# CHAPTER 2

# DEFINITIONS OF ENERGY SECURITY

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## 2.1 INTRODUCTION

Energy security has often been viewed by governments from engineering and geopolitical perspectives. The engineering perspective is concerned with the safe and reliable operation of energy technologies, and is achieved primarily through regulation. While this has mostly focused on individual plants, such as nuclear power stations, there is now a move to considering the stability of the wider electricity system in countries such as the UK, Germany and Australia, due to the increased penetration of low-carbon intermittent renewable generation. The geopolitical perspective has historically been mostly concerned with security of resource supply, with the aims of ensuring that the UK had access to a steady supply of fossil fuels at a stable price, and to some extent promoting energy independence and the development of domestic fossil fuel reserves [17, 18].

More recent academic research has attempted to widen the scope of energy security to focus on the entire energy system, from primary energy resource acquisition to final energy consumption, and has proposed that energy security is not just about ensuring a reliable supply of fuel, but also ensuring that there is reliable infrastructure in place to carry energy to the end user [8, 19–22]. The affordability of energy to all users has become a part of some definitions of energy security, along with ensuring that energy use does not have an overly detrimental impact on the environment. Security, affordability and environmental sustainability have become known as the energy trilemma, and are the overarching aims of the UK Government. This chapter examines a range of energy security definitions from the literature. These concentrate primarily on the geopolitical aspects of energy security, although they are in some cases also applicable to the engineering aspects.

There is no accepted quantitative measurement of energy security, but a range of indicators have been proposed to measure various aspects. These examine, for example, the diversity of energy supplies, import dependence, and more recently infrastructure reliability, load factors and price levels, along with many others [8, 20, 22–25].

This chapter examines the academic debate surrounding energy security. Section 2 reviews some of the definitions of energy security in the literature. Section 3 considers how hydrogen might affect UK energy security. Section 4 identifies indicators that could be used to measure aspects of energy security. Section 5 explains the definition of energy security used in this White Paper, and the relevant indicators that are used in subsequent chapters.

## 2.2 DEFINITIONS OF ENERGY SECURITY

Many definitions have been proposed for energy security. Much of the academic literature in this area proposes frameworks for describing energy security, and general policies to improve energy security, rather than trying to measure energy security. Where energy security analyses have been performed, a wide range of methods from economics, engineering, political science, system studies and natural science have been adopted [26], and these tend to be one-off rather than holistic studies. Very little consideration has been given to energy security in future low-carbon energy systems.

### 2.2.1 Early definitions

No concrete definition of energy security has emerged from the literature, but definitions have evolved over time. Several papers trace the origins of interest in energy security back to the oil shocks of the 1970s [17, 18, 20], and cite this as a reason for much of the energy security debate being focused on security of supply, and specifically the security of the oil supply (and more recently, gas).

Some argue that liberalisation of UK energy markets, which resulted in reduced prices and greater availability, increased energy security during the 1980s and 1990s, with energy security becoming less of a concern until increasing price volatility in the early 2000s brought it back into focus [20].

Nevertheless, geopolitical energy security at government level is still primarily concerned with the supply of fossil fuels, with a typical definition in OECD countries being summarised as ‘the availability of sufficient supplies at affordable prices’ [17].

### 2.2.2 Widening the definition of energy security

The definition of energy security has expanded beyond the initial focus on security of supply to include a wider range of factors, often referred to as the “four As” of energy security – availability, affordability, accessibility and acceptability (Box 2.1) [19, 20, 27]. These tend to be applied to security of supply. Cox [22], in a study focused on current and future electricity systems, argues for similar framework consisting of availability, affordability, reliability and sustainability. Reliability is defined as the ability to cope with short-term shocks. Sovacool and Mukherjee [28] identify five dimensions: availability, affordability, technology development, sustainability and regulation.

### BOX 2.1 THE “FOUR As” OF ENERGY SECURITY

**Availability** ensures that energy supplies are available in sufficient amounts.

**Affordability** aims to have these resources available at sufficiently-low prices.

**Accessibility** focuses on ensuring all citizens have access to energy, which is to some extent about ensuring that reliable infrastructure is in place to ensure a robust supply for the end user, but this is generally interpreted in practice as ensuring that energy prices are kept low and fuel poverty is minimised.

**Acceptability** is concerned with the negative impacts of energy, such as pollution and environmental damage, and ensuring that these impacts are minimised in order to make the energy acceptable to the customer.

While the “four As” approach has made progress in expanding the focus of energy security, a criticism is that they only define certain aspects of energy security, rather than providing a robust and comprehensive definition of what energy security actually is. These definitions are difficult to interpret in a practical, holistic and quantitative manner, in order to measure energy security.

### 2.2.3 A vulnerability-based approach to energy security

Cherp and Jewell [19] believe that it is necessary to answer three key questions to identify vital energy systems: (i) ‘security for whom?’; (ii) ‘security for which values?’; and, (iii) ‘security from what threats?’. They argue that energy security is underpinned by vital energy systems having low vulnerability, with the identities of vital systems defined by answering the three questions. Vulnerability is defined as a combination of exposure to risk and resilience of the system. Jewell et al. [24] explore this approach by identifying vital energy systems and their vulnerabilities.

Mitchell et al. [20] define energy security as a property of energy systems, which are vulnerable to a range of risks that shift with time and location, requiring a range of strategies for the resilience of the energy system as a whole. They identify four key aspects: stability (the ability to cope with internal shocks, e.g. infrastructure failure), resilience (the ability to deal with external shocks, e.g. supply disruptions), durability (the ability to cope with long term internal stresses, e.g. increased demand) and robustness (the ability to cope with long term external stresses, e.g. resource depletion).

In contrast to those that provide a wide ranging and comprehensive concept of energy security, Winzer [29] suggests narrowing the definition to the concept of energy supply continuity, concerned with risks to the continuity of supply. The risks are classified as technical (e.g. failures in infrastructure), human (e.g. demand fluctuations, withholding supplies or underinvestment), and nature (e.g. intermittent renewables, resource depletion or natural disasters).

One reason for the diversity of definitions is that stakeholders have different perspectives on energy security. It has different meanings in different markets; for example, energy security means different things for the gas market than it does for the electricity market, and more generally means different things to producers, consumers, countries, companies, policymakers and other stakeholders [18]. The government approach to national energy security depends to some extent on these perspectives; for example, if a reliable electricity supply is the norm, then an increase in interruptions is likely to have far more serious political repercussions than if a reliable supply is not normally available.

### 2.2.4 Timescales

The vulnerability-based approaches highlight that different aspects of energy security occur on different timescales. For example, stability and resilience are focused on short-term shocks, while durable and robust systems are those that cope well with longer-term changes to aspects of the energy system [30]. Winzer [29] argues that most studies focus on short-term shocks and that there is a need for examination of long-term discontinuities. If a risk-based approach is taken to energy security, then the temporal dimension should be considered as risks differ across short, medium and long-term horizons [18].

Cox [22] asserts that there is too much focus on improving current energy security, with little thought of energy security in the future, and that the literature differentiates too much between short- and long-term aspects of energy security. It is argued that a more comprehensive approach is needed to assessing all aspects of energy security, both now and in the future, and presents the framework shown in Figure 2.1.

### 2.2.5 An emerging focus on the electricity system

Although the supply of fossil fuels has been the principal focus of governments historically, security of supply from the electricity system is attracting increasing attention. One reason is that capacity margins to meet peak demands have been steadily eroded in many countries since liberalisation in the 1990s, due to the creation of markets focused on short-run costs, and the margin in the UK for peak winter demand is now very tight. This has led to the recent creation of an electricity generation capacity market in the UK. Another reason is the increased penetration of inflexible generation such as renewables, as the electricity supply is decarbonised, which could increase the risk of supply interruptions and require a fundamental change to the electricity system [18].

In the future, some scenarios have suggested an increasingly-important role for low-carbon electricity as a replacement for natural gas in heating and oil in transport [31]. Electricity supply is increasingly becoming the subject of energy security studies. Chester [18] argues for a greater focus on electricity, as it is now the ‘world’s most dominant form of energy supply to the economy’. Some believe that long-term energy security threats are mostly related to a lack of generation capacity in the system, and identify a trade-off between increasing security and increasing cost [20]. Others have argued that energy policy should focus on supporting system flexibility, for example through network reinforcement, demand-side response and storage, rather than providing additional capacity [22].

A general theme of these studies is the wider focus on infrastructure and systems, compared to previous studies, with Yergin [17] arguing that the concept of energy security should be updated to include the protection of the entire energy supply chain and infrastructure.

### 2.2.6 UK Government perspective on energy security

The UK Government’s Energy Security Strategy (ESS) [8] states that the ‘Government is primarily concerned with ensuring customers have access to the services they need (physical security) at prices that avoid excessive volatility (price security)’. In stating that customers must have access to energy services, the strategy implies that physical security applies to the whole energy system, from primary resources right through to distribution networks. However, the definition of price security is less comprehensive, with the focus on excessive volatility and no consideration of long-term affordability. The ESS recognises the need to deliver energy security in conjunction with reductions in greenhouse gas emissions, and that growth of renewable energy can improve energy security by reducing reliance on energy imports. It acknowledges that energy infrastructure should be resilient to increasingly-volatile weather that might result from climate change. The ESS recognises that major changes to energy systems are coming, and recognises that there will be capacity and balancing challenges, requiring investment in infrastructure, and the development of new infrastructure technologies such as storage and interconnection. However, beyond these recommendations on specific areas of investment, it does not provide a comprehensive strategy for how to ensure these challenges are met or when these they will have been met.

The Government's Energy Sector Indicators report [32] states that their approach towards energy security is concerned with the level of energy demand, diversity of fuel supplies, energy prices, fuel stock levels and spare capacity. This heavy focus on resources is somewhat limited compared to the more comprehensive definition proposed in the ESS. A parliamentary report on energy security [25] similarly states that energy security targets include maximising domestic fuel reserves, reducing demand and diversifying imports, but also discusses infrastructure challenges and also threats from low investment, weather disruptions and market inefficiencies.

While there is an appetite for a comprehensive energy security policy for the UK, and an acknowledgement of the principal systems that should be analysed, there is not a holistic plan that considers the energy system as a whole and states what acceptable levels of energy security should be across the system and how they can be achieved.

### 2.2.7 Actions to improve energy security

A number of policies have been proposed to improve energy security. Energy security is not a policy but a set of policy measures that are implemented by governments to achieve their energy security objectives, however they define these [18].

Many of these policies are focused on energy resource availability, and include diversification of supply [17], which is achieved through not relying on a limited number of energy sources and not being tied to a specific geographic region for energy sources, for countries without abundant local energy resources [18].

More generally, building a resilient system that can withstand external shocks through managing risk is a key priority [17, 18]. Infrastructure investment has a key role in a resilient system [20], and there needs to be a continual flow of investment and technology in order for new resources to be developed [17]. Yergin [17] argues that governments should recognise the reality of integration and the importance of information.

It is difficult to assess changes in energy security without using quantitative analyses. For an electricity system, this might for example include high-resolution modelling of electricity dispatch for a range of scenarios. More widely, a wide range of energy security indicators have been developed to measure different aspects national energy security. For example, Jewell et al. [24] identify vital energy systems, including those that may emerge in future, along with identifying their vulnerabilities, and develop indicators to measure these vulnerabilities.

**Figure 2.1 Framework for the assessment of low carbon energy security, source: [22].**

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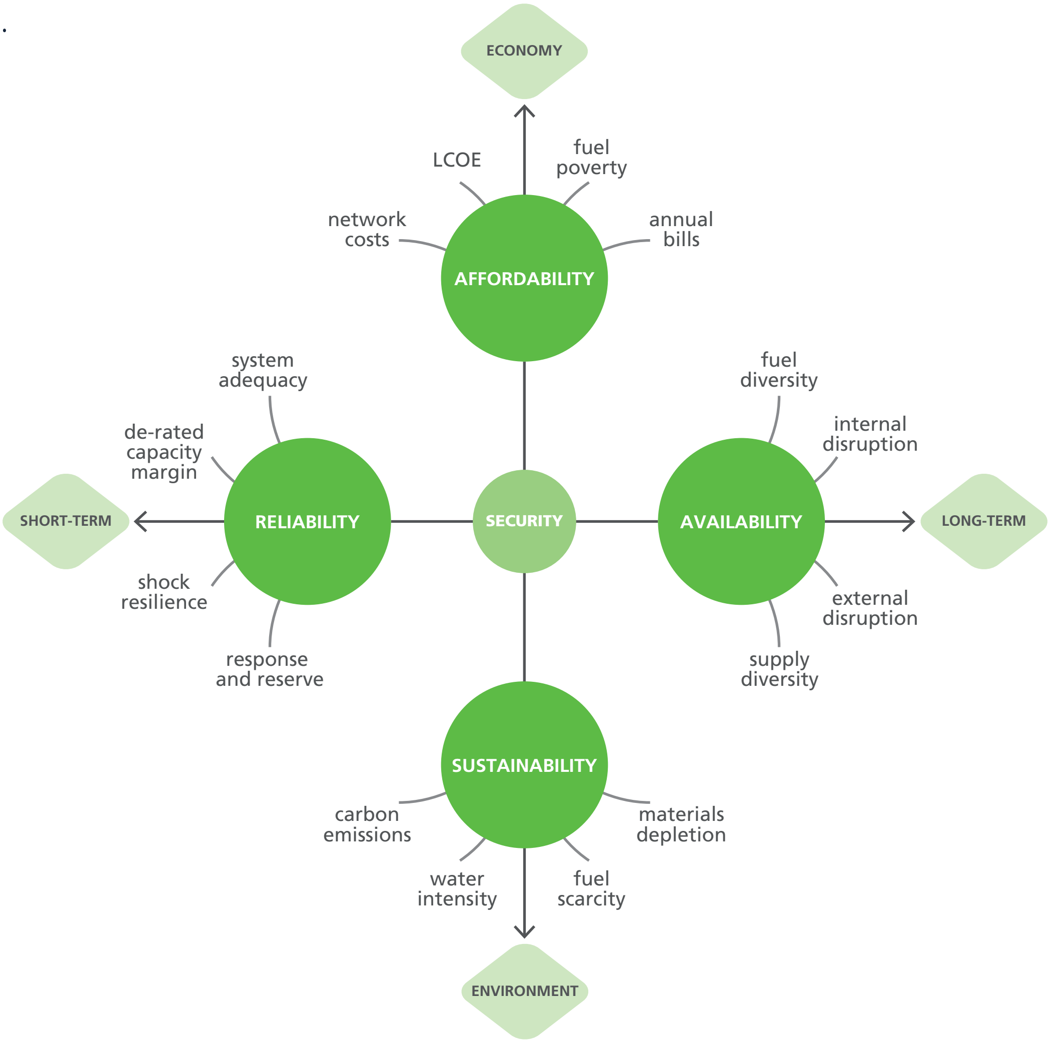

## 2.3 INDICATORS OF ENERGY SECURITY

Indicators are used to quantitatively measure aspects of energy security, and enable us to compare countries or systems and to explore changes in energy security over time. The choice of indicators depends to some extent on the energy security policies of a country and the definition of energy security that is being used [20].

### 2.3.1 Energy security indicators used by the UK Government

The UK Government, in their Energy Security Strategy [8], set out a list of indicators used to measure energy security:

- Electricity, gas and oil capacity.
- Electricity, gas and oil diversity.
- Electricity, gas and oil reliability.
- Short-term capacity margins.
- Forecast prices.
- Spare OPEC production of oil.
- Demand-side response.

These indicators are primarily concerned with security of supply and affordability, but consider both energy resources and the electricity system.

In addition to these energy security indicators, the UK Government produces a much wider range of energy system indicators [32], covering all parts of the energy system from fuel supply to infrastructure and price data. Some of them could contribute to a more comprehensive energy security strategy for the UK. More generally, the wide range of data collected in the annual Digest of UK Energy Statistics (DUKES) [33] could be used to create new indicators.

### 2.3.2 Complex indices

A widely-used energy security indicator quantifies the diversity of energy supply using the Shannon-Wiener diversity index [34], in which the diversity index, *H,* is defined as:

$$H = \sum_i \cdot p_i \ln p_i$$

where $p_i$ is the share of final energy generated by primary energy source *i*. $H$ is always a real positive number, in the range 0–2, with higher values indicating greater diversity. Some example calculations for the UK are shown in Box 2.2.

*The Shannon-Weiner index has been used to measure import dependence* [24, 25, 35], although some studies do not consider import dependence as an energy security issue if imports are obtained from a diverse range of suppliers [18, 20, 36, 37] (in fact, increasing imports could arguably improve energy security by increasing the diversity of the energy system). Neumann [38] proposes a modified Shannon-Weiner-Neumann index that accounts for the proportion of a resource that is produced indigenously:

$$H = \sum_i \cdot p_i \ln p_i (1 + g_i)$$

where $g_i$ is the share of indigenous production. This index varies in the range 0–4, with higher values indicating greater diversity and lower reliance on imports.

Lefèvre [39] defines two market-focused indices. The energy security price index (ESPI) is based on the measure of market concentration in competitive fossil fuel markets. The energy security physical availability index (ESPAI) is based on the measure of supply flexibility in regulated markets.

### 2.3.3 Assembling a holistic dashboard of energy security indicators

Assembling a holistic set of indicators is a difficult challenge. Mitchell et al. [20] identify four key issues: (i) the range of indicators often doesn't account for all relevant factors; (ii) there may be a reliance on data with weak and varying collection methodologies; (iii) correlations can arise between different indicators, which can increase the risk of problems due to hidden dependencies; and, (iv) the use of dimensionless scales (such as the Shannon-Wiener index) can be difficult to interpret and compare.

Jewell et al. [24] split indicators into three categories: (i) sovereignty; (ii) robustness; and, (iii) resilience. Sovereignty indicators include import dependence and the geographic concentration of a particular fuel or energy carrier. Robustness indicators include the risk of electricity blackouts and concerns about resource scarcity. Resilience indicators consider factors such as resource diversity and energy intensity. They recommend that present and future indicators should:

- be policy relevant to current and/or historical energy security concerns;
- be sufficiently generic to be applicable to energy systems which are radically different from present ones;
- be calculable from available and meaningful data in the model/scenario;
- provide information which is additional to that provided by other indicators; and, reflect key vulnerabilities of vital energy systems.

One approach to organising indicators would be to categorise them according to the energy security framework that has been adopted. Sovacool and Mukherjee [28] present a large number of indicators, categorised according to their proposed energy security framework and according to their complexity (simple, intermediate or complex). Table 2.1 lists a smaller set of potential indicators for the framework proposed by Cox [40].

Table 2.1 **Potential categorisation of energy security indicators, indicator sources: [8, 20, 22, 24].**

| Area of Energy Security | Related metric | Indicators | Notes |
|---|---|---|---|
| Availability | Internal disruption | Diversity of fuel types in the electricity mix | Using the Shannon-Wiener index |
| | | Public acceptability of electricity generation plants | Willingness of the public to accept construction of new electricity generation plants or domestic fuel extraction |
| | | Likelihood of disruptive opposition | Through such things as strikes or protests by staff, for which low commodity power could be an underlying driver |
| | External disruption | Diversity of fuel imports | Using the Shannon-Wiener index |
| | | Stability of fuel exporting nations | Likelihood of disruptions to fuel supplies due to civil strife in resource-rich nations |
| | | Import dependence | UK's reliance on imported fuels |
| | | Supply chains and choke points | Points at which the supply of fuels to the UK could be disrupted |
| | | Geographic concentration of fuel exporting nations | Is there over-reliance on a particular world region for fuels |
| | | Spare OPEC production of oil | Likelihood of oil shortages |
| Affordability | Fuel costs | Forecast prices | Will prices of fuel increase in future? |
| | Generation costs | Levelised Cost of Electricity | Current and future costs of electricity generation |
| | Network costs | Transmission upgrade costs | What are the expected costs to the transmission networks given planned/ expected developments |
| | | Distribution upgrade costs | What are the expected costs to the distribution networks given planned/ expected developments |
| | | Annual losses of reserve capacity plants | Estimation of the cost of maintaining back-up generation |
| | Cost to households | Annual electricity and heating bills | Do consumers have reasonable access to energy? |
| | | Number of households in fuel poverty | Are energy prices putting an unsustainable burden on households? |
| | | Number of poor quality inefficient homes | Are households suffering high bills due to poor quality buildings? |

| Area of Energy Security | Related metric | Indicators | Notes |
|---|---|---|---|
| Sustainability | Emissions | Carbon intensity of energy supplies | Measuring progress toward decarbonising the UK's energy supply |
| | | Cumulative GHG emissions | Measuring the UK's contribution to climate change |
| | Depletion and resource scarcity | Total energy use | Are we successfully reducing the UK's energy demand? |
| | | Energy use per capita | Are we successfully reducing the UK's energy demand? |
| | | Energy intensity | Are we successfully decoupling economic performance from energy demand? |
| | | Reserve to production ratios | A measure of how long until we start to run out of major fuels |
| | | Primary fuels depletion | The rate at which were are using irreplaceable fuels |
| | | Secondary materials depletion | Rate of depletion of essential materials such as rare earth metals |
| | Environment | Water consumption and withdrawals | Is power generation putting an unsustainable burden on the UK's water resources? |
| | | Air quality levels | Is the UK's power generation compromising the respiratory health of its citizens? |
| Reliability | System adequacy | Generation adequacy | Is supply sufficient to meet demand on an hour-by-hour basis? |
| | | Network adequacy | Is the network able to cope with peak demand levels? |
| | | Spare capacities for electricity generation | Is there enough spare capacity to cover intermittent generation? |
| | | Average age of infrastructure | Is the UK's power infrastructure up to date |
| | | Oil refinery capacity in the UK | Does the UK have adequate oil refining capacity? |
| | | De-rated generation capacity margin | The amount of excess supply above peak demand |
| | | Load factors and oversupply | Plant load factors used to identify areas of oversupply |
| | Resilience | Frequency response capability | Capability of types of generation in the mix to provide frequency response |
| | | Short-term operating reserve | Quantity of generation available to cover unexpectedly high demand |
| | | Demand-side response | Demand available to be turned off as a part of demand-side response |
| | | End-use sector diversity of carriers | How diverse are methods of delivering energy to the public? |
| | | National grid response and reserve requirements | National grid requirements for Frequency Response and Short Term Operating Reserve |

### 2.3.4 Interpreting indicators to quantify energy security

Some papers use aggregates of indicators to provide a single measure of energy security (or a few aggregated measures) [23, 41]. Others advocate a different approach, labelled the ‘dashboard’ approach, with a range of energy security indicators rather than an aggregated measure, and if one of the indicators is flagged as being too low/ high (depending on the measure), then that would be an indication that the energy system is not secure.

While aggregated measures can provide an easily interpretable single measure, they are heavily-dependent on the aggregation methodology, and the resulting measure is likely to be overly simplistic, to miss some nuances of the energy system, and yet be difficult to interpret. On the other hand, dashboard indicators, while not providing an easily readable single value, can provide a comprehensive range of measures which is less vulnerable to the methodology used, and can easily identify the aspect(s) of the energy system that lack energy security, or are at high risk of becoming insecure.

## 2.4 ASSESSING THE IMPACT OF HYDROGEN AND FUEL CELLS ON ENERGY SECURITY

Most energy security analyses examine current energy systems (Section 2.4). Fuel cells can contribute to improving energy security by providing back-up power supplies to critical parts of the energy system (Chapter 4). To understand the potential implications of large-scale adoption of hydrogen and fuel cell technologies, we need to examine low-carbon future energy systems. Chapter 7 examines the implications of hydrogen for several future scenarios.

Hydrogen is an energy carrier rather than a resource, and can be produced from a similar range of fuels as electricity. It is the only zero-carbon energy carrier other than electricity that is thought able to make a major contribution to low-carbon energy systems in the future. Deploying hydrogen technologies would likely increase the diversity of a low-carbon energy system. Hydrogen technologies could also improve the stability of the electricity system if high levels of renewables were deployed, through grid balancing and energy storage.

From a supply-side perspective, since hydrogen can be produced from a similar range of fuels to electricity, similar indicators to electricity can be used to measure the energy security of hydrogen. From a demand-side perspective, hydrogen is similar to natural gas, so gas-focused indicators are likely to be suitable. Any of the energy security frameworks developed in Section 2 are likely to also be applicable to hydrogen and fuel cells. Hydrogen is unique compared to counterfactuals in that it can be stored relatively cheaply in large quantities, interseasonally if necessary, and new indicators could be developed to reflect the benefits of this characteristic.

### 2.4.1 Framework for energy security in this White Paper

Energy security is underpinned by vital energy systems having low vulnerability [19]. This White Paper examines key parts of hydrogen and fuel cell systems in Chapters 3, 4 and 6.

The focus of this White Paper is on assessing energy security rather than developing another new framework. We have chosen to use the broad framework proposed by Cox [22], and summarised in Figure 2.1, which broadly defines energy security in terms of availability, affordability, reliability, and sustainability, and focuses on reducing external threats, namely short term shocks and long term stresses, respectively. In our view, energy security means having access to energy at an affordable price with a reliable and robust delivery system, which is produced in a way that does not unacceptably damage the environment or come to rely on depleted resources. We take a system viewpoint and examine key energy infrastructures as well as resource availability.

### 2.4.2 Indicators to measure energy security with hydrogen and fuel cell systems

Indicators should cover most of the relevant aspects of energy security, both for the present and in the future. The definitions of some of them are likely to change as the energy system evolves. For example, if hydrogen started to replace natural gas, then indicators involving gas capacity or delivery would instead (or additionally) measure hydrogen capacity. If fossil fuels were phased out, their energy security implications, at least in terms of global reserves, would likely reduce. Similarly, hydrogen generation capacity would not become important until hydrogen were a significant energy carrier.

Some indicators for UK energy systems with hydrogen and/or fuel cells might include:

- Diversity of energy sources (Shannon-Wiener Index).
- Diversity of energy sources, adjusted for import dependence (Shannon-Wiener-Neumann Index).
- Level of fossil fuel dependency.
- Capacity of hydrogen producers.
- Capacity of electricity generators.
- Level of redundancy of infrastructure.
- Diversity of infrastructure.
- Capacity of energy storage.
- Hydrogen capacity and comparison to peak load.
- Total level of investment in the energy system.
- Fuel price indices for domestic, industrial and commercial sectors.
- Interruptions per 1000 customers for gas and electricity supply.
- Minutes lost per customer for gas and electricity supply.
- Ratio of final to primary energy consumption (total conversion efficiency).

## 2.5 CONCLUSIONS

Most definitions of energy security have focused on security of resource supply, reflecting their origin in the oil shocks of the 1970s. More recent studies have widened the scope across the energy system, with a particular focus on electricity systems, and have taken a vulnerability-based approach that widens the definition of energy security to include reliability of systems and sustainability. These aim to account for the varied timescales and severity of threats to energy security and the ability of the energy system to respond to these, which can be measured in terms of the stability, durability, resilience and robustness of the system.

A wide range of indicators have been proposed to measure national energy security. Diversity is one of the most common measurements, but indicators also measure resource reserves, capacity utilisation, fuel prices, energy consumption and greenhouse gas emissions. The choice of indicators should depend on the energy security goals of the government. Some studies take a dashboard approach that assesses energy security using a wide range of indicators, while others calculate a compound index to represent the whole system. There are advantages and disadvantages with both approaches, but the dashboard approach tends to be adopted as the indicators are easier to understand and it better captures nuances in the energy system.

Hydrogen could broadly improve energy security by increasing the diversity of primary energy sources and providing an alternative energy carrier to electricity, for example by decarbonising the gas networks, as well as helping to balance the electricity system if high levels of renewables are deployed.

Based on the insights presented in this chapter, this White Paper takes two approaches to examine the energy security implications of hydrogen and fuel cells. First, key hydrogen and fuel cell systems are examined in Chapters 3, 4 and 6. Second, the broad framework summarised in Figure 2.1, which broadly defines energy security in terms of availability, affordability, reliability, and sustainability, is used to explore the implications of deploying hydrogen and fuel cell technologies in the UK energy system in Chapter 7.