Imperial College
London

The UK in 2050

Final report - 15 May 2009

This report supersedes all previous drafts of this report, presentations and any other input to DECC on this project, and should be considered as the definitive project output.

1 Introduction

This report analyses the possible technological pathways and options for meeting the UK's 2050 GHG mitigation targets in a context where the government is also concerned about energy security and energy affordability. It stems from a series of workshops between March and May 2009 between DECC officials and researchers at Imperial College, co-ordinated by the Grantham Institute for Climate Change at Imperial College. The work draws extensively on the expertise of many Imperial researchers working at the cutting edge of the relevant disciplines and on emerging large-scale research programmes being developed at Imperial to address these questions. It does not, however, attempt to provide forecasts or scenarios of the future - of which there are already several. Instead the report aims to address some of the following key issues:

- Are there any major technical obstacles to high-level options for meeting these targets?
- What are the interdependencies and how should we sequence actions?
- Are there critical timelines for the development and deployment of technologies?
- What might be key areas of contention (political or technical) and cost?
- What might be feasible by 2020 and how does this relate to 2050?
- Implications for energy demand of deploying or not deploying a specific technology.

On a 2050 time horizon, technological, demographic, political and social uncertainties dominate. The key conclusions highlighted here provide a best judgement of what can be said reasonably robustly against this context given what we know now. Much more research and innovation will be needed to map out feasible technological pathways and develop the new integrated systems solutions that we believe necessary to meet this huge challenge.

2 Key conclusions

a. **The scale of the mitigation challenge** means that some trajectories to a low-carbon economy, suitable to meet more modest targets (i.e. 50-60 percent reduction), are no longer appropriate for 80-90 percent reduction targets. While it may be possible to meet 2020 targets through incremental change, **meeting the 2050 targets will require systemic change**, which must begin in the period before 2020.

b. **Energy vectors must be decarbonised**. No fossil fuels should be delivered to the final consumer by 2050 without the deployment of offsetting negative emissions technologies to remove CO_2 from the atmosphere. Some fossil fuel may still be required for transport at this stage (e.g. heavy goods, long distances); emissions will need to be offset. Fossil fuel generation must be with carbon capture and storage.

c. A **whole-system approach** to designing both supply and usage of energy will be critical. Decarbonisation could be undertaken separately in the areas of electricity generation, heat, and transportation but mitigation targets can be most cost-effectively met by a combination of demand reduction with efficient and intelligent use of available energy and integration between supply and demand for power, heat and transport.

d. **There is no single optimal trajectory for the evolution of energy generation and supply**. Several options exist for removing CO_2 from electricity and for providing decarbonised heating and transport services. The precise portfolio chosen would have major implications for longer term infrastructures, in particular for grid design and development. While there are dependencies in the development of specific technologies, the required rates of decarbonisation in different sectors may be flexible, depending on the feasibility and convenience of each step (e.g. decarbonising electricity supply, introduction of electric vehicles and associated infrastructure).

e. **Whatever the electricity generation portfolio in 2050, it will require intelligent electricity grid systems**. To absorb large intermittent renewable capacity while constraining investment costs, a paradigm shift will be required in which network control shifts from the generation assets to the network and the demand side. Strong complementarities exist between next generation grid(s) and transport options; to exploit these will require **large scale pervasive sensing systems technologies**.

f. **Carbon capture and storage (CCS) will be a key technology for several reasons**. An electricity system where generation capacity is provided only by intermittent renewables and nuclear could be very expensive and difficult to run. Fossil fuel generation with CCS provides short-term flexibility in response to demand and also offers one of the few options for negative emissions technologies - burning biomass with CCS. **Development and deployment of CCS is therefore an urgent challenge**. Two phases of commercial-scale CCS need to be completed in time for reliable reference plant designs to be available for at least one CCS option by 2018, and this probably also needs to be a retro-fittable technology. Without these it will be difficult for policy-makers or industry to commit to a post-2020 regime that relies on CCS for success.

g. **The provision of heat must be designed more intelligently**, by systematically using higher grades of heat before lower ones and utilising heat pump technology to increase efficiency.

h. **Major changes to the transport sector are unavoidable**, but there exist a variety of options for provision of both personal transport at different ranges and heavier goods or passenger transport. Electric vehicles are appropriate for short-range, light-duty journeys; efficient ICEs for long-haul heavy goods; a range of hybrid and mixed options including biofuels and hydrogen fuel cells for the intermediate cases. Technology for and efficient design of public transport systems will also be crucial.

i. **Demand reduction** in the non-transport sectors, particularly through efficiency gains, is in many cases a cost effective “no-regrets” measure which not only contributes directly towards meeting emissions goals, but also increases flexibility and improves prospects for meeting concurrent targets on energy security and affordability. Demand reduction in the transport sector is far more difficult.

3 Energy supply options

Electricity

Strategy and timing

How quickly the UK needs to decarbonise electricity and its choices on generation mix depend critically on assumptions about the evolution of electricity demand. If demand can be reduced, the rate of decarbonisation can be less rapid and may allow more flexibility in the energy supply trajectory up to 2050. On the other hand, if demand reduction proves more difficult, progress in decarbonising electricity supply would need to be accelerated. Early decarbonisation might, however, bring to the fore concerns about energy affordability, which would then force action on the demand side.

There is a strategic issue about to what extent decarbonised electricity is used to meet energy demand in areas such as electric vehicles and in heating buildings (with heat pumps). There are significant potential synergies in doing so, allowing better management of demand, and thus better utilisation of generating capacity. Bioenergy, together with some microgeneration technologies, is also a means to provide some of these energy services. It is likely that electrification and biomass utilisation can take place in combination in different market segments.

System considerations

Several options exist for removing CO_2 from electricity supply. The precise portfolio chosen would have major implications for longer term grid design and development. There are three distinct “flavours” of electricity generation: inflexible baseload supply (currently primarily AGR nuclear in the UK - but see discussion below), flexible supply which may be baseload, mid-merit or peaking (currently primarily fossil fuels in the UK) and intermittent supply (primarily wind in the UK, but could include other renewables such as tidal, solar, etc). There is a range of constraints on the amount of each type of generation that could contribute to delivered electrical energy, some of which are discussed below.

The current generation paradigm is to rely on a large capacity of flexible thermal stations (mainly unabated fossil fuel plants). These can provide controllable response, and their output is adjusted to meet demand.

Use of 100 percent inflexible baseload generation presents difficulties for the Grid because it cannot respond quickly to changes in load. This would result either in blackouts (if the level of supply chosen is too low), deliberate wastage of energy at off-peak times (if level too high), or unacceptable fluctuations in the voltage and current supplied. Again, demand management and storage capacity could to some extent mitigate for this disadvantage.

Use of 100 percent renewable but intermittent energy sources without some form of storage capacity cannot provide reliable supplies unless there is very large overcapacity in the system; clearly an expensive option. However, in the UK renewables, especially wind power, have the potential to be a prominent feature of a decarbonised electricity system. Proposed EU targets for 2020 are likely to require penetrations of wind power in excess of 30 percent by energy. Large amounts of electrical energy from intermittent sources can be accommodated provided sufficient fossil (or other flexible) stations are available to maintain reliability at peak demand and a range of other measures are put in place, such as additional system balancing services.

Intermittent generation

In the context of the Government Renewable Energy Strategy (2020), a significant contribution from variable and difficult-to-predict wind generation when combined with potentially less flexible nuclear plants, may challenge the ability of the system to absorb wind energy, particularly during high wind and low demand conditions. The reason is the need to increase the amount of various balancing (reserve) services to deal with uncertainty in wind output given that the provision of these services is inherently accompanied by energy production from part-loaded generation plant leading to a surplus of generation.

The ability of the British system to accommodate intermittent generation in 2020 has been analysed in some detail, considering various levels of penetration of intermittent wind generation and various levels of electricity demand under a range of assumptions associated with the flexibility of conventional generation, particularly nuclear. In an extreme case with reduced demand, in the presence of 10GW of inflexible nuclear generation significant curtailments of wind output would occur when the level of penetration of wind generation exceeds 25 percent (of electrical energy). This result, although based on an extreme set of assumptions, suggests that the issue of system balancing may be of considerable concern and that it should be monitored and analysed further. In this context, incorporating heat and transport sectors into the electricity system - resulting in an increase in electricity demand - would enhance the ability of the system to accommodate intermittent wind energy. Furthermore, recent investigations show that appropriately controlled wind turbines could provide part of the fast balancing services at low cost and reduce wind generation curtailments.

Demand management

At present there is very little management of electricity demand by time of day/year. The UK also has a modest amount of storage capacity available through pumped storage schemes. Under this “business as usual” scenario, if intermittent generation were to meet (say) 40 percent of electrical energy, a large amount of fossil generation capacity would be needed, but would be used much less. The average system load factor could fall to below 30 percent and the capacity margin would become very large. Our analysis suggests that there could be more than 25GW of conventional generation operating below 10 percent load factor, which raises a question of the delivery of required investment in such plants under the present market conditions. Our work, however, also suggests that there could be significant opportunities for the demand side to provide “backup” for wind. The potential shortages of generation would be low in magnitude and infrequent with short durations (of the order of a couple of critical hours given the duration of peak demand). This shows that the very low utilisation generation plant that provides “backup” for wind may be less competitive than the demand side.

Network control

To manage intermittency more cost effectively, network control (“Smart Grid”) technologies could facilitate more action on the demand side. This could be enabled by smart metering through a range of smart devices and appliances (e.g. frequency sensitive refrigerators, smart dishwashers, washing machines, air-conditioning etc). Our preliminary investigations show that incorporating heat and transport sectors into the electricity system, given their inherent energy storage capacity, could potentially offer significant additional flexibility in balancing the system and would further increase the potential to incorporate intermittent generation without excessive costs. This assumes, however, operation of an intelligent integrated energy system (primarily coordinating electricity generation with transport and heat sectors) which would require deployment of appropriate information, communication and control infrastructure. The exact functionality of such an infrastructure has not been established, the exact benefits are yet to be fully quantified and the cost is not fully understood.

Carbon capture and storage (CCS)

Burning fossil fuel for energy has advantages:

- it is cheap compared to alternatives and current price levels could be reduced to meet future competition;
- UK coal and (some) gas resources are available, improving energy security;
- supply can be varied on short timescales to meet predicted demand and respond rapidly to "unexpected" changes in both supply and demand.

However, the key disadvantage is large carbon dioxide emissions. To meet UK targets, unabated fossil fuel burning cannot continue to 2050, but there is no large-scale option for replacing fossil fuel power plants with other flexible generation. Carbon capture and storage is therefore a critical technology allowing us to increase use of other low carbon generation options while maintaining the flexibility of supply to meet variations in demand.

The level of residual carbon emissions from power plants with CCS is of concern when very high levels of overall emission reduction are being considered. It is expected that, with some additional expenditure, even relatively conventional post-combustion technologies could be operated with up to perhaps 95 percent capture. Pre-combustion capture could achieve similar levels with more attention to hydrogen purification. Higher levels of oxygen purity in oxyfuel capture systems plus scavenging of CO_2 from vent streams could probably achieve around 98 percent capture or higher, as could some of the more novel capture technologies being studied.

The scope also exists to co-utilise biomass in CCS plants and obtain negative emissions to the atmosphere. Co-utilisation levels of 20 percent biomass can be obtained with current pulverised coal plants, and even higher levels are technically feasible.

The most cost-effective way to obtain carbon-neutral electricity from CCS plants is likely to be a combination of increasing capture levels to a value justified by the cost of carbon and co-utilisation of biomass. This approach could be applied to any of the coal plants with CCS (post- and pre-combustion capture) currently being considered and also to coal gasifier retrofits of the carbon capture-ready (CCR) NGCC (natural gas combined cycle) plants being built. It could also be applied to post-combustion capture at CCR NGCC plants if these were fired on a mixture of natural gas and biogas. Otherwise additional biomass utilisation with CCS at other power plant sites could just as well be used to offset residual emissions from NGCC plants with post-combustion capture firing natural gas alone.

Reaching the UK Climate Change Committee implied requirements of 8-20GW of CCS in 2030 from levels (after recent announcements) of 0-1.2 GW of demonstration projects in 2020 would represent a step change and a serious technological challenge. To meet this 2030 target, technological, engineering and infrastructure capacity is needed by around 2020 that can only be gained by work on additional commercial scale projects. From a technical standpoint, "roll-out" of CCS technology could proceed as shown in Figure 1, with sequential but overlapping construction of projects in a series of "tranches", so that expertise gained in each stage can be applied as soon as possible to the next phase.

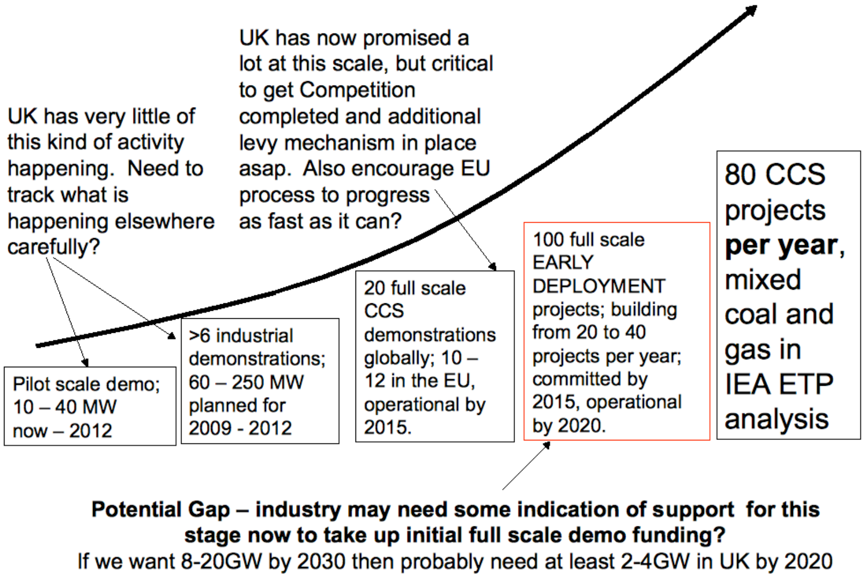


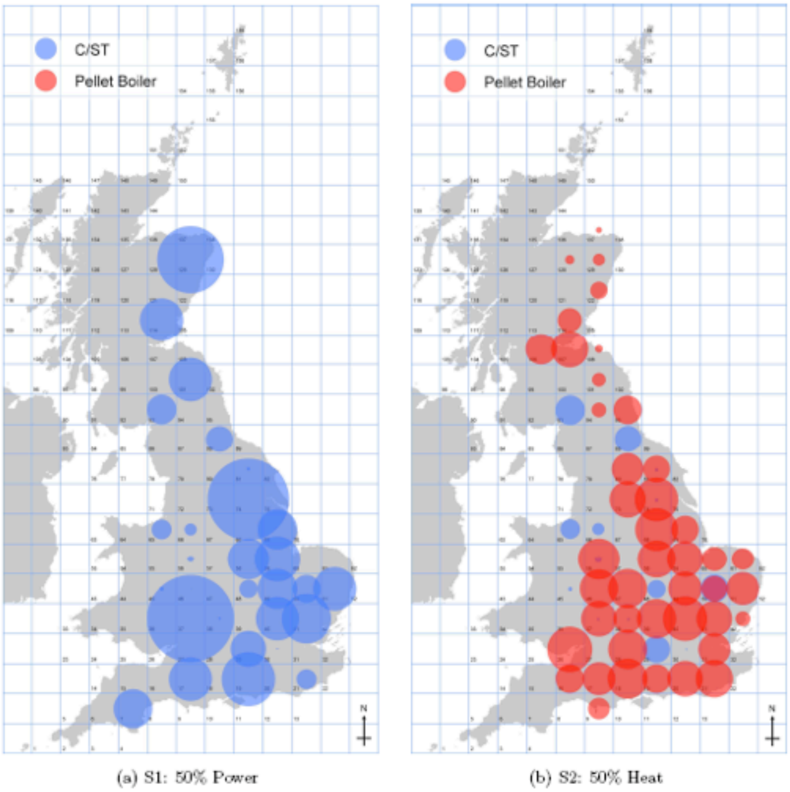
Figure 1: Scaling-up of CCS capacity needed to commercialise the technology by 2020. Credit: Paul Fennell/Jon Gibbins/Hannah Chalmers, Imperial College; after a slide by Dr Mike Farley, BCURA Coal Science Lecture, 2008.

Returning to the whole-systems paradigm, storage of carbon emissions from power generation could also be integrated with other industries. Current manufacturing processes for cement and steel involve a large and unavoidable emission of CO_2; co-location of these industries with CCS-fitted power generation would allow concurrent abatement of emissions from these sources with no further investment in technology.

Biomass

For fossil fuel-based heating and power systems, location, time and scale generally have little importance. For renewables including biomass and biofuels, however, these become key considerations. In terms of location, Figure 2(a) shows the potential for UK use of biomass for electricity (note that different geographical constraints apply to biofuel for heating, which is considered below). Studies show that 17-20 percent of power (electricity) could be produced from this source with no practical food impact. Although the study considered power demand, the advantage of lignocellulosic biomass is that it is not predicated on a particular conversion pathway and could also be used for heat and/or liquid fuels. Again, a whole-systems approach is needed to determine which crop should be grown where; the plant should be matched to the land and available technology, set alongside supply chain considerations. The optimal choice in one location may not be optimal for another.

The current generation of starch and sugar based biofuels plants can be seen as a transition technology; they are likely to be superseded by lignocellulosic biofuel plants (currently in demonstration mode) which should have the best energy/emissions balance, and 80 percent of the plant mass can be used. Over time, breeding could further improve yields and efficiency of the process. Large scale cultivation of plants for energy could even have positive impacts



(a) S1: 50% Power (b) S2: 50% Heat

Figure 2: UK potential by location for use of biomass to provide (a) power and (b) heating using pellet boilers. Credit: Nilay Shah, Imperial College.

on biodiversity. Next generation biofuel plants could be widespread by 2020 at demonstration scale and rapid developments are likely in the period from 2020-2050. The challenges of upscaling include a balance between the time constraints of growth for cultivars and growth for energy.

Nuclear

The two main technologies currently in use for electricity generation by nuclear power plants are AGR (Advanced Gas-cooled Reactor) and PWR (Pressurised Water Reactor). Of the UK's current stock of nuclear generation capacity, all except one (Sizewell B) are AGR. In the context of this report, a key difference between these technologies is that AGR plants cannot load-follow (vary output on short timescales to meet fluctuations in demand) whereas PWR plants are able to load-follow to a limited extent, because the coolant (water) is also the neutron moderator.

Any new nuclear reactors installed in the UK are likely to be PWR plants, with which it would therefore be possible to provide more than just a constant baseload supply. However, the timescale of variation could not be reduced below 1-2 hours, a limit unlikely to improve without development of fundamentally new technology. Thus, appropriate use of the variable capacity could be to provide a slowly-changing daily "baseload" capacity responding to highly-predictable daily and seasonal fluctuations in demand. This generation capacity would not be able to respond to steep (morning and evening) or short-term (eg, half-time at football matches) changes in demand but would nevertheless significantly reduce the amount of fully-flexible generation capacity needed to meet a varying demand profile.

The technological and economic implications of such a regime are not clear. Load-following certainly has an effect on the fuel lifetime and therefore on both efficiency and cost of the reactor, but little open research exists to quantify this loss. In France, where load-following has been necessary due to the high proportion of demand met by nuclear power, this sort of data may be available but is not publicly released. Fuel performance remains a topic of ongoing research and contributing factors, including load variation, are not well understood.

A further issue is the availability of uranium. There is much difference of opinion on this subject, similar to the Peak Oil debate. Sufficient quantities are certainly available for the UK to meet capacity with PWR for many years; however, if China/India/etc all decide to pursue nuclear power with similar technologies then supplies may well become constrained. In this case, alternative fuel cycles (eg use of thorium) and technology such as breeder reactors are available and could become economically optimal; however, it is not possible to upgrade conventional reactors to the breeder type.

In the medium term, greater technological flexibility by modular construction of reactors allows partial upgrade and easier maintenance of reactors if parts begin to degrade or new technology becomes available.

We do not here address the sensitive issues of nuclear waste and storage.

Microgeneration

Certain microgeneration technologies have become mature and offer a cost-effective means for reducing demand on centralised power sources. The technology for microgeneration is becoming increasingly cost-effective and can contribute significantly to the CO_2 emission targets; with the potential to achieve a 30MtCO_2 reduction by 2030 in the UK. Many of the technologies under consideration are not commonly employed in the UK, especially ground source heat-pumps and solar energy collectors.

In 2008, 5.5GWe of photovoltaic panels were installed globally. Germany represents one of the largest markets and a sustained feed-in-tariff has enabled 2 percent of electrical capacity in Bavaria to be met by photovoltaics. The cost of photovoltaics is decreasing and will soon reach residential grid parity in certain countries; in the UK it will require government support until about 2020. It represents a technology option for large-scale deployment post-2020, that complements wind power in terms of its seasonal availability in the UK.

Summary

To meet demand in 2050 as well as stringent emissions reduction targets, the range of options is likely to include some or all of:

- Electricity demand reduction - a key “no-regret measure”.
- Intelligent grid management. The predict-and-provide paradigm could be replaced by a system directed more towards control of demand than supply, collecting and acting on information about loads. Development of a “Smart Grid” could be the easiest “no-regret” option in electricity supply.
- Greater renewable generation, including wind and biomass.

- Nuclear taking on a larger proportion of the baseload generation.
- Coal or co-fired biomass with carbon capture and storage (CCS) taking on the role of flexible backup for intermittent renewables.
- Demand management. The exact role played will depend on the generation mix; in a future dominated by nuclear and CCS, we would expect demand side management to smooth out daily and seasonal peaks and troughs, while in a future dominated by wind generation and other intermittent renewables, to follow renewable generation availability.
- Increased storage capacity. Pumped storage hydroelectric is a current technology; future developments could include distributed storage in electric vehicle batteries and as heat in buildings. Distributed storage represents a key opportunity for integration of demand side and could also contribute to resilience of the network. Large-scale centralised electricity storage is inefficient with current technology and even more expensive than maintaining the same flexibility through redundancy (it is better to have plants with low load factors available to use when required).

Heat

Solar hot water

Use of solar energy for heat is a mature technology which is already cost-effective in the UK; however, installation rates for evacuated glass tube collectors in this country are low. Typical households in the south of England could expect to fulfil most of their hot water needs between March and October with a solar hot water system on the roof (decreasing as you go north). Energy from other sources would be required to top this up either when solar influx is low or when demand is high. The potential to integrate solar heating and cooling into larger buildings and industrial systems remains untapped in the UK.

Biofuels

Figure 2(b) shows the potential geographical distribution of biofuel production for heat in the UK. Development of biofuel production for heat is interdependent on the choices made for provision of electricity and transport fuels, and as such the timescales are very difficult to predict. There are also a very large number of possible sources, pathways, and end products which can be put to different uses. This flexibility of production means that the most efficient use of bioenergy crops is processing in modular biorefineries which can take various inputs and alter production on short timescales to produce different outputs. This allows production of the most useful end products at any given time; however, bottlenecks to development of these systems include a lack of sufficient microorganisms and inadequate pre-treatment methods. With a favourable environment, 2nd generation biofuel plants could be widespread by 2020, but at demonstration scale. In the period from 2020 to 2050, we would expect rapid developments although technologies remain uncertain and the great unknown is algal biofuel production.

On the policy side, whole chain certification will be critical, as will “normative” approaches to indirect land use change. Liquid sources of C and H are likely to be useful under almost all energy scenarios for materials and chemicals as well as for power and transport.

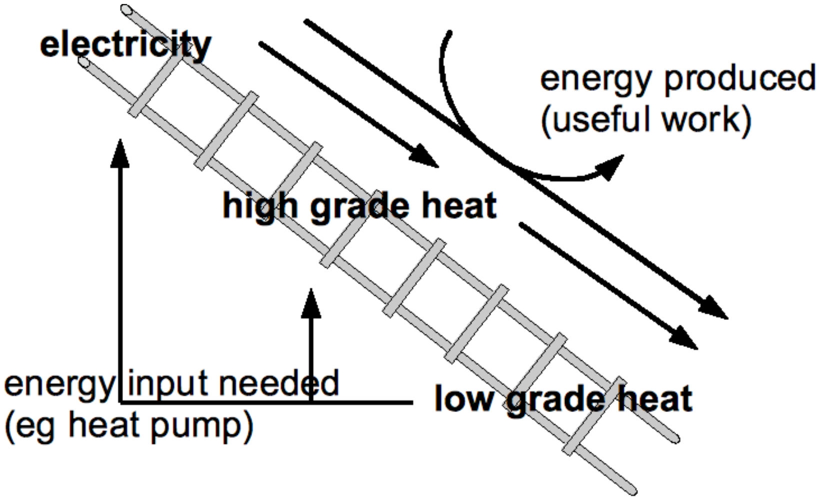


Figure 3: Conversion of electricity into heat, and higher grade heat into lower grades, can produce useful work at each step of degradation. In order to produce higher grade heat or electricity from low grade heat, however, energy input is needed.

System considerations

Space and water heating is a sector in which an intelligent, whole-system approach could lead to considerable energy savings. We are used to a system in which air and water are provided at some ambient or supplied level, heated to the desired level and discarded back to the ambient after use. This is inefficient. Thermodynamically, any difference in temperature between two objects or areas can be used to produce energy, and in order to create a difference in temperature, we must use energy. A more efficient heating paradigm would involve differentiation between quality or grade of available heat, as shown in Figure 3.

Heat can be used at all steps on the “ladder”, starting at the top, if the output from each process is captured and used again. For example, waste heat in kitchen sink- or bath-water could be re-used for low-grade space heating. Many industrial processes produce a great deal of heat which requires cooling systems to remove it. The energy in this waste heat could also be re-used for low grade space heating or other purposes.

Intelligent hierarchical design of heating systems could therefore eliminate the need for use of other energy for low-grade heating, in conjunction with insulation measures to reduce wastage, thermostats to prevent overheating, and heat pumps. Heat pumps are a very efficient way to use electricity to deliver heat for low-grade uses. Alternatively, there is combined heat and power (CHP), where we raise the condensation temperature of a power generator to give useful heat, although with reduced electricity generation, again using up electricity to deliver low-grade heat. Formally, the two approaches are equivalent and it is easy to find examples where the solution has mixed CHP and electric heat pumps; the latter upgrading the heat from the former. This is another case where future technology application is more flexible than at first sight, even if heat pumps at low density and CHP at high density are natural outcomes for a low-carbon electric economy.

In terms of meeting emissions targets for 2050, then, it is the design of buildings and their space/water heating systems which will contribute the most to reduction of demand for energy, with or without reduction in demand for the service. Integration of systems can make intelligent use of all grades of heat both within buildings and, in areas of higher population density, within districts. Insulation and installation of thermostats represent the first “no-regret” measures to be taken, after which installation of locally-appropriate choices of heating systems can begin. Architectural practice should include both good initial design and lifetime monitoring of efficiency standards to check that systems are working as intended and identify any problematic areas.

Transport

Personal light vehicles

Internal combustion engine technology that uses any sort of hydrocarbon fuel will not be able to meet the requirement of 20-30g/km of CO_2 at point of use to achieve 80 percent cuts by 2050. The clear solution for personal transport in light vehicles over short distances is the electric battery. With current technology, however, the range of these vehicles is limited and unless significant developments in battery technology are made, the route to achieving the 2050 targets for light vehicles would be progressive electrification of the vehicle platform. From the micro (approximately 5 percent CO_2 reduction) and mild (20-30 percent) hybrids available currently, through strong hybrids under development and available in 5-10 years to full electric vehicles, possibly with a small on-board range-extender generator based on a highly efficient internal combustion engine or fuel cell. The latter could use a range of fuels including bio-fuel or hydrogen. Full electric vehicles with large traction batteries still require significant developments in battery technology to bring cost and weight down

The price of electric vehicles remains the main barrier to take-up; at present a battery for a 40-mile range costs approximately £10,000 and for 300 miles £25,000+. The Toyota Prius hybrid car markets at £22,000. Lower carbon vehicles cost more money to make than they deliver savings in fuel bills today. For these vehicles to become a competitive consumer option relative to internal combustion engined vehicles will require either considerable reduction of the battery cost, increase in the oil price, or appropriate government incentives. It is not clear how long technological development alone would take to achieve this.

The environmental winner over very short distances is of course the bicycle. In many cities, for example London, cycling is strongly encouraged by local government but facilities such as bike lanes are provided only in some areas because roads are too narrow to incorporate them.

Heavy-duty transport

Battery technology will always be constrained by the fact that they are both an energy conversion and an energy storage device. When large amounts of energy are needed on board (for long-range or for heavy vehicles) there is no question that ICEs, fuel cells and hybrid systems have a clear advantage over batteries alone. In the near future it is likely that the only option for these vehicles is an internal combustion engine. Technical improvements to the ICE have resulted in a 1.6 percent per year gain in thermal conversion efficiency, but future legislation now requires that this pace of change must be substantially increased. Step changes in automotive technology typically take 10 years for a net return (and around £1bn), meaning that 2020 targets may already be difficult to reach. However, large improvements in the ICE both for heavy-duty transport and as range extenders for lighter vehicles are certainly within reach by 2050.

The distinction between long-haul trucks and urban delivery fleets is important. The former are characterised by extremely long range and diesel engines used mostly at constant regime

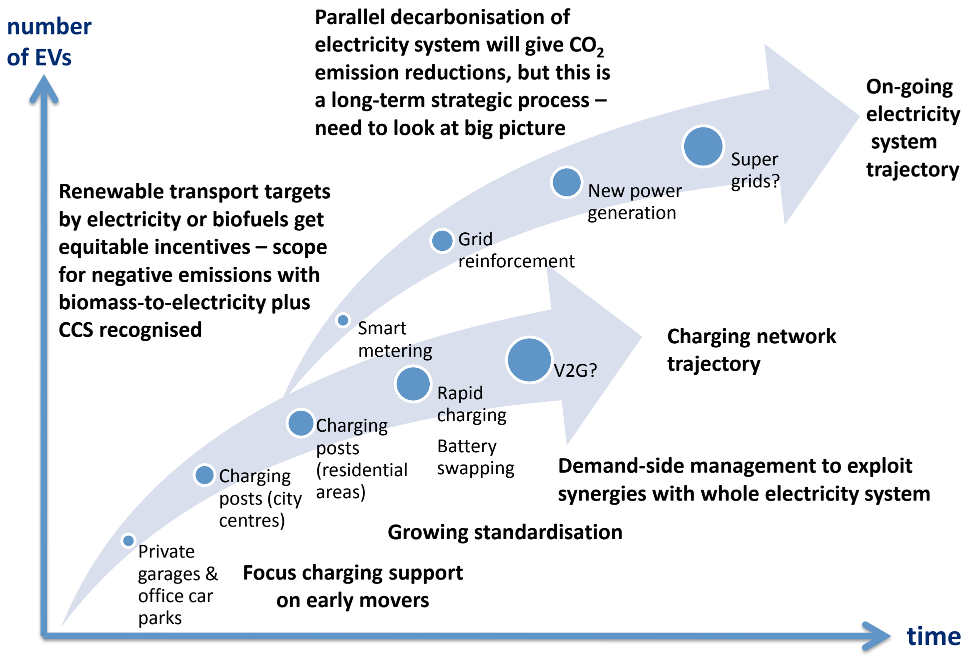


Figure 4: Staged rollout of electric vehicles (EVs) and decarbonisation of electricity generation. Credit: Alexandre Beaudet/Ricardo Martinez-Botas, Imperial College.

(and therefore with high efficiency). Substituting ICEs on these vehicles with either batteries or fuel cells may not make a lot of sense; instead, biofuels could be used in the medium to long term to fuel long-haul trucks. The case of urban delivery fleets is rather different: due to the typical driving cycle a hybrid powertrain architecture could be appropriate and range would be less of an issue. However, pure battery vehicles may still not be the best option from the point of view of cost and range, and either ICE or fuel cells could be used as a main motive power source or as range extenders.

Hydrogen

There are clear constraints on the choices at each end of the spectrum: battery power is optimal for small vehicles over short distances and the ICE remains the only technologically feasible option for heavy-duty transport over large distances. However, in between these extremes lie a wide variety of mobility options including most public transport systems and medium-duty vehicle fleets. For these modes of transport there are a lot of options: hydrogen could represent a viable option for fleets of vehicles with one operator even if it is not used for private vehicles; electric trains and trams could take passengers away from the car for both long and shorter journeys as at present; and hybrid vehicles for lighter longer-distance journeys or heavier short-distance journeys (vans) are possible. Hydrogen fuel cell urban buses have been successfully demonstrated for several years in many cities worldwide (including London) and are now entering a pre-commercial phase with joint procurement of larger numbers of buses being negotiated at the moment by the “hydrogen bus alliance” (of which again London is part). Moreover, their use in other fleets is being considered; for example Royal Mail are currently looking to introduce hydrogen (both ICE and FC) vehicles in their fleet. Hydrogen fuel cell (hybrid) powertrains are an interesting technology for both light goods and heavier passenger transport vehicles, with potential for significant penetration of these fleets before 2050.

For lighter vehicles, the issue of hydrogen transport and storage remains one of the biggest barriers to widespread fuel cell use. A very plausible use of fuel cells is as on-board range-extender generators, this substantially reduces the volume of hydrogen fuel required and could possibly allow for home generation from photovoltaics.

System considerations

A high take-up of electric vehicles might result in something like 20 percent increased load on the National Grid network for charging, probably concentrated overnight when vehicles are not in use. A "Smart Grid" system could be used to distribute this load over the full course of the night hours, currently a trough of electricity demand. As touched on above, there are options here for deep integration of the transport system with the electricity supply, for example by using car batteries as a distributed storage system for the network.

Shifts in service and ownership concepts could contribute further to a more integrated and more efficient use of vehicles, with car pools, fractional ownership and battery swapping representing possible new business models for personal transport provision.

Redesign of the road transport system to improve the flow of traffic and reduce stopping and starting presents an opportunity for some improvements in efficiency by preserving momentum. The gain is less for electric vehicles than for those using ICEs because of the opportunity with the latter for some degree of regenerative braking (about 30 percent).

The range of options represents a challenge for Government in regulating to stimulate new technology while avoiding "picking winners", but should be considered a help rather than a hindrance in meeting targets. There is clear need for a coherent and consistent strategy of long-term fiscal/policy support.

A little discussed point is that the envisaged electrification of the vehicle implies progressive electrification of the vehicle ancillary systems such as heating, ventilation and air-conditioning (HVAC), coolant pumps, power steering pumps, etc. At present many of these ancillaries are mechanically driven from the crankshaft and the supply chain for electric versions is not in place. Once electrical ancillaries are common it makes sense to integrate photovoltaic cells onto the vehicle to power these, particularly the air conditioning, which is more often required when the sun shines. The UK has a strong market presence in the design and manufacture of vehicle ancillary systems and should be encouraged to invest in research and development of high efficiency, electrical ancillaries.

Shipping and aviation, not considered above, must be a key part of long-term strategy.

4 Demand

Demand projections

Projections of demand for energy are uncertain due to the high degree of uncertainty in various contributing factors:

- the UK's population growth to 2050 is very uncertain (see, for example, ONS predictions)

- the demand for services/appliances is hard to predict and generally increases rapidly into new areas (cf the internet, the mobile phone, plasma TV screens...)
- the demand for energy will depend on the efficiency of all energy-consuming devices as well as on their total volume and usage.

Given these uncertainties, it seems unwise to try to predict what energy demand will be in 2020, let alone in 2050. However, we can say that service demand is almost certain to increase, and it is therefore likely that under a “business-as-usual”-type scenario UK energy demand would continue to increase to 2020 and probably further increase by 2050.

Is demand reduction needed?

If electricity can be decarbonised completely, there is no mitigation need for demand to be reduced. And, if affordability and security of supply were no object, it would technologically be possible to meet almost any feasible increase in demand for low-carbon electricity. So in this context electricity demand reduction is necessary only to the degree that mitigation policy impacts on affordability and security.

Reducing demand

There are two main ways to reduce non-transport demand for electricity and heat:

- Technological improvement, either by simple energy efficiency or by clever engineering and control systems. For example, fridges do not need to refrigerate constantly as they are well-insulated, and could be programmed to switch off for brief periods during peak times. In public buildings, automatic lighting and other measures can save energy when not in use.
- Behavioural changes of end consumers (switching lights off, choosing energy-efficient products, deciding to take public transport, choosing to install a new home heating system, etc). To some extent these can be “nudged” in the right direction by financial and other incentives but solid empirical evidence on the effects of such measures is very difficult to come by, in part because the effects are often very small and hence difficult to measure. Behavioural change takes time (eg seat belts, smoking), and there can also be social or transactional barriers even when the decision is otherwise economically sound (inertia, lack of information, peer pressure, “fear of builders”). “Smart meters” allowing inhabitants to see how much energy their home is consuming have shown a good behavioural response. However, behavioural change in the transport sector (see below) presents a greater challenge.

All of these non-transport measures are “no-regret” or “win-win”. Reduction in demand for energy will in all instances make it easier to meet government targets of mitigation, affordability and security. There are no contexts in which non-transport energy demand reduction is undesirable if the underlying service level and cost remains at least the same (and in many cases it could improve this as well).

We need to again distinguish between the demand for the transport service and the demand for the energy required to deliver that service. Given current technological and other constraints, transport service demand reduction in the near term predominantly means changing people’s behaviour so that they use their cars less. Reducing car use can bring a range of non-carbon social benefits including reduced congestion, fewer accidents, improved air quality. However, whilst alternative modes can be competive with the car in urban areas and certain inter-urban corridors, for the overwhelming majority of trips in the UK, car is the preferred mode, hence if people are prevented from using their cars by pricing, regulation or other means, then there is a loss of individual welfare and choice, which would manifest through reduced opportunities for engagement in economic, social and recreational activities.

Demand reduction in transport is therefore more difficult than in electricity and heat. It is *not* a “no-regrets” option. Moreover, policy measures seeking to limit car use can be unpopular and politically difficult , as illustrated for example by the 10 Downing Street petition on national road user charging and the recent referendum on road user charging in Manchester.

This suggests that efforts in the transport sector should focus on improving the energy efficiency with which transport services are delivered, both through improved vehicle and powertrain technologies such as low-carbon vehicle technologies and highly efficient ICEs as range extenders and more efficient strategies for the management and control of transport network operations. On the demand side, both short term measures such as pricing and regulation and longer term adaptations to infrastructure and urban form are also important but there are very considerable challenges involved in devising measures that are able to achieve significant reductions in CO_2, preserve individual welfare and attract public support.

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