20] http://uk-air.defra.gov.uk/reports/cat07/1104140943_LULUCF_DA_GHGI_report_2009_v4.pdf

---

[21] Crawford, M, Director, Agroforestry Research Trust, Dartington, Devon, personal communication (January 2010).

[22] Interestingly, many of the small agricultural enterprises which are probably in the best position to consider this activity seem to be profitable today without external subsidy, something which cannot be said for many large UK farms. See Maxey, L, et al, *Small is Successful: Creating Sustainable Livelihoods on Ten Acres or Less*. Ecology Land Cooperative Ltd., London, www.ecologicalland.coop (April 2011).

[23] http://www.carbonfarming.org.nz/documents/InfoSheet_2_v2a.pdf

[24] http://www.carbonfarmersofaustralia.com.au/Carbon%20Farmers%20Of%20Australia/HOME.html

[25] Examples of existing land uses which gave/give rise to high levels of sequestered organic matter include peat bogs, ancient woodland and species-rich permanent grassland which has never been ploughed.

[26] Akbari, H, et al, *Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas*, Heat Island Group, Lawrence Berkeley National Laboratory (5 February 2001).

[27] Rosenfeld, A H, “Raising Efficiency - By Demanding It”, *Wall Street Journal* (17 April 2010).

[28] Ref. 5, *op. cit*.

[29] http://climatesight.org/2010/11/12/geoengineering-the-climate/

[30] http://www.arb.ca.gov/cc/inventory/archive/tables/ghg_inventory_ipcc_90-04_all_2007-11-19.pdf.

[31] http://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_scopingplan_00-08_2010-05-12.pdf.

[32] http://www.gad.gov.uk/Demography%20Data/Population/Index.aspx?dp=Past+projections

[33] McGlashan, N, et al, *The Potential for the Deployment of Negative Emissions Technologies in the UK*. AV/WS2/D1/R18. Workstream 2, Report 18 of the AVOID Project, Imperial College, London (2010). http://www.metoffice.gov.uk/avoid/files/resources-researchers/AVOID_WS2_D1_18_20100730.pdf

[34] Slightly surprisingly, though, a container of pressurised H_2 gas at 20 bar has a similar volumetric Energy density to a tank of 80°C hot water using a 55 K temperature drop. Both systems store around 60 kWh/m^3 although the gas is higher-grade energy than the hot water. The energy density of a pumped storage scheme on a good site with 75% round-trip efficiency and a 600 m height difference, such as Dinorwig, is lower by a factor of 50 at 1.2 kWh/m^3.

[35] In units of £ per kWh capacity, the costs of bulk energy stores span four orders of magnitude:
(a) One for small hydrocarbon fuel stores; e.g., a £500 domestic bunded kerosene tank holding 10,000 kWh, 5p per kWh of capacity.
(b) Ten for hot water storage in large excavated pits, as developed in Denmark, 25-40 p/kWh.
(c) Ten to 100 for large insulated above-ground steel hot water tanks, as used in Denmark on heat networks, £1-2/kWh.
(d) 10,000 for electricity in lead-acid battery banks, as used by some electric utilities, £150/kWh upwards.

[36] Another advantage of fuel is that it can be stored from year to year. Hot water tanks slowly lose heat to ambient, although the loss slows to around 5%/year on very large stores. Batteries self-discharge at differing rates. Because the energy outputs of some renewable energy sources fluctuate from year to year, very long-term energy storage would be essential, implying storage in the form of fuel rather than heat.

[37] http://www.postcarbon.org/article/322207-complaining-about-mosquito-bites-while-a

---

[38] Ciscar, J C, et al, “Vulnerability of the EU Economy to Oil Shocks: A General Equilibrium Analysis with the GEM-E3 Model” (2004). http://www.e3mlab.ntua.gr/papers/Ciscar.pdf.

[39] http://www.theoildrum.com/node/3810.

[40] Rapier, R, “An EROEI Review”, The Oildrum (18 March 2008). http://www.theoildrum.com/node/3707. See also http://www.theoildrum.com/node/3412.

[41] The main exception is high-head hydro, whose EROEI can sometimes be above 100, but there is very little scope for this in the UK See Hagens, N, *The Energy Return of Industrial Solar Energy*. http://www.theoildrum.com/node/3910

[42] It has been suggested that oil from tar sands, conversion of maize into bio-ethanol and nuclear fission “burner” power stations fuelled by future low-grade uranium ores may come into this category. See; e.g., http://www.stormsmith.nl/.

[43] http://www.theoildrum.com/node/5051

[44] http://www.theoildrum.com/node/8526#more

[45] Morgan, T, *Money is Energy: An Exponential Economics Primer*. Strategy Note 17. Tullett Prebon Ltd., London (16 November 2010).

[46] House of Commons Energy and Climate Change Committee, Session 2010-11. *Shale Gas*. SG14. Memorandum by Royal Dutch Shell (3 February 2011). See http://www.publications.parliament.uk/pa/cm201011/cmselect/cmenergy/writev/shale/sg14.htm. It looks unlikely on that basis that UK reserves of shale gas will be very high, although the rest of Europe may have more. Claims have been made though that the reserves discovered in the Bowland shale in north-west England are very significant. See http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/795/795we09.htm

[47] Arguably a gas-fired CCGT emits 50-60% less per unit of electricity than an advanced coal-fired steam turbine and 70% less than an older coal-fired plant. Similarly, a condensing LPG boiler emits around 60% less per unit of heat than a non-condensing coal-fired boiler and 80% less than a closed solid-fuelled stove.

[48] There are growing concerns though that not all emissions associated with natural gas drilling and transport have been fully accounted for. See http://www.technologyreview.com/energy/37390/?nlid=4357&a=f

[49] http://www.decc.gov.uk/assets/decc/What%20we%20do/A%20low%20carbon%20UK/2050/216-#2050-pathways-analysis-report.pdf. p.13.

[50] Hirsch, L R, et al, *Peaking of World Oil Production*. Report to US Dept. of Energy, Washington DC, USA (February 2005).

[51] http://www.theoildrum.com/node/8044#more.

[52] http://en.wikipedia.org/wiki/Hubbert_peak.

[53] Murphy, P, *Peak Oil - Peak Technology*. http://www.energybulletin.net/node/3735

[54] http://geoheat.oit.edu/bulletin/bull28-2/art1.pdf

[55] The Dyfi Valley in west Wales generated an estimated 34 MW of mechanical power in the waterwheel age. See Ashby, M, *Hydro Power*. Pamphlet from Centre for Alternative Technology, Machynlleth, Wales (1979).

[56] Cited by Lovins, A B, *Soft Energy Paths: Towards a Durable* Peace, p. 134. ISBN 1-84407-194-4.

Penguin Books (1977).

[57] Lovins, A B and L H, *Brittle Power*, Brick House Publishing Co., Massachusetts, USA (1982). See too earlier article http://nexus.som.yale.edu/design-selco/sites/nexus.som.yale.edu.design-selco/files/imce_imagepool/LovinsArticleExcerpt.pdf.

[58] A distinction is that the costs of some energy efficiency improvements are made up of capital repayments only. Most energy supply systems have operation and maintenance costs too.

[59] Ref. 5, *op. cit.*, p. 63.

[60] www.theoildrum.com/node/6207 (12 February 2010).

[61] http://www.oilpera.co.uk/presentations/Corrosion1002/GEP_0003.PDF.

[62] http://www.corrosioncost.com/pdf/techbreif.pdf

[63] http://www.nationalgrid.com/uk/sys_06/chap2/images/fig2-4.gif

[64] Anon, *Great Expectations: The Cost of Offshore Wind in UK Waters*. UKERC (September 2010). http://www.ukerc.ac.uk/support/tiki-index.php?page=Great+Expectations%3A+The+cost+of+offshore+wind+in+UK+waters -

[65] Gross, R, et al, *Investment in Electricity Generation: the Role of Costs, Incentives and Risks*, ISBN 1-903144-0-5-1. Imperial College Centre for Energy Policy and Technology and UK ERC (2007).

[66] Sharman, H, Incoteco A/S, Aalborg, Denmark, personal communication (October 2010).

Danish offshore wind farms cost £2,500/kW(e), or less than their UK counterparts. This is apparently due to the shallower water and to seeking competitive bids for the available sites. Toke, D, Birmingham University, personal communication (October 2010).

[68] *Technology Data for Energy Plants*. ISBN 978-87-7844-857-6. Danish Energy Agency, Copenhagen (June 2010). http://www.ens.dk/Documents/Netboghandel%20-%20publikationer/2010/Technology_data_for_energy_plants.pdf

[69] Orchard, W, Orchard Partners Ltd., London, personal communication (August 2010).

[70] Orchard, W, Orchard Partners Ltd., London, personal communication (September 2010).

[71] Most UK peaking plants are natural gas- and not oil-fired. However, they use interruptible gas tariffs, so there is a possibility that they would need to use a stored fuel; i.e., oil or LPG, in severe winters.

[72] Boyle, G, *Renewable Energy and The Grid*. Earthscan, London (2007).

[73] http://www.alternatefuelsworld.com/files/altfuels.pdf

[74] The AEA Technology report to DECC at http://www.decc.gov.uk/assets/decc/what%20we%20do/supporting%20consumers/saving_energy/analysis/fes-appendix.pdf does not mention that government-funded work currently uses materials which are non-airtight and have relatively high λ-values. Such policies block the achievement of better thermal standards in cavity-walled buildings. Up to 70-75% of UK buildings could be affected. In reality, some walls have already been filled to a low standard or are unsuited to CWI.

Kirk, M, Technitherm Ltd., personal communication (September 2010). PU foam is rarely used today for cavity fill, except for structural reasons. Other firms suggest similar figures but costs would probably decline in a mass market, due to increased sales volumes. Bulk contracts could also make savings.

[76] Taylor, G, chartered engineer, personal communication (October 2009).

---

[77] The oil and wind energy supply systems would cost more if one includes end-use devices and evaluates the whole system cost to deliver heat to the rooms of a building, in £ per average kW(t). Thus, if the energy is used for space and water heating, the end-use equipment needed could be respectively an oil-fired condensing boiler and tank, costing £2.5-3k, or a GSHP, both plus radiators.

The mature market cost is about £10k in Sweden for a 7 kW(t) GSHP with vertical borehole, suited to use on quite small sites. The cost of normal GSHPs is similar to this in the USA. It is estimated that it could be reduced by another 19% in wider use. See Im, P et al, "Ground Source Heat Pumps: Value Rising", *Solar Age* pp. 28-29 (March 2011). However, the US estimate is for a system with horizontal evaporator coil. This usually takes up too much space for the UK.

[78] In 2010, the Gulf of Mexico had 50,000 offshore oil wells.

[79] This view is cited at http://www.energybulletin.net/node/52182. Other views have been expressed that, at present levels of energy productivity, $100-120/barrel is the limit for developed countries, while developing countries can afford somewhat more as their economies use oil in somewhat higher value-added applications. See http://www.theoildrum.com/node/8410#more.

[80] Mobbs, P, *Peak Oil, The Decline of the North Sea and Britain's Energy Future*. Presentation to the All Party Parliamentary Group on Peak Oil, London (24 November 2009). http://www.fraw.org.uk/mei/papers/appgopo_presentation-20091124.pdf.

[81] As ref. 5 discusses, opposition to the siting of renewable energy equipment can also be a potent constraint on availability, especially for onshore wind but sometimes for other sources too.

[82] http://www.publications.parliament.uk/pa/cm201011/cmselect/cmenergy/writev/742/emr.pdf

[83] Rosenfeld, A H, "The Art of Energy Efficiency: Protecting the Environment with Better Technology", *Annual Review of Energy and the Environment*, no. 24, pp. 39-82 (1999). http://www.energy.ca.gov/commissioners/rosenfeld.html. The paper also noted on p. 69: "For me, the most interesting outcome was not the official one, which was that an alert, motivated design team could save 50% of the energy with a reasonable payback time, but was how hard it was to find any competent design team and any competent 'third party' to do the measurement and verification."

[84] An example is the maximum theoretical efficiency of turning electricity into white light, but this is several times higher than today's leading fluorescent lighting systems, which achieve around 100 lm/W.

[85] Measured in terms of the percent saving at a marginal cost less than or equal to current energy prices. To give two examples: (a) The best available fluorescent lighting systems have improved 5.5-fold in efficiency since 1975; see Figure 7. The efficiency of a typical UK system has probably improved less than three-fold. (b) The heat loss of the best-insulating windows has fallen 2.5- to three-fold since 1978, from plain triple or 2+1 glazing in wood frames to Passivhaus windows in insulated frames. The heat loss of an average window in use has probably fallen two-fold, with a move from universal single glazing to reportedly around 30% single glazing, mainly in conservation areas and listed buildings, and 70% double glazing, some of it low-e and argon-filled. We suspect that the single glazing fraction is misreported and that some of it has secondary glazing, which can perform similarly well to double glazing.

[86] Giant oil and natural fields are usually defined as those containing more than 500 million barrels or 800 TWh. The largest discovered in recent years is Brazil's Sugar Loaf field. It is estimated to contain 75,000 TWh. The water is 2 km deep and the oil is located 4 km below the ocean floor.

[87] Mann, P, et al, "Emerging Trends from 69 Giant Oil and Gas Fields Discovered from 2000 to 2006", *Proc. Annual Meeting of American Association of Petroleum Geologists,* Long Beach, California. (2 April 2007).

---

[88] Anon, *UK Electricity Generation Costs Update*. Report prepared for DECC by Mott McDonald, Brighton (June 2010).

[89] Some of the cost reflects the recovery of fixed capital investment which does not change with load and recurrent costs in wayleaves, metering and billing. This cost element is virtually independent of consumption. In the past, it was said to be reflected in the standing charge. The rest of the costs decline if consumption falls.

[90] Porter, D, Chief Executive, Association of Electricity Producers, interviewed by File on 4, BBC Radio 4 (4 October 2011). He stated: "... Whether £200 billion can be raised is a huge question. There are serious doubts about whether that money will be forthcoming ..."

[91] http://www.epa.gov/air/caaac/coaltech/2007_05_mckinsey.pdf

[92] *Sustainable Urban Infrastructure. London Edition - A View to 2025.* http://www.siemens.com/entry/uk/features/sustainablecities/all/pdf/SustainableUrbanInfrastructure-StudyLondon.pdf

[93] An updated version dealing with the recession was published at https://solutions.mckinsey.com/climatedesk/default/en-us/Files/wp211154643/ImpactOfTheFinancialCrisisOnCarbonEconomics_GHGcostcurveV2.1.pdf

[94] http://downloads.theccc.org.uk.s3.amazonaws.com/4th%20Budget/CCC-4th-Budget-Book_with-hypers.pdf

[95] This term was first used by the US Rocky Mountain Institute, www.rmi.org in the 1980s to refer specifically to investment in more efficient use of electricity instead of new power stations. It has been used loosely too to mean the more efficient use of other forms of energy, such as gas, liquid fuels and heat.

[96] http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm. The notional limit put forward by Stern of 1% of UK GDP is £14 billion/year. This is consistent with spending an average of no more than £30/tonne to achieve a 80% reduction by 2050.

[97] OFGEM, *Project Discovery* (2009). http://www.ofgem.gov.uk/Consumers/Pages/ProjectDiscovery.aspx. Cited by Secretary of State for Energy and Climate Change in speech to London School of Economics (2 November 2010). http://www.decc.gov.uk/en/content/cms/news/lse_chspeech/lse_chspeech.aspx.

[98] This other planned spending is made up of £36 billion on the RHI, £3 billion on the FIT, an undetermined amount on ROCs and possibly £15 billion on solid wall insulation via the ECO not the GD.

[99] *Energy Trends*, DECC (September 2010). http://www.decc.gov.uk/assets/decc/Statistics/publications/trends/558-trendssep10.pdf. This estimate allows for the higher efficiency of electricity at the point of use than fossil fuels.

[100] 34% of domestic electricity was used for space and water heating and cooking in 2005. Some was used to heat air or water in appliances where hot water fill could have been used. 26% of electricity in non-domestic buildings was used for thermal purposes. Possibly some of the "catering" and "other" categories could have been substituted too. http://www.decc.gov.uk/assets/decc/what%20we%20do/supporting%20consumers/sustainable%20energy%20research%20analysis/1_20090710101642_e_@@_1theimpactofchangingenergyusepatternsinbuildingsonpeakelectricitydemandintheukfinal.pdf

[101] Everett, R C, Energy and Environment Research Unit, Open University, personal communication (March 2011).

---

[102] The highest fraction reached by DH in any scenario appears to be 20% of space and water heating by 2050. http://www.decc.gov.uk/assets/decc/What%20we%20do/A%20low%20carbon%20UK/2050/216-2050-pathways-analysis-report.pdf.

[103] Best available technology could easily reduce the electricity consumption of new refrigerator-freezers by 60-65%, assuming that typical appliances sold are near the middle of the A-rated scale. According to a US company making best practice “cold appliances”, it could greatly improve its energy performance by using more energy-efficient compressors. But until mass-produced appliances become more efficient, there is no demand for small and energy-efficient compressors; i.e., a catch-22 situation exists. Sun Frost, Inc., Arcata, USA, personal communication (July 2010).

[104] The principal author has recommended separate lintels on energy-efficient cavity-walled buildings for the last 25-30 years. This avoids creating a major thermal bridge across the wall insulation. However, the concept of separate lintels appears to remain an alien concept on “mainstream” building projects. They have been unaffected by this modified practice.

[105] The thermal problems of buildings with thick masonry walls may have been slightly overstated. If the original windows and doors have been replaced, thick solid-walled buildings with solid ground floors are often easier to heat than mid-20th century buildings. So although the improvement allowed by legislation may be more limited, the starting point is also less bad than modern buildings.

A Grade 1 listed building in Cambridge is likely to be given internal wall insulation in the near future. There may be scope to allow more changes than are permitted today, so long as in theory they are reversible. Brown, A, Cambridge Architectural Research Ltd., personal communication (September 2011.)

Work in Germany and Switzerland in the 1980s and 1990s confirmed that on average the buildings with the worst thermal performance are not from the 18th or 19th century or 1920s but from the mid to late 20th century. Matters improved again after the 1970s. Feist, W, Passivhaus Institut, Darmstadt, personal communication (1990). Most of these mid to late 20th century buildings in the UK are not legally-protected, so their thermal performance can be greatly improved.

See “Warmer Front”, *Cornerstone*, vol. 31. no. 3, pp. 60-61 (September 2010). But we are concerned at the confusion herein between static and dynamic thermal performance. Thermal capacity does *not* improve a wall’s static U-value.

[106] http://www.decc.gov.uk/assets/decc/Statistics/enefficiency/946-stat-release-insulation-30112010.pdf. This suggests 18.6 M cavity-walled dwellings out of a total of 25.5 M dwellings in mid-2010, or 73%.

[107] The only other European countries where cavity walls are as common appear to be Denmark, Ireland, the Netherlands and Belgium.

[108] In many respects, the UK’s cavity walls, especially post-1960s, are *harder* to treat than its older solid walls. Significant thermal bridges/defects remain, even if modern walls are treated with a material which totally fills the gaps. See below. These defects are due to features such as one-piece metal lintels crossing the cavity, masonry returns and cavity trays. The steel ties, which were galvanised in the past, form a series of point thermal bridges.

The cavity is usually 50 mm wide, but it varies widely; e.g., from 25 to 75 mm. Common insulants at 50 mm cannot reduce the U-value much below 0.6 W/m^2K and hardly affect airtightness. Improved insulants may reach a U-value of 0.4-0.45 W/m^2K, depending on inner leaf construction, and can improve airtightness; see http://www.technisol.nl/en/cavity_wall_insulation.html. Or if the wall is fully-plastered, as with older cavity construction, new combinations of pervious insulants, such as mineral fibre and aerogel, might achieve 0.35 W/m^2K. But these are indifferent U-values by today’s standards and the impact of thermal bridging must also be considered, especially in more modern walls.

It appears that up to 11 M cavity-walled dwellings remain to be filled and offer opportunities for either using a superior material, such as PU foam, or EWI. The other cavities have been filled to varying standards and the poorer ones may be economic for EWI, where more expensive heat sources must be used.

Many cavities were less than fully-filled when the work was done, as seen on subsequent IR photographs. Or else the insulant has since shrunk or settled, as happened to UF foam in the 1970s. Attempts to rectify such deficiencies by EWI lead to very high costs in £/tonne, unless they are saving an expensive fuel; e.g., oil or LPG, where the cost may be acceptable if the investment is amortised using *Green Book* rates.

EWI is a viable approach on walls whose cavity is unsuited to insulation, because the initial wall U-value is usually 1.0-1.8 W/m^{2}K. But unless the work is carefully-approached, convective bypasses reduce the effectiveness of the work. The other option, internal insulation, gives the same “building physics” problems as it does in solid-walled buildings.

Such issues make it hard to reach a thermally satisfactory solution. By comparison, external insulation of older solid-walled buildings may seem to be of relative simplicity. Convective bypasses rarely cause a problem and if the roof is treated at the same time at rafter level, the work is not dissimilar to that on new solid-walled buildings.

[109] This stock, mostly built pre-1939, is “hard to treat” according to those working on the Green Deal. We consider that this description is inconsistent with practical experience; see refs. 101 and 104. The principal author is aware of several solid masonry-walled buildings retrofitted over 30 years ago with 100 mm EPS or more on the outside of the masonry walls. They are located in Cambridge, Milton Keynes, Mendip, Macclesfield and Glasgow and appear to have worked well since. The UK’s first certified Passivhaus retrofit (EnerPHit Standard) is on a solid-walled Victorian house, to which 250 mm of EPS was applied. To date, no cavity-walled buildings are known to have gone this far.

In our view, based on experience abroad with ancient heritage buildings, the greatest difficulties are likely to arise with a smaller fraction of dwellings, in particular, those of hardwood- and softwood-frame construction. However, even some of these can be safely-improved if those in charge are aware of the known risks.

[110] This is documented by *Marginal Abatement Cost Curve*. Report to the NHS England Sustainable Development Unit by AEA Technology Ltd. (February 2010). The two largest and cheapest savings identified are replacing gas boilers by CHP and installing more efficient lighting systems. Added insulation does not feature in the analysis, which concentrates on large, short-term, high-return savings. http://www.sdu.nhs.uk/documents/MACC_Final_SDU_and_AEA.pdf.

[111] An early example was the headquarters of the Zurich Electricity Board, 1994. Notable too are the offices of WAGNER GmbH, 1998, the Lamparter office, Weilheim, 2000 and the first German Passivhaus school, constructed in 2003. Monitored examples are reported in *Proc. 10th. Passivhaus Conf.*, Hannover (May 2006.)

[112] http://www.ecofys.com/com/publications/documents/EURIMA-ECOFYSVIIreport_FINAL_fullreport.pdf, sec. 1, pp. 17-25.

[113] ??? Ref. 8, *op. cit.*, para. 9.7.

[114] http://dbdh.dk/images/uploads/pdf-cooling/District_cooling_a_hot_issue.pdf

[115] http://www.lsta.lt/files/events/36_holler.pdf

[116] Boardman, B, et al, *40% House*. ISBN 1-874370-39-7. Environmental Change Institute, Oxford University (February 2005). Also further work by AECB on future domestic sector electricity consumption for TSB “Retrofit for a Future” project.

[117] Norgaard, J S, et al, “Turning the Appliance Market Around Towards A++”, *ECEEE Summer Study Proceedings*, pp. 155-164 (2007).

---

[118] Contributions to the forum http://www.whitegoodshelp.co.uk/wordpress/i-want-a-washing-machine-with-a-hot-water-valve/ discuss the apparent failure of the EU washing machine energy rating system to deliver machines with lower CO_2 emissions and/or better washing performance. The perception is that washing and rinsing performance has declined and that water consumption has been reduced beyond reasonable limits. Washes have become slower due to (a) local electric heating replacing an intake of gas-heated water and (b) longer agitation to compensate for reduced water usage. Allowing for inevitable consumer attempts to get around these restrictions, which nullifies the A or A+ label, there are suggestions that the electricity consumption and overall CO_2 emissions for a given wash may have risen. The forum received so many postings that it was closed for becoming unwieldy.

The 2000 prototype machine discussed in http://www.eci.ox.ac.uk/research/energy/downloads/lcfreport/appendix-k.pdf replaces some of the electricity by hot water and cuts CO_2 emissions. It was not launched, probably because the EU rating scale gives no credit for hot fill savings.

[119] Informal, unpublished survey by principal author of two-door refrigerator-freezers sold by John Lewis PLC, a major UK department store (June 2010). Total volume of most appliances surveyed was 200-300 litres. Excluded US-type refrigerator-freezers and smaller single-door refrigerators with icebox.

[120] DECC, *Energy Consumption in the UK*, table 5.6. (2009).

[121] *Ibid.*

[122] The rationale for withdrawing only 100 and 150 W incandescent lamps is unclear. 25, 40, 60 and 75 W lamps have a lower efficacy. So do LV halogen lamps when their transformer losses are included.

[123] One response to the ban on 75, 100 and 150 W incandescent lamps may have been more fittings taking two or three 25, 40 or 60 W lamps. These combinations give a similar light output and *increase* electricity consumption. This cannot have been the intended result, but past experience shows many such perverse consequences. They should have been foreseen by policy-makers. It is a little misleading to cite incandescent lighting as wasteful, if some consumers prefer the colour temperature to warm white CFLs. We think that LEDs will overcome this point. Resistive heating systems provide a larger target for reduced CO_2 emissions. The capacity savings on a design winter day would exceed those from lighting.

[124] http://osram.com/osram_com/Professionals/General_Lighting/Fluorescent_lamps/index.html

[125] Lighting in dwellings is often used more frugally. See; e.g., http://www.iea.org/papers/2008/cd_energy_efficiency_policy/4-Lighting/4-light2006.pdf .
In our view, banning 60 W incandescents and encouraging electric resistance heating is perverse.

[126] http://tinyurl.com/7aece4f
At the extreme, the gap would be seven-fold if one compared, say, T12 tubes of 40 lm/W net of old magnetic ballasts in 33% efficient luminaires to T5 “eco” tubes of 100 lm/W net of electronic ballasts in 90% efficient luminaires. The respective efficacies are 13 and 90 lm/circuit W; i.e., a seven-fold gap, although admittedly not many T12s are still in use in such inefficient luminaires.

Another trend which has worsened lighting efficiency in many non-domestic buildings is the tacit assumption that, because CFLs are new, they are more efficient than what went before. They are much less efficient than T8, T5 and sometimes worse than T12 tubes of the same light output.

[127] Bordass, W, Improving Building Energy Performance and Sustainability”, *Proc. OGC Conference,* QE2 Conference Centre, London (10 July 2009). The lighting in a Birmingham office refurbished in 2003 appears to resemble best available technology of the early 1990s. Its connected load is 18 W/m^2.

---

[128] The Passivhaus-certified offices of Disability Essex (DE) in Rochford, Essex, which were designed from 2006 to 2008, have a connected internal lighting load of 5.9 W per m^2 and an external lighting load of 0.3 W/m^2. The space is divided evenly between open-plan and cellular offices, plus a large foyer and seminar room. Ceiling heights are mostly 2.5-4.0 m

Such fluorescent lighting was available in 2007 from several manufacturers. In 2007, consumption by the small fluorescent lamps in DE's toilets and lobbies might have been reduced 25-35% by using concealed 14 W T5s instead, reducing the total building load by 4-5% to nearer 5.7 W/m^2.

By 2010, more efficient T5 fluorescent lamps had become available in all sizes. They arrived too late for use at DE, but their use could reduce the connected lighting load in future low-energy offices to 5.2 W/m^2. This is about 72% lower than many "refurbished" UK offices, as per ref. 123.

[129] http://www.esta.org.uk/EVENTS/2010_04_2020_vision/documents/2010_05_06_Falkirk_danlers_web.pdf

[130] http://www.nationalgrid.com/uk/sys_06/print.asp?chap=2

[131] http://www.carbontrust.co.uk/SiteCollectionDocuments/PDF/Lighting%20Workshop-PM%20Session.pdf. But with the rate of technological progress, this study gives best practice as 7 W/m^2 for 300 lux and it is now 5 W/m^2.

[132] http://www.ico.gov.uk/upload/documents/library/corporate/detailed_specialist_guides/ico_opportunities_assessment.pdf. In one office, replacing 20 year-old compact fluorescents and T8 tubes prematurely by T5s saves electricity for 2.5 p/kWh. In another case, in an office which already has energy-efficient T5 fluorescent lighting, occupancy/PIR controls save electricity for a marginal cost of 2.9 p per kWh.

[133] http://www.somareluma.com/html/pay-as-you-save.html discusses how it can pay a business owner to take out a three year high interest bank loan arranged by the lighting supplier and scrap 10-15 year old warehouse lighting, saving 50-80% of lighting energy and improving colour rendering. It would be helpful if policy makers would re-do such calculations at UK PLC real interest rates, with long-term loans and in a full range of buildings, to assess what would happen if utilities invested in negawatts rather than in megawatts.

[134] http://www.energyrating.gov.au/library/pubs/2009-ref-manual-lighting.pdf

[135] http://www.lga.sa.gov.au/webdata/resources/files/Sustainable_Public_Lighting_-_Technical_Feasibility_Report_-_August_2009.pdf

[136] On the principal author's estimate, many major supermarkets have T8 lamps with electromagnetic ballasts and 50-60% efficient luminaires, with two lamps per luminaire. The tubes' axis is perpendicular to the aisles, so 30% of the light output is wasted lighting the top of the shelves. Little of it is directed sideways to light the food.

A few smaller chains have fitted or retrofitted T5 lighting systems with 75-85% efficient luminaires and electronic ballasts. The lamps are parallel to the aisles, so they direct more of their light sideways onto the merchandise, with less supplementary lighting needed. Separate T5 lighting is provided above the checkouts. The power density appears to be 70-75% lower than the lighting in the major chains.

[137] Unpublished report on energy-efficient office electrical equipment, submitted to Disability Essex when it was commissioning a new building in Essex to the Passivhaus Standard (June 2009).

[138] www.topten.info.

[139] www.topten.ch.

[140] Bush, E, et al, *Top Ten: Global Project for the Most Energy-Efficient Products.* http://www.topten.eu/uploads/File/037_Eric_Bush_final_Topten.pdf

---

[141] http://www.fishnick.com/equipment/techassessment/5_range_tops.pdf

[142] *Retrofit to Exceed Code 4 with Low-CO_2 Piped Heat Supply from Condensing 500 kW(e) CHP*. Submission by Wates Living Space Ltd., Leatherhead to Technology Strategy Board for Retrofit for a Future Project. Ref. ZA 596T. (November 2009). These dwellings had a cavity width of 75 mm, which is very unusual for the 1960s and 1970s. To make the analysis more representative of the UK stock, we have redone the calculations with a 50 mm cavity.

[143] For a discussion of the rebound effect from a scientific perspective, see: Lowe, R J, (2009), "Policy and Strategy Challenges for Climate Change and Building Stocks", *Building Research and Information*, 37 (2) 206-212. http://dx.doi.org/10.1080/09613210902727960

[144] For a discussion of the rebound effect from an economic perspective, see: Sorrell, S, *The Rebound Effect: an Assessment of the Evidence for Economy-Wide Energy Savings from Improved Energy Efficiency*. Report by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre. (October 2007). ISBN 1-903144-0-35. http://www.ukerc.ac.uk/Downloads/PDF/07/0710ReboundEffect/0710ReboundEffectReport.pdf.

[145] A study for DEFRA suggested that the rebound effect could reduce energy and CO_2 savings by up to 25%. However, much of this impact reflects the positive effects on the economy from energy efficiency having lower costs than energy supply. Three UK government objectives are (a) a more buoyant economy, (b) a reduced current account deficit and (c) CO_2 reductions. It is very hard to follow the lack of emphasis being placed on a policy which could apparently produce a combination of all three.

[146] Too much exploitation of wind energy; i.e., on a scale of many TW, could damage the climate. Direct solar and clean forms of bioenergy would have less or no impact. See Buchanan, M, "Wind and Wave Farms could affect Earth's Energy Balance", *New Scientist* (30 March 2011). http://www.newscientist.com/article/mg21028063.300-wind-and-wave-energies-are-not-renewable-after-all.html.

[147] http://www.efficientpowersupplies.org/pages/Steps_towards_a_2000_WattSociety.pdf

[148] http://www.chichilnisky.com/pdfs/globalwarmingcarbonnegative.pdf

[149] *The Renewable Energy Review*. CCC (May 2011).

[150] http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/energy/whitepaper/2003/page21223.html

[151] The UK definition includes not only what we usually think of as biofuels; e.g., methane from digesters, ethanol from sugar beet and biodiesel from oilseed rape but also combustion of waste rubber tyres, landfill gas and livestock remains.

[152] Some further energy comes from stored nuclear fuel. But present-day nuclear fission reactors cannot produce a flexible on-off power output or a portable fuel for transport in the same sense as oil or natural gas.

[153] http://www.decc.gov.uk/assets/decc/what%20we%20do/supporting%20consumers/sustainable%20energy%20research%20analysis/1_20090710101642_e_@@_1theimpactofchangingenergyusepatternsinbuildingsonpeakelectricitydemandintheukfinal.pdf

[154] Anon, "Enlightening Blackouts", *RMI Solutions*, pp. 5-6 (Winter 2003-04). http://www.rmi.org/Content/Files/RMI_SolutionsJournal_FallWint03.pdf

[155] Outside city and town centres, the UK uses largely overhead electrical cables. Some other European countries put more cables underground.

---

[156] Until now, the greatest difficulty in accommodating intermittent outputs has occurred with Danish windpower. It generates 20% of electricity and uses neighbouring countries' hydro plant for balancing. German PV now causes stability problems at 1% of generated electricity. See http://www.upi.com/Science_News/Resource-Wars/2010/10/19/German-grid-aching-under-solar-power/UPI-13471287518368.

Given the need to supplement such plant by fuel-burning generators; e.g., OCGTs, the risk is that additional UK electric heating at the margin could turn out more CO_2-intensive than heat distribution from a mix of natural and biogas CHP plant and heat-producing renewables.

[157] Ref. 135, *op. cit*.

[158] http://www.oilandgasuk.co.uk/cmsfiles/modules/publications/pdfs/EC022.pdf

[159] Anon, *Fake Firemen: Why Are We Cheating Ourselves on Energy*? IIER, Switzerland (June 2010). http://www.iier.ch/content/fake-firemen-why-are-we-cheating-ourselves-energy

[160] Triodos Renewables saw a 35% wind energy shortfall in the first half of 2010 compared to the 15 year average. See: http://www.triodos.co.uk/downloads/Triodos-Renewables-Half-Year-Report-2010.pdf, p. 6.

[161] Ref. 158, *op. cit*.

[162] *Ibid*.

[163] It seems that this strategy was first proposed in Germany. It makes a 100% renewable energy system more of an engineering feasibility. See Sterner, M, *Bio-Energy and Renewable Power Methane in Integrated 100% Renewable Energy Systems*. ISBN 978-3-89958-798-2. Kassel University Press (2009) http://www.uni-kassel.de/hrz/db4/extern/dbupress/publik/abstract.php?978-3-89958-798-2.

[164] *Options for Low-Carbon Power Sector Flexibility to 2050*. Report to Committee on Climate Change by Pöyry Energy (Oxford) Ltd. http://www.ilexenergy.com/pages/Documents/Reports/Electricity/655_Poyry_%20power%20sector%20flexibility%20to%202050_Oct10_v2_0.pdf. (October 2010).

[165] http://dbdh.dk/images/uploads/pdfbladet/EU%20aim%20at%20great%20expansion%20of%20large-scale%20solar%20thermal%20plants.pdf and http://www.e-pages.dk/dbdh/2/

[166] http://www.solarthermalworld.org/node/766

[167] http://www.e-pages.dk/dbdh/16/12

[168] http://www.solarthermalworld.org/files/Solar%20District%20Denmark.pdf?download

[169] http://dbdh.dk/images/uploads/pdfbladet/EU%20aim%20at%20great%20expansion%20of%20large-scale%20solar%20thermal%20plants.pdf and http://www.e-pages.dk/dbdh/2/

[170] www.solarmarstal.dk

[171] http://social.csptoday.com/industry-insight/csp-counters-oil-price-volatility-gains-credibility-fuel-saver?utm_source=http%3a%2f%2fcommunicator.csptoday.com%2flz%2f&utm_medium=email&utm_campaign=CSP+eBrief+4+April+11+OK&utm_term=CSP+counters+oil+price+volatility%2c+gains+credibility+as+a+fuel+saver&utm_content=494612

[172] http://www.energybulletin.net/stories/2011-07-26/bright-future-solar-powered-factories.

[173] http://www.petroleum-economist.com/Article/2878529/News-and-Analysis-Archive/Solar-EOR-first-for-Mideast-Gulf.html

---

[174] http://www.dongenergy.com/SiteCollectionDocuments/NEW%20Corporate/Geotermi/WGC%202010%20-%20Paper%200131%20-%20Country%20Update%20Report%20for%20Denmark.pdf

[175] Anon, *How Much Bio-Energy can Europe Produce Without Harming the Environment?* Report No. 7/2006. Energy Environment Agency, Brussels (8 June 2006).

[176] http://ec.europa.eu/environment/integration/research/newsalert/pdf/234na2.pdf

[177] Others have expressed similar concerns. See for instance: http://www.climateactionprogramme.org/news/biomass_combustions_green_credentials_in_question/ and http://www.manomet.org/sites/manomet.org/files/Manomet_Biomass_Report_Full_LoRez.pdf.

[178] http://www.lemvigbiogas.com/BiogasPJJuk.pdf

[179] http://www.telegraph.co.uk/earth/energy/6253225/Anaerobic-digesters-provide-green-energy-where-wind-turbines-fail.html. Some councils are unfortunately opposed to anaerobic digestion and insist that all waste go into incinerators. This reduces the net energy yield and gives a poorer CO_2 balance. It produces no fertiliser, soil conditioner or gaseous fuel, just relatively small yields of heat or electricity. In Switzerland, putrescible or digestible wastes are separated off and the incinerators are usually fed by dry plastic and residual items of no commercial value, not by unsorted waste.

[180] Comparing gas-fired CCGTs to reciprocating engines, generating electricity at respectively 51% and 38% efficiency (HCV), the CCGT produces 36% more exergy output. In low-temperature CHP mode, we assume that the CCGT produces 48% electricity, 41% heat and that the gas engine produces 38% electricity, 48% heat - a spark ignition engine's electrical output is unchanged by using the reject heat. The respective exergy outputs are 0.56 and 0.47 kWh per kWh of gas input. So the CCGT produces 18% more. In an energy-constrained world, the increase appears very important.

[181] Ref. 73, *op. cit*.

[182] Or rather, if only the other fuel value, represented by the H_2, is burned and a large fraction of the C content is separated off, pre-combustion.

[183] Another route could be to use wood in an integrated gasification CCGT CHP plant, with pre-combustion CCS.

[184] http://www.carbonrecycling.is/

[185] http://thinkgeoenergy.com/archives/2738).

[186] http://www.greencarcongress.com/2011/05/egas-20110513.html

[187] Ref. 3, *op. cit*., chapter 14.

[188] This is the total for the seven largest schemes if the Severn crossing extends from Minehead to Aberthaw. A reef has also been put forward as an alternative to a barrage or lagoon(s); see http://www.severntidal.com/info.html.

[189] One company has identified a series of Severn lagoons which they state could generate 3.8 GW or 33 TWh/yr, or 3.5 GW delivered. This is slightly more than a Minehead to Aberthaw barrage and appears more economic, thanks to lagoons' use of much shallower water. See: http://tidalelectric.com/projects-uk-severn.shtml.

[190] http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/renewable%20energy/severn-tp/621-severn-tidal-power-feasibility-study-conclusions-a.pdf

---

[191] Using lifespans of 30 years for nuclear or wind, and 120 years for tidal, the annuity factor is 30% lower for the second type of technology at the standard *Green Book* real discount rate. Further, the *Green Book* suggests lower discount rates be used for the later years of very long-lived projects by dividing the interest rate into 3.5%/yr for the period up to 30 years, 3%/yr for the period 31-75 years, 2.5%/yr for 76-125 years and successively less for periods beyond 125 years. The procedure leads to an annuity factor 38% lower for a project with a life of 120 years than one with a life of 30 years. The longer-lived project could have a capital cost 1.6 times higher in £/kW(e) and yet send out cheaper electricity. This assumes that all options have the same operation and maintenance costs.

On UK estimates, operation and maintenance (O&M) for offshore wind and O&M and fuel costs for nuclear are both likely to be around 2.5 p per kWh of delivered electricity. See Mott McDonald, ref. 81, *op. cit*. The cost of maintaining tidal barriers, whose only moving parts are the turbines, appears unlikely to be as high as 2.5 p/kWh.

[192] Consulting engineers have costed the Swansea Bay lagoon at around £1,500 per installed kW(e) at today's prices. See ref. 182. http://tidalelectric.com/resources-feasibility.shtml

[193] http://www.scotland.gov.uk/Resource/Doc/917/0064958.pdf.

[194] Birkett, T G, "Review of Potential Hydroelectric Development in the Scottish Highlands", *Electronics and Power*, pp. 330-346 (May 1979).

[195] Based on theoretical potential. Calculated by principal author in ref. 4, *op. cit*., pp. 232-233.

[196] http://publications.environment-agency.gov.uk/pdf/GEHO0310BRYF-E-E.pdf

[197] Anon, *England and Wales Hydropower Resource Assessment* (October 2010.) http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Renewable%20energy/explained/microgen/753-england-wales-hydropower-resource-assess.pdf.

[198] http://www.enbw.com/content/en/group/_media/_pdf/water_is_energy.pdf

[199] The 1.6 MW(e) run-of-river plant on the Trent at Beeston, Nottingham, built in 1999, is a rare UK example of large-scale lowland hydropower.

[200] *Hydropower in the Netherlands*. http://www.microhydropower.net/nl/index_uk.php

[201] www.econsultation.**decc**.gov.uk/**decc**.../86262050%20Pathways_COMPLETE.pdf

[202] http://www.tvenergy.org/pdfs/Final%20Hydro%20Report%2022April04.pdf, pp. 108-113 describes schemes in Sweden and the Netherlands. The first, with a 2 m head, gave a 14%/yr return on investment. Older UK studies discounted types of low-head site which are exploited in these rather flat European countries.

[203] A French company has since developed a turbine which improves the economics at very low heads; e.g., 1.5 m. http://www.vlh-turbine.com/FR/PDF/evenements/MJ2_Technologies_HYDRO09_Lyon_paper_colour.pdf. Some projects were apparently economic despite needing new civil works.

[204] Ref. 191, *op. cit*.

[205] Anon, *Comparing Energy Options: Energy Payback Ratio*, Hydro Quebec Ltd., Montreal, Canada (2005).

[206] Ref. 195, *op. cit*.

[207] Typically needing concealed fluorescent lamps; e.g., 13 W and 20 W T5s or the higher-efficacy 9, 11, 16 and 22 W CFLs.

---

[208] http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/2050/216-2050-pathways-analysis-report.pdf

[209] http://www.ngvaeurope.eu/downloads/fact-sheets/2020-biomethane-production-potential.pdf

[210] *National Grid PLC Biogas Forecast*.

[211] http://www.alternatefuelsworld.com/files/altfuels.pdf, p. 41.

[212] http://www.biogasin.org/files/pdf/Biogas_permitting_in_Denmark.pdf

[213] http://www.narola.ifw-kiel.de/das-narola-projekt/veranstaltungen/2-workshop-febr.-2009/prasentationen/round3_boese.pdf.

[214] Ref. 157, *op. cit*.

[215] http://www.rwe.com/web/cms/mediablob/en/86206/data/86134/30/rwe-innogy/dl-factbook-new.pdf

[216] “Floating LNG: The Final Frontier of the Gas Age” (6 June 2011). http://www.theoildrum.com/node/7987

[217] Anon, *Technology Data for Electricity and Heat Generation Plants*. Elkraft and Danish Electricity Authority, Copenhagen (2005.)

[218] Ref. 54, *op. cit*.

[219] http://energy.plan.aau.dk/IDAClimatePlan-files/BV_Mathiesen_UK_IDAs_Climate_Plan_2050_Background_Report.pdf. p. 20.

[220] A sample calculation for Herefordshire takes today’s electricity consumption of 1 TWh/yr, reduced by “negawatts” and a switch away from electric resistance heating to 65% less or 350 GWh/yr. Ten 3 MW(e) turbines on fairly good sites are assumed to operate at 30% load factor and deliver 9 MW x 8,766 h x 0.94 = 69 GWh/yr of electricity = 20% of electricity consumption after very extensive energy efficiency investment. It is assumed that the plant is embedded within the 400 V distribution system and has 6% T&D losses. The electricity consumption is from http://www.herefordshire.gov.uk/docs/Herefordshire_Renewable_Energy_Study.pdf.

[221] http://www.energy.eu/publications/a07.pdf indicates that Denmark had 3.1 GW(e) of installed capacity on 43,098 km^2 of land area by the end of 2005. The area of Herefordshire is 2,180 km^2.

[222] Gough, I, *Climate Change and Public Policy Futures*. British Academy, L
London, http://www.britac.ac.uk/policy/Climate-change-and-public-policy-futures.cfm (2011).

[223] House of Commons Select Committee on Energy, 6th Report (Session 1980-81). Also cited by Warren, A, in *Energy in Buildings* (March 2005 and February 2011).

[224] House of Commons Select Committee on Energy, HC 401-1, para. 66 (Session 1981-82).

[225] See http://www.ukace.org/publications/Consultation%20response%20%282011-01%29%20-%20DECC%20NPS%20for%20Energy%20Infrastructure.pdf pp.3-4.

DECC stated in a letter to the main author in July 2011: “The government has resisted the idea of a specific assessment of the costs and benefits of energy efficiency against investment in energy generation capacity because it believes that the information is already provided by existing publications.” Attempts are being made to clarify the meaning of this sentence and to identify the existing publications but it is likely that there are none. A subsequent letter from DECC in December 2011 identified nothing significant. This sentence appears contrary to the statements made to ACE; see above.

[226] Barker, Greg MP, *Hansard*, col. 872 (30 June 2010).

---

[227] This low priority could have affected the EU too. Its renewable energy and GHG targets for 2020 are legally binding. But its energy efficiency target is aspirational and may be missed by a wide margin. See Warren, A, “Some Targets Are More Equal Than Others”, *Energy in Buildings and Industry*, p. 14 (May 2011).

[228] If energy efficiency had been at the heart of policy, and policy had been coordinated, the UK would not have built houses for at least 25-30 years with a party wall construction detail which gives rise to elevated heat loss. In hindsight, a whole generation of semi-detached houses and terraced houses may potentially have higher heat losses than detached houses of the same size and age.

The crucial research on this took place at Leeds Metropolitan University in the late 2000s. It featured the Stamford Brook housing development, Cheshire. In 2009, an architect found out that this problem had been known about in the USA since about 1940. Siddall, M, personal communication (2010). But even the USA had not applied the knowledge properly until the problem was rediscovered in 1977 by Princeton University researchers when working on terraced houses at Twin Rivers, New Jersey.

[229] 13.6 GW of CCGT plant is set to be built from 2009 to 2018 inclusive. See *Transporting Britain’s Energy: Development of Energy Scenarios*. National Grid PLC (2009).

[230] In 2008, UK power stations rejected heat at an average rate of 68 GW(t).

[231] Via the grants for electric heat pumps, some of which default to resistance heating in severe weather or because of incorrect design and installation. There could be concern over promotion of BEVs, relative to vehicles running on liquid fuels. BEVs are likely to give a slight winter peak, thanks to their use of electric space heating and the poorer battery performance in cold conditions. But BEVs seem less likely than heating to cause a sharp increase in winter peak demand and raise the loss-of-load probability.

[232] Warren, A, “The Penalty for Losing Out to Germany”, *Energy in Buildings and Industry*, p. 14 (April 2011).

[233] Close to Danish COPs of respectively 3.2 and 2.6. See *Sustainable Transition away from Individual Natural Gas Heating*. http://vbn.aau.dk/files/32308768/Report_SEPM8-1_2010_PrintEdition.pdf p. 26

[234] http://www.energysavingtrust.org.uk/Media/node_1422/Getting-warmer-a-field-trial-of-heat-pumps-PDF

[235] http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=CTC513&respos=0&q=ctc513&o=Rank&od=asc&pn=0&ps=10

[236] http://www.aecb.net/UserFiles/File/Biomass%20-%20A%20Burning%20Issue%20-%20published%20September%2020101.pdf.

[237] http://www.greenpeace.org/raw/content/eu-unit/press-centre/reports/green-power-for-electric-cars-08-02-10.pdf

[238] Consumption of the Nissan Leaf, measured by the US EPA, with the space heating system on in one out of the five tests. Reported by http://en.wikipedia.org/wiki/Nissan_Leaf.

---

[239] Suppose that one wishes to reduce gross UK CO_2 emissions by 95% to 30 Mtonnes/yr. If the average abatement cost is £250/tonne, the implied expenditure is £0.14 trillion/yr or 10% of UK annual GDP. One doubts the feasibility of spending so much without harming the economy. It would be advisable to aim to achieve most of it by measures at negative or zero cost, which are abundant. We suspect that that the CCC means that the most expensive measures needed have a marginal cost of £250/tonne.

[240] Such as systems with weather compensation control. This is compulsory for condensing boilers in most continental countries and appears to save as much as 15-20% versus normal UK condensing boiler practice, from the combination of higher boiler efficiency and an end to mild weather overheating. The improvements are especially proven for natural gas and LPG fuels, because modulating burners are widely available. Unfortunately, some boilers and controls are specifically “dumbed-down” for the UK market. See; e.g., www.ecotechnicians.co.uk, also Taylor, G, chartered engineer, personal communication (2010).

[241] Greasley, J, DECC, remarks at Energy Efficiency Partnership for Homes RHI consultation event (19 March 2010).

[242] The reported cap of £10,000/dwelling is inadequate for a typical rural oil-heated detached house. See Appendix 3. The high nominal interest rate will lead to fitting of sub-optimal insulation thicknesses. The Golden Rule focusses on current bills, most of which reflect chronic inability to afford warm homes. So underinvestment is likely, along with suboptimal thicknesses. Noting this in hindsight in 2020-30 is too late, if 5-10 M dwellings have by then been retrofitted with low insulation thicknesses.

It is planned to ask consumers to repay the loan on the electricity bill. But 93% of UK dwellings are heated by gas, oil, LPG or solid fuel. The program excludes any role for low-resource piped heat. In towns, this would be one of the principal measures to consider. The importance of suspended floor insulation and draughtproofing in the older 40-50% of the UK building stock had apparently not even been appreciated until an expert raised the point in a meeting. Elton, M, ECD Architects Ltd., personal communication (August 2010). The program omits several floor and wall construction systems, which is surprising for a “comprehensive” approach.

[243] Fundamental breakthroughs in the following fields would be welcome but the probabilities may seem modest, given a background of 30-100 years’ research, development and demonstration and also the physical and engineering limits:

(a) low-cost, high energy density batteries to achieve £100/kWh or less.
(b) ASHPs with very high cold weather COPs when producing hot water for use in normal-sized radiators and DHW
(c) cheap, long-term electricity storage in countries that lack storage hydro.

[244] Phrase first used by Lovins, A B in Weizsacker, E, et al, *Factor Four: Doubling Wealth, Halving Resource Use*. ISBN 1-85383-406-8. Earthscan, London (1998).

[245] As an observer once noted: “The market is a very good servant, but a very bad master”.

[246] Businesses focussed on the bottom line are lothe to put time and effort into promoting cheap and elegantly simple means to resolve the energy problem if they can be subsidised to install expensive and complicated ones.

[247] An impact of forcing electricity suppliers to supply CFLs to consumers was boxes of CFLs paid for by consumers but languishing unwanted in cupboards or occasionally seen on sale in charity shops, in part because no market survey was made to check acceptability and suitability; e.g., for the light shades in use in a particular dwelling. LEDs were not even on offer, although high-quality ones replace tiny incandescents or halogens more effectively than CFLs can. If this is the best that a deregulated retail structure can deliver, it looks unfit-for-purpose.

[248] Calculated from the stated coal, oil and natural gas consumption in Danish statistics, using the emissions coefficients quoted herein for the UK.

---

[249] These small devices may appear to suppliers to be of trivial importance, but measurements on a few mains-powered doorbells with an AC/DC transformer suggest standby consumption of up to 5 W. If this anecdotal finding applies more widely, total mains-powered bell consumption could be up to 100 MW; i.e., 0.5% of a 20 GW(e) base load. Shaver sockets in dwellings, hospitals, hostels, hotels and halls of residence probably impose a larger baseload demand. There is usually one socket per bathroom, not under one per building. Even if standby is only 2 W per device, the combined standby loss could possibly be 200 MW, equating to the delivered output of 240 large wind turbines.

[250] See discussion by Lovins, A B et al, *Factor Four*, pp. 65-67 of experience in Dow Chemical, Inc. Senior management failed to appreciate profitable process modifications which were only fully understood by junior staff and managers. They re-organised out of existence a unit which had uncovered thousands of investments per year with returns of 100-500%/yr.

[251] http://www.trampower.co.uk/city_class.html

[252] Calculated on the basis of the *marginal* cost of larger south windows, amortised over a lifetime of 50 years for the frames and 25 years for the sealed units. Assuming that a standard UK building includes enough thermal capacity to absorb the winter gains. The cost of improving new housing layouts to give all buildings a reasonable orientation was estimated to be zero in the past on several projects; e.g. Pennyland, Milton Keynes.

[253] On the basis of reaching the mature market costs that apply today in Scandinavia and Germany. The average cost in Denmark to connect an existing detached house on a plot 30 m wide x 35-40 m deep to piped heat is £6,000-6,500. The typical cost to connect a new detached house at this density is £3,000-3,500. Costs are lower for smaller plots, although not *pro rata*. Lauersen, B, Danish District Heating Association, personal communication (June 2011.)

[254] By far the lowest cost we can find is for "superinsulated retrofits" in central Canada, where work has been going on at a low level since 1980. Work to insulate roofs or walls of low-rise buildings on the outside costs some £25 per m^2 installed, even if the claddings do not need replacement. But it costs more in countries which require tile or slate roofs and rendered or masonry walls, even in a mature market. See http://solaralberta.ca/pdfs/Harold%20Orr.pdf.

[255] It also accelerated the development of these technologies in the EU and other developed countries. See http://online.wsj.com/article/SB10001424052702303695604575181472012887264.html.

[256] Ref. 65, *op. cit*.

[257] Feist, W, *Profitability Calculation for [Warm Edge] Spacers*. Passivhaus Institut, Darmstadt, Germany (November 1998). The technology quoted in this document, a "Thermix" spacer replacing an aluminium one in a sealed glazing unit, saved heat for 0.63 p/kWh at 1998 prices, using a real interest rate of 4% per year over a lifespan of 20 years. Analogous calculations can be made for any technology whose cost and performance is known, giving the cost of saved heat, saved natural gas or oil or saved CO_2.

[258] Tyler, R, "Decline in Bank Lending to Businesses Slows", *Daily Telegraph* (7 November 2010). http://www.telegraph.co.uk/finance/yourbusiness/8153837/Decline-in-bank-lending-to-businesses-slows.html.

[259] This comment predated the Japanese earthquake and tsunami on 11 March 2011. The subsequent serious accident at four nuclear reactors may place in doubt the acceptability of so much new UK nuclear. But the point remains that several capital-intensive energy systems supplying the same energy market do not so much cooperate as compete. The capital investment must be repaid even if the energy produced has no market. Fuel storage and distribution systems and combustion plants have much lower sunk costs per unit of energy throughput.

[260] Given France's availability of base load nuclear generation, it might not want to buy electricity on summer nights. It usually has more interest in selling power to adjacent countries by night and buying back peak power by day. Other interconnectors are smaller .

---

[261] A possible qualification is that the heat utility in Braedstrup, Denmark is now experimenting with connecting solar collectors on house roofs to the heat network. See; e.g., the English language video on http://www.braedstrup-fjernvarme.dk/. However, the majority view seems to be that this is very expensive versus building; e.g., a 20,000 m^2 bulk solar collector field with optimised controls and connecting this via a single line to the DH system.

[262] CO_2 emissions from a solar-electric resistance water heating system with 60% solar fraction are 0.30 kg per kWh heat. This calculation assumes winter emissions of 0.75 kg/kWh to LV loads because the solar displaces summer electricity but very little winter electricity. This is higher than or level with natural gas, LPG or oil condensing boilers with no solar, giving respective emissions of 0.22, 0.26 and 0.30 kg/kWh. The solar-electric combination system also costs more to install and does not reduce peak electricity demand.

[263] The UK was not alone. A similar trend was seen in the Netherlands as electricity and gas were deregulated. http://nws.chem.uu.nl/publica/Publicaties2005/E2005-123.pdf.

[264] http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file20331.pdf.

[265] http://www.decc.gov.uk/assets/decc/consultations/certextension/121-iacertextension.pdf.

[266] Warren, A, *Energy in Buildings* (March 2011.)

[267] An account of utility pricing in the USA after least-cost planning was introduced revealed unexpectedly that unit prices sometimes fell. See http://www.electricitypolicy.com/index.php?option=com_content&view=article&id=2526:reinventing-competitive-procurement-of-electricity-resources&catid=99:article&Itemid=710#_ftn8. In principle, this is only likely to happen if the marginal costs of energy supply are correctly-signalled and are much higher than the average costs.

[268] Another claim may be that a company invests more than other suppliers in “green” electricity. But in the past many “green tariffs” were found to be double- or triple-counting. They are certainly difficult to verify. Some claims, such as “100% renewable electricity” are particularly misleading.

[269] The greatest influence is winter temperature. This causes energy consumption for space heating to vary from year to year. Rising real energy prices also depress consumption. This seems to be happening at the present time.

[270] http://www.watercommission.co.uk/UserFiles/Documents/Staff%20paper%203.pdf suggests real costs of capital in the range 2.5-4%/yr for Welsh and Scottish Water.

[271] In September 2011, National Grid PLC launched an issue of ten year index-linked bonds which offer a real interest rate of 1.25%/yr before tax. This was considered attractive to the market, despite the company’s credit rating being lower than the UK government’s AAA. See http://www.redmayne.co.uk/sharedealing/new-issue-info.htm?iID=25

[272] There might also be a return to single tariffs for gas, heat and electricity in a region, comprising one standing charge in £/year and one variable charge in p/kWh, to reflect long-run marginal costs. There seems to be significant dissatisfaction with the proliferation of tariffs since utilities were “de-regulated”. The number on offer reportedly exceeds 400.

[273] The EU now appears to want electric utilities to act to reduce their customers’ consumption by 1.5%/yr. While this could work in the non-profit sector; i.e., with consumer or municipally-owned suppliers, we think that it ignores historic US experience under private ownership showing that regulation *and* “shared savings”, or equivalent mechanisms, are needed to release the desired flood of energy efficiency investment. With neither retail regulation nor shared savings in place in most of the EU, it seems very unlikely. http://economicsnewspaper.com/policy/german/european-union-oettinger-adheres-to-strict-energy-saving-targets-23822.html

---

[274] The English private water companies are jointly-financed by debt and equity. The proportion financed by debt has steadily risen. They are allowed real returns of 3.6%/yr on debt and 7.1%/yr on equity. Since 2001, Welsh Water has been a non-profit privately-owned company, financed 100% by debt and limited by guarantee; i.e., with no shareholders. In the early 2000s, when some English water companies wanted to move in this direction, OFWAT did not allow it. Scottish Water is publicly-owned.

[275] If use of system charges were fair and reasonable, the charge to electricity producers for using the "public wires" would be less than the cost of laying duplicate wires and they would not go to the expense.

[276] Such as the rules in the Energy Act, 1983.

[277] http://www.publicpower.org/files/PDFs/Renegotiating%20a%20Franchise.pdf

[278] http://gala.gre.ac.uk/2946/1/PSIRU_Report_9757_2008-02-W-UK.pdf. This suggests that water companies do not usually need equity financing.

[279] But their practices are regularly investigated by the Office of Fair Trading or Competition Commission. It appears necessary to regulate LPG more strongly than happens today. See; e.g., the 2006 report at http://www.competition-commission.org.uk/inquiries/current/gas/proposed_final_report.pdf

[280] Ref. 265, *op. cit*.

[281] Lovins, A B, "Negawatts: Twelve Transitions, Eight Improvements and One Distraction", *Energy Policy*, vol. 24, no. 4, pp. 331-343 (1996). Also available at: http://www.rmi.org/rmi/Library%2FU96-11_NegawattsTwelveTransitions.

[282] In Denmark the budget to lay a 10 m heat main to a detached or semi-detached house from the street and fit a new DHW tank giving a low return temperature is similar to the cost of a new natural gas-fired boiler. To achieve a level playing field, it seems reasonable to finance this work, if not the pipe in the street, as part of a package of retrofit insulation measures.

[283] The UK dwelling stock is in large part owner-occupied and cavity-walled. The German dwelling stock is mostly of solid-walled construction and is often RSL-owned. For technical and institutional reasons, large thermal improvements are easier to bring about in the second case. Germany is partway through a program to improve its pre-1980 buildings.

[284] http://www.pu- http://www.pu-europe.eu/site/fileadmin/Other_reports_Other_research_projects/Low_and_Zero_Energy_Buidling_Info_Note_250909.pdf.

[285] On Canadian experience, it may sometimes be possible to retrofit non-listed suburban and rural buildings for at most £25 per m^2 external wall area, and the same on the roof, plus costs of improved or replacement windows. See ref. 123. This only applies if planning and spatial constraints are insignificant. This appears fairly unlikely in the urban UK or in designated rural areas; i.e., AONBs, National Parks, Green Belt, curtilages of listed buildings, et al. It might apply in some rural areas.

Where such costs can be achieved, this translates as about £14,000 for work on a detached house of this size, plus the cost of work on the windows. So far, UK projects have cost very much more. The £31,000 is an intermediate figure and itself assumes some saving from experience and more mature markets.

[286] http://www.nea.org.uk/nea-welcomes-npower-price-cut.

[287] http://www.decc.gov.uk/assets/decc/Statistics/fuelpoverty/2203-pn062.pdf.

[288] http://www.cse.org.uk/projects/view/1148

---

[289] Anon, *Energy Policies of IEA Countries - Denmark, 2006 Review*, Paris: IEA. http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=1694

[290] https://docs.google.com/viewer?a=v&pid=sites&srcid=bGJsLmdvdnxjb29sLXdoaXRlLXBsYW5ldHxneDoyMDgwNDcxYzY4NjA5Yzg

[291] Rosenfeld, A H, personal communication.

[292] On a typical DH system, adding solar, but without extra heat storage, can provide about 30% of the annual heat consumption. See http://issuu.com/adufred/docs/r-046_phd_thesis

[293] Danish Board of District Heating, E-Newsletter (February 2011).

[294] Norgard, J S, Danish Technological University, personal communication (2010).

[295] http://www.iea.org/work/2007/chp_oct/Lauersen.pdf

[296] https://ktn.innovateuk.org/c/document_library/get_file?uuid=4e1cedd0-b536-4a4e-b639-660f687f856c&groupId=3342358.

[297] http://www.epbd-ca.org/Medias/Pdf/country_reports_14-04-2011/Denmark.pdf.

[298] Danish consumers in built-up areas are encouraged to switch from electric space or water heating to DH. The usual timescale for the heat supplier to remove the wires, fit plumbing and connect the house to the pipe in the street is a week. See; e.g., http://www.savingtrust.dk/news/consumer/standby-still-problematic.

[299] There was an exemption for Low Energy Class I buildings, using less than half as much heat as the Building Regulations demanded. With advancing DH technology, it now seems economic to connect such buildings.

[300] Danish District Heating Association, personal communication (October 2010).

[301] Denmark's policy appears to breach EU directives, because it does not allow competition in all fields and instead chooses to regulate suppliers as natural monopolies. It was queried by the IEA too. Copenhagen Energy Ltd. states that EU electricity deregulation now makes it illegal for different CHP plant owners on its system to coordinate their operations to minimise energy waste, which previously happened. This interpretation places EU competition law directly at odds with a principal objective of energy policy; i.e., to minimise energy waste. See http://www.copenhagenenergysummit.org/applications/Copenhagen,%20Denmark-District%20Energy%20Climate%20Award.pdf.

[302] http://www.braedstrup-fjernvarme.dk/files/files/Low%20Resource%20District%20Heating.pdf

[303] Letter from Minister of Climate Change and Energy, Copenhagen to Danish municipalities (27 January 2009).

[304] Anon, *Sustainable Transition Away From Individual Natural Gas Heating*. http://vbn.aau.dk/files/32308768/Report_SEPM8-1_2010_PrintEdition.pdf.

[305] *Heat Plan Denmark: The Danish Heat Sector Can Be CO_2-Neutral Before 2030.* http://www.e-pages.dk/dbdh/6/10.

[306] Ref. 209, *op. cit*.

[307] http://www.annex51.org/media/content/files/publications/EEC-First_results_IEA_Collaboration_Project_R_Jank.pdf

[308] http://www.endseurope.com/docs/110511a.pdf

---

[309] http://www.electricitypolicy.com/articles/reinventing-competitive-procurement-of-electricity-resources.

[310] Independent Energy Producers' Association, *The Power of California* (2007). http://www.iepa.com/video/IEPA_Power_of_California.pdf

[311] Rosenfeld, A, ref. 76, *op cit*.

[312] For an account of this in other states, see ref. 213, *op. cit*. and http://www.raponline.org/docs/RAP_Shirley_DecouplingUtilityProfitsFromSales_2006_09_18.pdf

[313] Olivier, D, *Energy Efficiency and Renewables: Recent North American Experience*. ISBN 0-9518791-0-3. Energy Advisory Associates, Herefordshire, UK (1996).

[314] http://www.nrdc.org/onearth/06spr/ca.pdf

[315] Chang, B, et al, *Energy Efficiency in California and the United States: Reducing Energy Costs and Greenhouse Gas Emissions*. http://www.energy.ca.gov/2007publications/CEC-999-2007-007/CEC-999-2007-007.PDF

[316] http://www.energy.ca.gov/2007_energypolicy/documents/2007-12-05_meeting/2007-12-05_EXECUTIVE_SUMMARY.PDF

[317] See the Edison Electric Institute's Energy Efficiency Foundation, http://www.edisonfoundation.net/iee.

[318] http://www.aceee.org/energy-efficiency-sector/state-policy/aceee-state-scorecard-ranking

[319] Morrow, A, personal communication (November 2010.)

[320] Pett, J. and Guertler P. (2004) User Behaviour in Energy Efficient Homes, Energy Saving Trust p.20

[321] Shipworth, M et al (2010): Central heating thermostat settings and timing: building demographics, Building Research & Information, 38:1, 50-69. See page 66 specifically for the lack of understanding. http://dx.doi.org/10.1080/09613210903263007

[322] Stevenson, F, and Rijal, H B (2010) "Developing Occupancy Feedback from a Prototype to Improve Housing Production, *Building Research and Information*, (38) 5, pp.549-563.

[323] Gill, Zachary M. , Tierney, Michael J. , Pegg, Ian M. and Allan, Neil(2010) "Low-Energy dwellings: The Contribution of Behaviours to Actual Performance', *Building Research & Information*, 38: 5, 491-508. To link to this Article: DOI: 10.1080/09613218.2010.505371 or http://dx.doi.org/10.1080/09613218.2010.505371. See page 501 for the evidence of lack of understanding of controls.

[324] Combe, N., Harrison, D., Dong, H., Craig, S. and Gill, Z. (2010) "Assessing the Number of Users who are Excluded by Domestic Heating Controls". *International Journal of Sustainable Engineering*. DOI: 10.1080/19397038.2010.491563.

[325] Such a system can operate at similar flow and return temperatures to UFH. At retail level, the marginal cost of larger radiators, rated at 80/60°C, is around £30-40/kW(t), although the marginal installed cost may be more.

[326] There may be risks associated with the use of MEV in a building containing open-fuelled heating appliances. MEV depressurises a building. So boilers, stoves, fires, etc, can backdraught. CHP, heat pumps and balanced-flued condensing boilers are unaffected.

[327] Stevenson, F and Rijal, H B (2010), "Developing Occupancy Feedback from a Prototype to Improve Housing Production", *Building Research and Information*, (38) 5, pp.549-563.

[328] Ref. 323, *op. cit*.

---

[329] Combe, N., Harrison, D., Dong, H., Craig, S. and Gill, Z. (2010) Assessing the number of users who are excluded by domestic heating controls. International Journal of Sustainable Engineering. DOI: 10.1080/19397038.2010.491563.

[330] Crump et al (2009), “Indoor Air Quality in Highly Energy Efficient Homes - A Review”, NHBC Foundation, http://nhbcfoundation.org/LinkClick.aspx?fileticket=O2KJ3j%2fSnkM%3d&tabid=339&mid=774&language=en-GB
A wide-ranging study that includes research demonstrating the connections between poor IAQ and poor user understanding of complex ventilation system controls.

[331] http://en.wikipedia.org/wiki/Exergy

[332] http://yeroc.us/articles/exergy-crisis.

[333] Johannesson, G, “Energy or Exergy - A Matter of Quality”, *Swedish Research for Sustainability*, no. 3, pp. 8-9 (March-April 2001). Part of IEA Annex 37.

[334] This probably explains current enthusiasm for injecting biomethane into the gas grid and burning it in heat-only boilers. This is a similarly inefficient of resources to burning natural gas in heat-only boilers and not in CHP plants.

[335] Ref. 79, *op. cit*.

[336] Fuel cells are not subject to the Carnot limit. In theory they can generate electricity more efficiently than burning gas at 1,800-2,000°C in a heat engine. But so far, their development has not led to economic machines for power generation in the way that some may have hoped.

[337] Rohles, F H, “Temperature and Temperament: A Psychologist Looks at Comfort”, *ASHRAE Journal*, vol. 49, no. 2, pp. 14-22 (February 2007). This applies to working age adults wearing normal indoor clothing of 0.75 clo; e.g., a light pullover and medium-weight long trousers. Elderly people desire higher temperatures.

[338] Reviewed briefly by *New Scientist*, p. 28 (2 October 1975).

[339] Lowe, R J, “Combined Heat and Power Considered as a Virtual Steam Cycle Heat Pump, *Energy Policy*, in press (2011).

[340] Sumner, J, *Domestic Heat Pumps*. ISBN 13-97809047271-0-4. Prism Press (1976).

[341] Department of Energy, Energy Paper 20, p. 118, appendix 13. HMSO, London (1977).

[342] *IEA Heat Pump Newsletter*, no. 2, p. 15, figs. 1 & 2 (2004). http://www.heatpumpcentre.org/.

[343] http://www.agenda-energie-lahr.de/WP_Jahresbericht2006-08.html

[344] Ref. 196, *op. cit*.

---

[345] Early examples known to the principal author, and with measured energy bills, include the Reyburn House, London (1985), the four Two Mile Ash Houses, Milton Keynes (1985), the Lifestyle 2000 House, Milton Keynes (1986), Lower Watts House, Charlbury (1992), the Elizabeth Fry Building, UEA (1994), the Embleton House, Twyford (1995) and many late 1990s/early 2000s Passivhaus offices and schools in Germany. More can be found in Willoughby, J, and Olivier, D, *Review of Ultra-Low-Energy Homes*, BRECSU (1996). A more recent example is the Disability Essex headquarters in Rochford (2008).

Urging users to behave radically differently may deliver long-term savings. To help ease the transition away from fossil fuels, some changes in attitude seem useful and worthwhile. But behavioural changes which are seen by the public as deprivation may confuse energy productivity in their mind with hardship and curtailment. This is not a good idea, if our future prosperity depends on major investment in energy productivity to stretch more constrained energy supplies.

[346] http://www.eia.doe.gov/oiaf/1605/ggrpt/methane.html.

[347] http://www.vtwoodsmoke.org/pdf/Johansson03.pdf

[348] http://pubs.giss.nasa.gov/docs/2007/2007_Hansen_etal_2.pdf

[349] It would also be useful to regulate the prices of rural fuels. Regular Competition Commission investigations lead one to suspect that oil and especially LPG margins are higher than on electricity and natural gas, although the margins on mains energy supplies have also widened since “retail deregulation”. Most rural areas have only two or three oil or LPG suppliers. For natural gas and electricity, six major suppliers seems to be considered inadequate.

[350] http://www.nationalgrid.com/uk/sys_06/chap2/images/fig2-4.gif

[351] Ref. 70, *op. cit*.

[352] Olsen, P K, et al, “A New Low-Temperature District Heating System for Low-Energy Buildings”, *Proc. 11th. International Symposium on District Heating and Cooling* , Reykjavik, Iceland (31 August to 2 September 2008). http://www.annex51.org/media/content/files/publications/Low_Energy_Ddistrict_Heating_S_Svendsen.pdf

[353] We requested a LDC for the Southampton DH system, to indicate demands for space and water heating in a mix of less well-insulated buildings, and with different loads and varying lengths of heating season amalgamated. But we were told that the information is treated as “commercially confidential”. Cofely District Energy Ltd., personal communication (4 September 2010).

[354] Buildings with very high thermal capacity *and* low heat loss may have slightly lower peak demands than standard procedures predict. With such long cooling time constants, they would not experience such severe demand peaks. This would be experienced as an apparent diversity factor of less than 1.0. Some heat utilities do report these, especially in German-speaking countries such as Austria. But this would be confined to the tiny minority of the building stock and hardly affects the overall LDC for a large group of buildings.

[355] The lighting load has considerable diversity, but demand for light is greater on typical dark winter evenings than spring or summer evenings. This contributes at least part of the 17.30 h peak load seen on the winter but not on the summer daily load curve.

[356] 199 GW was the load after disconnecting large buildings on interruptible gas tariffs. On the other hand, 199 GW excludes the load to supply rural buildings heated today by oil, LPG and coal and it excludes the potential demand from buildings which are unheated today because users cannot afford the cost. Conversely, it would decline if one deducts the losses of gas-fired heat-only boilers under peak conditions.

[357] GSHPs could help to give this level of network security. The COP of ASHPs drops as the outside air temperature drops.

---

[358] Heap, R D, "Heat Requirements and Energy Use in British Housing", *Energy and Buildings,* vol. 1, no. 4, pp. 347-366 (June 1978). The hours between -5 and -6, -6 and -7°C, etc are estimated to give a smooth curve.

[359] http://www.cetiat.fr/docs/newsdocs/166/doc/R744%20Technicians%20Manual%20CETIAT%20GRETH.pdf

[360] http://www.sussex.ac.uk/spru/documents/sewp175

[361] http://www.iea.org/textbase/nppdf/free/2006/unitedkingdom2006.pdf

[362] http://www.iea.org/papers/2008/cd_energy_efficiency_policy/7-Energy%20utilities/7-savingElec.pdf

[363] The UK has avoided this outcome to date with the gas network, which is mainly used for heating, by insisting that some large consumers are supplied on interruptible tariffs. It seems that the piped heat systems in Southampton, Sheffield, London et al have avoided it too.

[364] The most noticeable correlation between the two is that statistically there *is* more wind energy in winter than in summer. Mean monthly wind output varies about 2:1 from a summer low to a winter maximum, but there are great variations either side of the monthly mean. Heat demand in a low-energy building varies about 15:1 from the summer low, which is the hot water load, to the winter maximum over a design day. It also varies about three-fold from average to very cold winter weather. Matching the two would need a mix of (a) wind energy spillage (b) seasonal electricity storage and/or (c) consumption of stored fuel in fuel-fired power stations.

[365] Dept. of Energy, Energy Papers 20 and 35. HMSO, London (1977 and 1979). These papers are not available online but the findings from EP20's economic comparison of CHP, electric heat pumps and other options after natural gas appear at this URL: www.claverton-energy.com/?dl_id=45.

[366] http://www.energysavingtrust.org.uk/Media/node_1422/Getting-warmer-a-field-trial-of-heat-pumps-PDF. We do not follow the claims that low COPs reflect climate differences and user habits. In our view, low COPs probably reflect design and/or installation deficiencies, including the UK tendency after decades of government promotion of it to use time-controlled intermittent heating rather than continuous heating and weather compensation. The highest COPs in the UK survey match the COPs of 3.2-3.7 measured on Swiss, German and Danish GSHPs.

[367] As compressors became more efficient, heat exchangers were often made smaller, to keep manufacturing costs under control. Smaller exchangers need defrosting at an air temperature a few degrees higher and accentuate the problem.

[368] Cantor, J, John Cantor Heat Pumps Ltd., Machynlleth, personal communication (November 2010).

[369] Ref. 54, *op. cit*.

[370] This is before allowing for the scope for electric heat pumps. On the other hand, with the gas scenario there would possibly be some scope for gas-fired heat pumps and/or small gas-fired CHP fuel cells.

[371] Ref. 65, *op. cit*.

[372] In 2009, more heat was rejected from gas-fired power stations and discharged into air and water at respectively 100°C and 30°C than the quantity of gas delivered to buildings for space and water heating. The other 2% of the gas supplied to buildings is used for cooking. 15% of electricity is a reasonable estimate of the proportion of peak demand used for urban heating and displaceable by piped heat.
The heat from gas CCGT plants comprises cooling water losses at 30°C and the flue losses at around 100°C. The former are around 35-40% and the latter are around 10% of the fuel input. The latter could be captured by condensing operation, as happens with condensing gas heat-only boilers. Orchard, W, Orchard Partners London Ltd., personal communication (November 2010.)

---

[373] http://www.dbdh.dk/artikel.asp?id=463&mid=24

[374] http://www.utilicom.co.uk/documents/SGHCBrochure211107.pdf

[375] http://www.energymap.dk/Cache/03/0347cf9a-32da-429a-a1ca-2dbc68431158.pdf.

[376] Ref. 50, *op. cit*.

[377] http://intraweb.stockton.edu/eyos/energy_studies/content/docs/effstock09/Session_11_1_Case%20studies_Overviews/107.pdf

[378] Report by AEA Energy and Environment, BRE Ltd. and PB Power, *Potential for CHP in the UK*. http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/emerging_tech/chp/potential-report.pdf. DEFRA. (October 2007). This assumes that CHP systems would operate at flow and return temperatures of 95/65°C and applies real discount rates in the range 9 to 15%/yr.

With modest insulation and draughtproofing, the flow and in particular the return temperatures can be set lower. The trend in Denmark is to lower temperatures. 40°C return is common on existing systems, 25°C has been proposed for new systems and even 15°C has been suggested in areas of new low-energy housing, using a counterflow heat exchanger to cool the return water with the aid of the incoming cold mains water.

[379] Many UK DH systems which attempt to supply low-rise housing report high percentage heat losses. It is important to introduce new DH practice quickly, based in large part on lessons from Denmark; possibly via agreed design parameters for new schemes or extensions. Ref. 296 and the papers below set out the scope to redesign DH systems for low-density and/or low heat loss buildings. With redesign, it appears that losses can generally be kept at 10-14%, the same as the 12% from 230 V electricity networks:

(a) http://www.annex51.org/media/content/files/publications/Low_Energy_Ddistrict_Heating_S_Svendsen.pdf
(b) http://www.iea-dhc.org/reports/pdf/Energiteknik_IEA-Final-report-5.pdf
(c) http://www.fconsistent bbb.dk/Files/Filer/Peter_Kaarup_Olsen_-_COWI_29-10_2009.pdf
(d) http://heating.danfoss.com/xxNewsx/5d29feb8-5c97-4f3f-bf18-a8e1f9e5ef45.html
(e) www.passivhaustagung.de/zehnte/englisch/texte/PEP-Info1_Passive_Houses_Kronsberg.pdf
(f) http://www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-sr0804.pdf
(g) http://orbit.dtu.dk/getResource?recordId=224206&objectId=1&versionId=1
(h) http://heating.danfoss.com/PCMPDF/Technical_Article_OptimumDesign_lores.pdf
(i) http://dbdh.dk/images/uploads/medlemsmode/cowi%2024%20oktober.pdf
(j) http://www.dhc12.ttu.ee/artiklidkoos27aug.pdf
(k) http://www.braedstrup-fjernvarme.dk/

[380] http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file43609.pdf

[381] http://www.legislation.gov.uk/ukpga/1991/56/contents

[382] http://www.nationalgrid.com/annualreports/2010/delivering-performance/transmission/about-transmission.html#1 gives the real rates of return allowed on new infrastructure by National Grid PLC.

[383] Ref. 275, *op cit*.

---

[384] Report by Pöyry and Aecom, *The Potential and Costs of DH Networks.* http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20mix/distributed%20energy%20heat/1_20090505121831_e_@@_204areportprovidingatechnicalanalysisandcostingofdhnetworksv30.pdf (April 2009). This notes that UK civil costs for piped heat; i.e., digging trenches, burying pipes and making good are more than the rates paid on the continent. As of June 2011, the report could no longer be found on DECC's website but was found at http://www.poyrycapital.com/assets/files/downloads/Technical%20Analysis%20&%20Costing%20of%20DH%20networks%200904.pdf.

[385] Danish consultancies dealing with DH appear to include *inter alia* Ramboll, Cowi, Grontmij and Carl Bro A/S.

[386] http://downloads.theccc.org.uk/docs/NERA%20Renewable%20Heat%20MACC%20report%20final%20revision.pdf.

[387] By amalgamating fixed and variable costs, and not critically evaluating why costs are lower in mature DH markets, ref. 287 seems to overestimate connection costs to existing housing. It quotes up to £15,000/dwelling for a case where a Danish heat utility would probably expect to spend £6,000-7,000. It cites £6,000/dwelling to lay DH to new construction. A Danish study cited a budget cost of £3,000-3,500 for low-density detached bungalows. See Ramboll, *Heat Supply to New Residential Areas: Consequences of New Energy Requirements for New Dwellings*. Report EFP05, 0549516 /K00126-2-JEML(2) (May 2006). Reports such as http://www.lsta.lt/files/events/6_reidhav.pdf have more detailed cost models.

[388] The central piece of legislation was the Electricity Supply Act of 1926. http://en.wikipedia.org/wiki/National_Grid_%28Great_Britain%29. Rural areas of the UK were only connected to electricity in the 1960s.

[389] Willoughby, J, *Domestic Fuel Price Guide* (May 2010). www.johnwilloughby.co.uk. Heat from LPG and oil costs about 50% more than from natural gas condensing boilers. Heat from solid fuel or electricity costs more, given respectively the low efficiencies of most solid fuel appliances and the high unit cost of electricity.

[390] Clee Hill village in Shropshire is 400 m higher and an estimated 2.5 K colder than the town of Tenbury Wells in Worcestershire, which is only 8 km away.

[391] *Air Quality Strategy*. DEFRA, London (2007). http://www.defra.gov.uk/environment/quality/air/airquality/strategy/documents/air-qualitystrategy-vol1.pdf

[392] Anon, *Air Quality*. 5th Report of Session 2009-10. Volume 1. House of Commons Environmental Audit Committee. http://www.publications.parliament.uk/pa/cm200910/cmselect/cmenvaud/229/229i.pdf

[393] Ref. 67, *op. cit.*, p. 46.

[394] See http://www.ctc-uk.com/products.php. According to information provided by the company's UK office in 2010, it recommends turning off ASHPs at outside temperatures such as -15°C and using electric resistance heat. However, ASHPs are made for Sweden with COPs of above 1.0 at -15°C or -20°C.

[395] *Transcritical CO_2/R744 Heat Pumps*, pp. 18-62-20/62. Technician's Report. Rapport 2414173, CETIAT, France (October 2007).

[396] Lockwood, M et al, "The Solar Influence on the Probability of Relatively Cold UK Winters in the Future", *Environ. Res. Lett.* **6** (2011). http://iopscience.iop.org/1748-9326/6/3/034004/pdf/1748-9326_6_3_034004.pdf

---

[397] http://www.metoffice.gov.uk/weather/uk/wm/pershore_latest_weather.html. The chart was compiled by manually typing the temperatures into a spreadsheet on the day after publication. The Met. Office does not issue figures in spreadsheet form and deletes them after 24 hours.

[398] At today's flow and return temperatures of 80/60°C, the uninstalled marginal cost of radiators appears to be at least £30-40 per kW(t). A drop to temperatures of 75/25°C, as suited to low-temperature DH, could increase costs by of the order of £50 per kW(t) because the radiator output per unit area is now about 50% of the output at standard temperatures. But at 50/30 or 45/25°C, aiming for a high heat pump COP and to avoid supplementary electric resistance heating, the cost increase could be several £100 per kW(t), because the radiator output per unit area is now 20-25% of the output at standard temperatures. A 1.3 power law is assumed in making these calculations.

[399] The backup generating plant for these could presumably be reinstated, making them less critical than the other loads.

[400] Rendering a masonry wall directly, or rendering on mesh on rigid insulation, typically costs £30-40/m^2. Even if the need to re-render this wall is 25 years away, there should be a credit for the expenditure deferred by rendering the whole house now. To simplify the calculation, we omit this.

[401] Grove Cottage, Hereford, a typical Victorian detached solid brick house upon an unheated basement, reached 0.87 ac/h @ 50 Pa (test report, using Passivhaus conventions recalculated to reached 1.0 ac/h @ 50 Pa) . The architects and builders had not done a similar retrofit before. See http://retrofitforthefuture.org/projectPDF.php?id=199. A characteristic early 1950s cavity-walled detached house in Oxford, with possibly equally-skilled builders, reached 3 ac/h @ 50 Pa. It appears to have a degree of recalcitrant air leakage via the cavity. This may prove to be a common problem unless cavity-walled buildings are (a) detached, (b) very simple in shape and (c) not built up to the boundary line.

[402] Ref. 157, *op. cit*.

[403] Since this sentence was written in late 2010, the world oil price has risen by another 30%.

[404] http://www.erec.org/fileadmin/erec_docs/Projcet_Documents/RESTMAC/Brochure4_Cogeneration_low_res.pdf

[405] http://www.esru.strath.ac.uk/EandE/Web_sites/99-00/bio_fuel_cells/groupproject/library/chp/pageframe.htm

[406] This Austrian diesel CHP project, burning biomethane, was installed for £450/kW(e), although it is not fully clear what associated equipment it includes. http://www.cogeneurope.eu/challenge/Downloadables/Best%20Practice%20factsheets/Austria/CC_BP%20Factsheet_Biogas%20plant%20Zeltweg.pdf

[407] DECC estimates today's price for firm gas as 1.98 p/kWh at the system notional balancing point. Andrews, D, EU Joint Research Centre, Institute for Energy, Petten, the Netherlands, personal communication (March 2011). It is assumed that the extra use-of-gas-system costs for a plant near to final consumers offset the value to the system operator of interruptible tariffs.

[408] Andrews, D, JRC, Petten, the Netherlands, personal communication (2010). The engine lifespan is said to be indefinite if this much is budgeted for maintenance costs.

[409] Ref. 79, *op. cit*.

[410] Olivier, D, "Energy Efficiency in Transport", *Proc. Claverton Energy Group Conf.*, Claverton, Bath (October 2008.)

[411] *Rail Electrification*. Dept. of Transport, London (August 2009). http://collections.europarchive.org/tna/20100408232230/http:/www.dft.gov.uk/pgr/rail/pi/rail-electrification.pdf.

---

[412] Lesley, L, Prof., presentation at Claverton Energy Group Conference, Bath (October 2008). See also http://www.pteg.net/NR/rdonlyres/ED820DBC-1FC3-4F6F-B70A-49BDD404D0C5/0/Day3Session1Transcriptapprovedfinal.pdf

[413] This support comprises a capital grant of £5k per vehicle plus a NPV of £12k/vehicle in lost fuel duty and VAT revenue over a 15 year life and a NPV of £2k/vehicle in respect of lost vehicle excise duty. All these figures are at *Green Book* discount rates.

[414] The Nissan Leaf is an example. Its payload is 40% lower than a normal sub-compact car's 500-600 kg, whereas its unladen weight is 1.5 tonnes, more than the typical 1.2 tonnes. It appears that the designers had to trade away payload to produce an acceptable combination of range and unladen weight.

[415] At an assumed 80 kWh/100 km for ICEVs, 30 kWh/100 km including heating for BEVs, with the battery bank repaid over 20 years and with both vehicles driven 15,000 km/yr. The resulting costs of the energy consumed plus the battery repayments are £540/yr for the ICEV and £1,750/yr for the BEV. A fuller comparison should include the higher servicing costs of an ICE, which has more moving parts. On the other hand, it should also take a more realistic battery lifespan of ten and not 20 years.

[416] This assumes 30M battery banks, each 80 kWh in capacity, giving 25 kWh/100 km battery-electric vehicles (BEVs) a range of 320 km = 30% the range of ICEVs. It assumes battery system costs of £600/kWh today and £150/kWh in 2030. It covers cars and light vans but excludes HGVs, buses, rail, air or sea transport or motorcycles. Smaller battery banks can be used, such as 40 kWh, costing a theoretical £6,000 in 2030, but they restrict the range to only 200 km, assuming that the lighter vehicle which results uses 20 kWh/100 km.

[417] http://www.cggc.duke.edu/pdfs/Lowe_Lithium-Ion_Batteries_CGGC_10-05-10_revised.pdf

[418] Anon, "A Commercially-Available Electric Vehicle", *CADDET Journal* (July 1998) reported that resistance heating reduces a BEV's range in cold conditions by 35%. The percent reduction would be more severe in town driving and less severe in rural or motorway driving.

[419] Nissan UK Ltd., Customer Service Dept., personal communication (March 2011). This avoids using the battery but does not save energy *per se*. Rather, it transfers electricity consumption from car to building.

[420] Audi, part of the VW AG group, is working on synthetic methane as a vehicle fuel. See: http://www.worldcarfans.com/111051333371/audi-a3-tcng-e-gas-project-announced---methane-powered

[421] The pre-tax cost of synfuels to road users could be slightly lower than today's post-tax price of motor fuel. This would reflect the lower cost of distribution and storage and the facility to use spilled windpower which has a lower value than electricity which the national grid can utilise directly. We have not named the researcher concerned. He believes that, despite the lower cost of synfuels today, battery breakthroughs will occur.

[422] A typical filling station petrol pump delivers fuel at a rate at a rate of 15-20 MW; i.e., 50 litres in under two minutes. Diesel pumps for HGVs deliver nearer 30 MW. These are more than the peak electricity consumption of a small town! Given the capacity limits, BEV recharging usually takes 8 hours. More rapid charging is possible but it is problematic for battery life, not to say for the local electricity distribution system.

[423] US prices today for Li-ion complete battery systems. Pearson, R, Lotus Cars, personal communication (2011). Nickel metal hydride batteries are, however, about £450/kWh. See http://www.spinnovation.com/sn/Batteries/Battery_Electric_Vehicles_-_An_Assessment_of_the_Technology_and_Factors_Influencing_Market_Readiness.pdf.

---

[424] Sometimes forecast to be in the range £100-150 per kWh. See ref. 94. The discussion therein does not distinguish clearly between bulk prices to distributors or car-makers and retail prices. We assume that it means retail prices to motorists.

[425] http://www.energypolicy.co.uk/The%20CAST%20Proposal%2017a.pdf. The other 6% of today's motor fuel is biofuels.

[426] http://www.sgc.se/nordicbiogas/resources/Peter_Boisen.pdf. As the author states: "Promises offer no help today".

[427] Feebates are rebates on new fuel-efficient vehicles, plus penalties on fuel-inefficient ones, in a program which is revenue-neutral overall but creates a sufficient price differential between; e.g., 175 and 55 g/km cars to change their market shares dramatically and quickly. Discussed in detail in the past by the Rocky Mountain Institute, www.rmi.org.

[428] See; e.g., http://www.theengineer.co.uk/Articles/312241/Driving+down+costs.htm

[429] We suggest use of the GEMIS database. It is independent of governments and considers some emissions which national figures do not always include. See http://lca.jrc.ec.europa.eu/lcainfohub/database2.vm?dbid=129.

[430] The EU fuel economy figures now being quoted for new models in 2010 and 2011 appear optimistic under normal driving conditions. 4 litres/100 km on the label may translate to 4.8 litres/100 km in reality. Consumers deserve realistic figures. The USA changed its test method after cars' average fuel consumption proved to be higher than the quoted "combined" figure, thanks to cold starts, cold days, short journeys, varying driving habits, etc. See http://www.fueleconomy.gov/feg/why_differ.shtml

[431] See http://www.oeko.de/service/gemis/en/faq.htm.

[432] http://www.aecb.net/UserFiles/File/Biomass%20-%20A%20Burning%20Issue%20-%20published%20September%2020101.pdf

[433] The Skoda Fabia Greenline II, rated at 89 g/km. http://www.energysavingtrust.org.uk/Resources/Energy-saving-news/Cleaner-Cars/Which-lists-top-cars-exempt-from-Congestion-Charge

[434] We find proposals to raise motorway and dual carriageway speed limits unconvincing. Some continental European countries have historically had a higher limit of 130 km/hr but the speed limits in Canada, New Zealand, Australia and the north-eastern USA are lower than they are in the UK. More useful we think would be public information campaigns to explain to drivers how significantly fuel consumption rises on cruising at speeds of not 90 but 110 or 130 km/hr, followed by a plan to slowly lower limits to around 100 km/hr. A further concern is that because higher speeds reduce road capacity, they might be counterproductive anyway on busy routes such as the A1, M1, M6, etc.

[435] Anon, *Transport, Energy and CO$_2$*. IEA, Paris (2009). http://195.200.115.136/textbase/nppdf/free/2009/transport2009.pdf

[436] Ref. 318, *op. cit*.

[437] http://www.energypolicy.co.uk/CAST_52c.pdf. See also http://www.CO2star.eu/publications/Well_to_Tank_Report_EU.pdf

[438] http://www.sustainablebusiness.com/index.cfm/go/news.display/id/21566. Any competition must be open to all market players. Sun Frost, the manufacturer of the USA's most energy-efficient refrigerators, claimed that it was excluded from the Golden Carrot competition.

[439] http://www.central-railway.co.uk/resources/cr_FreightConsultation2006.pdf

---

[440] Ref. 305, *op. cit*.

[441] http://www.sci.manchester.ac.uk/medialibrary/realistic_fuel_saving_on_hgv_via_aerodynamic_drag_reduction-finalprojectreport.pdf

[442] Ref. 305, *op. cit*.

[443] Ogburn, M, et al, *Transformational Trucks: Determining the Energy Efficiency Efficiency Limits of a Class-8 Tractor-Trailer*. Rocky Mountain Institute, Old Snowmass, Colorado, USA (July 2008).

[444] *Scaling Up Energy Efficiency: Bridging the Action Gap*. Workshop, IEA, Paris (2-3 April 2007). http://www.iea.org/work/workshopdetail.asp?WS_ID=298

[445] Hurst, T B, "Six Ways Trucks Will Meet New Fuel and Emissions Standards", *Earth and Industry* (1 November 2010). http://www.matternetwork.com/2010/11/6-ways-trucks-will-meet.cfm

[446] http://www.economist.com/node/18329444

[447] http://atwonline.com/aircraftenginescomponents/article/rolls-royce-pursues-open-rotor-0309

[448] See; e.g., *New Scientist* (27 April 2007).

[449] http://www.greenaironline.com/news.php?viewStory=684.

[450] Lovins, A B, et al, *Winning the Oil Endgame*. Rocky Mountain Institute, Old Snowmass, USA (2004).

[451] http://www.aopa.org/pilot/features/2004/feat0411.html and http://en.wikipedia.org/wiki/Diamond_DA42

US work on turbprops in the mid to late 1970s is described at http://history.nasa.gov/SP-4219/Chapter14.html. These changes offered to save 30% of aircraft fuel. They were not taken up by the private sector when fuel prices fell back to pre-1973 levels, but the work remains available for when it *is* needed.

[453] Roughly half the weight of a long-haul jet at take-off is fuel, along with the weight of structure needed to hold the fuel. There is a net saving *after* allowing for the fuel consumed in extra landings and take-offs. The optimum refuelling distance is around 5,000 km. See also ref. 2.

[454] This has been proposed by a company developing a new supersonic aircraft. If it is feasible there, it is hard to see why it could not be feasible for sub-sonic planes. They seem likely to be a larger market.

[455] http://www.byg.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r021.pdf, p. 78, ref. 39.

[456] http://www.parliament.uk/briefingpapers/commons/lib/research/briefings/snbt-00523.pdf

[457] http://www.pmmonlinenews.com/2010/05/new-trends-in-marine-propulsion.html

[458] Given the high part-load efficiency of diesel engines, fuel usage should fall almost linearly with the reduced load.

[459] Anon, *Air Pollution: Action in a Changing Climate*. Report PB13378. DEFRA, London (March 2010).

[460] Batteries in short-range BEVs, plus an electric motor, weigh no more than a diesel engine. They might be a viable means, say, to carry people 20 km to the local railway station or shops and back before recharging, especially if the battery rating is conservative enough to ensure that it lasts as long as the vehicle, say 20 years. Even this technology needs cost reductions on present batteries, but at least the battery lease payments would not equal the payments on the car. Likewise in

---

short-range electric mopeds where an electric motor can replace a small, relatively inefficient petrol engine.

[461] Electricity used by vehicles carries 5% VAT if the 13A socket is on domestic premises, amounting to ~0.5 p/kWh. But if the socket is in a public or commercial building, the VAT is usually reclaimed, so the electricity is untaxed, suggesting that a typical tax rate might be ~0.25 p/kWh.

Petrol and diesel carry ~6.0 p/kWh duty. 20% VAT is charged on the total retail price, including the duty. VAT on diesel at its retail price of 132 p/litre = 13 p/kWh amounts to 2.2 p/kWh. So the total tax is 8.2 p/kWh. Unlike VAT on electricity, VAT on motor fuel is not reclaimable by business users unless they keep extra records. The effective tax on motor fuel to a range of users is likely to be ~6.0-8.2 p/kWh, roughly 20 times the tax on a mix of domestic and non-domestic electricity.

[462] For example, Galway in Ireland. An advantage of trams over light rail is that they do not incur the high costs of signalling.

[463] Ref. 9, *op. cit*.

[464] *Ibid.* p. 217 onwards discusses the aluminium industry. There has been an energy efficiency improvement since 2000, but as this discussion confirms, even large companies will not usually invest in an energy efficiency improvement unless the minimum return on investment is 20-50%/yr. The threshold varies between companies.

[465] http://www.washerhelp.co.uk/buying-advice-2.html

[466] Reinforced concrete elements are usually less CO_2- and energy-intensive than structural steel frames, if near minimum steel is used. If they are overdesigned, though, embodied energy can be as high as a steel frame.

[467] However, the use of wood-based insulants in buildings could be attractive. Being denser than conventional insulation materials, they help with summer cooling *and* sequester CO_2. In favourable cases, a large detached house might sequester eight tonnes in the roof, external wall and ground floor insulation and 12-15 tonnes of CO_2 overall, including the timber roof and other elements. See; e.g., http://www.src.sk.ca/images/house_notes.pdf.

[468] http://www.ecogeek.org/alternative-materials/3441.

[469] Stephenson, R L and Smailer, R M, *Direct Reduced Iron: Technology and Economics of Production and Use*, Iron and Steel Society, AIME, 250 pp. (1980). http://md1.csa.com/partners/viewrecord.php?requester=gs&collection=TRD&recid=8103720084MD&q=&uid=790307246&setcookie=yes.

[470] *CADDET Energy Efficiency Newsletters*. These were published monthly in the late 1980s, 1990s and early 2000s plus several hundred leaflets on individual industrial, transport or buildings projects. However, they are no longer published and no electronic version could be found on the internet. They were, however, preserved on DVD so it should be possible to make them available on the internet. Everett, R, Energy and Environment Research Unit, Open University, personal communication (June 2011).

CADDET's somewhat later renewable energy leaflets can be found online at http://www.caddet-re.org/html/techlist.htm.

[471] http://www.smartcommunities.ncat.org/articles/indecol.shtml

[472] Werner, Prof. S, Halmstadt University, Sweden, personal communication (March 2011).

[473] Cases have been documented where the net profit of a factory in a year equalled the reduction in overheads that it had attained by investment in energy efficiency in recent years; e.g., in heat recovery. Energy efficiency literally kept the company in business.

---

[474] See http://scholar.lib.vt.edu/theses/available/etd-04202006-172936/unrestricted/Sovacool-Dissertation-v10-Final.pdf p. 222.

[475] Royal Commission on Environmental Pollution, *Nuclear Power and the Environment*, 6th Report. HMSO, London (1976).

[476] Fortunately for metropolitan Tokyo, the worst of the airborne radioactive plume from Fukushima Dai-Ichi was blown eastwards over the Pacific, not west or southwest over the main Japanese landmass.

[477] See; e.g., *The Swedish Reactor Safety Study: Barsebäck Risk Assessment*', Energy Commission, Dept. of Industry, Stockholm. Ds I 1978:1 (1978). This stated that an accident could seriously contaminate an area of up to 100,000 km^2. The area of England is 130,400 km^2.

[478] http://www.fooledbyrandomness.com/notebook.htm

[479] Analysis of soil samples on the coastal plain shows that a very high tsunami occurred in the year 869 AD. Despite Japan's long history, records of the event were lost and/or forgotten and did not inform the design of the nuclear reactors at Fukushima Dai-ichi. In effect, such events were treated as “incredible” . No action was taken on publication of the analysis in 2001. http://www.newscientist.com/article/mg21028092.500-time-to-rethink-megaquakes.html. The 1896 earthquake appears to have generated a similar tsunami height to 2011, but was not allowed for either. See http://en.wikipedia.org/wiki/1896_Meiji-Sanriku_earthquake. In modern times, a 1986 analysis predicted a risk of a 15 m high tsunami. But by then the plants had been operating for 10-15 years and were protected by roughly 5 m high sea walls. Nothing further was done by the government, the nuclear regulator or the electricity companies. See http://library.lanl.gov/tsunami/00394740.pdf

Human errors and fallibility make it impossible to predict in advance all the sequences of low-probability events which might lead to a severe release of radiation. The above experience suggests that even a correct prediction of a event is not followed by preventative action, if this is perceived as too commercially or politically difficult.

[480] http://www.bee-ev.de/3:720/Meldungen/2011/AKW-nicht-versicherbar-BEE-verlangt-ehrliche-Kostendebatte.html. If one considered the possibility of all insurers joining together to insure all the world's nuclear plants, whose output is tens of times more than the German ones, it appears that the industry would still be uninsurable.

[481] http://www.mng.org.uk/gh/private/nuclear_subsidies1.pdf

[482] http://www.nuclearpowerdaily.com/reports/Arevas_Finnish_EPR_reactor_delayed_again_999.html

[483] 6th. Report of the Royal Commission on Environmental Pollution, chaired by Sir Brian Flowers (1976).

[484] http://www.nationalgrid.com/NR/rdonlyres/A4B42E9E-A315-47FC-B819-5BE812CE3E6F/41716/GBECM19Consultationv1_0.pdf. This is the extra cost if one divides the extra annual cost of £160 M by the annual output of four 1.6 GW(e) nuclear plants operating at 75% capacity factor.

[485] House of Lords Science and Technology Committee Report (2005-06). See table, p. 107. http://www.publications.parliament.uk/pa/ld200506/ldselect/ldsctech/21/21i.pdf

[486] *Ibid*. paras. 4.10 and 11.17.

[487] http://www.iea.org/textbase/nppdf/free/2006/unitedkingdom2006.pdf

NOTE: Web documents cited as references were accessed between July 2010 and July 2011. If any URLs have since become unavailable, due to organisations reorganising their websites, we apologise.

---

[488] *The Green Book: Appraisal and Advice in Central Government*. HM Treasury, London (2003). http://www.hm-treasury.gov.uk/data_greenbook_index.htm

[489] In practice, the public sector may be able to borrow for lower real rates via index-linked bonds. Wright, S, et al, *A Study into Certain Aspects of the Cost of Capital for Regulated Utilities in the UK*. Section 6.7, pp. 48-49 (February 2003). http://www.ofwat.gov.uk/legacy/aptrix/ofwat/publish.nsf/AttachmentsByTitle/cost_of_capital130203.pdf/$FILE/cost_of_capital130203.pdf

[490] *Draft SAP-2009*. http://www.bre.co.uk/filelibrary/SAP/2009/Draft_SAP_2009_main_document.pdf. Figures for electricity vary significantly between summer and winter and between LV domestic and high-voltage industrial loads. Average transmission plus distribution losses for 230/400 V and 25 kV consumers are 12.2% and 2.6% respectively. Delivered electricity in Great Britain in 2006 seems to have averaged 0.59 kg/kWh, or 0.62 kg/kWh for the 230/400 V loads and correspondingly less for the loads supplied at high voltage, such as railways and large industry. It is likely that winter and summer electricity averaged around 0.45 and 0.75 kg/kWh respectively. See http://www.berr.gov.uk/energy/statistics/publications/dukes/page39771.html.

AECB
the sustainable building association

Contact: PO Box 32, Llandysul, SA44 5ZA
Tel: 0845 456 9773
Website: www.aecb.net

Company Registration No: 5336768

Registered Name/Address:
Association for Environment Conscious Building
30 Linden Road, Earby, Barnoldswick, Lancashire, BB18 6XR