CHAPTER 7
ENERGY SECURITY IMPACTS OF INTRODUCING HYDROGEN TO THE UK ENERGY SYSTEM

Paul E. Dodds – University College London

7.1 INTRODUCTION

There is no single accepted methodology for assessing energy security. Methods are used from a range of disciplines [26]:

- economics (e.g. macro-economic modelling; micro-economic surveys; financial theory);
- engineering (e.g. power and robustness engineering; operations research);
- political science (e.g. international relations theory);
- system studies (e.g. complex systems analysis; energy system scenarios); and
- natural science (e.g. geological depletion models; diversity indices).

This chapter examines the implications of the long-term introduction of hydrogen technologies to the UK energy system, primarily through the lens of energy system scenarios.

7.1.1 Energy security in low-carbon energy systems

It has been asserted that introducing hydrogen technologies would improve energy security by reducing reliance on imports of energy commodities such as oil [179, 180]. But such propositions often involve producing hydrogen from renewable electricity, which is substantially more expensive than producing it from fossil fuels (Chapter 3), and affordability is a key requirement for energy security.

The UK energy system is expected to be transformed over the coming decades into a low-carbon system in order to meet a mandated 80% reduction in greenhouse gas emissions in 2050, relative to 1990 [31]. Scenario analyses are often used to identify potential evolutions that are internally-consistent and cost-effective. These analyses tend to focus on the affordability and sustainability aspects of the energy trilemma and overlook energy security, perhaps because security has a relatively strong socio-political context that might be quite different in the future. Yet if some potential evolutions are substantially more resilient than others, and the costs of these are acceptable, then these would likely be favoured by policymakers.

Resilience, through fuel diversity, has been explored in one scenario for the UK using the UK MARKAL energy system model [181]. No previous studies have examined the system-wide impacts of introducing hydrogen on energy security using scenario analysis with an energy system model. This chapter examines how UK energy security might change as a result of the evolution to a low-carbon energy system. Three scenarios are examined using the UK TIMES energy system model (UKTM); two have varying levels of hydrogen technologies in 2050 while the third is a counterfactual with no hydrogen deployment. All three scenarios are compared with the current UK energy system using Shannon-Weiner indices to examine fuel and technology diversity in key parts of the system.

7.1.2 Structure of this chapter

The three scenarios are described in Section 7.2. Section 7.3 explains how the scenarios are modelled in UKTM, compares the results from an energy security perspective and analyses changes in diversity and import dependence. Section 7.4 considers how the resilience of these three scenarios could be improved, and analyses the economic implications of increasing diversity and reducing imports. Some key limitations are identified in a discussion in Section 7.5 and key conclusions are presented in Section 7.6.

7.2 DESCRIPTION OF THE SCENARIOS

Three scenarios are examined in this study, of which the two hydrogen scenarios were developed for the UK Committee on Climate Change [51]:

- **Full Contribution**: hydrogen is used extensively across end-use sectors, including for most transport and heat provision, by 2050.
- **Critical Path**: hydrogen is adopted in strategically-important end-uses by 2050, primarily in the transport sector, that are difficult to decarbonise through electrification.
- **No Hydrogen**: a counterfactual scenario in which hydrogen technologies are not adopted.

7.2.1 Full Contribution scenario

The Full Contribution scenario is an aggressive hydrogen uptake scenario characterised by early, consistent and long-term commitment to the extensive use of hydrogen across the economy. This commitment is equally strong throughout the timeframe of the scenario, allowing strategic, anticipatory investments in hydrogen-enabling infrastructure in advance of the materialisation of hydrogen demand, which the model shows is more cost-effective. It is driven by an early decision to decarbonise heat provision across the UK by delivering hydrogen using existing infrastructures, and this subsequently provides some of the infrastructure for FCEV adoption in the transport sector.

Around 85% of UK homes are heated using natural gas and these households are accustomed to a small, quiet, reliable, responsive, low-cost, high-power heating system on demand. For these reasons, gas heating is very popular [182]. This scenario builds on their popularity by continuing the status quo for heating in on-gas areas, but with a national conversion programme replacing natural gas with hydrogen across the country to greatly reduce CO_2 emissions.

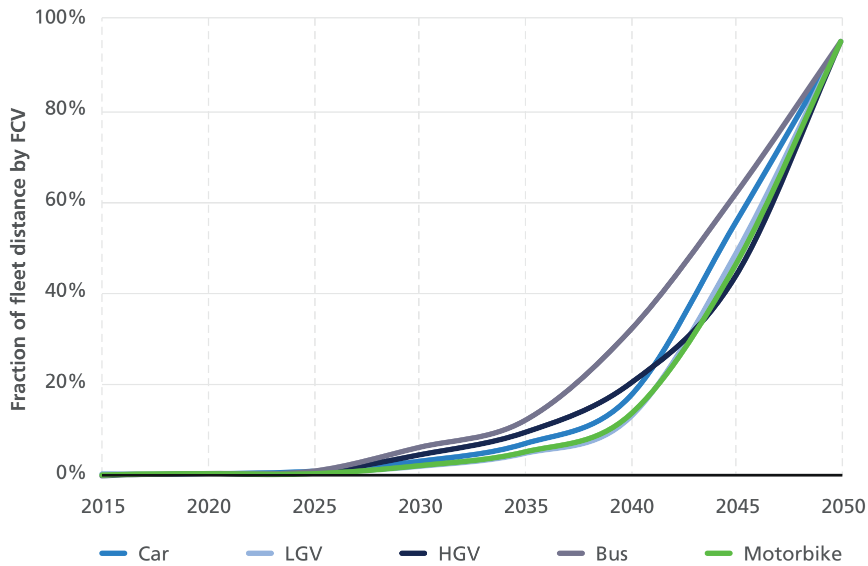
The use of hydrogen in the Full Contribution scenario in 2050 can be described as follows:

- Hydrogen fuel cell vehicles are the dominant technology for all private road transport, buses and light and heavy goods vehicles (HGVs), as shown in Figure 7.1.
- Hydrogen is piped into buildings in the UK that are currently heated by natural gas, across the residential, public and commercial sectors, where it is used to generate heat in hydrogen boilers (with similar operational characteristics to existing gas boilers) and, in larger homes with higher heat demands, hybrid heat pumps. Where district heating infrastructure is developed, hydrogen may also

be used as a zero-carbon energy carrier for small CHP units and for district heat boilers. The conversion of the existing gas networks to deliver hydrogen occurs over a 20-year period from 2025, roughly in line with the assumptions in the H21 Leeds City Gate study [128].
- Hydrogen is used extensively as a clean fuel in some industry sectors – it provides high-temperature and low-temperature heat for iron and steel production, non-metallic minerals, non-ferrous metals, paper, chemicals and food and drink.
- Hydrogen is used as a storage medium for excess renewable electricity generation, primarily at a large scale (salt caverns and other large scale storage). Hydrogen is also used in power generation for peak generation and also for some mid-merit generation in CCGTs.

The key to the supply of hydrogen in this scenario in 2050 are the existing gas distribution networks, which have been repurposed to carry hydrogen to domestic users and to local refuelling stations. The high-pressure gas network cannot be repurposed to carry hydrogen and a new high-pressure hydrogen transmission network has been constructed.

Figure 7.1 Fuel cell vehicle deployment in the Full Contribution scenario, source: [51].



7.2.2 Critical Path scenario

The Critical Path scenario is based on keeping open the option to use hydrogen in end-uses that are seen to be 'strategically important', which are defined as end-use demands that are hard to decarbonise by means other than hydrogen, or for which low-carbon options other than hydrogen have inferior performance characteristics relative to incumbent technologies (e.g. vehicles with a substantially shorter range or a long refuelling time).

In this scenario, there is no wholesale and technologically-specific commitment to an extensive roll-out of hydrogen technologies, in preference to other options. It avoids large anticipatory investment commitments, such as hydrogen delivery infrastructure, ahead of an absolutely clear evidence of demand. The strategy that policy makers wish to follow is to "buy" some optionality for allowing a contribution from hydrogen in some key sectors, at some point in the future, but without a wholesale commitment to it, and with a view to not paying too much for the "option". This means that hydrogen has a minor role in the energy system prior to 2030, in this scenario.

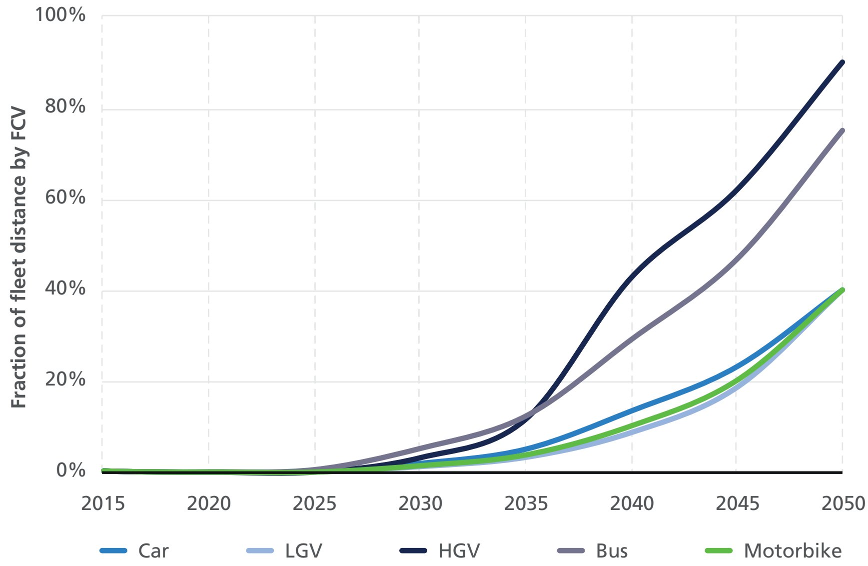
In end uses such as heat and power provision in buildings, and private road vehicle transport over short distances, it was judged that while hydrogen could be envisaged to play a role in a 'Full Contribution' scenario, there are also strong alternative options to hydrogen, such as electric, bioenergy or district heating technologies. Therefore, these end uses were not judged to be strategically important, and thus hydrogen was not envisaged to play a strong role in delivering them.

This leaves a number of end uses in which for different reasons, there remains greater uncertainty around the availability of viable low carbon options. The most strategically-important end-use demands were judged to be heavy goods vehicles (HGVs), buses, cars and light goods vehicles (LGVs) when required to undertake journeys greater than 100km, heavy industry and flexible back-up generation in the power sector. It was for these strategically-important end uses that it was judged that policy makers would value keeping open the hydrogen option.

The use of hydrogen in the energy system in 2050 is primarily for road transport, which is summarised in Figure 7.2. In particular:

- 90% of HGVs run on hydrogen – corresponding to the proportion of HGVs that operate within the UK only.
- 75% of buses and coaches (long distance and urban), operating within the UK, run on hydrogen. This is an estimate of the proportion of buses that operate on routes outside of dense urban areas where electric buses are more likely to be viable.
- 40% of private car vehicle kilometres are fuelled by hydrogen. This portion corresponds to the portion of total vehicle-kms that are travelled on journeys longer than 100km. This is considered a strategically important portion of this end use demand because while electric vehicles may operate comfortably over ranges of 100km of less, there is uncertainty that their range will be able to extend beyond 100km.
- Hydrogen is used in power generation for flexible peaking plant, to help balance a system with high penetrations of variable renewables and less-flexible nuclear.
- Hydrogen may have a limited role in decarbonising fuel supply for heat demand in industry, especially for end uses where electrification is not suitable.

Figure 7.2 Fuel cell vehicle deployment in the Critical Path scenario, source: [51].



7.2.3 No Hydrogen scenario

The No Hydrogen scenario is a counterfactual that is analysed in order to assess the energy security implications of adopting hydrogen against an alternative low-carbon system with no hydrogen. In this scenario, hydrogen is used only for ammonia production in industry, in line with current practice.

7.3 LONG-TERM CHANGES IN ENERGY SECURITY ACROSS SCENARIOS

In this section, the UK energy systems in 2050 from each scenario are compared. The Shannon-Weiner Index is used to examine the impacts of using hydrogen on fuel diversity across several parts of the system that are particularly important for energy security. The same metrics are also compared with the current UK energy system.

7.3.1 Modelling the scenarios

These three scenarios have been modelled using the UK TIMES model (UKTM). UKTM is a multi-time period, bottom-up, technology-rich cost optimisation model of the UK energy system. It is the successor of the UK MARKAL model, which was originally developed to provide insights for the Energy White Paper 2003, and was under constant development until 2012 [183]. It was recently used by the UK Department of Business, Energy and Industrial Strategy to inform its Fifth Carbon Budget Analysis [184].

The simplest formulation of UKTM is to minimise discounted energy systems cost, under a wide variety of physical and policy constraints. This minimisation takes into account evolving costs and characteristics of resources, infrastructures, technologies, taxes and conservation measures, to meet energy service demands.

General description of data sources and assumptions in UKTM

UKTM is a very large model, with 2000 technology types, 600 energy carriers plus constraints, taxes, emissions and other model parameters. The model has more than 200,000 data elements. Model data have been obtained from a wide range of sources and have undergone quality assurance checks. Model documentation will be available from the UKTM website.[7]

The transport sector is broadly similar to that developed in Dodds and McDowall [46] and Dodds and Ekins [47] while the residential sector is derived from Dodds [185]. Conversion of the gas networks to hydrogen is based on research in Dodds and McDowall [137] and Dodds and Demoullin [186]. The EPSRC HYVE project and the UK Energy Research Centre have produced a new version of the UKTM, based on v1.2.2, that includes improvements to the representation of hydrogen and fuel cell systems, as well as to UK fossil fuel resources.

Interpretation of the scenarios in UKTM

The Full Contribution and Critical Path scenarios are modelled in UKTM by specifying the hydrogen uptake in road transport over the period to 2050 for each transport mode. In the Full Contribution scenario, the conversion of the gas networks to hydrogen and the take-up of hydrogen for heating are similarly forced into the solution. Some constraints are also placed on hydrogen infrastructure, for example so that a minimum number of refuelling stations with on-site electrolysers are constructed in the early years of a transition when a comprehensive hydrogen infrastructure could not be justified. The remainder of the energy system is not constrained and the model identifies the least-cost evolution to achieve an 80% reduction in greenhouse gases by 2050.

In the No Hydrogen Scenario, no constraints are applied except those that exclude hydrogen technologies, so a least-cost evolution is identified.

In all three scenarios, the composition of the electricity generation portfolio is broadly chosen to minimise cost, as are the hydrogen production technologies in the Full Contribution and Critical Path scenarios.

7.3.2 Qualitative comparison of the scenarios

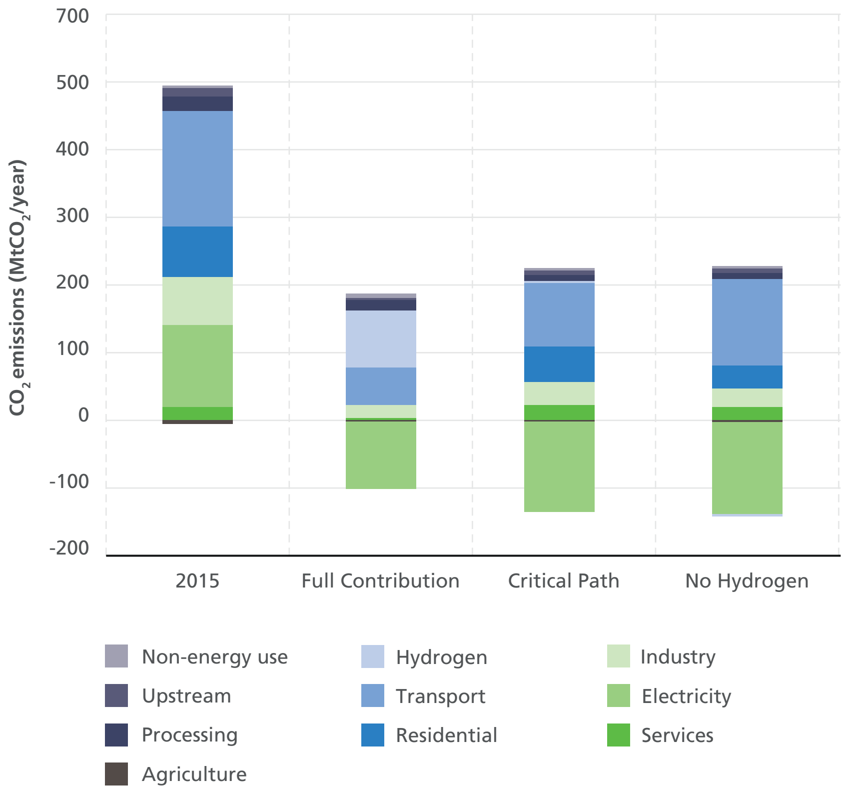
Carbon dioxide emissions from the scenarios in 2050 are compared with 2015 emissions in Figure 7.3. All three scenarios meet the 80% reduction in greenhouse gas emissions, relative to 1990, that is required by the UK Climate Change Act 2008 [187]. In all three cases, this is partly achieved through "negative emissions" from biomass CCS electricity generation plants, which facilitates higher emissions in other sectors. All scenarios have substantial transport emissions resulting from international aviation and shipping.

The emissions profile in the Full Contribution scenario is quite different to the other two scenarios. Since hydrogen is used to decarbonise most heat provision and road

7 The UKTM website is at: www.ucl.ac.uk/energy-models/models/uktm-ucl.

transport, end-use emissions are lower than for the other scenarios, which means that fewer negative emissions are required and that the upstream sectors such as hydrogen production have much higher emissions. This scenario offers the possibility to decarbonise further than the other scenarios, and the end-use consumer technologies are closest in operation to existing technologies, so it could be more resilient to the failure of some decarbonisation policies.

Figure 7.3 Sectoral CO_2 emissions in 2050 in the three scenarios, compared with emissions in 2015.



Hydrogen consumption in the scenarios is shown in Figure 7.4. Full contribution has high consumption across all end-use sectors, as well as for mid-merit electricity generation, while consumption in Critical Path is predominantly for road transport vehicles.

Electricity generation is dominated by nuclear power by 2050 in all three scenarios (Figure 7.5). The technology portfolio is similar in each scenario but quite different to 2015. Generation increases across all of the scenarios, with the No Hydrogen scenario having the highest generation due to the unavailability of hydrogen technologies in end-use sectors. Full Contribution is notable for the links between the electricity and hydrogen systems, with 70 TWh electricity generated from hydrogen in 2050 and around 35 TWh hydrogen produced from electrolysis. The rational is for hydrogen to generate electricity at times of high demand, while the hydrogen would be mostly produced at large refuelling stations that were geographically-remote from large-scale hydrogen infrastructure.

Figure 7.4 Hydrogen consumption by sector in 2050 in the three scenarios, and in 2015.

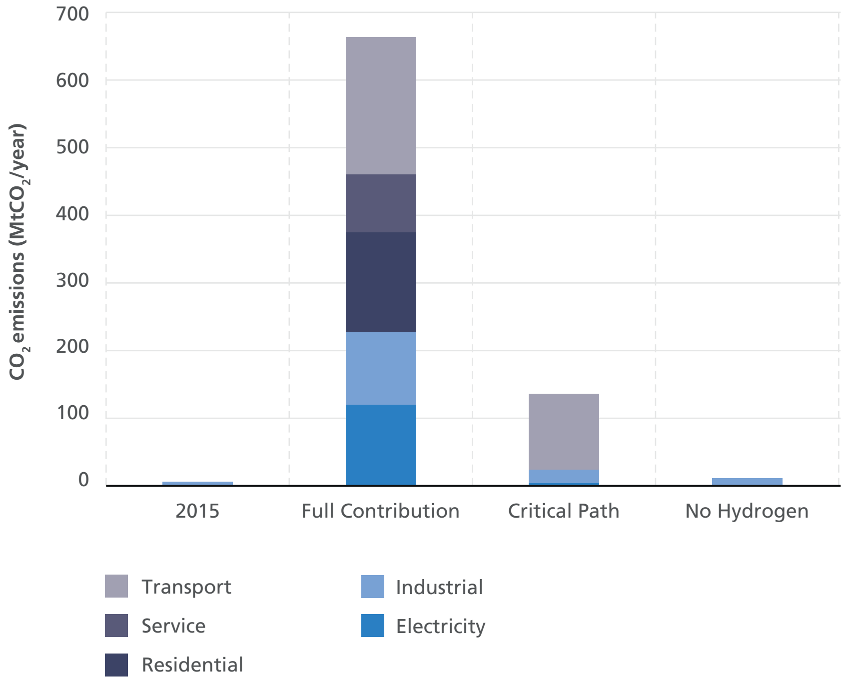
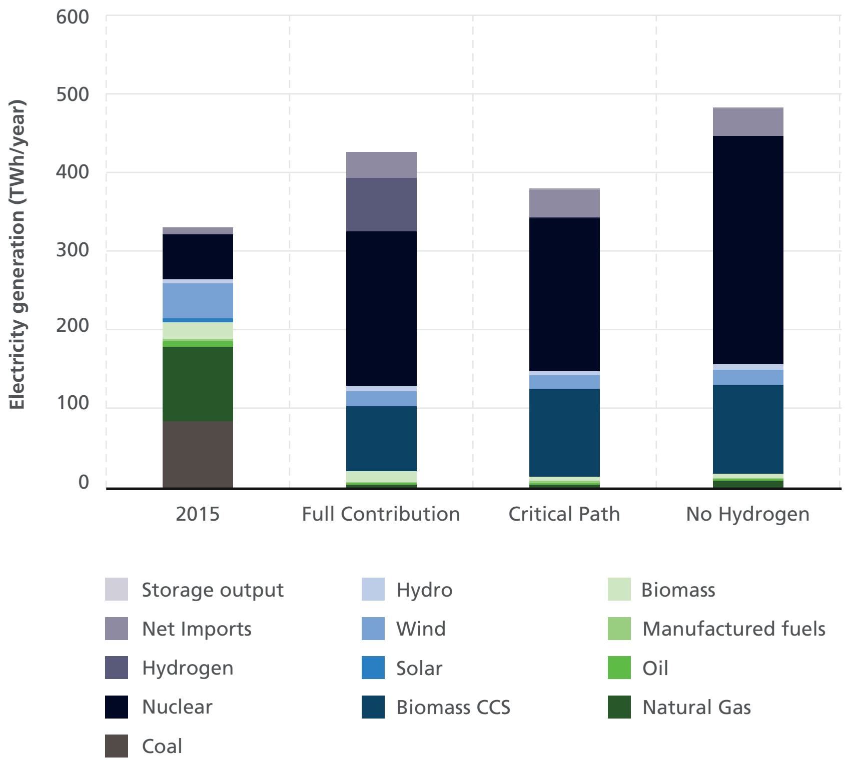


Figure 7.5 Annual electricity generation in 2015, compared to the three scenarios in 2050.



Total primary energy supply (TPES) in all three scenarios in 2050 is similar to the present (Figure 7.6), as improvements in the efficiencies of technologies are offset by higher energy service demands in the future. Nuclear and bioenergy have much larger roles in all three scenarios, at the expense of coal and oil in particular. The importance of SMR is shown by the higher penetration of natural gas in the two hydrogen scenarios than in the No Hydrogen scenario.

Final energy demand for each commodity is shown in Figure 7.7. The principal impact of hydrogen is to displace natural gas and petroleum in the end-use sectors (with the natural gas used to produce hydrogen in upstream SMR plants). Although the share of electricity increases compared to present, it doesn't exceed 30% in any of the scenarios, compared to around 20% at present.

Much of the energy security debate is concerned with import dependence. Figure 7.8 shows that most net commodity imports increase by 2050 in the three scenarios compared to 2015. This reflects a greater role for bioenergy and nuclear power, and the winding-down of indigenous oil and gas extraction from the North Sea.

Figure 7.6 Total primary energy supply in 2015, compared to the three scenarios in 2050. The physical energy content method is used to assess the share of nuclear and renewables.

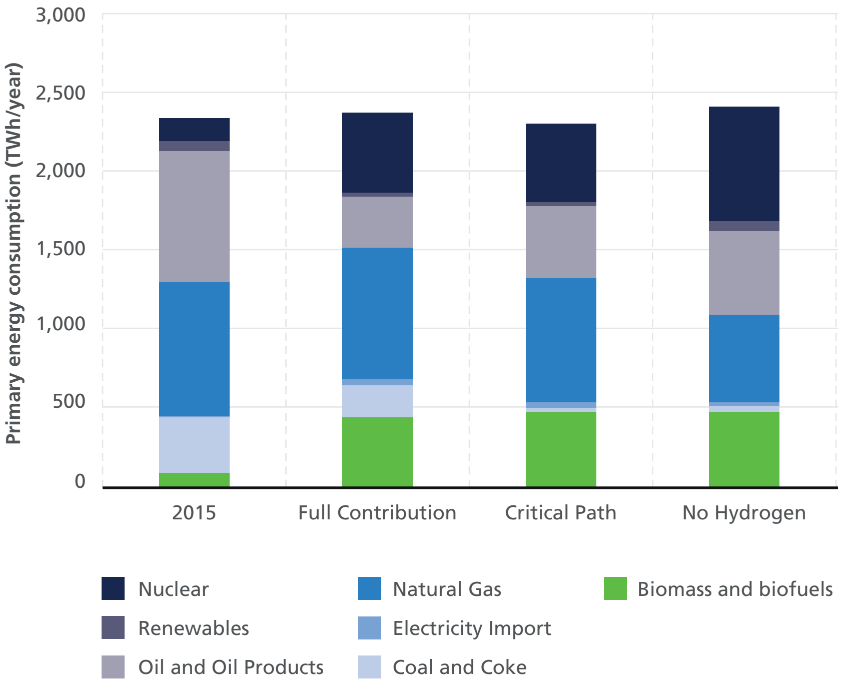


Figure 7.7 Final energy demand by commodity in 2015, compared to the three scenarios in 2050.

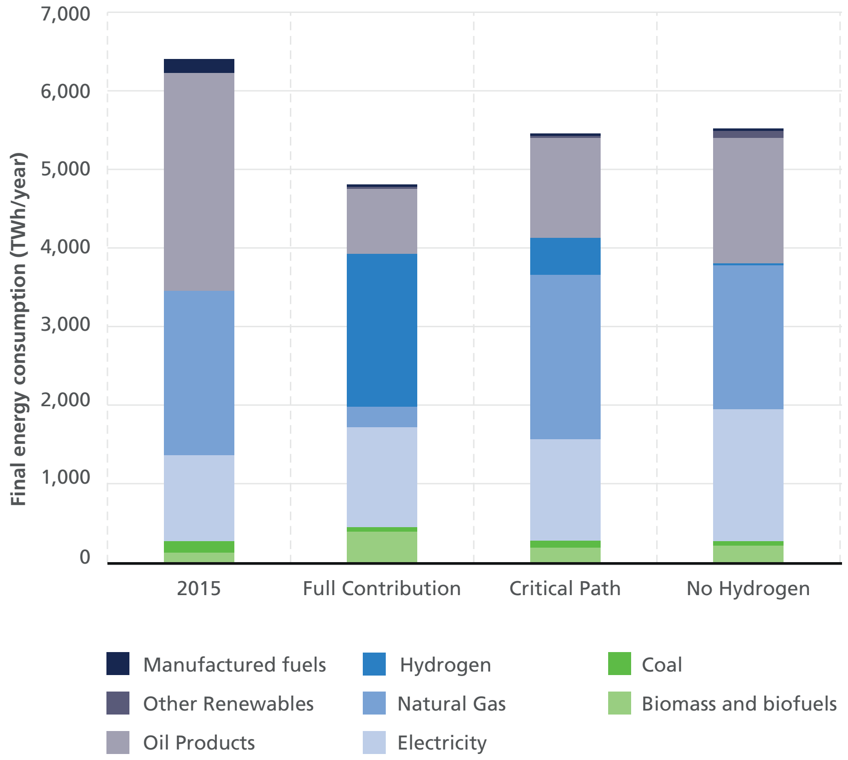
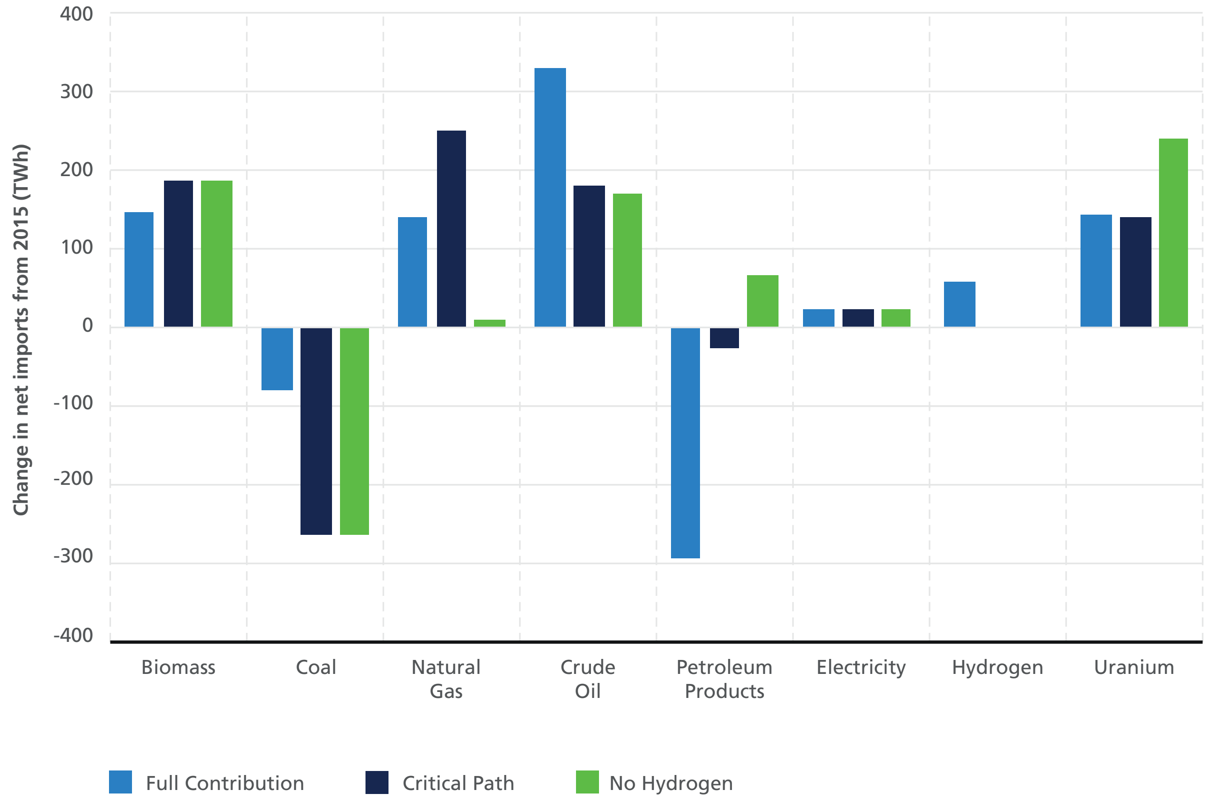


Figure 7.8 Change in net commodity imports in 2050 from 2015 in the three scenarios. The uranium figures have been reduced by a factor of 10 to aid visualization.



7.3.3 Analysing energy security changes using metrics

There are no clear differences between the scenarios from an energy security perspective. Hydrogen tends to broadly displace natural gas and petroleum-fuelled technologies rather than electrical devices, so diversity does not appear to greatly change. Although imports tend to increase relative to the present, they reduce substantially for some commodities.

A common measure of energy security is the diversity of a system, since increasing diversity is likely to spread the risk and reduce the impact of unexpected events [188]. The Shannon-Weiner index can be used to examine energy system diversity. Table 7.1 shows that all three scenarios have higher TPES diversity than the current energy system. On the other hand, if reliance on imports is taken into account using the modified Shannon-Weiner-Neumann index, then all three scenarios have lower diversity than the current energy system. For both indices, Full Contribution has the highest diversity of the three 2050 scenarios.

Table 7.1 Shannon-Weiner and Shannon-Weiner-Neumann indices for total primary energy supply (TPES) in the three scenarios and the current energy system. The Shannon-Weiner index varies between 0 and 2, with higher values indicating higher diversity, and the Shannon-Weiner-Neumann index similarly varies between 0 and 4.

	Shannon-Weiner	Shannon-Weiner-Neumann
Current energy system	1.43	2.15
Full Contribution	1.61	2.03
Critical Path	1.51	1.86
No Hydrogen	1.54	1.94

The Shannon-Weiner index can similarly be used to examine diversity across key parts of the energy system. Table 7.2 shows indices for electricity generation, hydrogen production and final energy demand in the residential and road transport sectors. Electricity generation has lower diversity in the three scenarios than at present. Higher hydrogen consumption leads to higher diversity in electricity generation and hydrogen production. The picture is more nuanced in the end-use sectors. For the residential sector, Full Contribution has the highest diversity while Critical Path has a lower diversity than at present. In contrast, Critical Path has the highest diversity for road transport and Full Contribution the lowest, although diversity in all three sectors is much higher than at present as the domination of petroleum products ceases.

Table 7.2 Shannon-Weiner indices for electricity generation, hydrogen production, and residential and road transport final energy demand.

	Electricity	Hydrogen	Residential sector	Road transport
Current energy system	1.76		0.82	0.08
Full Contribution	1.48	0.55	0.96	0.32
Critical Path	1.27	0.31	0.71	0.94
No Hydrogen	1.15		0.82	0.35

7.4 INCREASING FUTURE ENERGY SYSTEM RESILIENCE

The previous section showed that the evolution to a low-carbon energy system is likely to change the degree of diversity of the UK energy system, with diversity increasing in some areas and decreasing in others. Energy commodity import dependence increases in all of the scenarios. This section identifies strategies to increase resilience in the future and examines the financial impacts of these strategies.

7.4.1 Minimising fuel consumption

Fuel consumption can be reduced through several strategies:

- investing in end-use technologies with improved efficiencies, such as condensing boilers and hybrid cars with high fuel efficiencies;
- changing end-use fuels to reduce lifecycle fuel consumption;
- reducing energy service demands by investing in conservation measures such as building insulation, which has capital cost implications; and,
- reducing energy service demands by changing consumer behaviour, for example by travelling less or heating houses to a lower temperature, which reduces the utility of the energy service to consumers.

Regulations have tended to increase the efficiencies of end-use technologies in recent years, for example the requirement to fit condensing boilers in the UK and the minimum fleet fuel efficiency for car manufacturers in the European Union. Options for electricity and hydrogen in heat and transport are compared with current technologies, for the year 2050, in Table 7.3. Hydrogen fuel cell electric vehicles are substantially more efficient than fossil-fuel equivalents, but not as efficient as battery electric vehicles. In contrast, hydrogen boilers are no more efficient than natural gas boilers, and much less efficient than electric heat pumps.

In the future, the choice of end-use fuels is likely to become more limited due to climate change mitigation strategies, since it is difficult to capture CO_2 from the organic fuels that dominate heat and transport provision. Electricity and hydrogen are the only two zero-carbon energy carriers under serious consideration for end-use devices, with biomass also offering an option if it can be supplied sustainably and if the impact on air quality is sufficiently low.

Although switching fuels can enable an increase in the efficiency of end-use devices, for example when moving from natural gas boilers to electric heat pumps, this does not necessarily reduce fuel consumption across the energy system. This is because greater efficiency losses are incurred during electricity generation, as explained in Box 1. The impacts can be difficult to assess. For example, replacing hydrogen boilers with hybrid micro-CHP fuel cells would generate electricity in homes at high efficiency during times of peak demand, reducing central generation requirements and loads on the electricity networks and hence supporting the introduction of heat pumps in other homes [107]. The benefits of these technologies were examined in the H2FC White Paper on Heat [160].

Even if fuel consumption were reduced, supply interruptions would still have a similar impact. The frequency of supply interruptions could even be increased by fuel switching to reduce consumption, for example through an increase in electrification if it created much greater demand peaks that required high investment in both networks and generation capacity. The principal energy security benefit of reducing fuel consumption might be a reduction in import dependence for key commodities.

BOX 7.1 IMPACTS OF ELECTRIFYING HEAT ON NATURAL GAS CONSUMPTION

Natural gas is currently piped to homes and combusted in an efficient boiler at 84% efficiency.

A homeowner installing an electric air-source heat pump with an average efficiency of 250% would achieve a substantial reduction in home energy use. However, if the additional electricity were generated using natural gas, in a CCGT plant with an efficiency of 53%, then only a 37% reduction in gas use across the system would be achieved. If an OCGT were used then only a 4% saving would be realised. Nuclear power or renewables could of course be used to generate electricity instead.

Substantial capital investments in electricity generation plant, heat pumps and possibly home insulation would be required, meaning that the total cost to the consumer would likely increase. For this reason, UK Government incentives for heat pump installation, in the Renewable Heat Incentive, are targeted at homes without connections to the gas networks in which heating is much more expensive.

Table 7.3 Comparison of expected efficiencies of key end-use technologies across the energy system in 2050. The Conventional column lists the most efficient technologies in 2050 that use the dominant fuels of today in the UK (i.e. natural gas for heat and petrol/diesel for road transport. The Hydrogen and Electric columns list the counterparts of these technologies. For CHP and micro-CHP (mCHP), including fuel cells (FC), the values in brackets show the electricity fraction of the total output. The Heat rows show conversion efficiencies (%). The Road Transport row figures show the fuel economy.

Sector	Conventional	Hydrogen	Electric
Building heat	Gas boiler: 84%	Boiler: 84% mCHP FC: 95% (44% elc)	Heat pump: 250%
Industrial heat	Boiler: 90% CHP: 76% (42% elc)	Boiler: 90% CHP: 76% (42% elc) CHP FC: 83% (63% elc)	Immersion heater: 100%
Road transport	Hybrid car: 0.68 km/MJ	FC car: 1.14 km/MJ	Battery car: 1.89 km/MJ

7.4.2 Network challenges and strategic storage opportunities

A resilient energy system depends on resilient energy delivery infrastructure. The UK electricity and natural gas networks currently operate with very high levels of availability. In the future, the electricity network could be stressed by increased demand swings from electrification of heat and/or transport and from increased deployment of inflexible generation assets such as intermittent renewables and nuclear power plants. The impacts of these are a key research area for the UK research community.

Hydrogen networks would be expected to operate similarly to existing natural gas networks. Key pinch-points in the existing system are coastal import terminals such as Bacton, where an extended interruption during winter could cause a supply shortfall [189]. A hydrogen system would likely have fewer such pinch-points, as production assets would be much greater in number and would be much more distributed around the network. One issue is that the lower density of hydrogen compared to natural gas means that the amount of network linepack, which is energy stored in the network that is used to balance variable demands, would be around a quarter of the existing natural gas linepack in pipes of the same size. From a distribution network perspective, the H21 Leeds City Gate study concluded that very little network reinforcement would be required to deliver hydrogen through the existing natural gas networks [128].

One method to improve energy security and avoid disruptions is by constructing a strategic store for a resource. For example, the UK has strategic stores of coal, oil and gas at present. Table 7.4 lists the costs of some electricity and gas storage technologies. The only electricity storage technology with a sufficiently-low storage cost that would be suitable for a strategic store would be compressed-air energy storage (CAES). The cost of this is very sensitive to the cavern geology and is also uncertain as few commercial plants have been constructed [190]. In the past, it has been cheaper to deploy excess generation capacity in preference to electricity storage; for example, gas-fired OCGTs have lower costs per power output than CAES. While the costs of CAES might reduce in the future if substantial renewable deployments lead to periods during which generation substantially exceeds demand, this change is not relevant for a strategic store which would be expected to be permanently full and on standby.

Underground geological storage would also be the cheapest option for hydrogen; salt caverns are widely used for natural gas and have also been used to store hydrogen for industrial applications. There is also evidence that larger depleted gas fields could be used for strategic hydrogen storage, in a similar way to the Rough gas field for natural gas [191], and these have lower storage costs than salt caverns. In general, hydrogen can be stored at a large scale more cheaply than electricity and the technology is mature.

Table 7.4. Capital costs of electricity and gas storage (£ in 2016).

	Cost/storage (£/kWh)	Cost per power output (£/kW)
Electricity		
Lead-acid batteries	220	266
Lithium-ion batteries	399	266
Compressed-air energy storage	0.1–18	600
Pumped hydro	50	798
Hydrogen		
Salt cavern	2–5	305

Electricity cost sources: [190, 192]. Hydrogen cost source: [193].

7.4.3 Low reliance on imports

Reducing reliance on imports is widely considered a strategy to improve energy security. For example, the USA aims to achieve energy independence from OPEC and from any nations considered hostile [194]. The increase in energy commodity import dependence by 2050 in all of the scenarios, compared with the current energy system, could be therefore considered by some as reducing UK energy security.

The implications of reducing reliance on imports can be examined in the three scenarios by setting additional constraints:

- Total imports must be less than 10% of total resource consumption.
- Oil imports must be less than 20% of total oil consumption.
- Natural gas imports must be less than 20% of total natural gas consumption.
- Coal imports must be less than 20% of total coal consumption.

The Shannon-Weiner and Shannon-Weiner-Neumann indices for primary energy consumption in these scenarios are shown in Table 7.5. Comparing these with Table 7.1 shows that the diversity of resource consumption in 2050 is reduced to similar levels to today, but that import dependence is lower than today as the modified Shannon-Weiner-Neumann indices are higher. Full Contribution, with the highest hydrogen deployment, has the highest diversity for both indices.

Table 7.5 Shannon-Weiner and Shannon-Weiner-Neumann indices for total primary energy supply (TPES) in the three scenarios and the current energy system, taking an insular approach that minimises imports in the three scenarios.

	Shannon-Weiner	Shannon-Weiner-Neumann
Current energy system	1.43	2.15
Full Contribution	1.48	2.39
Critical Path	1.42	2.27
No Hydrogen	1.44	2.27

7.4.4 Diversity and redundancy

Energy security could be improved by increasing diversity and redundancy in key parts of the energy system [26].

Increasing redundancy for hydrogen production and electricity generation would require additional capital plant investments, with lower overall capacity factors across the fleets that would increase the overall production costs and the prices for consumers. In the event of a disruption to the electricity system, demand management measures would likely be a much cheaper short-term approach to cope with a disruption. The UK electricity system already operates with substantial excess generation capacity in order to avoid supply disruptions during winter peak demand. Demand management measures are used by National Grid to cope with high demands, in which large users agree to reduce their electricity demand during the winter peak if there is a shortfall in generation capacity, in return for lower electricity prices [195]. Such measures have been successful in other countries; for example, following the Fukushima disaster in Japan, 50 nuclear power stations that are located in areas of high earthquake and tsunami risk, with a capacity of almost 50 GW, were shutdown for stress testing. A public campaign led to peak summer electricity demand reducing by 18% in the affected areas [196].

If hydrogen were predominantly used in the transport or industry sectors, then the demand would be largely flat and production plants would ideally operate with a high capacity factor. It might be possible to reduce demand if a disruption occurred, but the lack of spare capacity might make it more difficult for the system to cope. It would be possible to build additional production capacity, but since hydrogen is much cheaper to store than electricity, there might be a stronger case for building a strategic reserve. If hydrogen were used for building heat provision then demand would be much higher in winter than summer, and the H21 Leeds City Gate study envisages deploying some production plants that are only used in winter [128]. In this case, the additional capacity, which would likely be composed of gas SMR plants as these have the lowest capital costs, would provide a buffer against supply disruptions in part of the system.

A resilient energy system might have sufficient diversity so that any disruption would affect a small-enough part of the system for in-built redundancy to cope. The implications of requiring diversity in electricity generation and hydrogen production portfolios can be examined in the three scenarios in UKTM by setting additional constraints to limit the capacity of plants using each fuel type. For electricity generators, a simple limit on capacity is insufficient as the aim would be for the remaining undisrupted capacity to generate on demand and intermittent renewable generation are not controllable in this way. The capacity constraints were therefore set up to account for the contribution of each type of generation to peak. They required each type of generation, with the exception of renewables, to account for no more than 25% of total capacity by 2050 for both electricity generation and hydrogen production. Table 7.6 shows that the electricity diversity in 2050 in all three scenarios approaches the levels of the current energy system when these constraints are applied, and hydrogen production diversity is also much higher.

Table 7.6 Shannon-Weiner indices for electricity generation and hydrogen production in 2050 for the base and diversified versions of the three scenarios, together with the current energy system in 2015.

	Electricity	Electricity diversified	Hydrogen	Hydrogen diversified
Current energy system	1.76			
Full Contribution	1.48	1.70	0.55	1.35
Critical Path	1.27	1.65	0.31	1.33
No Hydrogen	1.15	1.63		

7.4.5 Cost of increasing diversity and import independence

As explained in Chapter 2, one of the key requirements of a secure energy system is affordability. There is a cost to increase the resilience of a system and so trade-offs must be chosen between increasing resilience and decreasing affordability.

UKTM can be used to examine the cost impacts of increasing resilience through increasing diversity and increasing import independence (an insular approach).

Table 7.7 shows these costs relative to the least-cost method of meeting the UK's greenhouse gas commitments. A small cost increase is required in all three scenarios in order to diversify both electricity generation and hydrogen production. Diversifying electricity is generally cheaper than diversifying hydrogen, due to the greater number of generation options such as nuclear power and renewables, but neither is particularly expensive. On the other hand, achieving high levels of independence from imports is a very expensive approach that increases the cost of decarbonisation by a factor of 3–4. A strategy focusing on diversifying import sources would likely be much cheaper than a strategy focusing on avoiding imports, although further studies would be needed to provide evidence for this assertion.

Adopting an insular approach to imports does not lead to diversified production portfolios. Table 7.7 shows that the cost of achieving both diversified and insular systems is approximately additive of achieving either independently.

Table 7.7 Total discounted costs of constructing resilient and insular energy systems in each scenario. See the main text for definitions of "resilient" and "insular". All costs are relative to the smallest increase in costs required to meet the UK 80% GHG reduction target in 2050 in an unconstrained UKTM scenario, relative to the reference scenario with no GHG targets. So this unconstrained scenario has a cost = 1.

	Base	Diversified	Insular	Insular and diversified
Full Contribution	2.3	2.3	6.0	6.3
Critical Path	1.2	1.2	4.8	5.0
No Hydrogen	1.1	1.2	4.8	5.0

7.5 DISCUSSION

Hydrogen is the only zero-carbon energy carrier other than electricity under serious consideration for future energy systems. Introducing hydrogen might be expected to improve energy security by adding diversify to end-use technologies. In fact, although adopting hydrogen in the scenarios increases resource diversity, the impact on end-use diversity is scenario-dependent and there is no clear trend. This reflects that not adopting hydrogen does not lead to whole-scale electrification of heat and transport, with fossil fuels continuing to supply some demand in least-cost scenarios, particularly if negative emission technologies such as biomass CCS are cost-effective and available.

Nevertheless, hydrogen does not generally reduce energy security and offers a number of opportunities to improve it in addition to increasing resource diversity, for example by contributing to electricity system balancing if high levels of renewables are introduced, or offering a cheaper option for large-scale strategic energy storage. Moreover, hydrogen pipelines are widely-used and well-understood, and an infrastructure system could be constructed as resilient as the existing natural gas system if the substantially lower linepack could be managed. The infrastructural uncertainties for future electricity systems are arguably more uncertain than for hydrogen and are the subject of numerous research projects.

7.5.1 Improving resilience through diversity and reducing import dependence

The cost of increasing diversity in electricity generation and hydrogen production is comparison. Yet it is not clear than reducing import dependence would greatly increase energy security. Of the three energy security events faced by the UK in the last four decades, the oil refinery blockades in 2000 and coal miner strikes in the 1980s were domestic and unaffected by import dependence. The quadrupling of the oil price in the 1970s did have a substantial economic impact and underpinned the development of oil production from the North Sea. While this to some extent sheltered the UK economy from future high oil prices through increased corporate and government revenues, consumers were still required to pay higher prices. It is not clear that the high cost of reducing imports would greatly improve energy security, and a strategy to diversify suppliers and import routes would likely be much more cost-effective.

7.5.2 Systemic disruptions to energy systems

One method to increase electricity and hydrogen diversity is to use hydrogen to generate electricity in fuel cells or CCGTs, and vice versa using electrolysers, as occurs to a small extent in the Full Contribution scenario. There is a risk that systemic weaknesses could arise from this approach that would adversely affect security in both systems, for example through the loss of supply or price volatility of a key energy commodity that were used in both systems, which could be coped with by either system in isolation but not by the coupled system. Aggregation of data in large-scale models such as UKTM can disguise the vulnerability of certain sectors to systematic risk [22]. Such issues could be identified through stress testing.

7.5.3 Temporal resolution modelling issues

The general system analysis modelling approach used in this chapter can be used to examine how energy security might change as a result of long-term evolutions of an energy system. It necessarily has low resolution, which means that short-term imbalances are not considered in the analysis. A high-resolution model (e.g. an hourly dispatch model) would be an appropriate tool for verifying, for example, that sufficient peak electricity generation capacity is constructed when high levels of renewable generation are deployed. The scenarios in this chapter do not have high renewable penetrations so this is not an important issue. Nevertheless, a high-resolution dispatch model has been used to examine a range of UKTM scenarios and load curves, and the electricity generation capacity deployed by the model has generally been found to be appropriate.

Commodity prices have displayed high volatility in recent years. Important economic threats such as price volatility are not considered in this analysis as UKTM uses average prices in 5-year periods [27]. Increasing the fuel diversity of a system is a potential hedging strategy to reduce the impacts of price volatility, and the analysis in this chapter has not assessed these benefits. On the other hand, increasing diversity offers fewer opportunities to reduce costs of technologies through innovation. Further research to explore these issues would be valuable.

7.5.4 Limitations in the chosen scenarios

Only three scenarios have been examined in this chapter, and all contain substantial investments in biomass CCS plant. The costs and performance of biomass CCS are not well understood, and the unavailability of biomass CCS or even CCS in general would be likely to substantially increase the cost of decarbonisation. The provision of affordable, low-carbon hydrogen is more dependent on CCS than affordable, low-carbon electricity, so the unavailability of CCS would make hydrogen investments more difficult to justify, making increased electrification more likely and greatly reducing energy system technology diversity.

The total economic UK oil and gas resource base is uncertain. For the analyses of resource import independence, UKTM has an estimate of yet-to-be-discovered reserves, and identifies an optimal extraction strategy to meet energy system constraints. Historically, extraction strategies for gas in particular have depended on fossil fuel price expectations and resources have been extracted and exported when economic. It is unlikely that a long-term strategy to conserve resources, as implicitly envisaged in some of the insular scenarios, would be adopted.

Most end-use technologies can use only a single fuel, but some flexible technologies have been developed, for example:

- Hybrid heat pumps that primarily use electricity but have a back-up gas or hydrogen boiler.
- Plug-in hybrid fuel cell cars that can use electricity or hydrogen. These could potentially be a substantial electricity generator for houses if the electricity supply were disrupted. They could also be used in conjunction with solar PV and batteries to supply electricity to remote buildings without a grid connection.

Electric immersion heaters offer a back-up option for heat provision, albeit much more inefficiently than heat pumps. The particular benefits of these technologies for energy security has not been considered in the analyses presented in this chapter, but could be in the future.

7.6 CONCLUSIONS

This chapter has examined how UK energy security might change as a result of the evolution to a low-carbon energy system, using three scenarios examined using the UKTM energy system model.

The energy system diversity is likely to change in the future, with increases in some areas and decreases in others. Energy commodity import dependence increases in all of the scenarios. Hydrogen tends to increase diversity over strategies that focus on electrification, but not in all parts of the system or in all circumstances. Technology diversity for hydrogen production and electricity generation could be increased at low cost and are potential long-term strategies for the UK government.

Reducing reliance on energy commodity imports, on the other hand, would be much more expensive and alternative strategies would likely be more cost-effective.

Hydrogen offers other benefits for energy security. It can contribute to electricity system balancing if high levels of renewables are introduced, through the deployment of power-to-gas electrolysers. Hydrogen delivery infrastructure is resilient and well-understood, and hydrogen offers a cost-effective option for large-scale strategic energy storage with proven technologies.