The Royal Academy of Engineering

Generating the Future:
UK energy systems fit for 2050

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Executive summary

The Climate Change Act, that became law on 26 November 2008, has committed the UK to at least 80% reductions of greenhouse gas emissions by 2050. While there is a wealth of reports and studies on future energy systems and technologies, there is no clear and realistic overall picture of how these targets might be achieved and what such an energy system might look like.

This report, produced by a working group of Fellows of The Royal Academy of Engineering, considers possible energy scenarios that could meet the 2050 emissions reduction target. Four scenarios are explored. They describe the whole energy system in broad brush strokes and are illustrative rather than prescriptive, identifying the principal components of the system and contributing towards a better systems level understanding of the most salient issues.

Scenarios never predict the future; they only show a range of possible futures. However, some fundamental characteristics of all the possible energy futures for the UK can be deduced and these are described below.

The study shows that:

- There is no single 'silver bullet' that will achieve the required 80% cuts in greenhouse gas emissions. Fundamental restructuring of the whole of the UK's energy system will be unavoidable.
- Demand reductions across all sectors of the economy will be essential through a combination of increased efficiencies and behavioural change.
- The full suite of low-carbon energy supply technologies already available (or identified as credible) will be needed, including nuclear, renewables and carbon capture and storage brought together in a balanced way.
- The scale of the engineering challenge is massive.

No silver bullets

All the scenarios that we examined require action on both the supply and demand sides of the energy equation. They also require the UK to exploit its renewable energy resources to the fullest possible extent and supplement this with other forms of low-carbon energy such as nuclear or coal or gas stations fitted with carbon capture and storage.

All the scenarios show a requirement for significant change in power flows in the UK system, indicating that significant investment in new energy infrastructure will inevitably be required. The main shift in the scenarios is that much more of energy demand will be met through the electricity system and generation will be added both centrally and throughout the distribution system. The last major investment in the UK's electricity infrastructure was in the 1970s and much of the equipment installed then is reaching the end of its service life, so we expect to see the need for renewal coinciding with the need for major enhancement, offering a unique opportunity to develop state-of-the-art infrastructure.

Demand reduction

All the scenarios require varied and significant reductions in demand which can only be achieved with a combination of technical efficiency measures and behavioural change. Even scenario 1, which is nominally level demand, represents a reduction in demand compared to current predictions of UK energy demand.

We can expect energy using processes to become more efficient over the coming decades, driven by the need to reduce costs. Energy efficiency of processes, machines and appliances can be driven through regulation as well, as has been the case with condensing boilers and is currently the case with cars, but the behavioural changes required among the general population require more and better public engagement, and, inevitably, pricing messages. It was beyond the scope of this report, but it is easy to see that this will bring climate change policies into conflict with efforts to protect those classed as being in fuel poverty.

The full suite of low-carbon technologies

The timescales involved in re-engineering the UK's energy systems to respond to the need to reduce greenhouse gas emissions can be measured in decades and some of the assets put in place to do this will have economic lifetimes of over 50 years. There is no more time left for further consultations or detailed optimisation. Equally, there is no time left to wait for new technical developments or innovation. We have to commit to new plant and supporting infrastructure now.

Because the timescale for the proving and large-scale roll-out of major infrastructure is measured in decades, only the low-carbon technologies that are already known can make a significant contribution to meeting the 2050 targets. They are already in the marketplace, close to it or close to being demonstrated at scale. Untried developments, such as nuclear fusion, may contribute to the energy mix beyond 2050 but to meet the 80% target we have to use what we already understand.

The scale of the challenge

Although the scale of the challenge has often been acknowledged, very few have sought to try to put numbers to it. We do so in Appendix 1 and come up with numbers which are currently beyond the capacity of the energy industry to deliver.

In order to achieve the scale of change needed, industry will require strong direction from government. Current market forces and fiscal incentives will not be adequate to deliver the required shareholder value in the short-term or to guarantee the scale of investment necessary in this timescale.

Conclusions

The experience of engineers shows that implementing fundamental changes to a system as large and complex as the UK's energy system to meet the 2050 greenhouse gas emissions targets will bring with it many challenges for government, business and industry, engineering and the public alike. Turning the theoretical emissions reduction targets into reality will require more than political will: it will require nothing short of the biggest peacetime programme of change ever seen in the UK.

While the market will be the vehicle for technological and business solutions, the combined challenges of climate change, security of supply and affordability call for a more directed approach from government. This transcends political ideology: only government can facilitate and ensure delivery of the necessary infrastructure, some of which, being natural monopolies, do not respond classically to market forces. The market will not respond unless there is an appropriate long-term national plan and a framework set out by government to ensure the delivery of the necessary infrastructure in the wider context of Europe.

Implementing such fundamental and widespread changes across the planning, industrial, technological, economic, business and customer dimensions of the UK's energy system will only be achievable in the context of a national strategy to coordinate and drive the process. Such a strategy needs to be informed by a high degree of whole-systems thinking and be underpinned, from the outset, by critical evaluation of the economic, engineering and business realties of delivery across a system.

Despite positive steps, such as the creation of the Department of Energy and Climate Change, current government structures, including market regulation, are, as yet, simply not adequate for the task. This issue must also be addressed as a priority by means of a reorganisation of government departments to coordinate and drive action as well as to provide the clear and stable long-term framework for business and the public that is not currently in evidence.

It also needs to be recognised that the significant changes required to the UK energy system to meet the emissions reduction targets will inevitably, involve significant rises in energy costs to end users.

1 Methodology

1.1 Background

The Climate Change Act, which became law on 26 November 2008, has committed the UK to at least 80% reductions of greenhouse gases by 2050. While there is a wealth of reports on future energy systems and technologies, there is no clear and realistic overall picture of how these targets might be achieved and what such an energy system might look like.

In June 2000, the Royal Commission on Environmental Pollution (RCEP) was the first organisation to call for sweeping cuts in carbon emissions– 60% reductions of CO_2 by 2050 (see Box 1). The RCEP's report[1] described four scenarios that illustrated what such a future energy system might be like. This report adopts the same basic approach but updates the scenarios to the new target of 80% reductions in emissions.

The resultant scenarios describe the whole energy system in very broad terms. They identify the principal components of the system and focus on the most salient issues to illustrate the overall challenge rather than presenting prescriptions. The scenarios provide examples of possible systems, highlight the choices available and point to the engineering challenges ahead. Implicit are the underlying threats to security of energy supply and affordability.

Like the RCEP, while recognising that the whole basket of greenhouse gasses have an impact on climate change, we have only addressed reductions in CO_2 as these account for the vast majority of emissions from the energy sector and are the most amenable to large scale reduction.

Box 1: Why 2050?

In 2000, the RCEP was the first body to call for sweeping cuts in carbon dioxide emissions: 60% by 2050. The figure of 60% followed from the limit of 550 parts per million (ppm) of CO_2 equivalent in the atmosphere as an estimate for the tipping point beyond which the likelihood of catastrophic climate events becomes intolerable.

The change of target from 60% to 80%, as adopted in the UK's Climate Change Act, followed from stronger scientific evidence which lowered the limit from 550 to 450 ppm. However, the planning horizon of 2050 was not merely an arbitrary mid-century date, even though the date has been accepted without comment or review in most of the discussions around climate change and energy policy. The RECP adopted the date of 2050 because realistic advocates of hydrogen fusion then estimated that fusion power (which remains speculative) would be commercially available by that time. Therefore 2050 was the most remote date by which mitigation had to be achieved using only known technologies; more recent prognoses push this date to 2060 but we have not extended the time horizon in these scenarios.

Furthermore, even if the mitigation target for 2050 is met, that does not mean the problem is solved. The RCEP analysis shows that, for both the 550 ppm/60% and the 450 ppm/80% cases, a further halving in greenhouse gas emissions by 2100 will be needed to avoid serious climatic risk. Therefore, it must be remembered that 2050 is only one stage along a path that will subsequently need further, even more demanding measures.

1 www.rcep.org.uk/reports/22-energy/22-energyreport.pdf

1.2 The basic procedure

The introduction of emissions reduction targets for 2050 have led a number or organisations to investigate what this will mean for the UK energy system. Methods of approaching this question fall into two main categories: *forecasting* – assessing what effect policies currently in place will have going forward and whether they will achieve the desired outcome; and *foresighting* – constructing possible systems to meet the targets. Foresighting may be followed by backcasting: considering what changes are needed over time to move to these possible future systems.

This report uses the foresighting approach with a basic constraint of reducing carbon emissions by 80% from 1990 levels – as demanded by the Climate Change Act. Scenarios are then constructed to match an assumed level of energy demand with various energy sources with the aim of balancing supply and demand. Additional conditions are also imposed to define each of the scenarios.

The procedure for generating each of the scenarios follows five basic steps:

1. Set the demand level of each category of energy demand relative to the current level
2. Choose the primary sources of energy supply
3. Balance supply and demand by adjusting the levels of supply
4. Calculate the carbon emissions
5. Repeat steps 2 and 3 until carbon emissions have reduced by 80%

1.3 Description of the four scenarios

As in the original RCEP report, we restrict ourselves to four scenarios, chosen to highlight some of the most important aspects of the future energy system. In general terms, the scenarios are:

Scenario 1	Level demand Fossil fuel prioritised for transport
Scenario 2	Medium demand reduction Fossil fuel prioritised for low grade heat
Scenario 3	Medium demand reduction Fossil fuel prioritised for transport
Scenario 4	High demand reduction Fossil fuel prioritised for transport

1.4 The demand side

Four categories of energy end use are examined – see section 1.4.1 for a description of these categories. Different energy sources might be used to supply the demand for each of these categories of use and these are calculated in steps 2 and 3.

Each scenario assumes a certain level of energy demand – as shown above in section 1.3. The precise scale of reductions in each of the categories of energy end use is given in Table 1 and the actual amount of demand that this represents is given in Table 2.

The entries in Table 2 represent the level of energy demanded to provide the customer with the level of utility they expect. For example, in the case of low grade heat (LGH) in a domestic setting, a customer wants a warm home but does not necessarily care whether this heat is provided by a condensing boiler, a heat pump or any other means. Each of these methods will create different operational characteristics, efficiencies and carbon emissions. However, the concern here is for the total average demand in each of the four end use

categories; significant differences between different approaches to delivery will be dealt with when considering supply.

Although the levels of demand reduction in Table 1 are to an extent arbitrary, chosen to represent a range of possible scenarios, they are guided by judgements similar to those in the original RCEP scenarios – see section 1.4.1. They include technical changes to improve the efficiency of energy use and behavioural changes in the ways consumers use energy. For example, the benefits of improving building insulation (see below), can be reduced or lost if people react by expecting higher indoor temperatures or spend the money saved on foreign travel. Thus, in addition to developing improved technologies, public information and education programmes will be needed to prevent this kind of 'rebound' effect.

Section 1.4.1 Categories of energy end use

Low grade heat (LGH) is mainly used for space and water heating. The majority of LGH demand is in the domestic sector (60%) with the remainder split equally between the service and manufacturing sectors[2].

This category of end use presents greater potential for demand reduction than any other. This is because of the poor thermal efficiency of most existing buildings in the UK. Better insulation is the key to reducing this demand and, given that 90% of the buildings we will inhabit in 2050 have already been built, retrofitting will be essential.

The levels of demand reduction in this category have therefore been chosen to be 40% and 67% below current levels for the medium and high demand reduction scenarios respectively. The higher of these figures was deliberately chosen to be particularly challenging and represents the highest level of demand reduction that could reasonably be expected if all possible measures were implemented in the majority of UK buildings. However, a recent report from the Committee on Climate Change[3] indicates that progress towards such reductions in demand is already falling behind what is required.

High grade heat (HGH) demand arises predominantly from high temperature industrial processes in such settings as oil refineries and chemical plants. Economic pressures on commercial operations have already led to improvements in energy efficiency. The assumptions summarised in Table 1 therefore incorporate half the reduction in demand assumed for low grade heat.

Electricity for appliances, machines and lighting (appliances) is taken to be the demand for all types of electrical devices excluding LGH and transport. Currently roughly a third of electricity demand is from industry, a third domestic and a third from the public and commercial sector[4].

Demand reduction for this category is hard to predict. Reductions are possible from more efficient appliances and a greater awareness of wasting electricity but these may be offset by a growing demand for more appliances. The Government's Carbon Reduction Commitment (CRC)[5] should help in the commercial and industrial sectors and smart meters should make an impact in the in the domestic sector but the expansion of such sectors as ICT will pull in the opposite direction.

Assumed levels of medium and high demand reduction have therefore been set at 20% and 33% respectively - these being indicative of what might reasonably and optimistically be expected for this category of end use.

2 www.raeng.org.uk/societygov/policy/current_issues/energy/pdf/Heat%20workshop%20-%20draft%20report.pdf
3 www.theccc.org.uk/reports/progress-reports
4 Digest of UK energy statistics (DUKES 5.2)
5 www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/crc/crc.aspx

Energy for transport includes transport of people and freight within the UK but not international movements[6]. At present, road transport accounts for over 90% of this demand with passenger cars making up almost two thirds of that demand[7]. Energy savings are assumed to be achieved from more efficient vehicles, modal shifts (eg road to rail) and behavioural changes (eg driving less or driving more efficiently).

The King Review[8] provided an indication of what could be expected and the Academy is currently undertaking a study of low-carbon personal transport that is due to be published later this year. For the purposes of this study, the same reductions have been assumed as for HGH and electrical appliances.

(percentage reduction)	Level demand	Medium demand reduction	High demand reduction
Low grade heat	0	40%	67%
Electrical appliances	0	20%	33%
High grade heat	0	20%	33%
Transport	0	20%	33%

Table 1: Relative energy demand in the four scenarios

GW(av)[9]	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Low grade heat	80.8	48.5	48.5	26.7
Electrical appliances	32.3	25.8	25.8	21.6
High grade heat	14.4	11.5	11.5	9.6
Transport	78.1	62.5	62.5	52.3
Total final average power demand	**205.6**	**148.3**	**148.3**	**110.3**
Total percentage reduction	**0**	**27.9%**	**27.9%**	**46.4%**

Table 2: Final average power demand

1.5 The supply side

Whereas changes in demand require distributed developments (such as building insulation) and major infrastructure developments (such as transport systems), developments in energy supply will require major restructuring and investment. We have not attempted to estimate likely costs, but we have included some figures to indicate the extent of the investment which will be needed.

1.5.1 Renewable energy sources

For renewable sources of energy other than biomass, the four scenarios are the same, incorporating the highest levels that could realistically be delivered by 2050. Table 3 summarises the average power supplied from each of the major sources of renewable energy, along with the corresponding installed capacity and an illustration of what assets would be required to provide that capacity and the scale of the resulting challenge. This only shows the foreground assets

6 Allowing for increase in emissions from international transport will require even more reduction in domestic emissions.
7 www.dft.gov.uk/pgr/sustainable/carbonreduction/low-carbon.pdf
8 www.hm-treasury.gov.uk/d/pbr_csr07_king840.pdf
9 Throughout the report the main units used are gigawatts of power but averaged over a year – GW(av). Thus, the Digest of UK energy statistics will list energy units like mtoe or TWh supplied over the course of a year which are then converted into an average power load. This ignores the daily variation of demand seen on the real system, particularly in terms of peak loads and intermittency – see section 2.5.

required; in addition, huge investment in background infrastructure and infrastructure for ongoing maintenance will be needed. Appendix 1 gives details of how these figures have been reached.

	Average delivered power GW(av)	Total installed capacity (GW)	Equivalent assets
Onshore wind	6.5	24	9,600 2.5 MW turbines[10]
Offshore wind	11.4	38	38 London Arrays[11]
Solar photovoltaics	7.2	72	25 million 3.2 kW solar panels
Wave	3.8	9.4	1,000 miles of Pelamis machines
Tidal stream	1.4	2.8	2,300 SeaGen turbines
Tidal barrage	2	8.5	1 Severn barrage
Hydro power	0.9	2.3	1,000 hydro schemes
Total	**33.2**	**157**	

Table 3: Renewable power supply (excluding biomass)

1.5.2 Biomass

Table 4 gives the amount of biomass supplied to each of the end use categories for each scenario. In principle, biomass can be the primary energy source for any of the different end use categories. However, uses with the least processing give the greatest net yield, ie direct use as fuel for combined heat and power (CHP) and heat-only applications. In all scenarios, the level of LGH from biomass has been set at two to three times the level of electricity from biomass, corresponding to typical performance of biomass-fired CHP plants. The total of electricity and LGH from biomass in scenarios 2 and 3 corresponds to estimates for the resource available from residues, wastes and some energy crops subject to constraints on land use (see Appendix 1).

Any higher use of biomass would depend on imports of biomass or biofuel (or of food in place of the domestic production diverted to energy crops). Co-firing of biomass in power plants can provide electricity, as is currently practised using mainly imported biomass. Biomass can also be processed into liquid biofuels for transport, but the success of current efforts to develop 'second generation' biofuels cannot yet be assessed. Given the constraints on land availability, biomass for transport has been limited to approximately 10% of demand in scenarios 2, 3 and 4 following the current European target. For scenario 1 this has been doubled in order to help meet the higher demand.

GW(av)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Biomass (electricity)	9	6	6	4
Biomass (LGH)	21	14	14	11
Biomass (transport)	15	6	6	5
Renewables (ex. biomass)	33.2	33.2	33.2	33.2
Total renewables	**78.2**	**59.2**	**59.2**	**53.2**

Table 4: Total average power supplies from renewable sources

[10] Average turbine size in the UK is currently approx 1.5MW (BWEA website)

[11] The London Array is a proposed offshore wind farm in the Thames Estuary that will consist of 341 turbines to be installed over four years (www.londonarray.com/)

1.5.3 Non renewable sources of supply

The remaining sources of supply are either from nuclear power or fossil fuels and these are divided between low-carbon sources – nuclear or fossil fuels with carbon capture and storage (CCS) - or more conventional combustion, gasification or combined cycle plants. Deployment of conventional plants will be limited, constrained by greenhouse gas emission targets.

For the purposes of our analysis, nuclear and CCS are grouped together because, although they are very different technologies, they both supply large-scale, base load, low-carbon electricity[12]. The assumption has been that the supply will be split equally between the two but with the full chain of CCS still to be proven at scale there is a risk that CCS will not be available; in this case nuclear generation would have to meet the full requirement.

Table 5 summarises the supply side of the equation, showing the contributions from all renewable sources combined, non-renewable sources, fossil fuels and the total energy supply for each scenario as well as the current levels for comparison. It also gives the total amount of electricity supplied to the transmission and distribution system which shows the increases required to meet the demand for electricity from LGH and transport.

GW(av)	Current	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total renewables	3.6	78.2	59.2	59.2	53.2
Nuclear/CCS	5.4	77	30	39	13
Fossil fuels	198.5	38	49	43	45
Total average power supply	207.5	193.2	138.2	141.2	111.2
Total electricity supply	42	127	80.1	78.1	56.1
Total CO_2 reductions		79.0%	81.3%	79.6%	81.3%

Table 5: Summary of supply[13]

1.6 Intermittency and peak demand

So far, we have only considered the averaged yearly demand. What is of equal importance is the demand profile over various time intervals – half hourly, daily and seasonally. This will be influenced by a number of factors such as better demand management via a 'smart grid', increased amounts of intermittent supply, advances in energy storage, and electrification of transport and low grade heat.

Managing the demand profile with the introduction of a 'smart grid' is a hugely complex issue in its own right that is a currently being investigated by a number of organisations. Detailed consideration is deliberately omitted from our analysis beyond the recognition that this could require further investment on a similar scale to the foreground supply requirements.

[12] It is assumed that CCS will capture 80% of carbon but will be better able than nuclear generation to follow load variations in demand. This is a low estimate and the carbon balance could even become negative if co-firing of biomass in conjunction with CCS is employed.

[13] Comparing tables 2 and 5 will show an apparent anomally where the average power supply is lower than the average power demand. This is accounted for by the significantly higher efficiencies of electric vehicles and heat pump technologies compared to their fossil fuel equivalents.

2 The scenarios

This section will describe the engineering challenges inherent in the future energy scenarios including general aspects that apply to all of the scenarios followed by a separate analysis of each of the scenarios.

2.1 New territory

Before discussing the differences between the scenarios it is worth pointing out one major similarity resulting from the decarbonisation of the energy system. This can be best illustrated by reference to the UK energy flow charts, or Sankey diagrams, produced by BERR[14] (now held by DECC) shown in figures 1 and 2. Theses figures are shown below for illustrative purposes but are repeated at a larger scale in appendix 3 to enable the details to read more easily.

The most cursory assessment of figure 1 will show that the vast majority of the UK's energy is supplied by fossil fuels – gas, coal and petroleum. This creates carbon emissions. If emissions of carbon are to drop by 80% by 2050 the left hand side of this chart will change beyond all recognition with most of the fossil fuels disappearing to be replaced by either nuclear power or renewables such as wind, solar, marine or biomass. A small proportion of fossil fuel will remain and, if CCS proves successful, this could increase to a more sizeable proportion. But whatever happens, a major change is needed.

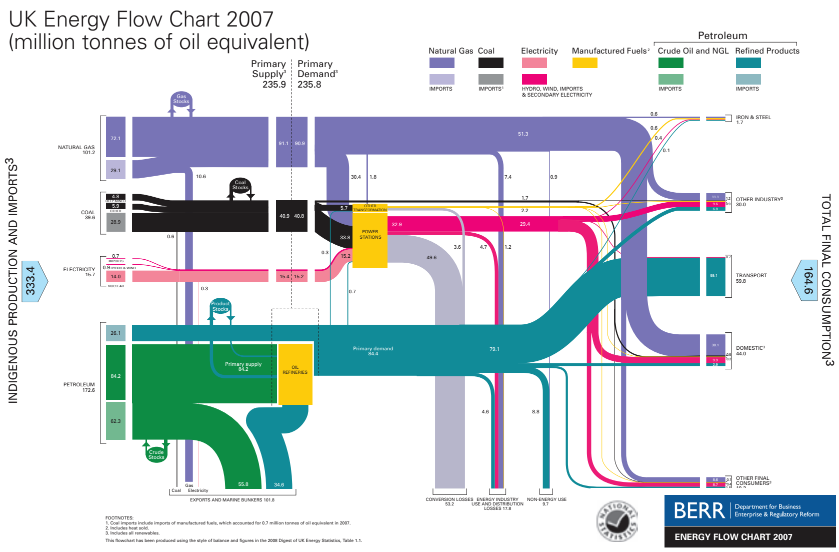

Figure 1: UK energy flow chart 2007 (repeated at a larger scale in appendix 3)

The scale of this change becomes even more apparent when one considers the energy flow chart for 1974[15] (figure 2). This is currently the earliest chart available online from DECC and shows the development of the UK energy system over the course of 33 years – only 7 years short of the period under consideration for the scenarios. A comparison of the 1974 and 2007 charts reveals that remarkably little has changed in the overall energy system. There were undoubtedly significant changes during this time, most notably the increase in natural gas from the North Sea, but the fundamental structure has remained the same.

The problem the UK faces now is to maintain economic growth while fundamentally reconfiguring an energy system that has remained relatively unchanged for more than three decades. This should be possible if barriers to

14 www.decc.gov.uk/en/content/cms/statistics/publications/flow/flow.aspx
15 *Ibid.*

change are removed and the right incentives put in place - but the scale of the challenge should not be underestimated.

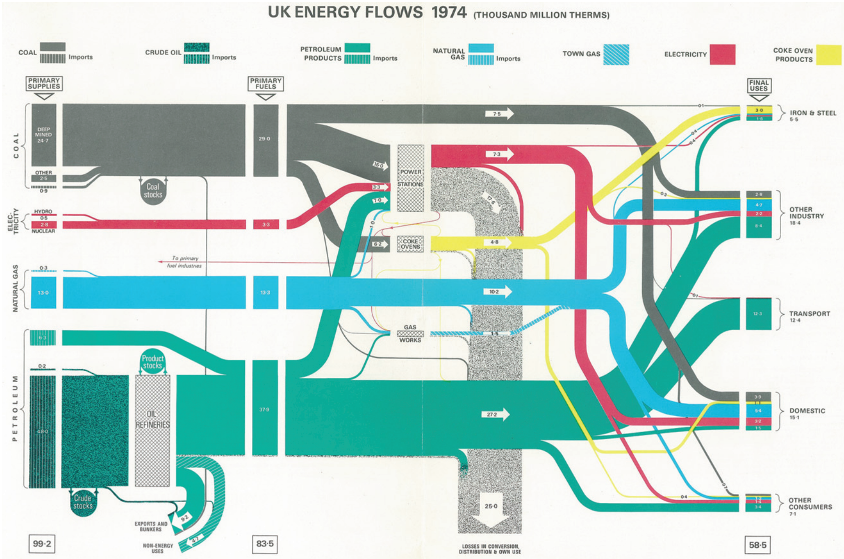

Figure 2: UK energy flow chart 1974 (repeated at a larger scale in appendix 3)

Most of the technologies required are already available. However, the length of time required to move from an early stage of R&D to greater than 90% market penetration is normally in the order of three or four decades – as illustrated by figure 3 below. Some technologies can achieve high levels of market penetration in a shorter space of time, for example the mobile phone. But even then, with the first mobile phone appearing in 1973, it still required two decades before they became ubiquitous. In addition, the mobile phone offered new functions and services which proved highly desirable - whereas, in the case of energy, most new technologies are simply replacing technologies that already provide the services required. At present there is generally insufficient incentive to make the switch to a new low-carbon technology, particularly when such a switch would be costly and disruptive.

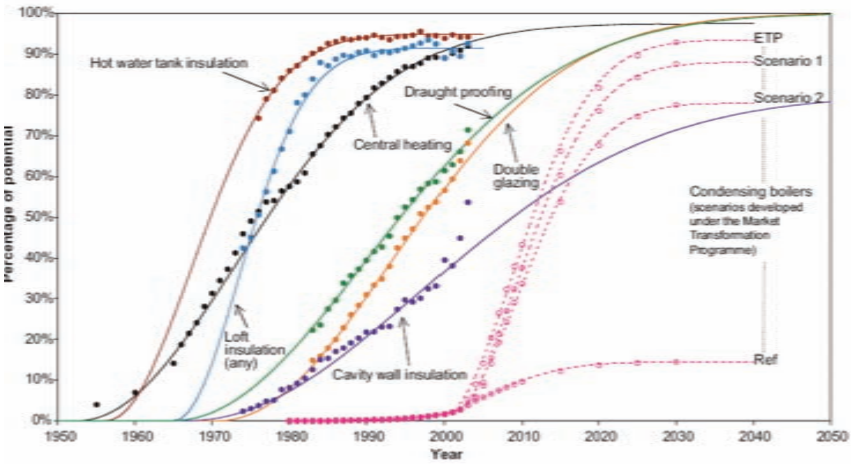

Figure 3: Market penetration of home energy efficiency measures[16]

[16] BRE: domestic energy use and carbon emissions: scenarios to 2050 (Utley and Shorrock, 2005) , adapted by Prof Loveday.

2.2 Buildability

The fundamental changes to the energy system highlighted in the previous section mean that all the scenarios face the same engineering challenge – that of constructing the new infrastructure. There is no doubt that this is a huge challenge, however, society has achieved great feats of engineering in the past, particularly when faced with significant threats to its stability. On a 'war footing' the UK has been able to shift the focus of the whole national manufacturing base in order to address a specific need and with four decades in which to effect the changes required, there is still time to act.

The major assets themselves – the power plants and renewables energy installations – will require a major construction programme. For the renewable sources of supply, table 3 gives an indication of the considerable number of assets required to provide a significant proportion of the UK's energy demand. For example, building over 1,000 miles of wave power machines equates to building almost three miles a month for the next 40 years or roughly the equivalent length of one London underground train a day – and that does not take into account the repairs and replacements that would be needed as sections age. Also, large numbers of different types of turbines would be needed for on and offshore wind, tidal stream and tidal range; all of which would need to be sourced from an increasingly competitive global market. The situation for the non-renewable sources is no less challenging.

Beyond the main assets, there is also all the related infrastructure to contend with; both to cope with the construction programme and to connect all the parts of the system. For example, installing the number of offshore wind turbines currently envisaged would require onshore port facilities at a similar scale to that required for North Sea oil and gas development at its peak. And, if CCS proves viable, it will need a network of pipes to transport the CO_2 at a scale also equivalent to the North Sea oil and gas industry.

All of the scenarios require a substantial increase in the capacity of the electricity grid. This will mean a major upgrading of the transmission and distribution systems - systems that have not seen significant investment since the 1970s. This alone represents a financial commitment of many billions of pounds.

Electrification of low grade heat and transport, along with improving the efficiency of buildings, will also require major systemic changes; and in this case the changes must be carried out on millions of individual assets.

Underlying all these engineering issues are a number of other concerns. Major training programmes would be required across all sectors and qualification levels to provide the personnel with the appropriate skills to build and maintain the new infrastructure. The bulk of this would consist of traditional engineering and technician training but, with new technologies becoming more prevalent, new disciplines will also be needed. Supply chains will come under increasing pressure as the UK competes in the global market place for low carbon technologies.

The risks posed by the potential inconsistencies between short- and long-term targets will also need to be carefully monitored. This could result in either technology 'lock-in' where technologies adopted to meet the short-term targets stifle the market for better technologies when they become available or 'stranded assets' where infrastructure becomes obsolete ahead of its planned commercial life due to market or regulatory adjustments.

In summary, the changes to the UK energy system required to meet any of the scenarios will be considerable and disruptive. Business as usual with increased investment will not be sufficient. Such disruptive changes to the UK energy systems have been implemented before, most notably in the 1970s with the introduction of natural gas. So while significant systematic changes are by no means impossible, transitions need to be carefully managed and guided.

2.3 Overview of scenario analysis

A brief description of each scenario will now be given with particular emphasis on the resilience of the system and the effect the modal shifts in technology have on the overall system.

In order to visualise the changes to the overall system a flow chart for each will be given. The aim here is to compare and contrast the most salient properties of each of the scenarios with each other and with the current system. To assist with this we have redrawn the 2007 flow chart (figure 1) using the same procedure as will be used for each of the subsequent scenarios (figure 4). What these diagrams show is the overall balance of the system, not the resilience or security of supply. Any significant interruption in the supply of energy for whatever reason would have a major effect on the ability of the system to meet the required demand.

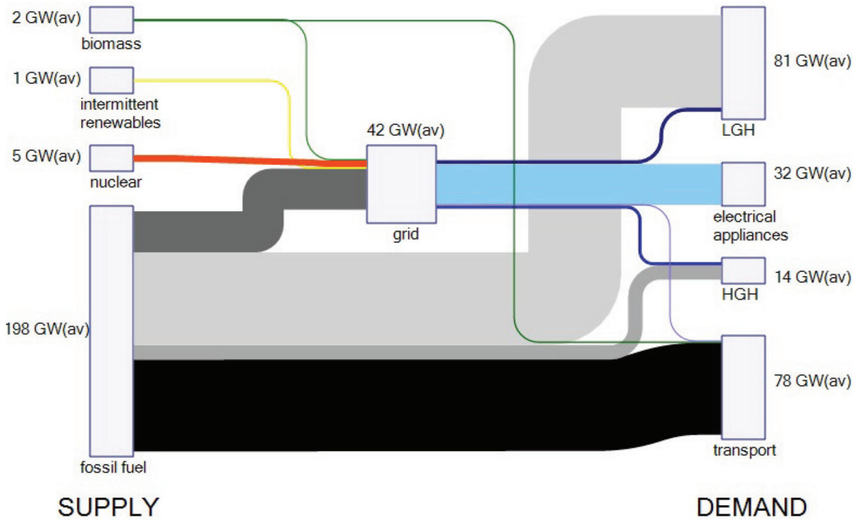

Figure 4: Simplified energy flow chart for the current energy system (2008)

Figure 4 is a much simplified version of figure 1. Most of the simplification comes from not detailing individual losses but nevertheless ensuring their effects are fully reflected in the overall figures. The emphasis is now on the supply and demand sides of the system – flowing from left to right with the size of the boxes and the thickness of the bars being representative of the scale of the relevant supply, demand or flow.

The box in the centre, marked 'grid' represents the transmission and distribution network. The various sources of electricity supply feed into the grid and are then distributed to the various categories of end use. The bars entering the left hand side of the grid are larger than those exiting the right hand side because of losses in the transmission and distribution networks; an example of where losses have been absorbed into the calculations.

Similarly the boxes on the left for each of the sources of supply represent the total average supply and do not show the conversion losses or load factors associated with each of the primary fuels or renewable technologies.

On the demand side it should be noted that demand for transport does not include the fact that the internal combustion engine is only approximately 30% efficient compared to more than 80% for electric drives. This means that, when the transport demand is partly met by electricity, it will be effectively reduced

and the flow required from the grid will not be as large due to the higher efficiency of electric motors. Similarly, electrification of low grade heat via heat pumps with a coefficient of performance of around 3 will also effectively reduce the level of demand for low grade heat. This will be represented on the charts by the flow entering the relevant LGH or transport box being smaller than the size of the demand. (This is the same issue as noted in the footnote for table 5 on page 11)

2.4 Scenario 1: level demand

The first scenario sets the demand level to be the same as current levels. It should, however, be stressed that this by no means represents business as usual. Simply keeping demand at a similar level to now will require considerable effort.

The enormous change required to move from figure 4 to figure 5 is clear to see. On the supply side the most obvious difference is the drastic reduction in fossil fuels; but that was to be expected. What is also to be expected is the increase in the electricity supply but the scale, 127 GW(av) from 42 GW(av) is huge. A sizeable proportion of this increase can be seen to come from both renewables and biomass, both of which are virtually negligible in the current system. However, even with renewables and biomass supplying as much as we believe is feasible, 77 GW(av) of nuclear or CCS power is still required to balance the system (comparing the red bars in figures 5 and 6 shows just how much of an increase this represents).

On the demand side the sectors with the biggest changes are transport and heating. The available supply of fossil fuel has been split between these two demands. However, the constraint on carbon emissions means that there are not enough fossil fuels to meet these demands and, as a result, significant amounts of electrification are still required.

In resilience terms, this scenario may not initially appear to be too challenging as only 25% of the electrical supply is intermittent – still a large proportion but not beyond the realms of acceptability according to current research. However, the increased electrical load from transport and LGH will almost certainly put an enormous peak load on the system at certain times. Thus, keeping the lights on would almost certainly require large amounts of demand management, marginal back-up generation and energy storage (pumped or chemical).

In technological terms there are no choices to be made – the demand is so large that every available technology will be needed as quickly as possible. The main problems for scenario 1 will be buildability and cost to the nation. With over 80 new nuclear or CCS power plants required – around two per year – along with vast increases in all forms of renewables, building the system would require an enormous effort, probably only achievable by monopolising most of the national wealth and resources.

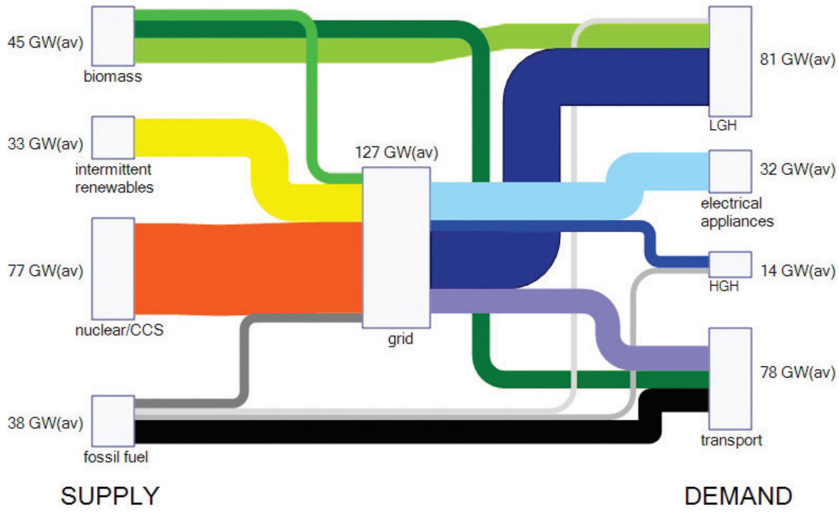

Figure 5: Scenario 1 (level demand)

2.5 Scenario 2: medium demand reduction, electrification of transport and Scenario 3: medium demand reduction, electrification of low grade heat

In scenarios 2 and 3, demand is assumed to have fallen by around 28% overall. Most of the savings are assumed to have come from low grade heat as the UK's building stock has the potential to greatly increase thermal efficiencies – see section 2.3.1. Comparing the blocks on the right hand sides of figure 5 and figures 6 and 7 shows that they have all shrunk noticeably with the LGH block reducing most in size.

This reduction in demand allows some choices to be made – most notably, where the remaining supply of fossil fuel should be employed. In scenario 2 the fossil fuel is predominantly used for low grade heat, thus requiring transport to be almost wholly electrified (approximately 80%). This level of electrification of transport may be unachievable but, as mentioned in the introduction, the scenarios are only designed to be illustrative of possible energy futures. In scenario 3 the opposite is assumed with most fossil fuel going towards transport and low grade heat being electrified (by a mixture of heat pumps and direct resistive heating). Even so, there is still not enough fossil fuel to meet the transport demand and so a significant proportion of transport is still electrified.

On the supply side, scenarios 2 and 3 are quite similar. The levels of biomass and intermittent supply are kept roughly the same as in scenario 1 and this, coupled with the demand reduction, means that much less nuclear/CCS is required – the red bars clearly reducing in size to 30 GW(av) in scenario 2 and 39 GW(av) in scenario 3. The relatively large drop from scenario 1 is accounted for because of the greater efficiency of heat pumps and electric vehicles compared to their fossil fuel equivalents. However, given that the methodology used only allows for a broad, strategic overview, this is one instance where a more detailed and comprehensive analysis would be required to assess the relative effectiveness of these technologies in their respective sectors.

In buildability terms both these scenarios have a much better chance of success given that less than half the number of nuclear/CCS plants are needed compared with scenario 1. This should not, however, be underestimated as a challenge. Comparing the red bars on figures 6 and 7 with figure 4 shows that several times the current level is needed. Also, both these scenarios require significant levels of biomass and intermittent generation to be built along with the associated networks. So, although in theory easier than scenario 1, both scenarios 2 and 3 will still require huge building programmes and face serious supply chain and skills issues.

Both scenarios will also have serious resilience issues. With around 40% of the electricity supply coming from intermittent supplies in each scenario, the system would be moving well into territory not currently encountered either in simulation or in practice. Both scenarios will also potentially have peak demand problems: in scenario 2 if demand for charging of electric vehicle batteries is not managed; and in scenario 3 during particularly cold spells. As already noted, the choice of technology – electric heating or electric vehicles – does have an effect on the overall system. Other changes in the choice of technology could have further effects although it is unlikely that the overall scale and appearance of the system will change to any great degree given the same level of demand.

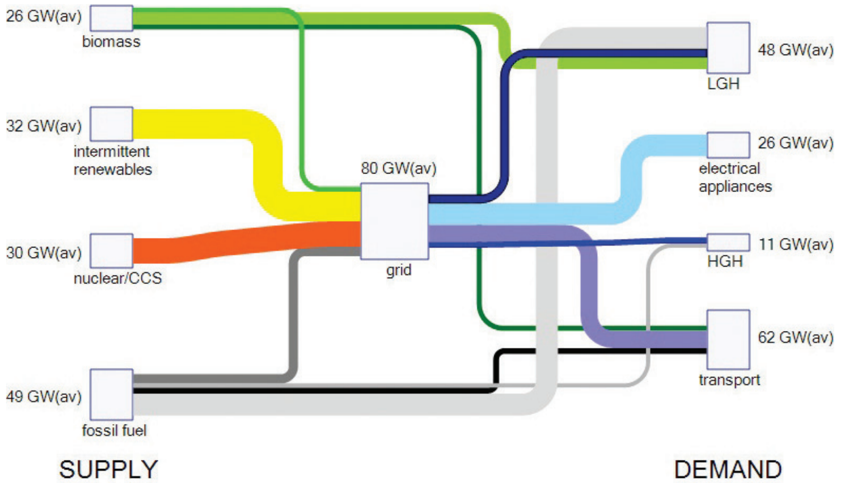

Figure 6: Scenario 2 (medium demand reduction, electrification of transport)

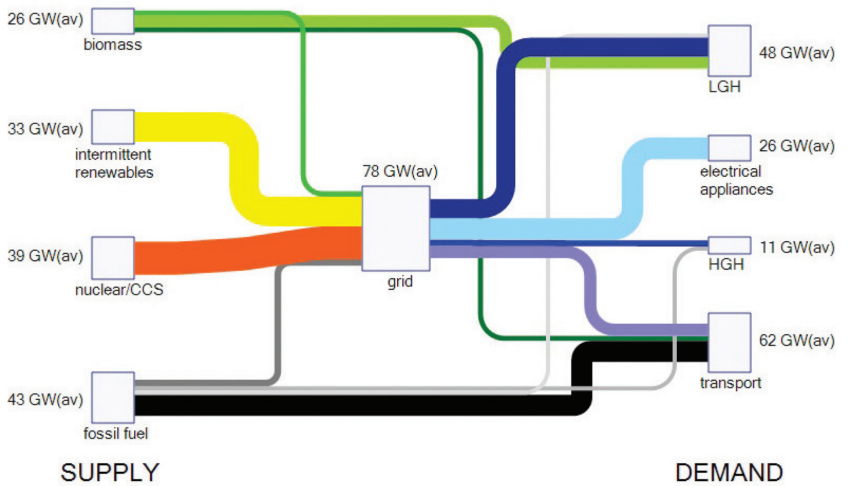

Figure 7: Scenario 3 (medium demand reduction, electrification of low grade heat)

2.6 Scenario 4: high demand reduction

In scenario 4 the demand reduction is increased to 46% overall, again with the bulk of the savings coming from low grade heat. This represents the highest level of demand reduction that is considered feasible assuming that all possible measures are implemented with almost complete penetration. In reality it would be dangerous to implement policy that assumed this degree of demand reduction as any slippage on the demand side targets would put undue pressure on supply side measures. For this scenario, fossil fuels are prioritised for transport, again resulting in almost complete electrification of low grade heat.

The higher level of demand reduction results in a flow chart that is generally 'thinner' than the others – meaning less energy is flowing through the system. That said, comparing the central grid blocks of figure 4 and figure 8 reveals that the electrical system of both are roughly the same size meaning that the electrical system would be broadly similar to today's. Also, the red bar for scenario 4 is still twice the size of the current system meaning that, in buildability terms, while better than the previous scenarios, it is still challenging.

For resilience, the main issue would be dealing with intermittency. Almost 58% of the electricity system is supplied by intermittent sources and at this level, well beyond anything within current experience; new and innovative solutions would certainly be required. One possibility, applicable to all the scenarios, would be to keep the current fossil fuel plants that are nearing the end of their expected life spans operational and ready to be used to supplement the system in case of shortfalls. This may seem a retrograde step but it would provide a safety net while adjusting to a new system and may prove less costly both in terms of money and carbon emissions. However, it would only be possible for a relatively short period of time to enable the transition to the new system and, in reality, would not form part of the energy system in 2050.

As with scenarios 2 and 3, different technology choices will have an effect on the system and, with each of the flows being smaller relative to previous scenarios, the effects would be correspondingly bigger. Further work is required to determine just how much technology choices could affect the system given a certain level of demand.

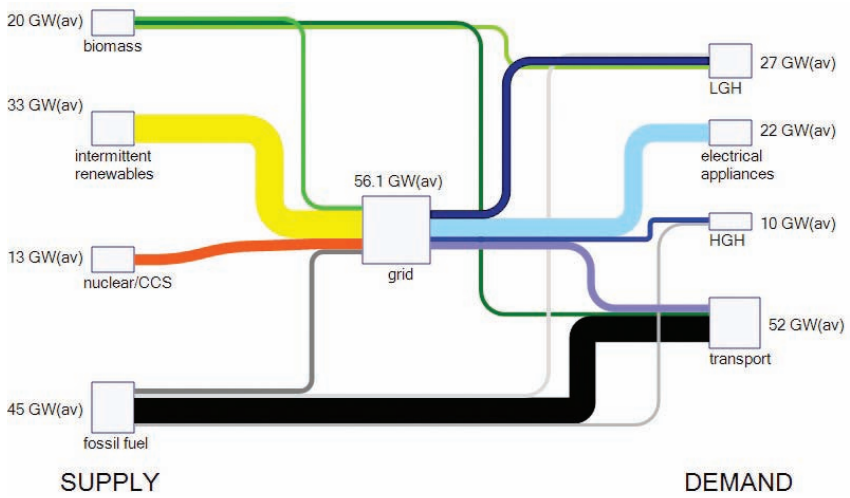

Figure 8: Scenario 4 (high demand reduction)

3 Conclusions

3.1 Main messages

Scenarios never predict the future; they only show a range of possible futures. However, some fundamental characteristics of all the possible energy futures for the UK can be deduced and these are described below. The study shows that:

3.1.1 There is no single 'silver bullet' that will achieve the required cuts in emissions

All the scenarios that we examined require action on both the supply and demand sides of the energy equation. They also require the UK to exploit its renewable energy resources to the fullest possible extent and supplement this with other forms of low-carbon energy such as nuclear or coal or gas stations fitted with carbon capture and storage.

All the scenarios show a requirement for significant change in power flows in the UK system, indicating that significant investment in new energy infrastructure will inevitably be required. The main shift in the scenarios is that much more energy demand will be met through the electricity system and generation will be added both centrally and throughout the distribution system. The last major investment in the UK's electricity infrastructure was in the 1970s and much of the equipment installed then is reaching the end of its service life, so we expect to see the need for renewal coinciding with the need for major enhancement, offering a unique opportunity to develop state of the art infrastructure.

3.1.2 Demand reduction across all sectors of the economy will be essential

All the scenarios require varied and significant reductions in demand which can only be achieved with a combination of technical efficiency measures and behavioural change. Even scenario 1, which is nominally level demand, represents a reduction in demand compared to current predictions of UK energy demand.

We can expect energy using processes to become more efficient over the coming decades, driven by the need to reduce costs. Energy efficiency of processes, machines and appliances can be driven through regulation as well, as has been the case with condensing boilers and is currently the case with cars, but the behavioural changes required among the general population require more and better public engagement, and, inevitably, pricing messages. It was beyond the scope of this report, but it is easy to see that this will climate change policies into conflict with efforts to protect those classed as being in fuel poverty.

3.1.3 The full suite of low-carbon energy supply technologies will be needed

The timescales involved in re-engineering the UK's energy systems to respond to the need to reduce greenhouse gas emissions can be measured in decades and some of the assets put in place to do this will have economic lifetimes of over 50 years. There is no more time left for further consultations or detailed optimisation. Equally, there is no time left to wait for new technical developments or innovation. We have to commit to new plant and supporting infrastructure now.

Because the timescale for the proving and large-scale roll-out of major infrastructure is measured in decades, only the low-carbon technologies that are already known can make a significant contribution to meeting the 2050 targets. They are already in the marketplace, close to it or close to being demonstrated at scale. Untried developments, such as nuclear fusion, may contribute to the energy mix beyond 2050 but to meet the 80% target we have to use what we already understand.

3.1.4 The scale of the engineering challenge is massive

Although the scale of the challenge has often been acknowledged, very few have sought to try to put numbers to it. We do so in Appendix 1 and come up with numbers which are currently beyond the capacity of the energy industry to deliver.

In order to achieve the scale of change needed, industry will require strong direction from government. Current market forces and fiscal incentives will not be adequate to deliver the shareholder value in the short-term and to guarantee the scale of investment necessary in this timescale.

3.2 Conclusions

The experience of engineers shows that implementing fundamental changes to a system as large and complex as the UK's energy system to meet the 2050 greenhouse gas emissions targets will bring with it many challenges for government, business and industry, engineering and the public alike. Turning the theoretical emissions reduction targets into reality will require more than political will: it will require nothing short of the biggest peacetime programme of change ever seen in the UK.

While the market will be the vehicle for technological and business solutions, the combined challenges of climate change, security of supply and affordability call for a more directed approach from government. This transcends political ideology: only government can facilitate and ensure delivery of the necessary infrastructure, some of which, being natural monopolies, do not respond classically to market forces. The market will not respond unless there is an appropriate long-term national plan and a framework set out by government to ensure the delivery of the necessary infrastructure in the wider context of Europe.

Implementing such fundamental and widespread changes across the planning, industrial, technological, economic, business and customer dimensions of the UK's energy system will only be achievable in the context of a national strategy to coordinate and drive the process. Such a strategy needs to be informed by a high degree of whole-systems thinking and be underpinned, from the outset, by critical evaluation of the economic, engineering and business realties of delivery across a system.

Despite positive steps, such as the creation of the Department of Energy and Climate Change, current government structures, including market regulation, are, as yet, simply not adequate for the task. This issue must also be addressed as a priority by means of a reorganisation of government departments to coordinate and drive action as well as to provide the clear and stable long-term framework for business and the public that is not currently in evidence.

It also needs to be recognised that the significant changes required to the UK energy system to meet the emissions reduction targets will inevitably, involve significant rises in energy costs to end users.

Appendix 1: Energy supply – technology potentials

Wind energy

The scale of the technology used to exploit wind energy has advanced more than any other in recent years. Indeed, from virtually zero in the early 1980s, wind turbines globally supplied over 150 TWh in 2006 from 94 GW of installed capacity[17]. Although this only represents about 1% of the global electricity supply, Denmark gets over 16% of its electricity from wind while Spain, Portugal and Germany all get over 5% from wind[18].

The UK, despite its ample wind resource, has lagged behind our European neighbours somewhat. It currently has just under 4 GW of installed capacity[19] accounting for just under 2% of electricity production in 2008[20]. It has, however, recently overtaken Denmark as the leading installer of offshore wind capacity[21]. So in terms of the current state of play, the UK in 2008 had 2.8 GW of onshore wind and 586 MW of offshore wind installed capacity that generated 5,792 GWh (0.66 GW(av)) and 1,305 GWh (0.15 GW(av)) of energy at load factors of 0.27 and 0.30 respectively[22].

Turning now to what we can expect by 2050, forecasts for wind seem to be larger and more optimistic than for any other renewable technology. The Government's Renewable Energy Strategy (July 2009)[23] and other supporting documents[24] conclude that 25 GW offshore wind capacity is permissible by 2020 without causing unacceptable strategic impacts. The Strategic Environmental Assessment[25] suggests 25 GW is feasible by 2020 on top of the 8 GW already planned. This seems remarkably optimistic. A rate of around 1 GW capacity installed per year for offshore wind out to 2050 and slightly more than half that for onshore wind is considered a more realistic figure but still at the limit of what might be plausible in engineering terms. This equates to 24 GW of installed capacity for onshore wind and 38 GW for offshore wind, or, assuming load factors of 0.27 and 0.3 respectively, 6.5 GW(av) average power supply from onshore wind and 11.4 GW(av) from offshore wind. Table 3 provides some idea of the equivalent assests required to provide these levels of supply.

Solar energy

The UK, as of 2008, only had 22.5 MW of solar photovoltaics (PV) capacity. Projecting out from such a small base to estimate by how much this capacity could realistically be increased would be problematic. Comparisons were therefore made with the world leader in this technology – Germany.
By the end of 2008, Germany had approximately 5.5 GW of installed capacity and it is estimated that around 2 GW more would be added in 2009[26]. Assuming this figure of 2 GW would be the most that the UK could reasonably expect to add per year, that would mean 80 GW of installed capacity by 2050 which, operating at a load factor of 9% (the current UK level[27]), would provide 7.2 GW(av). This installed capacity of 80 GW of solar power equates to approximately 14.6 m^2 of solar panels per person or 36 m^2 per household –

[17] International Energy Agency 'Energy Technology Perspectives 2008'
[18] *Ibid.*
[19] www.bwea.com/ukwed/index.asp
[20] Digest of UK energy statistics (Dukes 5.1)
[21] www.bwea.com/pdf/publications/CapReport.pdf
[22] Digest of UK energy statistics (Dukes 7.4)
[23] www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.aspx
[24] www.berr.gov.uk/files/file51989.pdf
[25] www.offshore-sea.org.uk/consultations/Offshore_Energy_SEA/OES_Post_Consultation_Report.pdf
[26] en.solarwirtschaft.de/fileadmin/content_files/Faktenblatt_PV_EN_sep09.pdf
[27] Digest of UK energy statistics (DUKES 7.4)

approximately 25 million 3.2 kW solar installations throughout he UK (assuming solar tiles operating at 90 W/m^2, a population of 61 million and 25 million households).

The above calculation is based on solar PV panels but solar energy can also be used to supplement the supply of low grade heat in the form of solar thermal energy or to generate electricity on a larger scale via concentrated solar power (CSP). Solar thermal power is equally effective as solar PV in the UK but would compete with it in terms of viable, south-facing roof space. It would also be dealt with in our system calculations as a reduction in the demand for low grade heat rather than a separate form of supply. For these reasons we have not included it explicitly in our scenarios.

CSP offers the potential to supply large amounts of centrally generated electricity. There are, however, few viable sites in the UK and CSP would therefore only supply the UK in the form of imports – possibly via a European 'supergrid'. It was considered that this technology was still at too early a stage for inclusion in the analysis. A more detailed appraisal of the issues can be found on the Academy's website[27].

Marine energy

The UK, by virtue of being an island is well placed to exploit all forms of marine energy. The basic mechanics of each of the types detailed below is well understood but, as of yet, none have been installed in large-scale, commercial quantities. With little or no base to extrapolate from, either in the UK or abroad, optimistic estimates have therefore been made as to how much each could realistically supply by 2050, based, where possible, on available data and prototype technologies.

Wave: Estimates of the potential of wave power to supply energy are based on the first commercially operational wave machine – the Pelamis at Aguçadoura wave farm in Portugal. Other devices are under development in other locations, such as Scotland and Cornwall. But it was felt that the Pelamis machines offered the most reliable prototype to base projections on.

Each Pelamis machine is rated at 750 kW power and is 180 meters long[28]. Operating at an estimated 40% load factor this equates to approximately 2 kW per meter for each machine. If arranged three deep in an array, this can be increased to 6 kW per meter for a 'wave farm'[29]. The rate at which wave farms could be installed is currently unknown, but taking an optimistic estimate to be the distance from London to Aberdeen, or approximately 625 km, this would mean a installed capacity of 9.4 GW supplying 3.75 GW(av) but a total of over 1,000 miles of actual machines.

Tidal stream: There are various estimates on the potential tidal stream resource available from UK waters. The most cited of these by Black & Veatch[30] estimates 18 TWh of technically extractable resource, of which 12 TWh would be economically exploitable or 1.4 GW(av). Recent reports suggest this figure could be higher but given that this technology is at such an early stage of development the level assumed still represents a challenging target in engineering terms.

[27] raeng.tv/default.aspx?item=19

[28] www.pelamiswave.com/content.php?id=161

[29] www.orkneycommunities.co.uk/OREF/documents/Wave%20Energy%20in%20Orkney.pdf

[30] www.carbontrust.co.uk/SiteCollectionDocuments/Various/Emerging%20technologies/Technology%20Directory/Marine/Other%20topics/PhaseIITidalStreamResourceReport.pdf

[31] www.marineturbines.com/18/projects/19/seagen/

Currently, the largest tidal stream turbine is the SeaGen device undergoing trials in Strangford Lough[31]. This is rated at 1.2 MW and is expected to operate at load factors of around 50%. This would mean the 1.4 GW(av) could be supplied by around 2,300 turbines.

Tidal range: The only tidal range facility currently in operation is the 240 MW unit at La Rance in France and a 254 MW unit is currently under construction in Korea[32]. In the UK we are in a somewhat unique situation given that we boast the second largest tidal range in the world in the Severn estuary.

It is therefore assumed that each scenario will include the largest of the projects currently under consideration by DECC[33] – the 10 mile Cardiff-Weston barrage with a capacity of 8.6 GW that would supply an estimated 17,000 GWh per year or 1.9 GW(av). Further discussion of the engineering issues connected with constructing a tidal range facility can be found on the Academy's website[34].

Hydropower

In a study commissioned by the Scottish Government in 2008[35], it was estimated that if all the rainwater in Scotland was used for hydropower it would generate 47.3 TWh, or 5.4 GW(av). Obviously, this would not be feasible, but the same report goes on to estimate that financially viable schemes could provide 2.8 TWh per year, or an additional 0.32 GW(av) from just over 1,000 schemes. A similar report from the Yorkshire Dales National Park Authority[36] only estimated a potential resource of around 1 MW(av). It is therefore assumed that only Scotland will provide any significant increase in hydropower in the UK.

Energy from biomass

Estimates for available biomass have been based on the UK Biomass Strategy[37] supplemented by the work of the TSEC - Biosys consortium, a recently completed project funded by Natural Environment Research Council. Agricultural and forestry residues and organic wastes are estimated as potentially providing 216 PJ/yr, corresponding to an average of 6.8 GW(av). Energy crops could provide a further 270 PJ/yr, ie 8.6 GW(av) of primary energy; this figure is ambitious but should be achievable within the UK in competition with food crops[38]. This does not allow for improvements in yield from plant breeding that can be expected to provide an increase of about 50%. The total primary energy from biomass in the UK could therefore reach more than 20 GW(av).

The figure of 20 GW(av) from biomass is therefore used in scenarios 2 and 3 for the total of electricity and low grade heat and a slightly lower figure in scenario 4 while imports of biomass would be required to provide the higher figures for electricity and low grade heat in scenario 1. Liquid biofuels are additional to this, underlining the need for imported biofuels (or imported food if UK production of energy crops reaches higher levels so that it displaces food production) to meet the EU targets for transport or the higher supply levels assumed in scenario 1.

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[32] cdm.unfccc.int/Projects/DB/DNV-CUK1143710269.08
[33] www.decc.gov.uk/en/content/cms/news/pn_007/pn_007.aspx
[34] www.raeng.org.uk/events/pdf/Severn%20Barrage%20transcript.pdf
[35] www.scotland.gov.uk/Resource/Doc/917/0064958.pdf
[36] www.yorkshiredales.org.uk/hydro-project-report-july09.pdf
[37] www.globalbioenergy.org/uploads/media/0705_Defra_-_UK_Biomass_Strategy_01.pdf
[38] Bauen, A.W., A.J.Dunnett, G.M.Richter, A.G.Dailey, M.Aylott, E.Casella and G.Taylor, 2010. "Modelling supply and demand of bioenergy from short rotation coppice and miscanthus in the UK", Bioresource Technology, in press.

Appendix 2: Working group

Contributions by the working group were made purely in an advisory capacity. The members of the working group participated in an individual capacity and not as representatives of, or on behalf of their organisations

Chair of the working group

Dr Sue Ion DBE FREng
Visiting Professor of Materials
Imperial College London

Members

Professor Roland Clift CBE FREng
Emeritus Professor of Environmental Technology
University of Surrey

Professor Nick Cumpsty FREng
Emeritus Professor of Mechanical Engineering
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Secretariat

Dr Alan Walker
Policy Advisor
The Royal Academy of Engineering

Thanks to Dr Peter Douben in helping to reconstruct the original RCEP calculations

Appendix 3: Expanded versions of Figures 1 and 2

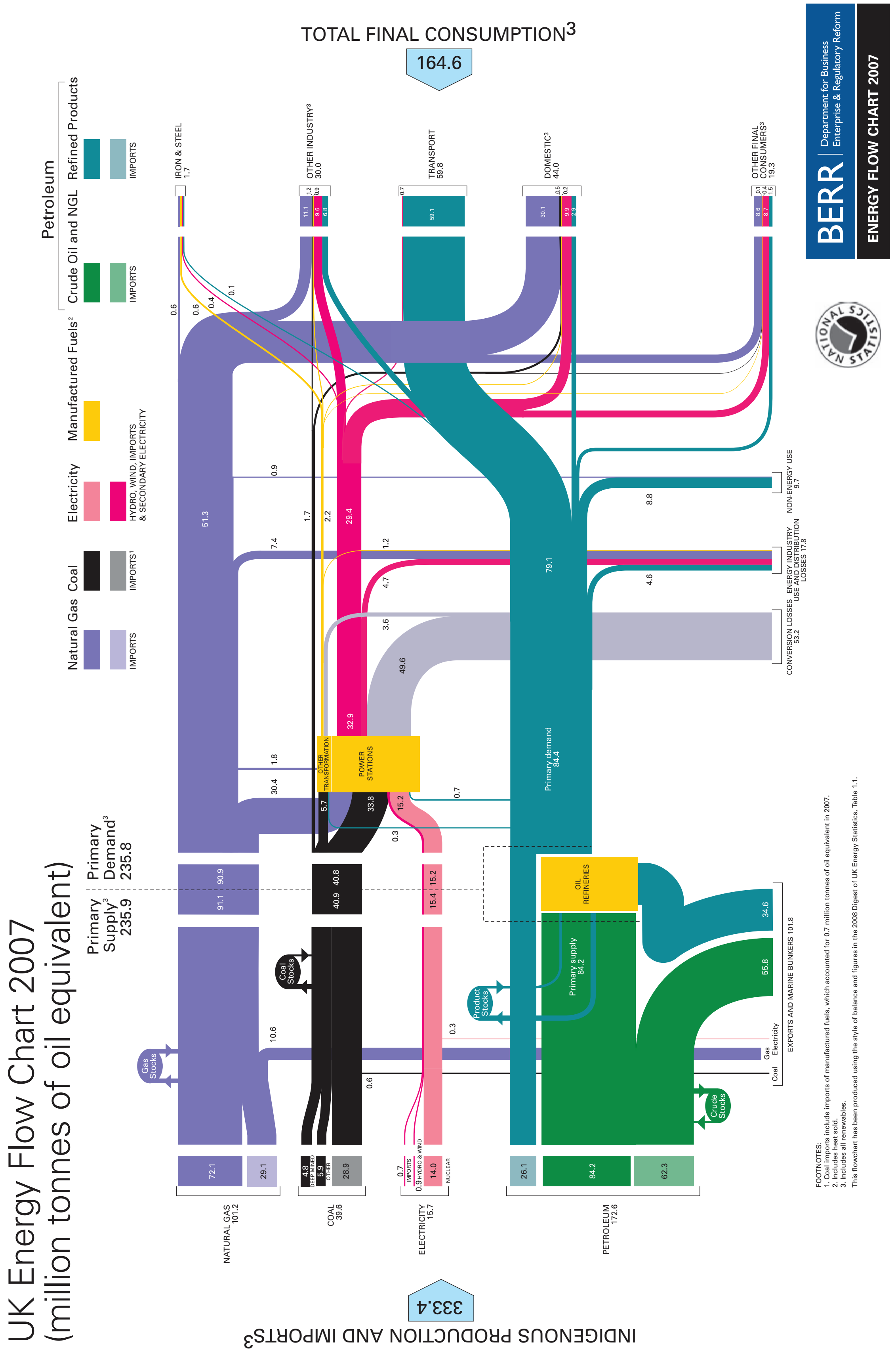

Figure 1: UK energy flow chart 2007 (www.decc.gov.uk/en/content/cms/statistics/publications/flow/flow.aspx)

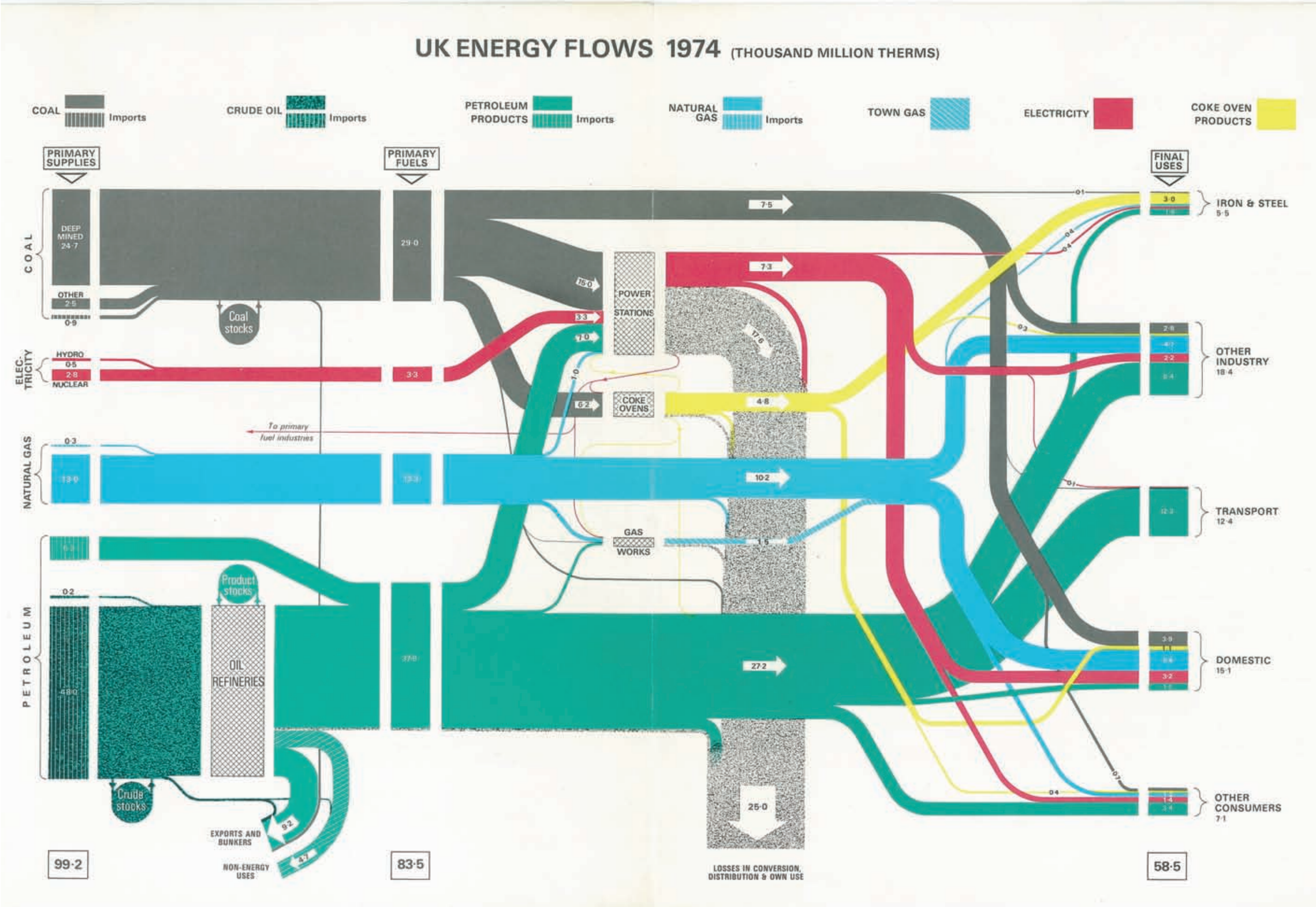

Figure 2: UK energy flow chart 1974 (www.decc.gov.uk/en/content/cms/statistics/publications/flow/flow.aspx)

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