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The Tyndall decarbonisation scenarios—Part II: Scenarios for a 60% CO₂ reduction in the UK

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ABSTRACT

This paper describes the Tyndall decarbonisation scenarios, the first to take account of CO₂ emissions from the whole of the UK's energy system, including emissions from international shipping and aviation. It builds on Part I, which outlined the backcasting methodology developed to generate the scenarios. The five scenarios produced through this process articulate alternative vision of a substantially decarbonised society in 2050, ranging from a halving of energy consumption from current levels to a near doubling. This work demonstrates that a 60% reduction in the UK's CO₂ emissions is achievable, even when all CO₂ sources are taken into account. The impacts and consequences of the scenarios were assessed by means of a multi-criteria framework which cautions us that the high energy demand scenarios will have a large impact on broader sustainability criteria.

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1. Introduction

The UK government has set out its ambition to reduce carbon dioxide emissions by 60% of 1990 levels in order to combat climate change (Department of Trade and Industry, 2003; Department of Environment Fisheries and Rural Affairs, 2007). In common with all industrialised nations, the UK is currently 'locked-in' to a carbon intensive energy supply system by the way the technologies, institutions, infrastructure and networks that supply energy for power, heat and transport have evolved (Unruh, 2000). With this in mind, achieving such substantial reductions in emissions will require new ways of thinking about the energy system, our levels of consumption and how that consumption is met. To this end, the Tyndall decarbonisation scenarios project has sought to develop a new approach for the generation of energy scenarios, and apply this to the UK.

The scenarios were developed using a backcasting approach with the consequences and implications of the different pathways and the trade-offs between them explored by means of a multi-criteria assessment (MCA) framework. The methodologies for both these elements are discussed in detail in Part I of this paper, which also outlines the project objectives. The paper serves as a companion to Part I, focusing upon the scenarios themselves, the MCA assessment and concluding with a discussion of the key findings to have emerged from this work. The broader project also sought to explore

the trends and drivers of energy intensity and carbon intensity through the use of decomposition analysis; work that is discussed elsewhere (Agnolucci et al., 2007; Anderson et al., 2006).

2. The Tyndall scenarios

The Tyndall integrated scenarios do not lend themselves to simple characterisation, therefore to avoid adding 'bias' to people's interpretation of the scenarios based on the title, they were allocated neutral descriptors and are referred to as red, blue, turquoise, purple and pink. The scenarios presented in Section 2, consist of a quantitative end-point and a qualitative description of the pathway for achieving that end-point. The qualitative descriptions are presented first for each scenario, followed by the quantified characterisations, which are presented together for the five scenarios, to allow comparison between them. The pathways were primarily written by the project team, based on the stakeholder-derived factors identified as critical during the backcasting workshop; the critical factors are listed before each scenario to provide some context for the issues upon which the scenarios focus.

2.1. The Red scenario

Workshop participants identified the following critical factors:

- Expanding the public transport network and deployment of low-carbon fuels.

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- Reducing the attractiveness of the private car; a complement to increasing public transport.
- New infrastructures to enable H₂ use in transport.
- Reducing the energy consumption of the building stock.
- Demand reduction through innovation to reduce the energy consumption of appliances and behavioural change.
- Supply-side changes and the deployment of CCS and H₂.

The Red scenario reconciles low energy demand with a high rate of economic growth that results in an economy in 2050 nearly five times larger than that of 2002 (the baseline year). The UK remains primarily a service economy, with the commercial sector contributing approximately three quarters of GDP, though there has been a gradual expansion of manufacturing, particularly in the non-energy-intensive and chemical industries. There has been conspicuously slow growth in the public administration sector, and its relative importance within the economy has declined as a consequence. While society is more affluent than today, the greater focus upon low-carbon lifestyles is indicative of changes towards more sustainable values that have occurred among a large swath of the population. Overall, significant energy demand reduction and moderate low-carbon supply measures have been achieved by a mix of market mechanisms operating within a 'joined-up' and sophisticated regulatory environment.

2.1.1. Demand-side characteristics

In this scenario, extensive demand-reduction is combined with a high rate of technological innovation in sustainable energy technologies, especially those used for demand management and reduction. The relationship between economic growth and carbon emissions has been uncoupled through innovation in the demand and supply technologies as well as more integrated and efficient operational approaches. This innovation has been driven by various mechanisms encouraging high levels of short and long-term investment in new enabling technologies, the alleviation of fuel poverty and in the fulfilment of low-carbon activities and services. The greater focus on long-term investment assisting low-carbon lifestyles and the inclusion of external costs in the pricing of goods and services has stimulated a large-scale shift towards the use of public transport, a curbing of aviation growth and a reduction of energy demand from households (Fig. 1).

There has been a reduction in passenger kilometre travelled by private car of almost a quarter, a modal shift that has been brought about primarily by three suites of developments:

- Providing a comprehensive public transport infrastructure and facilitating greater, safer and easier use of alternatives such as walking and cycling. The planning framework is used to prioritise low-carbon transport modes and new developments in urban areas are designed to reduce car use. New inter-urban transport networks are focused on public, not private, transport.

Fig. 1. Red scenario energy consumption by sector.

- In line with increasing public transport networks, the 'attractiveness' of the private car has been reduced through policy measures such as personal use charging, congestion charging and commuter plans. By 2050, a shift in values has taken place such that the private car is perceived as being much less acceptable within urban areas, though it remains a significant transport mode for longer journeys, with car share schemes and multiple occupancy lanes operating along all major roads to ensure high vehicle load factors.
- The focus of car design has moved away from conventional measures of performance, and instead focuses on improvements to vehicle fuel efficiency, facilitated by changes to taxation which drive consumer demand for the most efficient vehicles. As a consequence, the fuel efficiency of the mean car on the road in the future is close to that of the best car.

While passenger kilometres travelled by plane have doubled, annual growth in passenger kilometre in aviation has reduced from 8% in 2004 to a mean of 1.4% out to 2050. Changes include stagnation in business travel growth as innovative virtual technologies are rapidly accepted as a means of conducting international business. A significant reduction in short haul flights has been driven by the availability and relative cost of quality high-speed rail links within Europe.

2.1.2. Supply-side characteristics

Energy consumption in the home has more than halved through the following:

- Regulating the maximum energy consumption of appliances, initially through standards applied across the supply chain and ultimately through regulation of the energy consumption of domestic appliances. Stringent product standards have implications for international competition and international trade agreements to prevent trade-disputes arising from the prohibition of the import into the EU of appliances with energy consumption above levels set down in regulation.
- Improving the energy consumption of the housing stock through stringent building energy standards that drive demolition and rebuild where refurbishment is not possible. An increase in sustainability awareness fostered both through information campaigns and accompanying incentive mechanisms, has brought about more sustainable behaviour.

Given that in this scenario, the majority of the 60% carbon-reduction target is achieved through energy consumption reduction measures, only moderate decarbonisation of the supply system is necessary, and is achieved principally through the implementation of CO₂ capture technology linked to hydrogen production (Fig. 2):

- CCS is strongly promoted as the principle mechanism for decarbonising the supply system. Government and industry have invested in basic R&D and implemented carbon capture and storage obligation certificates (requiring generators to capture and store a percentage of their CO₂ emissions), a favourable tax regime and a public awareness campaign to promote CCS.
- By 2020, policies to encourage the production of hydrogen have ensured significant amounts of hydrogen production from both coal with CCS and renewables by 2030. Initially canals, coastal shipping and road freight are used to move liquid hydrogen around the country. This is gradually replaced by a shift to a piped mixture of hydrogen and natural gas, purpose built hydrogen pipelines and the introduction of 'hydrogen by wire' in more remote locations.

Fig. 2. Primary energy demand by fuel type.

2.2. The Blue scenario

Workshop participants identified the following critical factors:

- A large reduction in energy consumption, and radically changing energy use within the built environment.
- Energy industry restructuring through the development of an Energy Service Company (ESCO) framework.
- Extensive use of hydrogen for road transport, much of it produced from coal gasification with carbon capture and storage.

Fig. 3. Blue scenario energy consumption by sector.

While the rate of economic growth in the Blue scenario is modest, total energy consumption is reduced by a quarter between 2002 and 2050. Politically, a strong central government establishes targets and policy goals, but instructs appropriate tiers of local and regional government, or other accountable bodies, to develop the means for meeting or implementing them. This results in a significant expansion of the public sector, such that its contribution to national wealth is similar to that of the commercial sector. Local and regional governments become responsible for several wealth generating sectors, for example public transport. Society, while culturally outward looking, establishes a series of environmentally and ethically driven trade restrictions, that result in something of a minor renaissance for several domestic manufacturing industries, with non-energy-intensive industries representing almost 15% of the economy.

A scientifically, technically and culturally educated population embrace diversity and recognise the need for differing and evolving approaches to issues. Since climate change is an important policy issue with wide public support and understanding, sophisticated regulatory structures for the electricity industry, innovative market mechanisms for explicit carbon management and more collectivist approaches to public transport co-exist within a reflective and dynamic policy arena.

2.2.1. Demand-side characteristics

Energy demand has reduced by a quarter compared with the baseline year, which, with an economy over twice the size of 2002s, represents a slight increase in the historical trend in the energy intensity reduction of goods and services. In addition to demand reduction, there has been a moderate decarbonisation of the energy supply system (Fig. 3).

Reductions in energy consumption across the built environment, brought about by user behaviour and improvement to the fabric of buildings themselves, enabled by the emergence of ESCOs.

- ESCOs aim to achieve long-term improvements in energy performance and carbon-reduction targets and are regulated

by an independent regulator whose remit includes social and environmental, as well as economic, criteria.

- A reduction in energy consumption from appliances, both within the home and the workplace, has been driven by strong, internationally accepted standards. The growth of ESCOs with responsibility for a broad provision of services, such as sound and moving images, ensures that only appliances with high energy standards are used and regularly upgraded according to agreed replacement cycles.
- A reduction in energy consumption from the provision of services such as heating and lighting within buildings is achieved within a strong building regulation framework. Measures to reduce energy consumption are implemented by ESCOs and include responsibility for improvements to building fabric and the incorporation of integrated renewables within buildings. In the domestic sector, housing performance standards are required as part of the sale and rental of property, with low-cost finance in place for homeowners and landlords to implement improvements.
- While this is in many respects a society in which the essence of community is important, the interpretation of community is less geographically constrained. Consequently, this is a highly mobile society with growth in private and public transport. A comprehensive public transport infrastructure is in place, facilitated by a highly integrated policy and planning approach to transport. In urban areas, the planning framework is used to prioritise public and other modes of transport such as cycles over cars. New inter-urban transport networks are focused on public, not private, transport.

2.2.2. Supply-side characteristics

Climate change has been an overarching policy issue which has driven policy in other areas, particularly transport, where there has been an expansion of the public transport network and high penetration of low-carbon fuels. Driven by local air quality concerns, hydrogen is promoted as a transport fuel within niche

markets supported by local authorities who operate hydrogen buses and offer preferential licensing agreements for hydrogen taxis. The switch to hydrogen has been facilitated by the low cost of coal which has encouraged the construction of gasification with CCS plants for hydrogen production, and an infrastructure for liquid fuel purchased at 'Hydro-stations' is in place by 2020. A campaign to dispel concerns over the safety of hydrogen fuelled cars, combined with technological advances in hydrogen storage and fuel cells, and preferential fuel taxation and congestion charging, results in strong market growth for hydrogen fuels with a 75% share of road transport by 2050. Strong deployment of CCS within the UK is furthered by the successful implementation of a CO₂ transport network, and new build coal fuelled plant are supported via EU ETS (Fig. 4).

Energy utilities have been complemented by, or even restructured within, ESCOs framework. This has facilitated the implementation of CHP at the neighbourhood scale (within new build and retro-fitted) in most urban areas with appropriate building density.

By 2030, the price of buildings with integrated renewables has fallen, and strong building regulations ensure these technologies are incorporated into all new homes. Similarly, in areas with low building density, micro-CHP units are installed whenever conventional boilers are replaced.

2.3. The Turquoise scenario

Workshop participants identified the following critical factors:

- Expansion of airport and railways infrastructure to provide capacity for the high levels of mobility.
- Expansion of nuclear power plants to provide electricity and for hydrogen production.
- Support for biofuel production for use in transport applications.

The Turquoise scenario is a medium economic growth and medium energy demand scenario with the economy growing at a rate similar to that of today. By 2050, the economy is three-and-a-half times bigger, with an accompanying growth in energy consumption of around 17%. Three sectors are economically dominant, the commercial, construction and public. The remaining productive sectors collectively contribute the residual 8% of GDP, primarily from the non-energy-intensive and chemical industries.

Overall, the political context for this scenario has changed little from today's, with similar tiers of governance and many different departments and agencies involved in delivering decarbonisation

through low-carbon energy supply and energy efficiency. There is little close co-ordination of policy measures and implementation, and a somewhat confusing picture of what is happening in terms of different programmes, regulations and incentives, and who is responsible for their implementation and evaluation. Nevertheless, there is some strength in diversity, and over time, evidence-based policy begins to select the more effective policy instruments. Markets are used selectively, e.g. for electricity generation and delivery, and for providing incentives for decarbonisation in construction, private vehicle transport and aviation. Other energy-related activities are taken back into the public sector, such as railways and trams/light railway. The public sector also takes on a bigger regulatory role in commissioning and planning new energy supply. There is a wide range in the decarbonisation performance of local authorities, both in terms of strategies implemented and actual area-based CO₂ reductions achieved, with some having introduced congestion charges, local energy strategies and even new energy taxes in a few of the devolved regions.

2.3.1. Demand-side characteristics

Energy efficiency is an important factor in achieving the 60% target. While efficiency improvements across most sectors are similar to those of today, collectively they have the effect of reducing the nation's energy intensity by over 60% by 2050 (Fig. 5).

There are moderate increases in passenger kilometres travelled by ground transport but a reverse in patterns of modal growth from those of today, with no growth in private road transport and a noticeable rise in rail and public road. This reversal has been brought about through a variety of mechanisms:

- The prioritisation of public and other modes of transport over private cars through development control and planning regulations.

Fig. 5. Turquoise scenario energy consumption by sector.

Fig. 4. Primary energy demand by fuel type.

- Strong local authority control of traffic in urban areas with congestion charging to reduce urban congestion, tighter regulation of bus companies and the taking over of non-compliant operators by local authorities.

Passenger kilometres travelled by air are more than eight times greater in 2050 than in 2002 and this, along with the increase in rail transport, implies a significant growth in infrastructure. By 2015, the decision has been made for large-scale, centralised infrastructure planning since only limited increases in the railway network and runway capacity can be achieved through devolved management systems. Use is made of military runways and brown field sites for new airports, and there is a large-scale reinstatement of former railways. Compensation and planning gain are used as mechanisms to smooth the imposition of new infrastructure on local communities.

2.3.2. Supply-side characteristics

Hydrogen is widely used as a road transport fuel and provides about a third of fuel required by the aviation sector. By 2020, hydrogen end-use technologies are well-developed, licensed and fully commercialised and public concerns over the safety of hydrogen as a transport fuel have been addressed. Innovation in the aviation sector has been driven by the linking of expansion plans with the need for low-carbon fuel in order for the industry to keep within strong emissions limits (Fig. 6).

Within this scenario, the 60% carbon-reduction target is achieved through a diverse portfolio of supply options:

- R&D and a national debate into a new nuclear build programme begins in 2007. The nuclear industry is supported financially through the introduction of favourable financial instruments (e.g. a carbon tax). By 2015, the Government kicks-off the nuclear build programme with a policy of strategic site evaluation. Between 2015 and 2040, a significant build programme is delivering 20% of total primary energy supply by 2050. The private sector risk is reduced through long-term power purchase contracts, a comprehensive nuclear waste policy and underwriting of project investment by Government.
- From 2010, the Common Agricultural Policy is revised to offer land-use incentives to promote production of energy crops and help regenerate the rural economy. By 2015, central Government establishes a renewable fuels obligation on fuel distributors and biofuelled vehicles receive a favourable congestion charge rate. Research focuses on increasing crop yields, possibly through genetic modification. By 2030, decentralised biofuel stations are widespread.

- Hydrogen R&D is boosted by investment from airlines and aircraft manufacturers as they seek to maintain growth in mobility. As oil prices continue to rise and Government imposes taxes on aviation fuel, airlines work with the energy industry to develop hydrogen-fuelled planes. The first H₂-planes are commercially available in 2030. Hydrogen pipeline construction begins in 2030, transporting hydrogen from both nuclear and coal-CCS power plants.
- Public-private partnerships are established between research groups and the energy industry to develop a series of pilot carbon capture experiments to test the viability for both gas and coal-fired stations. By 2015, the success of the demonstration plants encourages investment by the energy industry to fund several large coal- and gas-fired power stations with CO₂ capture equipment and pipeline infrastructure to off-shore storage sites. The build programme continues to 2040.

2.4. The Purple scenario

Workshop participants identified the following critical factors:

- The development of integrated supply and demand infrastructure.
- Large-scale deployment of nuclear power, with a focus upon the development of new technology, siting, regulation and licensing.

The Purple scenario has high economic growth and high energy consumption, with decarbonisation achieved via a largely low-carbon grid combined with improvements in energy intensity. By 2050, the economy is over six times larger than today and energy consumption is approximately twice current levels. The economy remains dominated by the commercial sector, but with significant contributions from the non-energy-intensive industries and a lesser contribution from energy-intensive industries. While the two latter sectors are small relative to the commercial sector, in absolute terms they have undergone substantial expansion from their position at the start of the 21st century.

The UK's economic success is attributable to a vibrant, globalised and innovative UK market economy with a relatively small but supportive and market-oriented Government. The legitimate role of Government is limited to three principal functions: the strong defence of property rights; curbing the more extreme excesses of the market; and, where necessary, establishing targets (and the market mechanisms necessary to meet them) in accordance with international obligations. The drive towards a low-carbon society arises from two fronts. Firstly, the international obligation to significantly cut carbon emissions

Fig. 6. Primary energy demand by fuel type.

by 2050 and, secondly, the concern within energy markets over the insecurity associated with a heavy reliance on imported fossil fuels.

2.4.1. Demand-side characteristics

Demand for passenger transport has grown across all sectors with an overall six-fold increase in passenger kilometres travelled. There is a doubling and trebling of private and public road transport respectively, a seven-fold increase in rail, a four-fold increase in domestic aviation and a ten-fold increase in international aviation. Such large demand for all modes of transport requires the implementation of large scale increases in associated infrastructure, since by 2015 all possible increases in capacity through management systems have been implemented. By this date, a financing framework for a mixture of public and private money is in place to fund the necessary expansion. By 2030, the expansion programme is in full swing along with strong measures to incentivise high load factors and maximum capacity utilization (Fig. 7).

2.4.2. Supply-side characteristics

Initially, biofuels are substituted for fossil fuels for road transport, though by 2050, these are being displaced by hydrogen as fuel cell technologies diffuse. Electricity is used for trains and urban public transport. Since hydrogen technology does not penetrate the aviation sector, the nation's oil use is concentrated in this sector (Fig. 8).

Within this society, consumers have continued to increase their energy consumption hence carbon reductions are implemented though significant improvements in end-use efficiency and very substantial decarbonisation of the energy supply system. The large-scale expansion of nuclear and renewable generating sources is accepted by a highly mobile public as the price to pay for the consumer goods and services that are central to their

quality of life. The intermittency of renewables is partially compensated through the use of hydrogen production to smooth electrical supply output and through more sophisticated metering tariffs and arrangements.

Government has implemented policies to facilitate the expansion of the electricity supply system, addressing issues of research and development, finance and siting and planning. By 2010, the UK is a significant player within large multi-national nuclear research consortia, and has begun the process of licensing reactor technology from overseas to enable the early phases of a large-scale nuclear build programme to begin in 2015. The economic attractiveness of nuclear and renewable energy sources have been significantly increased through Government inducements to move away from carbon-based energy, such as a low-carbon obligation and the underpinning of the carbon price within a strong EU ETS. Commercial customers recognise the high economic risk associated with oil dependence and are encouraged to take out long-term power purchase contracts to further reduce the financial risks faced by private energy companies investing in new nuclear and renewable generating plant.

By 2010, Government establishes a nuclear waste policy and begins to address public safety concerns. Coal and gas-focused utilities diversify into renewables and nuclear power by 2015. These new players fund a big public awareness campaign concerning nuclear power, while sites for new plants are chosen and compensation strategies implemented. The markets have reduced the risks of such ventures by tending to construct somewhat smaller plants than previously. The awareness campaign also investigates the possibility of community and industrial involvement in small plant ownership with a majority of the public strongly in favour of anything with the word 'new-nuclear' attached to it. The extensive roll out of nuclear stations, both large and small, is full swing by 2030. As a result, by 2050 the UK energy system is dominated by electricity from numerous and relatively small nuclear power plants, complemented by a range of renewable energy designs.

2.5. The Pink scenario

The economic and demand characteristics of the Pink scenario are identical to the Purple scenario. This scenario was developed based on feedback from participants at the backcasting workshop concerning the supply mix of the Purple scenario, and the scale of renewables and nuclear capacity required to meet the level of energy consumption. The scenario responds to these concerns by offering an alternative, more diverse energy supply to that developed in the Purple scenario.

Fig. 7. Purple scenario energy consumption by sector.

Fig. 8. Primary energy demand by fuel type.

Fig. 9. Primary energy demand by fuel type.

2.5.1. Supply-side characteristics

In this market-led society, the dominant fossil fuel companies reject the idea of a hydrogen economy due to the slow pace of R&D and the potentially high capital cost of the new infrastructure, instead investing heavily in CCS for electricity production. By 2010, a public–private partnership leads to an industry-led public awareness campaign about CCS in conjunction with a boost in privately funded university research. Between 2010 and 2020, all the major storage sites are identified by the industries/universities involved, with new coal and gas power stations under construction in the vicinity. The construction of a new major gas pipeline from Russia is also complete and by 2030 the fossil fuel industry is booming with coal imports at an all-time high (Fig. 9).

It is soon recognised that within this high consuming society, mobility will continue to rise, and alternatives to petrol and kerosene are needed. By 2010 R&D, funded by the large energy companies, demonstrates that biofuels are the most viable low-carbon transport fuel. A new CAP of 2015 provides incentives to farmers to grow energy crops and new partnerships between farmers and an airline industry wishing to continue its expansion lead to the new 'biofly' initiative. By 2020, the first commercial bioplane enters the market, though sales rise relatively slowly. A new international agreement on a carbon tax on flying boosts sales and, by 2040, many dual-fuel planes are in operation. As imports of both coal and biofuels increase, new innovation within the marine sector sees the first wind/solar-oil ships in operation.

2.6. Quantitative descriptions

In reviewing the characterisation of energy consumed within the scenarios, it is evident that regardless of the *net energy growth rate* considered for any sector,¹ a pattern of relative energy consumption emerges. The principal message stands out clearly—the most intractable sectors in terms of energy demand reduction are International Aviation and Household—with the exception of International Aviation in the Red scenario, where growth rates have been severely curbed these sectors are the highest energy consumers in all the scenarios (Table 1).

The following sectors are also significant energy consumers: Private Road transport, International Shipping, Commercial, Industry (non-energy intensive) and Road Freight (unless ascribed considerably lower economic growth than currently experienced or subject to very substantial improvements in energy efficiency).

By contrast, even at very high rates of increase in activity within the sector (e.g. up to 6% p.a in some scenarios) Public

Table 1
Scenario energy consumption

	Energy consumption (Mtoe)				
	2002	Red	Blue	Turquoise	Purple/Pink
Household	48	19	18	55	53
Industry (intensive)	14	8	7	7	40
Industry (other)	19	13	18	9	48
Public administration	7	2	7	6	4
Commercial	12	12	6	17	41
Aviation domestic	1	0	0	1	3
Aviation international	9	9	34	53	62
Rail	1	1	2	1	3
Road freight	14	7	7	14	14
Private road passenger	27	8	21	13	35
Public road passenger	1	2	2	1	1
Inland shipping	1	1	0	1	2
International shipping	14	8	7	18	22
Total transport	68	36	73	102	142
Agriculture	1	0	1	1	2
Construction	1	0	0	2	1
Total consumption	170	91	130	199	330
Energy industry use	17	8	11	17	22
Total primary demand	243	140	191	304	475

Administration (Inc. hospitals, schools, etc.), Domestic Aviation, Rail, Public Road, Coastal/Inland Shipping, Agriculture and Construction individually have low energy consumption. However, while their respective *direct* energy consumption is low, several of the sectors are highly significant in terms of their impact on the energy consumption of other sectors. For example, in the Red scenario, there has been a 10-fold increase in the number of passenger kilometres travelled by public road transport, with a corresponding four-fifths decrease in the number of passenger kilometres travelled by private car. The 77% increase in energy consumed by public road transport (from 0.99 to 1.76 Mtoe) is more than compensated by the very substantial reduction in energy consumed by private cars (from 22.93 to 7.89 Mtoe).

Fig. 10 demonstrates that the Tyndall scenarios contain a range of supply portfolios, including diverse fuel choices, various options for generating electricity, and, to a lesser extent, different scales of supply with both centralised and on-site generation. The Purple and Pink scenarios illustrate that from a carbon perspective, very high energy consumption can be technically reconciled with the 60° carbon target through very low-carbon supply. That said, discussions between stakeholders attending the back-casting workshop highlight substantial problems in funding and

¹ Within the relatively wide range included in the Tyndall scenarios.

Fig. 10. Electricity mix.

overcoming political barriers to the deployment both of large-scale low-carbon supply and the associated demand-side infrastructure, such as airports and road expansion (Fig. 11).

The charts comparing electricity supply and primary energy demand across the five scenarios demonstrate that low energy consumption futures place far less reliance on the need for innovation in terms of fuel choice and generation technology than high energy consumption futures. In the Red and Blue scenarios, where energy consumption has been reduced, the UK can meet a 60% CO₂ target without relying on the wide-scale development of carbon capture and storage technology, or a large new build nuclear programme. As demand for energy increases (in the Turquoise, Purple and Pink scenarios) so does the need for large supply-side options, such as coal (and gas) with carbon capture and storage, and nuclear power stations, in addition to the extensive deployment of renewable energy, biofuel and possibly a hydrogen infrastructure.

As illustrated in Fig. 12, all the Tyndall scenarios envisage that oil will remain an important fuel, particularly for transport and most notably for aviation. While low-carbon fuel options for terrestrial forms of transport exist, and with appropriate policy levers will become more widespread by 2050, research demonstrates that kerosene is likely to remain the dominant aviation fuel in the medium term, with eventual part-replacement by biofuels and potentially hydrogen (Bows and Anderson, 2007; Royal Commission on Environmental Pollution, 2002). The difficulty of fuel substitution for aviation is well illustrated by the proportion of carbon emissions emitted by this sector, shown in Fig. 13. For comparison, total UK emissions in 2002 were in the region of 165 MtC, and all the scenarios achieve a reduction to 65 MtC by 2050.

Given the long lifetime of aircraft technical innovations take a long time to filter through the fleet, and the fact that within the industry no radical changes in technology are anticipated within the next 30 years, decarbonising the aviation industry is a unique challenge (Bows and Anderson, 2007; Royal Commission on Environmental Pollution, 2002). Therefore, as overall energy consumption in the scenarios increases, aviation emits a growing proportion of carbon emissions, despite embedded assumptions about penetration of alternative, low-carbon, fuels. Hence, other sectors effectively have to further decarbonise if the aviation sector is to grow. The only scenario in which aviation is not a significant emitter is the Red scenario, where growth has been significantly curbed. Although a high-emitting sector,

Fig. 11. Primary energy demand by fuel type.

Fig. 12. Transport fuels by scenario and fuel type.

Fig. 13. Scenario carbon emissions.

decarbonising shipping is less challenging as ships are relatively unconstrained in terms of weight, thus potentially more able to accommodate hydrogen as an alternative fuel to oil,² they may also be powered by renewable energy, or able to be bio-fuelled.

² Hydrogen has a lower energy density than oil, if used conventionally, fuel tanks need to be larger.

Households are an important source of relative emissions in all but the high energy consumption Purple and Pink scenarios. In the Red and Blue scenarios, energy consumption from appliances and buildings has been reduced to over half of current levels, but sectoral emissions remain high in the absence of a substantial decarbonisation of the electricity grid. The proportion of emissions from the household sector is highest in the Turquoise scenario where energy consumption in the home has not been reduced, and only moderate decarbonisation of energy supply has occurred. In the Purple/Pink scenario, high economic growth has funded an increase in energy efficiency, and corresponding reduction in energy intensity across the system. Although consumption in the homes remains high, energy supply has been decarbonised to accommodate the emissions from aviation within the stringent 60% target. Industry is a significant emitter in all the scenarios.

Overall the scenarios highlight that some sectors are harder to decarbonise than others, and suggest that these should be a policy priority for Government. For example, given the inherent difficulty of incorporating low-carbon fuels across the aviation industry, reducing the rate of growth in demand for flying should be a policy priority, with the possibility of concentrating bio-fuel use within the aviation sector. By contrast, there is a good understanding of the technologies required to bring about a 60% reduction in emissions from the household sector but implementing these changes across the whole building stock represents a different policy challenge in terms of implementing change across the whole UK housing stock, including regulation of energy appliances.

3. Multi-criteria assessment

The final stage of Robinson's generic backcasting framework (Robinson, 1990) is to explore the potential impacts and consequences of the scenarios, developed through the backcasting process. The Tyndall decarbonisation scenarios project used a MCA to perform this analysis; the methodology is described in Part I of this paper. The MCA took place over a day and a half; no attempt is made here to reproduce the vast amounts of data that emerged from the assessment, instead, the relative performance of the scenarios is discussed in general terms. The full details of the assessment can be found in Anderson et al. (2006). Given the broad range of impacts and possible consequences that could arise from the transition pathway and energy system described in each of the Tyndall decarbonisation scenarios, the assessment was sub-divided into four elements: natural environment, built environment or infrastructure, socio-cultural/political impacts and economics. Each of these broad categories of impacts was assessed by a group of experts, and the multi-disciplinary make-up of the group, with both practitioners and academics, contributed to the richness of the assessment. Overall, 196 criteria were identified, highlighting the wide reaching impacts of energy supply and use, and serving as a reminder of the complexity of energy policy in terms of impacts and how policy is delivered.

From the initial 196 criteria, the four groups each selected 12 criteria as priorities for scoring. A first general comment which can be made is that all the criteria defined by the natural environment group, concern impacts upon the environment e.g. habitat change or atmospheric deposition, as opposed to factors affecting implementation as is the case for the built environment or economic group. The scenarios have been scored on the underlying basis that the environmental impact from the scenarios increases as the energy consumption increases, though that said, the performance is not a simple reflection of energy demand within each of the criteria. Overall, only the Red scenario

results in an improvement in the UK environment relative to today. Similarly, the socio-cultural/political group criteria reflected the impact of the scenarios upon social sustainability, with the low energy demand scenarios once again performing better due to their greater use of planning, neighbourhood scales of activity and improvements in public transport.

The criteria devised by the built environment and economic group focused more on the implementation of the scenarios, rather than their impacts e.g. technical or institutional innovation in the case of the economic group, and joined up thinking or engaged population from the built environment group. For both groups, the lower energy demand scenarios performed better because the demand-side changes required were deemed to be more challenging, implying a less rigid way of thinking about energy which was regarded as positive thing. Large-scale generation plant locks society into a more rigid or confined energy system, which is less flexible, less reversible more vulnerable to catastrophic failure.

Several criteria emerged independently as common to more than one group. Employment was evaluated by both the built environment and economic groups; the evaluations differed since the economic impacts group considered that traditional energy supply sector jobs would be lost in a low-carbon future, although both considered that in the low energy demand scenarios, jobs would emerge as a consequence of the measures implemented. Ideas of resilience, reliability and safety emerged from three of the groups (socio-cultural impact, built environment and economic impact); while these were named differently, all of the definitions encompassed elements of supply system reliability and the ability of society to cope if the system fails. The low energy demand scenarios were scored more highly, and the high energy demand Purple judged to be worse than today.

Taken as a whole, the assessment explored the sustainability of the scenarios, with the low energy demand scenarios performing better than the high energy demand scenarios. This outcome is across all the impact groups, thus the Red and Blue scenarios were better in economic terms, and in terms of society itself as well as the built and natural environments. Although the primary driver for impacts on the natural environment was the level of energy demand, the picture is more complex for the other issue areas, where the different societal values and level of economic growth have a greater influence over the evaluation. The negative impact upon the environment of the high energy demand scenarios was expected; however, their poor performance in terms of other criteria was somewhat surprising. The analysis cautions that in a high energy demand world society is locked into an energy system that is less flexible, responsive and more resource intensive (economic as well as environmental) than where energy demand is reduced. By contrast a low energy demand future has the potential to be more adaptable and responsive, with a better natural environment.

4. Conclusion

The Tyndall decarbonisation scenarios project used a back-casting methodology to develop a set of energy scenarios for exploring a range of technical, managerial and behavioural options for reconciling a vibrant UK society with a *true* 60% reduction in carbon emissions by 2050. Unique to this analysis was the inclusion of carbon emissions from both international aviation and shipping.

The wide range of characteristics captured within the scenarios demonstrates the substantial scope for alternative low-carbon futures. In the Red and Blue scenarios, the carbon target is achieved principally through reductions in energy intensity and

absolute energy demand. For many sectors, natural cycles of equipment replacement offer opportunities for intervention, hence policies are required, firstly, to ensure appropriate technologies are available and deployed, and, secondly, to avoid society being further locked into unsustainable patterns of use. By contrast, in the Purple/Pink scenario, despite substantial improvements in energy intensity, the energy demand in 2050 has nearly doubled from 2002 levels; hence, in addition to the significant measures required to improve energy intensity, society has had to reduce substantially the carbon intensity of energy supply. The pathway towards the Purple scenario end-point involves the wide-scale deployment of low-carbon supply, incentivised by early government action to resolve issues such as uncertainty over nuclear waste policy and the licensing of new nuclear reactor designs. All of the scenarios demonstrate that reducing energy and carbon intensity, at the levels necessary for a 60% carbon reduction, urgently requires a coherent and stringent regulatory framework complemented with unambiguous market signals and the strengthening of appropriate market mechanisms.

The development of the Tyndall scenarios benefited significantly from the suggestions of stakeholders brought together for two workshops. The transition pathways defined by participants at the backcasting workshop implied a strong role for government, irrespective of how market-driven a particular scenario set out to be; this may, in part, have been a consequence of the policy focus of the workshop participants and a business oriented stakeholder group would have potential focused on more market-dominated pathways. The workshop participant's expertise also influenced the factors they considered critical to the scenarios and hence those chosen as the focus of the backcasts, and the subsequent scenario descriptions.

While the principal focus of the Tyndall scenarios was on reconciling alternative UK energy futures with the government's 60% carbon-reduction target by 2050, the MCA evaluated the scenarios against a broader range of criteria. This highlighted that those scenarios with high energy demand are likely to be less resilient to external shocks than those with low energy demand; for example, high energy futures would probably be more vulnerable to the increasing impacts of climate change upon weather patterns than would low energy futures. Consumers with more flexible expectations of the energy service they received were considered more likely to be able to respond to shocks to the energy system than were consumers who had become accustomed to very high levels of energy service.

Another important outcome from the MCA arose from the large and complex network of infrastructures contained within the higher energy scenarios. The wide-scale deployment of nuclear and renewable power stations, fossil plants with carbon capture and storage, and a biofuel or hydrogen system, allied with an extensive energy demand infrastructure (more roads, airports, etc.) would likely entail significant changes to the planning system. This would in turn imply an acceptance from the public of large projects, and potentially a more stream-lined planning system to facilitate such developments. While some of the workshop participants certainly found it difficult to envisage the levels of both demand and supply infrastructure implied by high

energy demand futures, the backcasting workshop provided mechanisms for articulating pathways to such futures. Moreover, the pathways developed illustrated how the political or economic feasibility of the scenario, along with other technical challenges associated with lowering energy and carbon intensity, could potentially be overcome.

While the scenarios illustrated the scope for reconciling the government's 60% carbon-reduction target with an economically growing society, the sustainability implications of the high energy futures raised considerable concern among many of the stakeholders. Several of the stakeholders considered the level of infrastructure development within the high energy scenarios to breach significantly any reasonable sustainability criteria.

There was agreement among the MCA stakeholders that, whatever the scenario, strong government leadership was essential if the 60% carbon target was to be achieved. For the high-energy futures, the successful deployment of a large-scale expansion of supply technologies would require long-term government policies to address issues of technology development and innovation, investment, regulation, siting, planning and mitigating opposition to developments. Furthermore, it was considered essential the flexibility and diversity within the energy supply system was maintained, so that useful options were not 'locked out' through short-sighted decision making.

Across all of the scenarios the role of international emissions, particularly those associated with aviation, were an important factor in driving down emissions from other sectors. The scenarios clearly demonstrated that the exclusion of international aviation and shipping emissions from both previous carbon-reduction scenarios and the government's 60% carbon-reduction target has led to highly misleading conclusions. Even when halving the rate of growth of international aviation and shipping, compared with the figure in 2002, and with significant use of alternative fuels in the longer term, these two sectors account for between 50% and 85% of carbon emissions by 2050. Given that the ultimate objective of climate change policy relates to a global atmospheric CO₂ stabilisation level, it is essential that all future analysis and scenarios be based on comprehensive inventories with aviation and shipping emissions included.

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