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Technology scale and supply chains in a secure, affordable and low carbon energy transition

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HIGHLIGHTS

- Energy systems need to decarbonise, provide security and remain affordable.
- There is uncertainty over which technologies will best enable this to happen.
- A strategy to deal with uncertainty is to assess a technologies ability to show resilience, flexibility and adaptability.
- Scale is important and smaller scale technologies are like to display the above characteristics.
- Smaller scale technologies are therefore more likely to enable a sustainable, secure, and affordable energy transition.

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ABSTRACT

This research explores the relationship between technology scale, energy security and decarbonisation within the UK energy system. There is considerable uncertainty about how best to deliver on these goals for energy policy, but a focus on supply chains and their resilience can provide useful insights into the problems uncertainty causes. Technology scale is central to this, and through an analysis of the supply chains of nuclear power and solar photovoltaics, it is suggested that smaller scale technologies are more likely to support and enable a secure, low carbon energy transition. This is because their supply chains are less complex, show more flexibility and adaptability, and can quickly respond to changes within an energy system, and as such they are more resilient than large scale technologies. These characteristics are likely to become increasingly important in a rapidly changing energy system, and prioritising those technologies that demonstrate resilience, flexibility and adaptability will better enable a transition that is rapid, sustainable, secure and affordable.

1. Introduction

In common with other countries, the UK faces a challenge to decarbonise its energy system whilst maintaining energy security and affordability. This paper examines the underexplored relationships and importance of technology scale within the context of supply chains, in enabling these goals for energy policy to be met.

The supply chains that make up the component parts of energy systems have evolved over many decades to meet society's needs for power, heat, transport, manufacturing and services. They are complex and dynamic, involving many different actors, technologies, fuels, operating at different scales and locations, and are shaped by the policies, rules and regulations that are in place. Most energy systems are dominated by fossil fuel supply chains, which for the most part, are mature and globalised, but they are prone to inertia; and are increasingly struggling to collectively deliver on the three main goals of energy policy (Section 2).

To move towards a more sustainable and secure energy system requires a significant transition within current energy systems. A number of scenarios have been developed to consider different transition pathways and these suggest a growing role for electricity within the energy system, which could be provided by a range of low carbon technologies, such as nuclear power and renewable energy. However, they also indicate that no single technology will be able to decarbonise the energy system, and as such options need to be kept open.

During a transition, energy security also needs to be maintained, and this requires energy systems that can deal with short term shocks and longer term stresses to ensure continuity between supply and demand. Resilience is a helpful way to consider this, as it describes the ability of a system or supply chain to return to its original state after a disruption. With the exception

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of unconventional oil and gas, fossil fuel supply chains have evolved to be quite resilient. However, it is less clear how effective alternative supply chains, such as nuclear power or renewable energy technologies, will be in providing security (Section 3).

Given the uncertainties that exist, and the range of technology options that could play a role, a key issue will be to identify those technologies that show characteristics of resilience, whilst also showing flexibility and adaptability. There are a number of factors that could help to determine this, such as the speed at which a technology can be deployed, how compatible it is with the system and other technologies, and any constraints it may face socially, environmentally or economically (Section 4). A focus on technology scale and supply chains could provide an important mechanism by which these sorts of issues can be considered. To examine this, two low carbon technologies are explored, large scale nuclear power and small scale solar photovoltaics (Section 5).

The paper is organised as follows: Section 2 provides context on supply chains, considers how they relate to energy systems, and examines how they emerge and become established; Section 3 examines the complexity of energy security and how it relates to the wider UK energy policy goal for decarbonisation; Section 4 considers these issues in relation to a low carbon energy transition, supply chains and technology scale; Section 5 provides a detailed examination of nuclear power and solar PV, considering their role within energy systems, their supply chains, possible costs, and what this may mean for the UK; and Section 6 summarises the findings and provides conclusions.

2. Conceptualising energy supply chains

Supply chains, or value chains, are complex, dynamic and often globalised interconnected networks which comprise the entire sequence of activities involved in the delivery of a service or a product, from production through to end use and disposal [1–3]. They include multiple actors, operating at different scales and locations and cover the process by which components and products are produced, combined and delivered [4–6].

At a macro level any energy system can be considered as a supply chain (Fig. 1 – [6]) that contains multiple and interrelated subchains relating to suppliers and customers, based on different fuels, technologies, and the infrastructure that connects them; as well as the materials, labour and equipment needed for the development, manufacture, installation and operation of the system [6]. These supply chains are shaped by the policies, institutions, regulatory frameworks and practices that are in place within a country, as well as the wider interconnections it has to other energy systems, and the markets, rules, and regulations that shape them [7,8]. The primary purpose of the system is to meet the energy service demands of end users for power, heat and transport, across the economy [6].

Historical energy transitions have played an important role in shaping the supply chains that are in place. Within the UK, the system has evolved from using wood as the primary source of energy, into coal, and more recently oil, gas and electricity [9]. With these transitions in fuel type there have also been multiple co-evolving innovations: socially; politically; institutionally; and technically [10,11]. An important recent innovation has been the liberalisation of the energy system in the UK (and a number of other countries) [12], resulting in a national energy system that is increasingly shaped at the international level, in terms of capital, technologies, fuels, and the ownership of equipment and energy companies [13].

Collectively these historical developments have resulted in a series of supply chains which are now mature, highly interconnected and complex [6]; and these have evolved over several decades, leading to a system that now relies on embedded technical and social commitments, making them prone to inertia and lock-in [14,15].

The mechanism by which different technology supply chains emerge and become established is, in part, a reflection of the innovation process [16]. For newer technologies, compared to incumbents, there are a range of internal and external risks, reflecting the immaturity of a technology and its supply chain, which will need to be overcome in order for technologies to be delivered [17]. As a technology comes to market, the supply chain associated with it broadens to bring in skills and resources associated with its deployment, such as: planning; design; manufacturing; construction and installation; operation and maintenance; and decommissioning; as well as associated sectors like legal and financial services [18].

For any technology there are a range of factors that influence its development. There can be bottlenecks or constraints along an entire supply chain, from the source of raw materials through to decommissioning that can, without mitigation, impact on the scale of development, deployment or operation [19]. These are important because technologies can only develop as fast as the tightest supply chain bottleneck allows [20]. There can also be more pervasive cross-cutting issues (Table 1) that impact across different technology supply chains (which can also be experienced as technology specific bottlenecks) [6]. To some degree these issues will vary between countries depending on the technologies and policies in place, although globalisation can also mean they are experienced across different regions simultaneously [21].

For a number of reasons the supply chains that make up energy systems are now under pressure, particularly in terms of their ability to deal with key challenges of ensuring energy security and the decarbonisation of supplies [12,29], which this paper goes onto consider.

3. Energy security in a carbon constrained world

Although no energy system can be completely secure [30], a central and high priority policy goal for all nations is energy security [31]. There is not a precise definition for energy security [32],

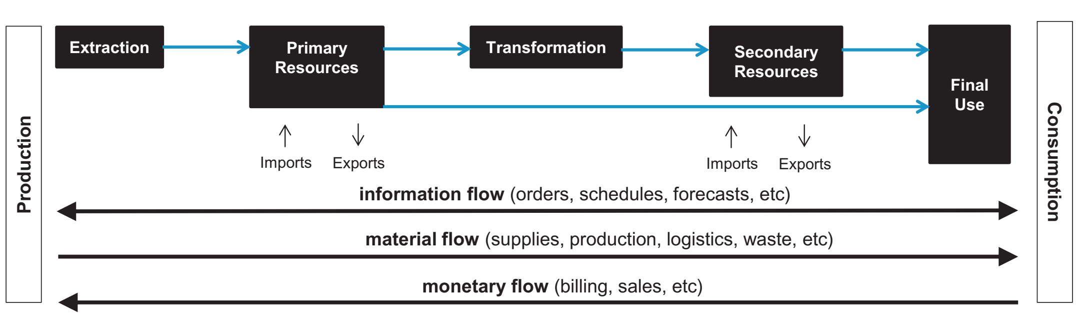

Fig. 1. The energy system as a supply chain. *Source:* [6].

Table 1
Cross-cutting supply chain issues.

Issue	Importance
Policy confidence	There is a need to reduce risk, or the perceptions of risk [9,22,23], as companies and investors are wary of entering a supply chain or scaling up their activity, unless they are confident of the policy regime that is in place [23–26]
Sufficient skills	There is a need to ensure there are enough people with the right skills to manufacture, install and operate technologies or deliver different approaches [27]
Access to materials	Companies need access to a consistent supply of materials at a reasonable price, as a shortage can alter the economics of a technology and impact their commercialisation [21,28]

despite a wide literature on what it is and how it can be measured [32–35] and as a result there is no single metric for it [7,36].

Despite these problems there is some consensus that at its core, energy security is about the uninterrupted availability or provision of energy for vital services [31]. To ensure security, energy systems need to be able to withstand shocks and longer term stresses [6,37]. Short-term shocks can include issues such as natural events, technical or human failures, as well as market failures; whilst longer term stresses can include concerns over resource competition, aging infrastructure and changing patterns of global demand and supply [31,37] – these factors can also combine [37]. There are considerable synergies between these findings and studies of risk within supply chain literatures [38], with a shared recognition that risks vary with time, scale and location, and increase as a result of globalisation [38,39]. Shocks and stresses can be experienced by individual companies and/or system-wide, impacting supply chains at multiple operations over a wide geographic area and they are difficult for individual actors to resolve [40].

Resilience is one way in which energy security [41] and supply chains more generally [40] can be framed; with resilience seen as the capacity of a system, or company to return to its original state after a disruption. Included within this definition is the ability of a system to respond to disturbances or risks [7,39–41]. This links to wider studies into energy security, including a recent survey of 130 countries [31], which have characterised an energy system's ability to deal with threats in terms of: robustness and the capability of the system to deal with risks to them; sovereign protection against external threats to a system; and resilience in terms of the ability of systems to withstand diverse disruptions (see also [7,36]). It is also recognised that energy security is a property of energy systems, rather than the individual components within it [37].

Within the UK, energy security has become an important driver of energy policy in recent years [37,42–44], in part reflecting the fact that the country recently became a net importer of fossil fuels after decades of self-sufficiency [9], as well as the need to secure significant investment in its aging energy infrastructure [45]. In 2012, the government produced its first Energy Security Strategy [44] whilst it was welcomed, analysts highlighted that it failed to link to, and be consistent with, the UK's wider energy policy goals [36] for reducing greenhouse gas emissions [46,47] and as far as practical ensuring affordability for both private consumers and business competiveness [12].

Climate change is also a key driver of international energy policy [48] and it is recognised that energy systems are both the primary cause of climate change and a primary means for mitigation [46]. In common with other countries [42], to reduce emissions within the UK, it is recognised that significant changes to the current energy system will be needed [47,49], based on the rapid and effective deployment of existing and new technologies, as well as changes to the wider non-technological social, economic and political frameworks associated with it [50,51]. This will require a low carbon transition, the speed and scale of which is unprecedented [8,37]. It will also create new risks and opportunities for the supply chains that shape energy systems [6], a challenge that in itself can be considered as a long term stress for energy security [9].

4. Energy transitions, supply chains and scale

The UK energy system currently uses large-scale technologies, centralised electricity and gas networks for transmission and distribution, and supporting institutional frameworks [11]. This centralised model has both delivered economies of scale and reliability [52] including the uninterrupted supply of vital energy services [6]. However, current supply chains are dominated by fossil fuels which provided 87.3 per cent of supply in 2012 [53], and these are increasingly incompatible with collectively delivering the UK's energy policy goals [37].

There is uncertainty over which technologies and supply chains will come forward into a future low carbon energy mix [6,12], implying the need to keep system options open [30,54,55]. To better understand this, numerous pathways and scenarios have been developed within the UK from a wide range of organisations [54,56,57] and there is a tendency within them to focus on technology adoption rates and economic outcomes [58]. There is some agreement that a desired approach will include: on-going improvements to energy efficiency; the almost full decarbonisation of electricity generation; and the extension of electricity into the heat and transport sectors [9,55,57,59]. The expectation that electricity will have a growing role within the future energy system, reflects the fact that it easier to decarbonise than other fuels [60], as it can be provided through a range of technologies [9]. A key challenge will be to strengthen existing supply chains and develop new resilient supply chains, relating to different technologies, fuels and infrastructures, at the macro-, meso- and micro-level [6]. This will require changes to the actors, markets, rules, regulations, institutions and governance of the energy system [8,61]. Collectively, such changes will lead to a more complex and diverse system than is currently in place [7].

To enable change it will be important to understand the potential risks any supply chain faces and take appropriate mitigating action if they are going to become resilient. Given the globalised nature of supply chains, this will require countries to set the right conditions and partnerships between the public and private sectors [56] to enable companies to enter and build a supply chain. This enables a supply chain to become diverse, creating capability and capacity, leading to benefits such as reduced lead-in times, increased learning and competition, which may both reduce cost and increase the pace of a transition [6].

It is also important to acknowledge that supply chains are developed within energy systems that are based on different technology pathways and interconnections, and there can be strong path dependency linking to technology choices, infrastructures and skills [62]. Given that the direction of future change is uncertain, the ability to make good strategic decisions about that future is difficult [63] as it is hard to understand, anticipate and manage the development of energy systems [13]. This is not least because the interdependencies that exist within the complex energy system [9] may mean that changing one part will have unintended consequences for other parts of the system [30,36]. Given this, an important factor in enabling a transition toward a low carbon and secure energy system will be to focus policy attention on the ability of the system to be resilient, adaptable and flexible [37]; as this would provide space to adjust policies to reflect new developments, including dealing with unanticipated outcomes [64]. Such an analysis can be applied at the system level and below it, in terms of technology choices and supply chains; it can also take account of developments in enabling technologies such as power storage, smart grids and demand-side management [13], which are not considered within this paper, but which may shape future system design and operation and could contribute to its resilience, flexibility and adaptability.

From a technology perspective, there is no single solution that can deliver a low carbon future [30], and therefore for security reasons it will be important to prioritise those technologies that show the above characteristics. This will require an assessment of issues, such as their potential for: rapid deployment; supply chain development and security; compatibility with current and future energy systems, including other technologies within them; dealing with social, political and environmental constraints; as well as their relative and projected costs [65]. An important consideration within this is the relationship between technology and scale, because markets, technological interrelatedness and infrastructures which are large and complex tend to change slowly [66]. Also in a general sense, large scale and complex technologies may have more points along their supply chain where there are fewer firms, or shortages in skills and face a bigger range of bottlenecks to deployment.

To better understand some of these issues this paper goes onto explore the potential role of, and the supply chains for, nuclear power and solar photovoltaics.

5. Large and small scale technology comparisons

5.1. Nuclear fission

Nuclear power is considered by many as an important low carbon technology that could help cut greenhouse gas emissions and improve national energy security [67–69]. It can provide large amounts of low carbon baseload power [70], although cannot easily be ramped up or down [71]. However, there are a number of concerns relating to this technology, including: costs; proliferation risks; and waste management [7,72]. The accident at Fukushima in 2011 also had an impact on public opinion and policy [73] and its future remains uncertain in many countries, including the UK [65,74,75].

Currently 'Generation II' nuclear plants are the most common in operation [69] and they came to market in the late 1960s with a typical operational lifespan of 40 years [76]; these are still being constructed in many parts of the world [77]. The first 'Generation III' reactor was built in the late 1990s [78] and these could operate typically for 60 years [76]. Fourth generation designs may be deployed from the 2030s [7]. The development within generations is based on innovations of previous designs [7] and typical gaps between each are around 30 years. The financial and technical commitment to design new reactors and get them licensed helps to explain why there has been a move towards global standard designs, such as Pressurised Water Reactors (PWRs), and why there is little desire by nuclear vendors to modify these systems [7].

As of June 2013 there were 434 nuclear power reactors in operation in 31 different countries [77], but shut downs in Japan mean this figure may be lower [65]. The current global installed capacity is estimated at 364 GWe and in 2012 a total of 2346 TWh of electricity was generated [65,77]. In terms of new build, it is reported that 68 are currently under construction [77], although nine of these have been listed as under construction for more than 20 years [65]. Most new build is taking place within Asia, central and eastern Europe, and the Middle East [79] and it is suggested that countries with existing nuclear programs have plans to build around 160 new plants by 2030 [80].

Within the UK, nuclear has been providing power since the 1950s [9] and there are currently 15 reactors in operation [81], with a capacity of 10.6 GW [53]. In 2012 these provided around 19 per cent of the UK's electricity [53], although its share within the mix has been in decline since 1997 [81]. This reflects the age of the UK nuclear fleet, and although life extensions may be approved in the future, currently all but one expected to close by 2023 [67]. It is suggested that between 12 and 16 GW [68,82] of new capacity could be added in the future, with the UK government saying nuclear is 'low-carbon, affordable, dependable, and contributes to the UK's diversity and security of energy supplies' [10,68]. So far the government has invested seven years of its time and resources [83] in supporting new nuclear, through a wide range of facilitating measures designed to: reduce regulatory and planning risk; encourage investment in skills and the supply chain; reform the market to reduce policy and revenue risk; and underwrite construction risk [67,81,84,85].

5.1.1. The nuclear supply chain

Nuclear power is based on a global supply chain for construction, operation and maintenance, and decommissioning. A typical nuclear plant contains millions of items, each with its own supply chain and unlike other low carbon technologies these are particularly complex, not only because of the vast number of components and materials that are needed, but also because many are critical to both safety and reliability [86]. It is reported that on average a new build project takes eight to ten years to commission [65,74], although it has taken considerably longer than this in many countries [65]. During the construction phase thousands of companies and workers will be involved along the supply chain. For example, the last plant built in the UK, Sizewell B, involved over 3000 companies and had over 4000 on-site workers [24]; the current Areva project in Finland has more than 4000 employees on site from 55 different countries [87] and their new French build has around 100 suppliers from the global supply chain [88].

The construction supply chain for a typical nuclear plant is characterised by the World Nuclear Association [68] as a pyramid made up of six tiers – Fig. 2. The top tier comprises the Technology Vendor, who are the main contractors for a plant, and these companies generally have a long history in the nuclear sector [86]. There are currently nine consolidated vendors operating in the global market [89], with four dominating the market (REVA, Hitachi-GE, Toshiba Power Systems, and Mitsubishi Heavy Industry) [65]. Below the vendors, the supply chain comprises: Tier 2 – System Integrators (e.g. reactor pressure vessel and steam generators); Tier 3 – Original Equipment Manufacturers (e.g. rod cluster control assembly); Tier 4 – Sub-component Suppliers/Distributors (e.g. control rods and heavy forgings); Tier 5 – Processors/Fabricators (e.g. alloys); and Tier 6 – Raw Material Suppliers/Miners (e.g. silver, zinc, etc.) [86,90].

This construction pyramid in Fig. 2, is one part of the overall nuclear supply chain, with the wider elements shown in Fig. 3 [4,24]. The cost and complexity of entering the nuclear supply chain can be prohibitive for companies given that there are significant upfront costs to gain the required quality accreditations [67]. This reflects the fact that nuclear facilities contain many components that have to be specifically designed, in certified facilities that meet stringent national and international, continuously increasing safety standards and regulations [65,86]. This is particularly important for the plant itself, given that once it has been commissioned, checking build quality or making modifications may be difficult or impossible [86]. However, the importance of safety also means a strong culture has to be applied right down through all the elements of the supply chain [91]. It is also worth noting that

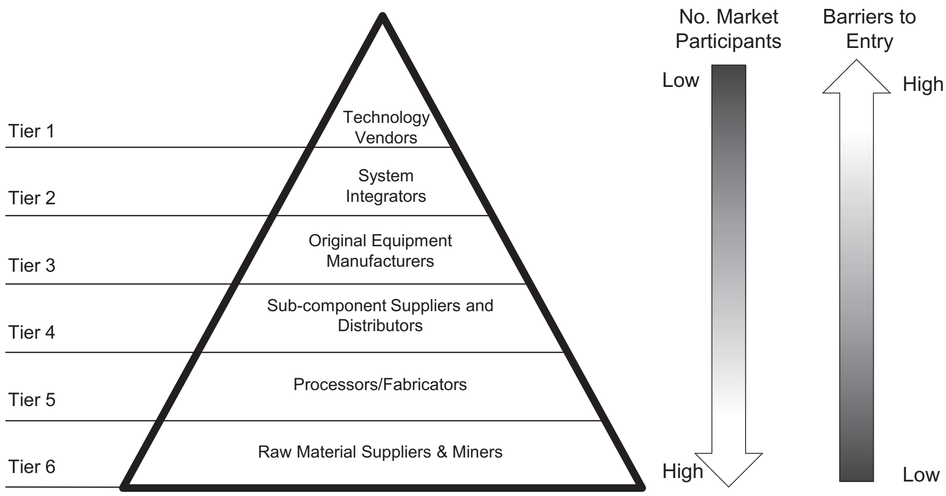

Fig. 2. The nuclear power plant supply chain (adapted from [68,116]).

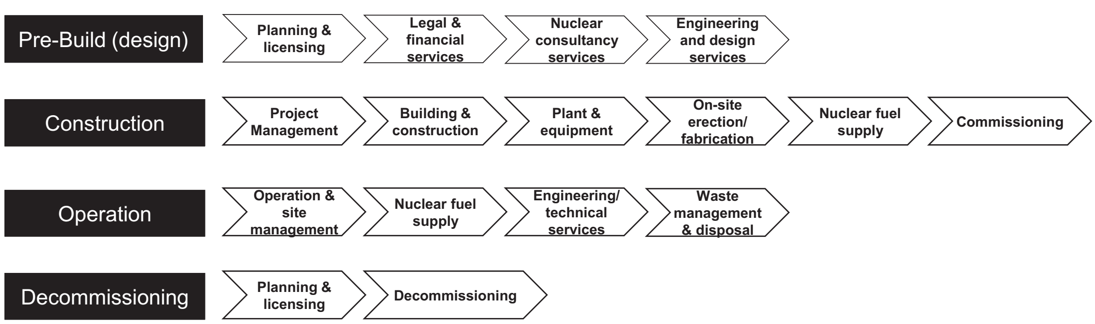

Fig. 3. Elements of the nuclear supply chain. *Source:* [24].

there have been cases of counterfeit and forged components entering the supply chain. In 2012 it was found that more than 5000 small components installed in Korea had forged safety documents, resulting in plant shut downs while the parts were replaced [86].

As well as there being a small number of vendors, the number of companies capable of supplying a range of key reactor components is also limited. This directly relates to the scale of the technology and the engineering challenges this creates, most notably for ultra-large forgings, with a typical new reactor requiring around 200 complex heavy forgings in total [71]. This includes items such as the reactor pressure vessels, steam turbines, generators and other engineering components; which are needed for both new build and lifetime extensions to existing fleets [24,92]. The high costs and specialist skills needed for these components means only a few companies are able to provide them. There are currently only four companies globally capable of producing ultra-large forging, operating in Japan, China and Russia and they are also servicing other sectors' heavy forging needs [92]. This could be a significant bottleneck for global new nuclear build [67,68,92]. Some new capacity is being built, but it is not clear if others will enter this market [92], given the high level of investment needed for a new heavy forge plant [86].

5.1.2. Analysis for the UK

In the UK, no nuclear plant has been built since 1995 and this has resulted in the domestic supply chain being 'withered away' [26,67]. It has been suggested that around 70 per cent of the elements of the whole nuclear supply chain could come from UK companies [67], possibly more with appropriate investment [74]. However, there is no UK based vendor [67] and a lack of capability for many key systems and sub-systems needed for a new plant [93,94]; and it is not expected that this capacity could be developed within the proposed timescale for any new build [68]. The UK will therefore be dependent on the global supply chain for the delivery of new plant [67] and this could be problematic because if a number of countries place reactor orders at the same time, vendors may not have the capacity to increase their operations. In addition, the UK is a relatively small market, so global suppliers, operators or investors may not prioritise it [93]. There are therefore concerns over availability, lead-in times and the possibility of cost escalations from global competition [24].

The lack of skilled nuclear workers is also recognised as a significant bottleneck by government and industry [93]. It is expected that many of those currently working within the domestic supply chain are now over the age of 50 and likely to be retiring within the next decade [67], with implications for the delivery of new build, given that their knowledge and experience could be vital for managing construction and safety risk within the UK. The availability of skilled workers could also be exacerbated by strong competition between countries with new nuclear build programmes; as well as competition for similar skills sets needed for both new build and decommissioning [24]. The language problems caused by using workers from different countries can also create significant problems and delays, an issue recently experienced in Finland [95].

The cost of nuclear is also an important consideration. Studies of learning rates often suggest that market growth leads to cost reductions, but this has not been the case for nuclear, despite significant deployment [15], with a suggestion that prices over the last ten years have increased from \$1000/kW to \$7000/kW [65]. The projected costs for the PWR reactors at Hinkley Point in the UK were estimated at around £7 billion [67], although it is suggested that this has now risen to £14 or £15bn [83,96]. Significant construction delays and cost overruns have been experienced for the new PWRs in Flamanville, France and Olkiuoto, Finland, and similar issues could be experienced in the UK [67,84]. Whilst this is not uncommon for 'first of a kind' projects and lessons can be learnt [97], there will be challenges that are unique to UK construction, such as, different working cultures, geography and regulatory regimes; and as such they should be considered quasi "first of a kind" [67]. The scale of the technology will also lead to additional system costs, with the UK network operator suggesting that additional operating reserve and back-up generation capacity could see costs rise to around £160 m a year [98,99].

The above issues and the lack of an established supply chain and skills base means that significant delays could be experienced within the UK [67] and this creates uncertainty for the future of nuclear [65,74] and its supply chain [94]. With high costs and complexity of regulatory compliance [15] already impacting on the willingness of companies to engage with the supply chain or invest in the training needed for accreditation [74], this uncertainty will increase the problem. This is because it is difficult for companies to make investment decisions to develop capacity in the hope that projects might be forthcoming and for a similar reason attract new workers [94]. Even though a potential deal between the UK government and EDF for the first new nuclear power plant has been struck [100], State Aid reviews by the EU could lead to a further two or three years of uncertainty before the project goes ahead [83]. Furthermore, a failure to manage the construction risk for the UK's first nuclear plant would have a significant impact on subsequent plants being built, including public acceptance and investor confidence [67,74].

5.2. Solar photovoltaic energy

Solar photovoltaic (PV) technologies that directly convert sunlight into electricity are small scale, and highly modular. Solar energy is abundant, offers significant opportunities for climate change mitigation and it can be used to meet a variety of energy service needs [101]. This section only considers PV, which in itself can be used in a wide range of applications [102], on-grid and off-grid, as stand-alone projects, rooftop installations or building integrated [103]. PV is a variable power source, with output following diurnal cycles and is influenced by changing weather patterns, such as passing clouds [104]. In recent years PV has shown dramatic market growth and price reductions to become one of the fastest growing renewable energy technologies [105] albeit from a very low base. It is now considered as an established technology and with installations rising year on year [106], it is recognised that it could have a significant role in global energy systems [7] and that of the UK [107]. As of 2012, the total global rated operating capacity passed 100 GW [108], and it is suggested by the IEA that it will produce at least 110 TWh of power in 2013 [109]. Looking forward, global PV rated capacity could increase to between 384 and 966 GW by 2035, depending on the policies adopted [73].

There is also growing interest and support for energy storage solutions that can be deployed alongside PV [110], and these could considerably increase its future role within energy systems. Recent developments in storage include support from the German Government who announced a 25 million Euro fund to incentivise storage alongside PV [111], with some companies are already offering domestic scale storage [112]. There has also been a marked development in the number of companies promoting different storage solutions at solar trade shows [110].

PV emerged in the 1960s from the NASA space programme [13] and there are three 'generations' of PV technology – first using crystalline silicon (C–Si), second based on thin film technologies and on-going research into a range of third generation technologies [7,106]. This paper only considers first generation mono- and multi-crystalline PV which have typical lifetimes of 25 years [106] and efficiencies of around 18 per cent [7]. They account for 80–85 per cent of the global PV market [19,113] and have dominated it for over 30 years [103]. Innovation efforts for C–Si have focussed on feedstock production, production processes, economies of scale and on-going improvements to efficiencies for cells and modules [15,106]. Typical innovation cycles for PV are up to ten times shorter than those for conventional power plants as they can be installed with very short timescales [114].

Globally PV has shown sustained growth in recent years, with annual growth rates ranging between 40 and 90 per cent over the last decade [115]. The top markets are currently within Germany, Italy, China, the US and Japan and these countries also have the most installed capacity [108,113]. Globally it is estimated that 31 GW of new PV rated capacity was commissioned in 2012 [113]. Whilst Europe has been the consistent leader of installed capacity, the market is changing rapidly and it is anticipated that the majority of new growth will now come from outside of the EU [115]. The main driver of growth has been government incentives to support development and foster domestic supply chains [103,116], including feed-in tariffs, investment subsidies or tax breaks [115].

Within the UK, support has been provided for PV and other renewable technologies from a number of grant programmes and since 2010 via a feed-in tariff [103]. Provisional data for 2012 suggests installed rated capacity stood at 1.7 GW, up from 0.9 GW in 2011, and generation was estimated at 1.1 GWh for 2012 [117]. As a result of falling costs and growing deployment, the UK government now identifies PV as a key technology in its latest Renewable Energy Roadmap [107], with a suggestion that by 2020, deployment could reach between 7 and 20 GW (equivalent to 6–18 TWh). These estimates reflect the falling costs of PV, its ease of installation, and high levels of positive public support [107]. A new PV strategy is due to be released in 2013 setting out a strategic approach to PV in the UK [107].

5.2.1. The PV (C–Si) supply chain

Analysis of the supply chain for PV suggests there are five main tiers which include: Tier 1 – the production of the polysilicon material; Tier 2 – production of ingots and wafers; Tier 3 –production of solar cells; Teir 4 – module assembly; and Tier 5 system installation [116] (Fig. 4). As with other technologies, there are a limited number of companies within the top tiers of the supply chain, reflecting the fact that the top tiers are capital and knowledge intensive with large production volumes needed to be competitive [116]. Data suggests that there are 25 plus companies manufacturing solar grade silicon in Tier 1, around 40 producing ingots and wafers and over 70 producing cells [116]. Some companies operate across all of these tiers, whilst some specialise in specific areas [118]. From Tier 4 onwards the supply chain considerably expands as the processes are less complex and capacity can easily be expanded in a short timescale [116].

Much of the supply chain has shifted towards Asia in recent years, and in terms of modules Asia accounted for 86% of global production in 2012, two-thirds of which came from China [108]. The rapid capacity build up in China has been enabled through a favourable industrial policy, access to credit and government support [116]. Globally, production capacity is now in excess of demand and this has resulted in overcapacity within the supply chain [108]. This has led to fierce competition between manufacturers and dramatic price reductions for PV modules, with prices

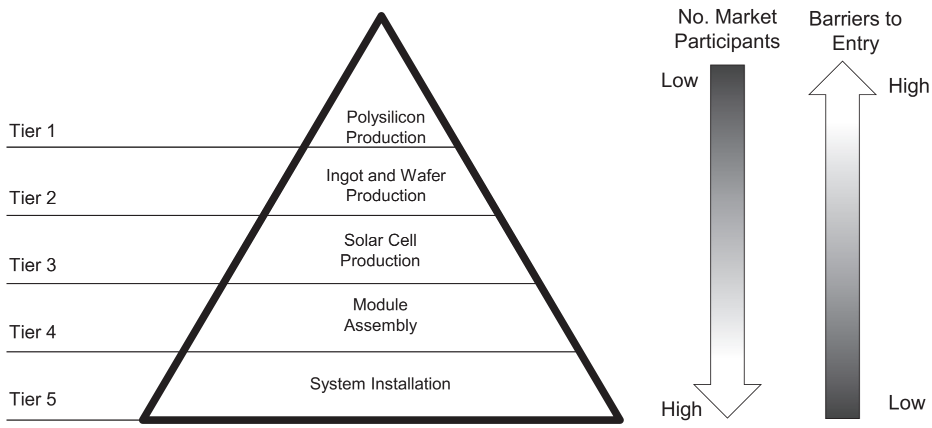

Fig. 4. The PV supply chain. Adapted from [116].

falling by more than 45% in two years to mid-2012 [119]. Production costs in China have particularly influenced the global market and price trends [116] and concerns have been raised that China is selling PV on the global market at below production costs, which has led to trade disputes, such as the recent one between the EU and China [120].

Falling costs are making PV increasingly competitive with electricity retail prices in many countries [106,108,115], but they are also impacting the supply chain through reduced margins for manufacturers [108]. This has resulted in bankruptcies, stopped production, scale-backs or cancellation of expansion plans [113]; as well as new business strategies including: mergers; buy-outs; diversification upstream and downstream in the supply chain; and companies moving into project development and new strategic partnerships [108,115,121]. Existing players in traditional markets are also continuing to invest in improving manufacturing processes to reduce costs, with innovation and product differentiation becoming increasingly important [108].

Despite these challenges, it is suggested that yearly production capacity may continue to grow, and some new facilities have been opened [108]. The slowdown in traditional markets, reflecting market maturity and reductions in the level of support available [116], has in part been balanced through openings in new markets, made possible through falling PV prices, particularly in regions with high solar insolation like Africa, the Middle East, South East Asia and Latin America, where markets are in their infancy [113].

There is uncertainty over future prices and their stability [108], but PV has historically shown consistent year on year price reductions [102]. There are multiple overlapping forces that impact on these price reductions [116] and modules only account for around half of the total installed costs, with the remainder coming from Balance of System equipment [106]. Falling costs and improved efficiency within this equipment could therefore play an important role in future PV installation prices. Other opportunities for savings within the supply chain include: running plants at close to capacity; on-going improvements to the efficiency of modules and cells; and further efforts to reduce cost across the whole supply chain [106,121].

There are some potential bottlenecks in the PV supply chain, mainly relating to raw materials. For C–Si manufacturing, the long term trends in falling prices was reversed in the mid-2000s when a shortage in silicon led to a serious bottleneck in the supply chain [19,122]. The market responded to this problem with significant new investments in capacity from both existing companies and new entrants [101], particularly within China [123] and it is now considered that global supply is secure, although market dynamics may mean further new capacity will be needed in the future [19]. Looking forward, a potential new bottleneck that could emerge, if mitigating strategies are not put in place, is access to silver [19]. This is used in forming the electrical contact grids within panels and in 2010 the industry consumed around 11 per cent of the world's silver supply [124]. However, there are a range of strategies available to reduce this risk, such as: securing primary and increasing secondary silver supply; reducing silver's intensity within production processes; and substitution for more abundant materials [19].

A further bottleneck that may emerge in some markets concerns grid access and challenges for grid management [113], with the cost of reinforcement potentially being prohibitive [19] or impacting on the competitiveness of PV [115]. Resolving this will depend on the policies and regulatory frameworks that are in place and how governments support changes to incentivise network operators to avoid locking out decentralised generation options [125]. This links to a wider discussion on system change and how far and how quickly countries move towards smarter grids, based on networks that are intelligent, efficient and secure [126], which this paper does not explore.

5.2.2. Analysis for the UK

Market analysis of the PV supply chain shows its global nature and how dynamic it has become. Most companies within the top tiers of the supply chain are globally based and within the top two tiers they dominate the market with around 90 per cent market shares [116], diversity increases within the supply chain from tier three onwards.

Whilst the UK was an early leader in PV [23], its role has since diminished reflecting both the rapid development of the global market and changes within the level of financial support offered within the UK. The dynamic nature of the market means that data changes rapidly, but in 2011 the UK had one global module manufacturer, over 60 other companies involved in the wider manufacturing supply chain and an estimated 4000 installation companies, which account for around 80% of the estimated 15,650 jobs in the UK sector [23,127].

Issues that could impact on the growth of PV within the UK include considerations, such as: how the global market restructures; how costs for installed systems change, relative to wider electricity retail prices; the level of support offered through government policies; and the wider decisions taken on how the energy system should be developed. In respect to the global market, recent research has suggested it will grow to a $155 billion industry by 2018, with the current imbalances in supply and demand expected to come back into balance by 2015, which will ease current pricing pressures and return manufacturers to profitability [128]. The forthcoming solar plan for the UK shows a new commitment from government for the future of PV and recognition of the need to address barriers, such as network connection and management [107].

6. Discussion and conclusions

This paper explores the relationships between technology scale, supply chains, and energy security within the context of a low carbon transition. The focus is the UK energy system, but the findings will be applicable to other countries, given there are similar characteristics between industrialised energy systems, and they are increasingly globally interconnected.

6.1. The need for, and uncertainty of, system change

A key problem for the UK is its energy system and supporting infrastructure is currently designed around, and dominated by, mature and globalised supply chains based on fossil fuels, which are increasingly unable to deliver on the collective policy goals for decarbonisation, energy security, and affordability. They therefore need to be replaced by new supply chains which, as well as being low in carbon, also need to be secure, in terms of their ability to deal with short term shocks and longer term stresses on the energy system. Furthermore, they need to be adaptable and flexible to changing system conditions and other technology developments.

Supply chains are complex, involving multiple actors operating at different scales and locations and they are influenced by the wider rules and regulations, etc. that are in place. The mechanisms by which they become established reflects their innovation process, and other factors, such as bottlenecks relating to skills or materials, as well as the certainty that policy does or does not provide. These issues need to be understood and acted upon to enable companies and investors to enter a supply chain or scale up their activity to create the resilience needed for a low carbon and secure transition.

A key issue is the considerable uncertainty in identifying which technology pathway and supply chains will be most effective in delivering on the goals for energy policy. Whilst a range of low carbon technologies are available (including some which are not yet at market), there is no single technology solution and therefore options need to be kept open. Also, it is expected that a more diverse energy system than is currently in place will emerge, and this creates further uncertainty as it is not clear how the widespread deployment of new technologies might impact the energy system, given the interdependencies that exist between its component parts. It is also not possible to predict with any certainty, issues such as emerging technology or system innovations, including those relating to: technologies; networks; and the operation of the system. A sensible strategy to deal with these uncertainties is to consider the ability of new technologies to provide resilience, adaptability and flexibility, as this would allow developments to be monitored and allow for any unintended consequences to be addressed.

Through an analysis of the different characteristics that low carbon technologies have, it would be possible to better identify where priority should be given. Assessment of factors that could be important, include: the potential for deployment; supply chain capacity and capability; compatibility with the system and other technologies within it; potential costs; and any constraints that they may face.

6.2. The importance of technology scale

Many of these issues discussed above have direct links to technology scale, as it can influence how technology supply chains develop, including the willingness or ability of companies to be involved, as well as the wider characteristics that a technology displays in terms of resilience, flexibility and adaptability.

Large scale nuclear power and small scale PV were compared to better understand the role of scale and the risks it may create for a secure low carbon transition. This shows that whilst they have some similarities, such as the importance of and need for policy support and some constraints within the capital and knowledge intensive top tiers of their supply chains; they also display very different characteristics and this could influence their potential role within system change.

6.2.1. Nuclear power

Nuclear power, compared to PV, is providing large amounts of low carbon power and as such its further deployment could have an important role in mitigating climate change. Its role in providing energy security and affordability is less clear. This is because its supply chain does not appear to be resilient or flexible, and this directly relates to the scale of this technology.

Nuclear has a mostly bespoke supply chain for key components, reflecting the complexity of this technology, including the need to meet stringent safety requirements. A number of significant bottlenecks are apparent, including within the top tiers, a limited number of global vendors and heavy forging capacity; as well as cross cutting issues like the number of skilled workers that are available. Building a nuclear plant is also a global project requiring workers and companies from many different countries, which can create construction risks. These issues are a particular concern for the UK, as the delivery of new plant will be dependent on the global supply chain and the UK is a small market relative to others. These supply chain constraints and wider policy uncertainties impact on the willingness of companies to enter the supply chain or invest in skills, reducing its resilience. These same factors will also impact on the potential deployment rate for nuclear power.

Nuclear also lacks flexibility in terms of its operational profile, as it cannot be ramped up or down easily. It is also not adaptable because once deployed, a generation III reactor is expected to run for around 60 years and it is impossible to know how the energy system might change within this time; it can therefore constrain other technology options, or system operational choices, as these will have to fit in around nuclear power. There are also innovation concerns for nuclear, because plant design is globally standardised, there is reluctance from vendors to make changes once licensed, and there are around 30 years between the developments of each generation. In respect to learning rates, despite widespread deployment the costs of nuclear are not falling and its role in providing affordable energy is open to question.

6.2.2. Solar PV

The large scale deployment of PV can play an important role in helping to tackle climate change, although its output is variable reflecting time of day and local conditions. How big a role it can play will therefore in part depend on what other technologies are on the system to help balance its variability. However, the PV supply chain does demonstrate resilience, adaptability and flexibility, and it therefore has an important role in the context of system change and energy security.

PV is small scale and highly modular, and can be deployed quickly in a variety of different applications and scales, providing flexibility. It is less complex than nuclear and its supply chain capacity can be quickly expanded, either in response to a bottleneck or to anticipated demand; it is also expected that the supply chain will quickly reorganise to deal with the issues of oversupply. It also has more companies operating at the top of the supply chain and very strong competition between them.

There are bottlenecks that may emerge in the future, as well as possible options to deal with them, including the potential use of alternative generations of PV, such as thin film, which this paper has not explored. In terms of innovation, PV has shown quick learning rates, with innovation cycles typically ten times shorter than for conventional power plants. In part this has led to dramatic cost reductions, which against a backdrop of rising retail electricity prices, are expected to make it quickly competitive in many markets. Developments in storage could also significantly increase the potential role that PV could play within energy systems.

6.3. Conclusions

Given the uncertainty that exists in bringing about a low carbon energy transition, a sensible strategy is to consider how effective different technologies are at providing resilience, flexibility and adaptability. Energy security also has to be ensured, and in a rapidly changing energy system, resilience and flexibility are likely to play a growing role in enabling security. From a supply chain perspective, risks appear to increase if a supply chain is reliant on a limited number of companies, technologies or markets, whereas resilience increases if the number of companies, networks, connections, etc., is large, as this creates alternative options for bringing forward a low carbon technology at an affordable cost. This requires policy makers to put in place effective technology and wider policies for rules and regulations to create an environment that increases the ability or willingness of companies to participate within the supply chain.

Resilience is not just a property of end-use technologies, but also the scale and complexity of the supply chain behind it. Large technologies like nuclear power appear to offer less resilience than smaller scale technologies like PV. This reflects the fact that the nuclear supply chain is complex, can have big barriers to entry, and faces a number of bottlenecks which are not easy to resolve. Innovation also appears to be slower, with long life cycles between generations of plant and once deployed they remain on the system for decades, potentially constraining the development of the system and other technologies. Smaller scale technologies like PV can show quick rates on innovation and can be quickly deployed and improved. Collectively these supply chain issues can impact deployment rates and therefore the potential role of these technologies in bringing about a low carbon transition whilst also ensuring energy security.

Arguably, then, from an energy security and low carbon transition perspective, there is something inherently more secure about smaller-scale technologies. Currently this sort of analysis is not considered by policy-makers within the UK, but given the multiple challenges in bringing about a low carbon transition, such an approach could better help to identify where support should best be directed. This is more likely to enable a transition that is rapid, sustainable, secure and affordable and it deserves more policy attention.

This paper has only examined nuclear power and PV, but it is possible that similar findings may exist for other large scale (e.g. carbon capture and storage) and smaller scale (e.g. wind) technologies. Neither has it explored the potential for enabling technologies such as smart grids or energy storage. This work would therefore benefit from further studies into the scale and supply chains of other low carbon technologies and enabling technologies and how they relate to resilience, flexibility and the adaptability needed within a rapidly changing energy system.

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