Accelerating innovation towards **net zero emissions**

REPORT PREPARED FOR THE ALDERSGATE GROUP

:vivideconomics

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Executive summary

Accelerated innovation is needed to meet a net zero emissions target by mid-century as recently recommended by the Intergovernmental Panel on Climate Change (IPCC, 2018). Moving from the existing target to cut annual greenhouse gas emissions by 80%, towards a net zero emissions target by 2050 implies a greater role for key technologies. For example, while Carbon Capture Utilisation and Storage (CCUS) is part of existing plans, the net zero goal is likely to require a greater level of deployment and new applications of the technology. An ambitious approach to rolling out technologies will also be needed across buildings, transport and in the hard to treat sectors such as industry and agriculture.

Moving from invention to widespread deployment can take many decades, yet only around three decades remain to meet the net zero emissions goal. The challenge for policy makers is to effectively catalyse the rapid innovation needed for net zero on a short timescale. Learning lessons from past transformations will be critical to achieve this.

The unique contribution of this report is to identify the lessons from successful and more rapid historical innovations and apply them to the challenge of meeting net zero emissions in the UK. We review a broad database of historical innovations and identify lessons for accelerating innovation to achieve net zero emissions in the UK (Figure 1 below). This includes an in-depth analysis of five international case studies from the energy, manufacturing and banking sectors. An important feature of the assessment is that we define innovation as learning that occurs during R&D, demonstration *and* the early stages of deployment. The lessons are therefore intended to accelerate learning related to any technologies that are not yet widely deployed.

The net zero goal implies a vast transition within a few decades and accelerating the progress and adoption of new innovations. This requires both programmes that enhance early stage technology development and a clear route to market for promising innovations. **History tells us that a broad programme of government actions is vital to the success of emerging technologies and systems.** This includes new institutions, testing and trialling new technologies and business models at scale. In many cases consistent and long-term policy goals are needed.

Key actions for government policy to accelerate low-carbon innovation in the UK are:

1. **Increase ambition in demonstrating complex and high capital cost technologies and systems.** The deployment of technologies and infrastructure at scale was integral to systemic transitions such as the roll-out of ATMs and the transition from town gas to natural gas. Similarly, **at-scale investment commitment is needed in the 2020s for CCUS (including in combination with bioenergy) and funding for demonstrations of Direct Air Capture**. Large scale demonstrations are also required to understand the feasibility of repurposing a significant section of the gas network to use hydrogen; and to show how industrial clusters can achieve net zero emissions through energy and resource efficiency and the use of low-carbon energy.

2. **Create new markets to catalyse early deployment and move towards widespread commercialisation.** Once tested, Feed-In-Tariffs for wind projects were vital to move towards industrial scale deployment, and the South Korean government's strategy for steel created a new domestic market which then provided a basis from which local industry could exploit export opportunities. New markets must now be created to fully commercialise early-stage low-carbon technologies. Market creation mechanisms to be considered include **CfDs for power sector CCUS** and **obligations or incentives**

for fossil fuel using industries to sequester their CO_2 emissions.

3. **Use concurrent innovations such as those happening in the digital sector to improve system efficiency and make new products more accessible and attractive to customers.** The diffusion of ATMs and cashcards, initially with offline machines, accelerated when online technologies were introduced, which offered a range of additional benefits for consumers and businesses. Similarly, the transition towards central heating was a relatively rapid transition, in part because it provided a higher level of service and benefits to the consumer. There is a clear opportunity for digital technologies to increase flexibilty and accelerate customer take-up of energy efficiency, low-carbon heating and clean mobility solutions. Government should co-ordinate the roll-out of new low-carbon technologies with new digital services, through providing **data controls and platforms**, and **trialling "energy as a service" business models at scale**. **Business models should focus on providing *smart* heating which is both low-carbon and a better experience for the customer.** Consumers should be given incentives to transition to these technologies. For example, **time of use pricing** for electricity will create cost benefits for consumers who shift demand to off-peak periods. Combined with **stronger regulations** on efficiency, this can help drive rapid improvements in the efficiency of our housing stock.

4. **Use existing or new organisations (cross-industry associations or public-private collaborations) to accelerate innovation in critical areas and co-ordinate early stage deployment.** Government-backed organisations in the UK and Denmark ensured successful wind designs proliferated more quickly. Third party organisations can bring together the right actors and promote knowledge sharing, counteracting corporate drivers to maintain exclusivity over innovation knowledge. Institutions with a clear mandate are also needed to coordinate efficient deployment in complex areas with multiple infrastructures. The Gas Council facilitated the development of bulk gas supplies at the same time as rolling out a gas network, and the conversion to gas boilers and central heating in homes. Similarly, **the low-carbon heat transition requires coordination of energy supply and new infrastructure**. In CCUS, new **CO_2 transport infrastructure (or repurposing of existing infrastructure) needs coordination with the development of CO_2 stores and rollout of capture plant**. The recommendation of the Parliamentary advisory group on CCS for a new public delivery body is one way to achieve this.

5. **Harness trusted voices to build consumer acceptance, through information sharing and rapid responses to concerns.** Rapid consumer transitions have happened in the past (for example, an average conversion rate from town gas to natural gas of over 1 million users per year, during the late 1960s and 1970s). This was facilitated through trusted institutions that provided a strong combination of information, technical assistance and response to consumer concerns (e.g. around safety). To facilitate the low-carbon heating transition, setting up a reliable system of certification of heat pumps and hybrid systems will build trust. The use of trusted organisations, for example **expanding the role of Ofgem or the Energy Savings Trust**, could be used to share information on technologies and respond rapidly to concerns. Where technologies are very novel, such as with CCUS and DACCS, government should commit to early, genuine, open and transparent public engagement.

6. **Align innovation policy in such a way that it strengthens the UK's industrial advantages and increases knowledge spillovers between businesses and sectors.** Innovations in the South Korean steel sector and adoption of new methods relied on a clear strategy that was tied to economic development and reducing costs

for downstream customers. In the UK, a focus on areas where technology spillovers are likely to be high could drive additional productivity benefits. For example, one assessment suggests that several low-carbon technologies, including CCUS, wind, batteries and biofuels, have high potential for economic benefits beyond simply the value of the goods, such as a contribution to economic productivity or local growth. These wider benefits can feedback into improved innovation investment overall. Government should take actions to prioritise innovation in sectors with positive technology spillovers such as CCUS, heating, ventilation and air conditioning (HVAC), biofuels, and wind.

The lessons identified above should be applied to areas where the UK should focus on in pursuing a net zero emissions target. These innovation priorities include:

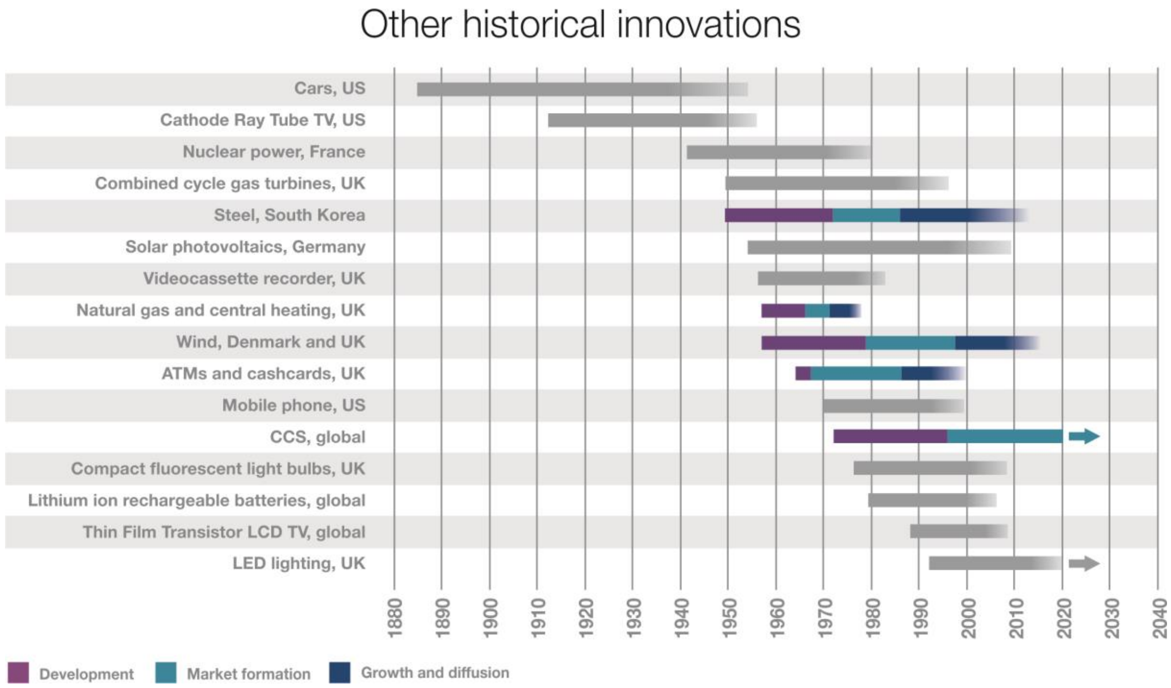
- **Supply side:** critical emerging technologies such as *CCUS, BECCS, DACCS and hydrogen production technologies* offer the potential to achieve deeper emissions cuts but require further deployment at scale to improve understanding and reduce cost. An accelerated deployment of offshore wind is also likely to reap extensive productivity spillovers and export opportunities for the UK while decarbonising the power sector.
- **Demand side:** transport and energy consumption in buildings will need to be decarbonised almost completely, particularly through an accelerated uptake of *heat pumps* and more rapid roll out of *deep retrofits* that achieve very low emissions in the existing housing stock. A more rapid deployment of *smart grid technologies* and *batteries* would be required to integrate higher shares of renewables and enable active demand response. Further deployment of *bioenergy*, and in the longer term, *hydrogen end-use technologies* (boilers and fuel cells in homes) would be responsible for significant emissions reductions in end-use sectors. The deployment of low-carbon *industrial technologies* is also required for the UK to remain competitive in the global market.
- **Supporting infrastructure:** negative emissions technologies, which rely to a far greater degree on the development of *CCUS infrastructure*, are even more important in a net zero scenario to offset any remaining emissions.

Implementing these lessons will require a further increase in government support for innovation – through both research, development and demonstration and through deployment policies to create new markets. The UK Government is already making significant investments in low-carbon innovation, though these investments tend to focus more on research, development and early deployment than on creating markets. The Committee on Climate Change is due to publish recommendations on meeting a net zero target in May 2019, which will help to focus on technologies that are particularly important in meeting a more ambitious target. The Energy Innovation Needs Assessments (EINAs), also to be published in 2019, will identify key technology areas that are important for the UK energy transition and UK exports. There is an opportunity for this analysis and advice to form the basis for a more comprehensive strategy for low-carbon innovation, backed up by specific policies to accelerate innovation towards net zero.

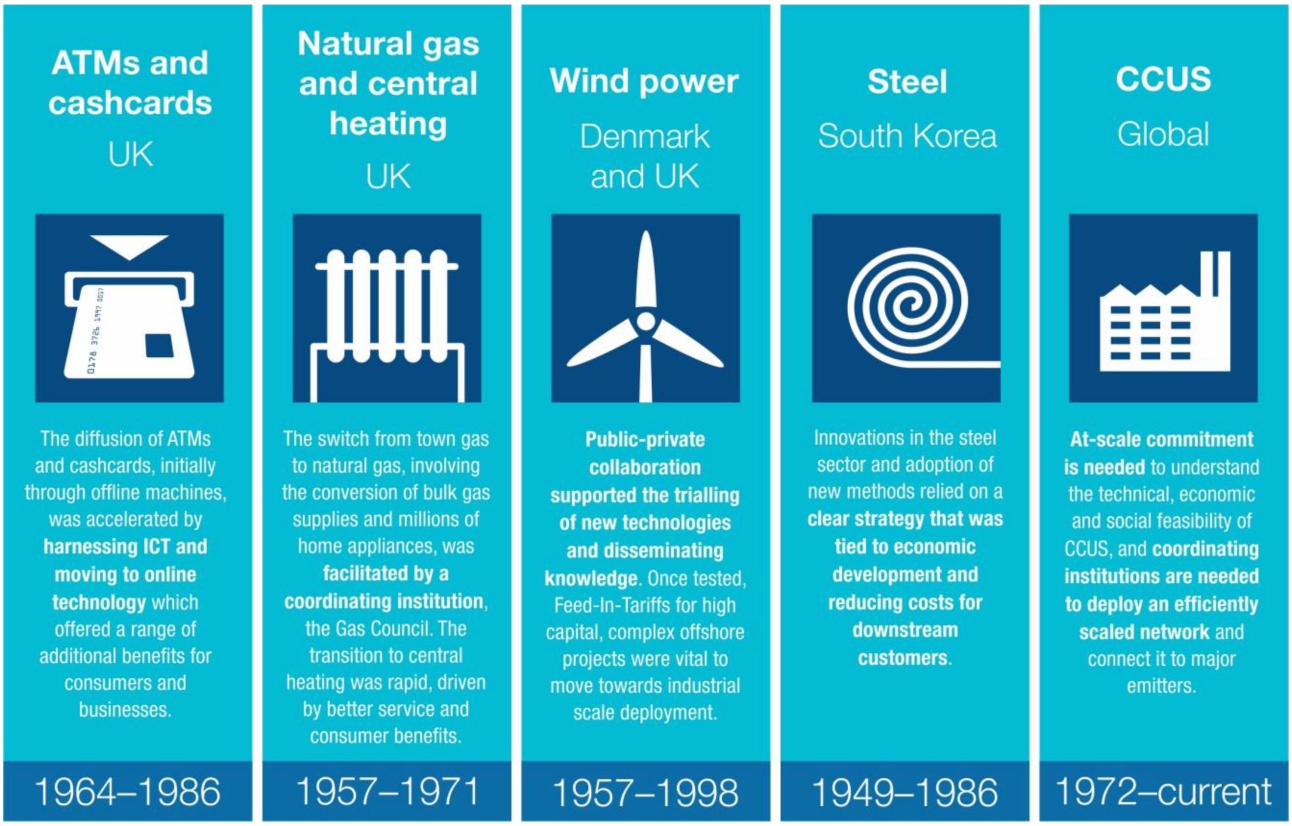
Table 1: Key recommendations

Recommendation	Application to UK innovation agenda
Increase ambition in demonstrating complex and high capital cost technologies and systems.	1. At-scale investment commitment is needed in the 2020s for CCUS (including in combination with bioenergy). 2. Large scale demonstrations are also required to understand the feasibility of repurposing a significant section of the gas network to use hydrogen. 3. Show how industrial clusters can achieve net zero emissions through energy and resource efficiency and the use of low-carbon energy 4. Funding for demonstrations of Direct Air Capture.
Create new markets to catalyse early deployment and move towards widespread commercialisation.	1. Market creation mechanisms to be considered include CfDs for power sector CCUS and obligations or incentives for fossil fuel using industries to sequester their CO_2 emissions. 2. A clear strategy and a public organisation to develop capture and storage infrastructure. 3. Market creation mechanisms and regulatory drivers to complete the full decarbonisation of the power sector, grow the market for zero emission vehicles and the market for energy efficiency in buildings.
Use concurrent innovations such as those happening in the digital sector to improve system efficiency and make new products more accessible and attractive to customers.	1. Government should co-ordinate the roll-out of new low-carbon technologies with new digital services, through providing data controls and platforms, and trialling "energy as a service" business models at scale. 2. Business models should focus on providing *smart* heating which is both low-carbon and a better experience for the customer. 3. Consumers should be given incentives to transition to these technologies. For example, time of use pricing for electricity will create cost benefits for consumers who shift demand to off-peak periods. Stronger regulations on efficiency can help drive rapid improvements in the efficiency of our housing stock.
Use existing or new organisations (cross-industry associations or public-private collaborations) to accelerate innovation in critical areas and co-ordinate early stage deployment.	1. The low-carbon heat transition requires coordination of energy supply and new infrastructure. 2. Electrification and decarbonisation of transport needs to be carefully co-ordinated with power sector decarbonisation, grid reinforcement, storage innovation and smart heating roll-out. 3. In CCUS, new CO_2 transport infrastructure (or repurposing of existing infrastructure) needs coordination with the development of CO_2 stores and rollout of capture plant. The recommendation of the Parliamentary advisory group on CCS for a new public delivery body is one way to achieve this.
Harness trusted voices to build consumer acceptance, through information sharing and rapid responses to concerns.	1. The use of trusted organisations, for example expanding the role of Ofgem or the Energy Savings Trust, could be used to share information on technologies and respond rapidly to concerns. 2. Where technologies are very novel, such as with CCUS and DACCS, government should commit to early, genuine, open and transparent public engagement.
Align innovation policy in such a way that it strengthens the UK's industrial advantages and increases knowledge spillovers between businesses and sectors.	1. Government should take actions to prioritise innovation in sectors with positive technology spillovers such as CCUS, heating, ventilation and air conditioning (HVAC), biofuels and wind.

Figure 1: Innovation timelines and case study lessons



Source: Vivid Economics and Gross et al (2018)



*Time period is from point of invention to widespread commercialisation (20% of ultimate market size).

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1 Introduction and approach

The UK's move towards net zero is part of an increase in global awareness regarding the importance of achieving net zero emissions. In 2015 the Paris Agreement called for *a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century* – the so-called net zero provision. Subsequent to the Paris Agreement, several countries have introduced net zero legislation: Sweden aims to reach net zero by 2045, Norway has legislated to be carbon neutral by 2030 and New Zealand is passing a 2050 net zero bill. At the time of writing, 19 countries, including the UK, had joined the international Carbon Neutrality Coalition, which pledges to set out *long-term, low-emissions, climate-resilient development strategies, in line with the agreed long-term temperature increase limit, as early as possible and no later than 2020.*

Tighter emissions reduction targets accentuate the need for accelerated innovation in the UK economy. Economic theory suggests innovation is vital to economic productivity and growth, and the role and importance of innovation in reducing emissions is also well established (Gross et al., 2018). International innovation initiatives such as 'Mission Innovation' seek to encourage countries to redouble efforts to innovate in low-carbon technologies. Policies to accelerate innovation, from invention (or basic research) to the creation of a market to commercialise technologies, are even more important in the context of aiming for net zero. Existing targets already involve large-scale capital stock transformation and economic adjustment; innovation will be vital to ensure the feasibility and affordability of achieving more ambitious targets.

Innovation has already played a crucial role in the ongoing global clean-energy transition. Progress in recent years has been driven by dramatic falls in the cost of key renewable energy technologies, contributing towards a cleaner energy mix. Improvements in the way energy systems operate, driven by trends such as the growing electrification of end-user sectors, the decentralisation and democratisation of power generation, and increased digitalisation, have also improved energy efficiency. However, according to the IEA (2018), only 4 out of 38 energy technologies and sectors were on track to meet long-term climate, energy access, and air pollution goals in 2017.

Against this backdrop, the Aldersgate Group has commissioned Vivid Economics and the UK Energy Research Centre (UKERC) to examine and explain how the conditions and policy approaches under which the cycle of innovation occurs, and could be accelerated, to achieve a net zero target. This report conducts a detailed assessment of five case studies from around the world. The case studies are used to illuminate common features that underpin rapid innovation or aspects which may be associated with slow innovation and should be avoided. In this introduction, we set out the key aspects of our approach to this report, including detail on the methodology (Box 1), a definition of the innovation lifecycle, how we selected innovation priorities, and the use of case studies.

Definitions of innovation and stages in the innovation lifecycle

The economic case for government innovation support stems from a coordination failure between firms that means valuable information about new inventions is typically not shared. As a result, innovation is commonly underprovided, and the rate of innovation is slower than the optimal level. There are two key perspectives that characterise the debate on innovation policy:

- *Supply-push:* Schumpeter (1934) conceptualised the supply-side view whereby more resources are put into research to hasten the journey from basic research through to commercialisation. Schumpeter's understanding of the innovation cycle involved a process of 'creative destruction', where the supply-push disturbs the system and creates the conditions for further innovation.

- *Demand-pull:* The demand-side perspective proposed that the market for products and services drives innovation more effectively than stimulating innovation (Carter & Williams, 1958). More recent discussions on innovation policy integrate both perspectives in a model of innovation called research, development, demonstration, and deployment (RDD&D).

There are many stages to innovation processes, which have important feedbacks between them. In this report, we focus on three broad stages of innovation: development, market formation and growth & diffusion (Gross et al. 2018). These three phases provide a simple and intuitive model with a clear definition of what conditions need to be present at the start and end dates of each phase. In this work, these phases are used to track the time taken to proceed through the innovation cycle for each of the case studies, and therefore to be able to determine whether progress was comparatively fast or slow.

In each phase, the roles of the key actors (government, business, and consumers) are analysed.

Selection of case studies

Case studies were selected to span a range of possible technologies that serve as good comparative examples to the priority areas for UK innovation to meet the net zero target. A long list of case studies was created based on existing literature, and a subset of five innovations were selected from this list based on the need to cover consumer goods (innovation in heating), supply-side technologies (wind), a case where whole systems change occurred (innovation in banking), a case that looked into the industrial sector (the steel sector in South Korea), and a case in which innovation has not proceeded quickly (CCUS). In each case, possible analogues can be identified in the challenge ahead of achieving net zero in the UK (Box 2).

Box 1 Summary of methodology

- ***Step 1: Review literature on innovation lifecycles.*** Several papers are particularly useful in the context of this study, including Gross et al. (2018) on innovation timescales, and Wilson (2012) on energy technology innovations. These papers help provide the stages of the innovation lifecycle, and a broader range of case studies to compare our assessments with.
- ***Step 2: Select examples of past innovations for case study analyses.*** The selection process is guided by the themes that emerge from Steps 1 and 2.
- ***Step 3: Review the literature for each of the inventions.*** First, an annotated timeline is created to describe the process of how the invention penetrated the market from development through to widespread commercialisation. Then, the following research questions are addressed: How long did it take to pass through each innovation stage? In each stage: What actions did government and business take? Were international links important in driving innovation?
- ***Step 4: Analyse the case studies to identify common features*** by synthesising the conditions that accelerated or delayed innovation.
- ***Step 5: Assess innovation priorities in the UK.*** This is based on the needs of the UK energy system, productivity, and export opportunities.
- ***Step 6: Develop recommendations for UK policy makers*** based on relevant parts of case studies and broader literature.

Selection of innovation priorities

A diverse set of technologies are required to contribute towards rapid decarbonisation. Before identifying *how* to support innovations, it is important to ask *which* innovations should be prioritised. A clear understanding of the potential of each technology helps to sharpen policy design and strengthen the case for intervention. This report considers three policy objectives to prioritise innovations in the UK: securing a cost-effective transition, increasing productivity, and capitalising on export competitiveness.

While this prioritisation informs the subsequent selection of case studies, it is not intended to be an exhaustive assessment of innovation needs.

Box 2 Case studies

- ***Case 1 - Innovation in banking (UK):*** In just over 20 years, banks moved from using the first offline cash machine to widespread deployment of fully automated online machines in the UK. The initial designs, operated through a punch-card facility, and the supporting systems, were rapidly built on through harnessing the benefits of computing and IT infrastructure, which provided a substantial value-add to the initial invention.
- ***Case 2 - Gas and central heating (UK):*** This complex, whole system transition of developing gas endowments, deploying grids, and converting appliances to accept natural gas reached 14 million homes in just over 10 years, from market entry. Strong direction by the Gas Council was vital in co-ordinating gas supply, distribution and delivery, and in providing information to consumers. The Morton Report in 1970 was important for allaying consumer safety concerns about the new fuel.
- ***Case 3 - Wind (Denmark and UK):*** Early development of wind projects in Denmark benefited from a strong culture of fluid information sharing between industry players and government about mechanisms for cost reduction. The move to GW-scale deployment took around four decades from the point of invention. Offshore wind built on the onshore industry, and has had a more rapid innovation timescale than onshore wind. Periods of strong market incentive have been associated with rapid scaling up and cost reduction in the UK.
- ***Case 4 - Innovation in steel (South Korea):*** Seeking to grow a domestic manufacturing base, South Korea rapidly adopted innovative steel production methods developed overseas and became a major steel producer in just 14 years from market entry. The adoption of new innovations enabled low-cost and higher quality steel to be provided to domestic industries, and for an export market to be created.
- ***Case 5 - CCUS (Global):*** This complex infrastructure is not proceeding on the innovation pathway required to meet the IEA's Sustainable Development Scenario (IEA, 2018) and has not reached widespread diffusion and deployment. While incentives have been implemented in countries including the US, UK, Canada, and Norway, many large-scale projects have stalled or not translated into a pipeline of future projects. A common feature of these cases is a stop-start approach to demonstration, which has been ineffective in the context of promoting CCUS deployment.

2 Lessons learned from global case studies

This section presents five international and cross-sector case studies of previous innovations. The purpose of undertaking this historical analysis is to identify the factors that accelerated past innovations, as well as those that impeded or slowed down their progress. It is therefore important in analysing the past case studies to be aware of the significant differences between them and the future innovations required to achieve net zero. Nonetheless, most past innovations contain an aspect in which they are analogous to some part of future net zero-focussed transitions.

A set of case studies has been selected that spans examples of consumer goods, supply side technologies, systemic changes, and a technology system that has not yet succeeded. The timeline of each innovation has been divided into three stages – development, market formation and commercialisation – following a classification provided by the UKERC (Gross et al., 2018). The line between market formation and commercialisation is defined as 20% of ultimate market size (as an approximate measure of widespread commercialisation). We assume that innovation and processes of learning occur throughout all three of these stages.

This section presents a summary of the timeline of each case study as well as their policy implications. The appendices include further information.

2.1 Cash dispensing systems and cash cards in the UK

Table 2: Key features of case study

Invention	Cash dispensing systems and cash cards in the UK
Invention definition	The cash dispenser and cash card were a complex set of innovations which drew together features of several earlier innovations and became inherently bound up with more systemic innovations in the digitalisation and centralisation of banking systems. This case study demonstrates a consumer-focussed innovation, but with systemic and infrastructure elements.
Market need	The original market need was driven by banks' interest in streamlining transactions, and in offering greater convenience to customers with multiple cash withdrawal points and access outside of branch opening hours. However, the convenience and attractiveness of the innovation was soon enhanced by related developments in centralisation and computerisation of accounting systems, leading to fully online ATMs.
Scope of study	The study focusses on the UK, which has claim to be a key location for this innovation. The timeframe covers the point of invention until the point where there was a single unified ATM network in the UK.
Link to UK innovation needs	Increasing integration with information technology systems will be essential in many aspects of decarbonisation, including energy efficiency, smart heating and domestic load shifting, and electric vehicle charging. These developments will require new kinds of system integration, and may involve upgrading of infrastructure and IT networks. New technological interfaces for consumers will emerge, which could bring about different behavioural patterns and social changes, and both require and enable new levels of consumer engagement.
Year of invention	In 1964, James Goodfellow, working at Kelvin Hughes, an arm of engineering firm Smith's Industries, developed a system for dispensing oil to tanker drivers at unattended loading areas. The driver would operate the automated delivery system using a punched card. This idea was later developed for the first cash dispensers (Bátiz-Lazo & Reid, 2008). Hence this original application is defined as the year of invention.
Year of market entry	Market entry year is defined as 1967. In this year, the first ever cash machine was deployed, at a branch of Barclays Bank in Enfield, UK, using a design by De La Rue Instruments. Shortly afterwards, the Westminster Bank deployed a cash machine built by Chubb & Sons Lock and Safe Company in collaboration with Smith's Industries, at its Victoria branch in London. In the same year, the Bankomat was also launched in Sweden (Bátiz-Lazo, 2007, 2015; Bátiz-Lazo & Reid, 2008).
Year of market commercialisation	Market commercialisation year is defined as 1986. The largest number of total installed ATMs in the UK during the period of study was recorded in 2003, when the total cumulative number was 46,461. Twenty percent of this eventual number was first breached in 1986, when the total cumulative number installed was 10,330 (22% of the 2003 number) (Bátiz-Lazo, 2007).

Cash dispensing systems and cash cards in the UK

DEVELOPMENT STAGE

1964
Smith's Industries develop punched card operated system for automatic dispensing of oil to tanker trucks

1966
James Goodfellow files the patent for a currency dispenser system, operated by a punched card in combination with a private identification number (PIN). Midland bank awards contract to develop alternative design to Speytec, who also liaise with the National Physical Laboratory (NPL). Decimalisation of UK currency announced to Parliament.

MARKET FORMATION STAGE

1967
Barclays / De la Rue Automatic Cash System (DACS) launched as Barclaycash, at Enfield branch. Westminster Bank / Chubb / Smith's Industries system launched at Victoria branch. Nine more machines installed over next four months. Other banks quickly adopt cash dispensers. Bankomat launched in Sweden.

1968
Royal Bank of Scotland has dispensers in 25 branches in Scotland and London

1969
Speytec research for Midland taken over by Burroughs (Detroit based computer mainframe manufacturer)

1970
Lloyds indicates it is waiting for 'online' cash dispensers. Lloyds moves customer accounting systems to a centralised computer

1971
UK converts to decimal currency. Lloyds orders 500 Cashpoint machines, developed in partnership with IBM – the first 'online' cash dispenser

1972
First Lloyds Cashpoint begins operation

1973
250 Barclaycash machines in operation in UK

1975
Barclays new online cash dispensers, 'Barclay bank', launched. NatWest launches online dispenser 'Servicetill', designed by US computer mainframe manufacturer, NCR.

1979
Deregulation of banking begins with abolition of exchange controls

1981
NCR machines now offering increased functionality, such as multiple currencies, print outs, data encryption. Total number of ATMs increases by 64% over the previous year.

1983
NatWest and Midland sign first reciprocity agreement, allowing customers to use each other's machines

1985
LINK network established

1986
MATRIX network established

COMMERCIALISATION STAGE

1990
IBM withdraws from ATM manufacture – NCR now main global designer and provider of ATMs

1999
Barclays, having joined LINK network, is criticised for attempting to impose transaction charges on customers of other banks using its machines

2000
All transaction charges dropped, meaning that there is effectively a single ATM network in the UK

Discussion

The cash dispenser and cash card innovation timeline was rapid, at 22 years (1964-1986). Gross et al. (2018) compare the time elapsed between invention and widespread commercialisation (20% of eventual installed capacity) of thirteen technologies, and find this period for cash cards and ATMs to be the second fastest, at 22 years (1964-1986).

The availability of digital and online technologies improved the proposition for customers and made the provision of banking services more efficient, accelerating adoption. While the timing of the spread of computer technologies was fortuitous, it demonstrates the potential of digital technologies. Online technologies radically increased convenience and the services that could be provided to customers. For businesses, it improved the efficiency with which banking services could be provided, thereby reducing cost. Other technical, social, and political conditions contributed to the rapid progress of the innovation.

Implications for the UK's innovation policy are:

1. **Capitalise on concurrent technological innovation, such as digital technologies, to make new products more accessible and attractive to customers**

This innovation accelerated when cash dispensers were linked to computerised systems. First-generation cash dispensers offered small increases in convenience. Once computerised, the benefits for customers and banks in terms of convenience and efficiency were greatly enhanced. Furthermore, other individual innovations were enabled together: video display units, magnetic tape, plastic materials, and automated cash counting and transportation technologies. A crucial new innovation was the PIN and the algorithm to associate an encrypted PIN with a customer account (Bátiz-Lazo, 2007, 2015; Bátiz-Lazo & Reid, 2008). The coincident timing of these innovations enabled rapid deployment of online machines.

Government can help encourage interactions of technologies, such as digital, to speed up early deployment. The digitalisation of the economy could offer benefits in terms of convenience and cost savings, whilst enabling the optimised integration of low-carbon technologies within energy and other systems (BT & Accenture Strategy, 2016). 'Energy-as-a-service' offerings harness digital technologies to increase convenience and controllability. Transitioning to low-carbon heating technologies could be accelerated by offering the technology as part of a service package which also combines increases in the level of service. Government policy support could accelerate early deployment by focussing on demonstrating and trialling of business models. There is also a need for new data sharing and trading platforms, as well as data sharing protocols, to ensure that digital services can be provided.

Digitisation can also increase efficiency, reducing costs for business and government and further accelerating adoption. Improving the information that is available, using digital devices, can help optimise the energy system. The use of decentralised resources, either by shifting demand or through decentralised energy generation, can reduce grid congestion and the need for investment in generation and grids. If realised, these benefits can improve the business case for digitised services and further accelerate innovation.

2. **Adapt innovations to the current social context**

Cash dispensers were rapidly adopted due to pre-existing technological familiarity. This case study took place in a context where there was familiarity with other kinds of automated dispensing equipment, as well as increasing consumerism and demand for convenience, seeding the idea that having access to cash at the weekends would be a desirable thing (Bátiz-Lazo, 2015; Bátiz-Lazo & Reid, 2008). Applying this to current innovation needs, the widespread use of apps and mobile technology paves the way for further use in homes and businesses to optimise the use of energy.

3. Facilitate cross-industry collaboration and innovation by bringing together the right actors

Initial industry relationships were with providers of physical hardware to support the offline banking transition. In the 1960s, in order to develop the first offline machines, banks logically looked for collaborations with companies whose expertise would suit the design of the physical hardware – thus they looked to Chubb for their expertise in secure safes, and to De La Rue for their expertise in automatic cash counting and transportation equipment. However, as soon as the online cash dispenser was conceived of, it rapidly became clear to banks that the critical expertise was in computational systems and infrastructure.

Pre-existing relationships between banks and IT companies accelerated the transition to online banking. A broader process of centralisation and computerisation of their accounting systems was underway. Partnerships with the right actors already existed, including computer mainframe manufacturers such as IBM, NCR, and Burroughs. This allowed for a seamless transition from offline to online models (Bátiz-Lazo, 2007; Bátiz-Lazo & Reid, 2008).

Where these relationships do not exist, cross-industry collaboration and innovation can very usefully be supported and encouraged by government. Successful examples of government helping to bring private actors together include the Offshore Wind Accelerator (discussed in a later case study), and the National Industrial Symbiosis Programme (NISP). Such a coordinating role would require a forward-looking perspective, sensitive to the evolving dynamics within the industry. This would enable an awareness not just of past relationships, but also of the kind of new actor relationships that might be key to the transition as it develops.

4. Support infrastructure to achieve economies of scale and maximise spillover effects

IBM's investment in networks (rails, pipes, standards, credit cards and point-of-sale terminals) generated significant spillover effects for companies that followed (Bátiz-Lazo, 2015). This is an example of a transition where networks and infrastructure could be put in place by private sector actors because, although there was competition, the first-mover actors were of sufficient size to make extensive network investment viable. The banks and the firms with whom they collaborated were of a large enough scale to be able to order in bulk – for example, with Lloyds going straight into the market with an order of 500 machines from IBM – which enabled economies of scale. The at-scale rollout of dispensers meant customers could access cash locally, rather than from a single branch (Bátiz-Lazo, 2007, Bátiz-Lazo and Reid, 2008).

In electricity systems, fractured deployment meant government intervention was eventually required to standardise and rationalise them. In the case of ATM networks, this seems to have been avoided by the size of the key initial players, which may have helped to avoid the proliferation of multiple competing and incompatible systems. Further, the mutual benefit of reciprocal ATM networks gradually became clear to banks, who were therefore prepared to relinquish the proprietary nature of their networks voluntarily (Bátiz-Lazo, 2007).

Technologies which rely on network infrastructure may require public investment and coordination. Network infrastructure has high fixed start-up costs, and the private sector may not be sufficiently well capitalised to deploy it, without government support. Banks had identified a substantial market opportunity resulting from developing infrastructure, and as a result, infrastructure development proceeded largely without public coordination. This will not be the case for CCUS and DACCS (which require CO_2 infrastructure) as there is not a strong market demand for these technologies. As a result, CO_2 infrastructure is unlikely to be invested in efficiently without government support. This may also apply to EV charging infrastructure and hydrogen refuelling stations for hydrogen heavy goods vehicles. **Government support is therefore essential to rolling out infrastructure at the efficient scale and supporting the transport of CO_2, deployment of EVs and hydrogen roll-out.**

2.2 Gas and central heating in the UK

Table 3: Key features of case study

Invention	Gas and central heating in the UK
Invention definition	This case concerns a specific technology embedded within a broader system change. The specific technology is domestic central heating, and the wider system change is the UK transition from town gas to natural gas, which largely took place from 1966 to 1977. The technology and the system change are not inherently linked in that it is possible to have one without the other. Nonetheless, as they happened to be introduced at similar times, they did evolve together and became mutually reinforcing. This innovation involves end-user consumer appliances, but is also linked to a wider systemic transition with a significant infrastructure element.
Market need	The market need was also, to a large extent, a public service or public good need, and in the era of nationalised public service industries these two were also strongly intertwined. In 1961, the Parker Morris report *Homes for Today and Tomorrow* raised the issue of a consistent minimum internal temperature throughout a home as a question of public health, which began to promote and legitimate the idea of central heating. The health impacts of smog events, such as that which occurred in London in 1952, were also becoming apparent. The contribution of domestic coal burning to such events was increasingly clear, giving impetus to alternative domestic fuels. Furthermore, the gas industry was under competition from other fuels, and was actively seeking more cost-effective ways of producing gas, other than coal and oil gasification.
Scope of study	UK, 1957–1978
Link to UK innovation needs	Low-carbon innovation in the UK requires end-user-focussed innovation, as well as systemic and infrastructure change.
Year of invention	In 1957, an Information Circular from the British Coal Utilisation Research Association (BCURA) described a small-bore hot water heating system, which could bring the cost of a central heating system 'within the reach of a much larger section of the population, and at the same time… produce a system with an improved efficiency of operation' (cited in Hanmer and Abram, 2017).
Year of market entry	Market entry year is taken as 1966, when a Conversion Executive was established to provide nation-wide coordination of the transition to natural gas.
Year of market commercialisation	Arapostathis et al. (2013) report that by 1977 the natural gas transition was complete. It had involved the conversion of 14 million users, 6 million of whom had been converted by 1972. Thus, in terms of users converted, in 1972 the transition was 43% complete. The two previous years show a rapid increase in natural gas consumption, rising from 10% of the eventual 1978 level in 1970, to 26% in 1971. Thus the 20% level was passed in 1971, meaning that this year is adopted as the year of market commercialisation. The BEIS historical data is represented in Figure 2 below, in terms of GWh total consumption.

Gas and central heating in the UK

DEVELOPMENT STAGE

1948
Gas Act initiates nationalisation of gas industry

1952
London smog disaster

1956
Clean Air Act allows local authorities to create smokeless zones

1957
British Coal Utilization Research Association (BCURA) publicises the small-bore hot water heating system

1959
LNG from Louisiana begins to be imported to Canvey Island

1961
Parker Morris report, *Homes for Today and Tomorrow*, presents guidelines on healthy internal temperatures of homes. Central heating becomes increasingly legitimated and desirable. Gas Council decides to import LNG from Algeria.

1962
Construction begins on LNG pipeline from Canvey Island to Leeds

1965
Natural Gas discovered in West Sole field, off the coast of East Anglia

MARKET FORMATION STAGE

1966
Conversion Executive set up to provide nation-wide coordination of the transition to natural gas

1968
Ronan Point explosion at Canning Town

1969
Guaranteed Warmth campaign aims to lock in more customers to gas central heating

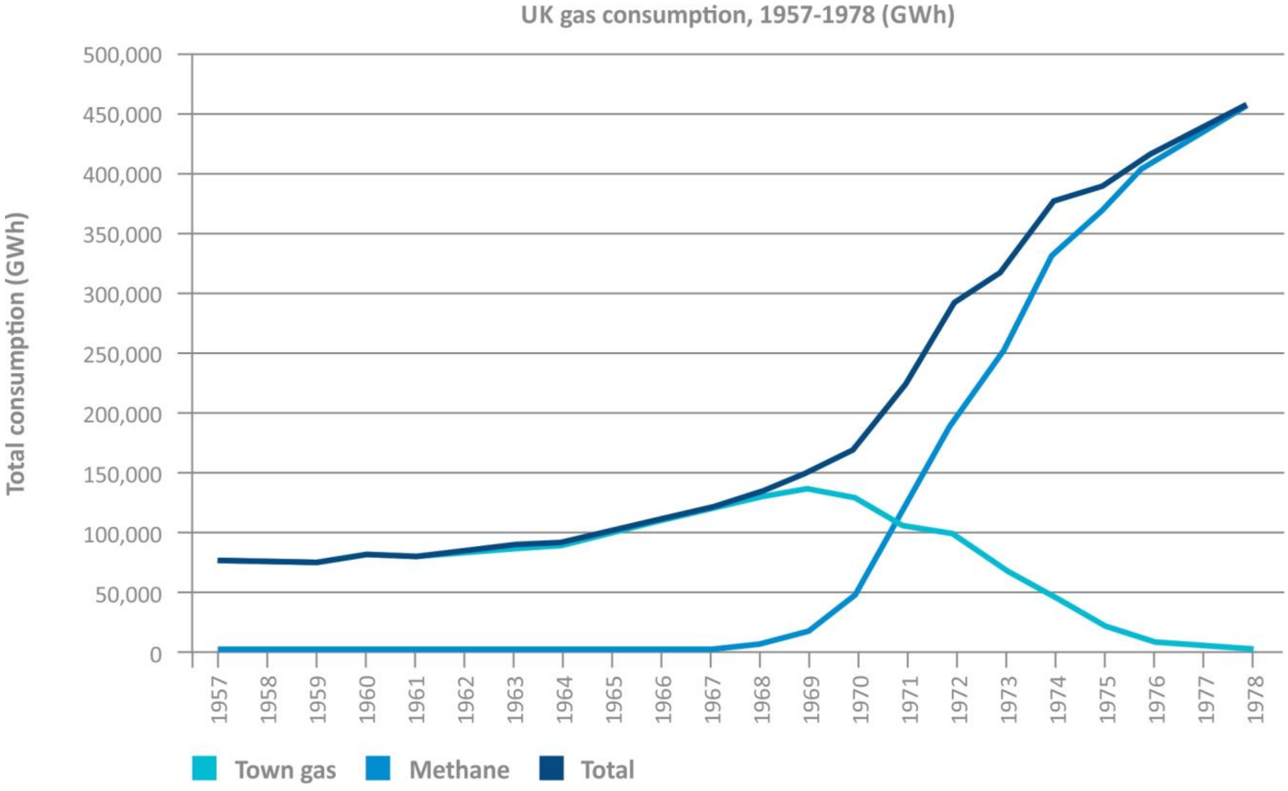
1970
Morton Report confirms that natural gas is at least as safe as town gas and would lead to a reduction in accidents and poisoning

COMMERCIALISATION STAGE

1972
Gas Act leads to the formation of the British Gas Corporation, an organisation with responsibility for gas supply across the whole country. 6 million users have been converted.

1977
Natural gas conversion complete. 40 million appliances from 14 million users converted, modified or replaced

Figure 2: UK gas consumption (GWh), 1957–1978, from town gas, methane, and the total. All demand sources are included: domestic, industrial, electricity, other energy, and services



Source: BEIS (2019)

Discussion

The speed at which the UK's gas and central heating transition went from 'invention' to 'widespread commercialisation' was the fastest of those analysed, at 14 years (1957-1971). 14 million consumers were converted during the ten-year town gas to natural gas conversion, which was completed in 1977 – implying an average conversion rate of over 1 million users per year, during the period. State bodies such as the Gas Council, and industry organisations such as the British Coal Utilisation Research Association, were vital to this success in a number of respects, to help coordinate early deployment and to ensure that the consumer response was favourable to this new technology.

Implications for the UK's innovation policy are:

1. Use new and existing institutions with a clear remit and mandate to make decisions and coordinate the efficient deployment of multiple infrastructures

The role of coordinating bodies is important when there are multiple infrastructures or technologies that do not sit well under one industry body. The Gas Council facilitated the development of bulk gas supplies at the same time as rolling out a gas network. Created as part of the industry's nationalisation in 1948, it had the authority to make decisions about bulk supply, and the remit to propose and carry out large-scale investment in a new gas grid infrastructure. For example, it acted rapidly and decisively following the discovery of North Sea gas, and proceeded to set up another specific body, the Conversion Executive, to oversee the conversion process (Hanmer & Abram, 2017; Pearson & Arapostathis, 2017). The Gas Council took a significant early decision not to undertake the transition via an interim stage, but to proceed to the complete transition directly. The natural gas conversion was a highly distributed challenge, with engineers required to access the homes or properties of 14 million users. The approach to this required the Gas Council to work with the private sector, conducting training programmes which were organised by Area Boards or private contractors (Arapostathis et al., 2013, Pearson and Arapostathis, 2017).

Similarly, CO_2 transport infrastructure (or repurposing of existing infrastructure) needs coordination with the development of CO_2 stores and rollout of capture plant. This is particularly critical in the early stages to capture economies of scale and ensure costs are reduced. Institutional coordination may also be required if hydrogen is used to replace natural gas in heating, both in terms of the infrastructure and the appliances within homes.

2. **Harness trusted voices to build consumer acceptance, through information sharing and rapid responses to concerns**

A key lesson from the transition from town gas to natural gas is that large-scale multi-infrastructure transitions involving consumers have been achieved in the past. This was facilitated through institutions that provided a strong combination of information, technical assistance, and response to consumer concerns (e.g. around safety). Considerable attention was paid to public relations, with a Conversion Strategy handbook directed at engineers, which looked at possible concerns or barriers that might be experienced with different social groups. The increasing alignment between the gas transition and central heating opened up the opportunity for the 'Guaranteed Warmth' campaign, through which the Gas Council was able to market the desirable effects of both gas as a fuel, and central heating as a technology, as an integrated package. Following the Ronan Point disaster, the Morton report was significant in allaying safety concerns about the new fuel (Arapostathis et al., 2013; Hanmer and Abram, 2017; Pearson and Arapostathis, 2017).

The British Coal Utilisation Research Association (BCURA) publicised information about new technologies, enabling learning by doing and quick responses to public concerns. BCURA is credited with the development of the small bore hot water heating system, which it then publicised through its Information Circulars, by making links among equipment manufacturers and heating system designers, and pulling together people, equipment and publications in support of this new way of designing central heating (Hanmer and Abram, 2017). The familiarity of individual engineers with such new systems was crucial to this part of the transition, which itself was intertwined with the wider natural gas transition, as has been discussed.

A trusted organisation which publishes information on new technologies and can respond rapidly to customer concerns will minimise the risk of negative public reaction to the new technology. Trustworthy institutions in sectors relevant to low-carbon transitions need to be identified, and efforts made to avoid their independence and trustworthiness being compromised. For example, Energy Savings Trust (EST) research (2011) suggests that homeowners are most likely to trust local authorities when making decisions on retrofitting their homes. Government should consider a similar function for Ofgem or the EST, in the context of the transitions to new technologies at the household level, such as low-carbon heating systems and EV charging.

3. **Innovation policy should be aligned with areas where there is strong customer demand for a higher level of service**

At the time of the transition, demand for central heating was growing due to generally increasing social aspirations. The fact that this increasing consumer desire for central heating was occurring at the same time as the gas transition was being rolled out provided an opportunity to 'package up' central heating systems with gas fuel to become both a desirable option, but also eventually the 'default' option for homes (Hanmer and Abram, 2017). Gas central heating systems offered greater convenience and an improved energy service compared to other central heating systems, and even more so in comparison to traditional coal grates. Additionally, following the discovery of North Sea gas, natural gas fuel was cheaper than previously manufactured gas had been (Hanmer and Abram, 2017). As such, the individual technology (central heating) and the wider system change (natural gas transition), became intertwined and mutually reinforcing, increasing the momentum of change for both.

Public health was also growing as a concern at the time of the transition. The Clean Air Act and its provision for the creation of smokeless zones was destabilising the main incumbent domestic fuel, coal. This provided an important window of opportunity for gas (Hanmer & Abram, 2017; Scarrow, 1972) to improve public health outcomes.

Current trends include demand for increased flexibility and the convenience of integrating numerous services through IT and mobile apps; increasing concerns about air quality in urban areas; and increasing interest in reducing waste and in dietary changes towards reducing meat consumption. Such trends cannot necessarily be controlled by governments; however, policy makers could identify windows of opportunity to support low-carbon innovations that align with these social changes. There is an opportunity to make the transition to low-carbon heating part of a broader transition to *smart* heating, including both low-carbon technologies and the higher level of service. Government should package low-carbon innovation together with increases in the level of service to increase the pace of innovation and early deployment.

2.3 Wind power in Denmark and the UK

Table 4: Key features of case study

Invention	Wind power in Denmark and the UK
Invention definition	A wind turbine for the generation of electricity. Turbines were being built as early as the late nineteenth century, however the focus of this case study begins with the mid-twentieth century. This is a power sector innovation, which required strong policy support in its early stages to overcome technical barriers. Support was called for and justified due to the positive externalities of the technology as a clean energy source. It is one of the UK's major sources of low-carbon energy and thus directly relevant.
Market need	The original market need arose from the desire for electrification in rural areas – particularly in Denmark and the US – which had not yet been reached by grid electricity. However, by the middle of the twentieth century this need tailed off as grid electrification became more extensive. New drivers arose from the early 1970s as interest in alternative energy sources was piqued by the effects of the oil shock, and environmental concerns over nuclear power (Jones & Bouamane, 2011).
Scope of study	The main scope of the study is Denmark, from 1957 to around 2000. The study then also picks up on the development of offshore wind in the UK, from around 2010 to the present.
Link to UK innovation needs	The UK needs to support and rapidly deploy substantial quantities of low-carbon generation. Although onshore wind is now considered a relatively mature technology, there is still substantial room for further innovation in offshore designs, including concepts such as floating turbines.
Year of invention	1957 was the year that Johannes Juul completed construction of the 200-kW turbine, subsequently known as the Gedser Turbine, for the electricity company SEAS at Gedser in the south of Denmark. Although quite substantial numbers of electricity-generating wind turbines had been constructed before this date, especially in rural areas of Denmark and the US, the Gedser three-bladed, upwind turbine design is regarded as the father of modern wind turbines, as it became a prototype for most subsequent designs (Danish Wind Industry Association, 2003a; Jones & Bouamane, 2011).
Year of market entry	The year of market entry is defined as 1979, the year that the first commercial wind turbine was built in Denmark (Ministry of Foreign Affairs of Denmark, 2018).
Year of market commercialisation	The year of market commercialisation is defined as 1998. At the end of November 2018, total installed capacity in Denmark (onshore and offshore) was 6.14 GW. Twenty percent of this capacity was breached in 1998, when total installed capacity in Denmark (onshore and offshore) was 1.44 GW (23% of November 2018 value) (Danish Energy Agency, 2018).

Wind in Denmark and UK

DEVELOPMENT STAGE

1957
Johannes Juul's Gedser turbine constructed

1958
Danish government establishes nuclear test plant at Risø – later moves into wind turbine testing

1967
Gedser turbine ceases operation

1975
Gedser turbine refurbished at request of NASA, to generate measurement results for the US wind energy programme. Christian Riisager begins to build a turbine using Juul's design.

1976
Danish government plans to build 6 new nuclear plants by end of century – Organisation for Renewable Energy formed in opposition. Windmeetings, during which firms exchanged learning, begin.

1977
Økær Vin Energi – turbine manufacturer – founded by Erik Grove-Nielson

1978
Danish Wind Turbine Owners Association, and Windmill Manufacturers Association, founded. Danish Wind Turbine Test Station established at Risø. In the US, the Public Utility Regulatory Policies Act (PURPA) opens the door to feed in tariffs; and the Energy Tax Act offers tax credits for renewables.

MARKET FORMATION STAGE

1979
Vestas licenses Jorgensen and Nielsen's turbine design and moves into wind energy. Danish Government institutes 30% wind investment subsidy, which subsequently rises to 50%. Beginning of voluntary power purchase agreements between utilities and wind turbine associations.

1980
The first Wind Turbine Guild established near Aarhus in Jutland

1983
California launches Interim Standard Offer 4 (ISO4) – wind energy contracts with ten year fixed price component

1985
Danish market reaches 50 MW

1987
Five of top 6 producers of turbines in California are Danish companies

1992
Danish government introduces feed in tariff for wind

1994
Government requires municipalities to plan for future wind turbines, and to subsidise the substitution of older machines for new ones

COMMERCIALISATION STAGE

2000
12% of Danish electricity comes from wind

2008
In the UK, the Carbon Trust sets up the Offshore Wind Accelerator

2012
UK Green Investment Bank launched

2013
The UK Energy Act legislates for 'contracts for difference' (type of feed in tariff) for large scale generators. Offshore Renewable Energy Catapult established.

2014
Contracts for difference (CfDs) awarded to 8 renewable energy projects including 5 offshore wind projects. Contract prices set administratively, at £140–150 / MWh.

2015
Competitive CfD auction awards offshore wind projects at £120 and £114 / MWh

2017
Competitive CfD auction awards offshore wind projects at £74.50 and £57.50 / MWh. Onshore wind excluded from auction. UK Green Investment Bank sold to private sector.

Discussion

The long view of wind power reveals a gestation period before wider technological changes and social and political concerns aligned to create the right conditions and accelerate the transition. This innovation took 41 years (1957-1998) to reach widespread deployment, a relatively rapid and successful transition. Key ingredients of this success include government-supported demonstrations and support for early deployment to ensure successful designs proliferated more quickly.

Implications for the UK's innovation policy are:

1. Support demonstration pilots and promote knowledge sharing

There were several ways in which the Danish Government supported and promoted the sharing of innovation. The government's Risø laboratory – originally a nuclear power testing centre, but which later moved into wind turbine testing – became a significant disseminator of knowledge. It conducted rigorous and independent tests, the results of which were made publicly available for private actors in the Danish wind industry to benefit from, enabling successful designs to proliferate more quickly. Certification from the Risø test centre also helped Danish companies as they expanded into US markets (Garud & Karnøe, 2003; Grubb et al., 2014; Jones & Bouamane, 2011; Maegaard, Krenz, & Palz, 2013).

This built on a pre-existing culture of shared knowledge in Denmark. Manufacturers would meet to discuss their experiences, eventually forming the Wind Turbine Manufacturers Association. The Wind Turbine Owners Association would also provide feedback from an owner perspective and would publish data on reliability and performance. Early manufacturers like Vestas would directly service their own turbines, which was another source of learning (Garud and Karnøe, 2003; Jones and Bouamane, 2011). These kinds of close interactions enable quick and direct feedback of learning.

The publicly funded Carbon Trust also played a similar knowledge facilitation role in the UK through the Offshore Wind Accelerator (OWA), bringing developers and potential supply chain providers together, clarifying needs, and leveraging R&D investment (Carbon Trust, 2019; Grubb et al., 2014).

In future, it is important for the UK Government to take part in the testing and promotion of new designs, and the standardisation and sharing of innovations. This could be particularly important in the heating transition, where different types of heating equipment would best fit different housing and consumer types, and in industry where energy efficiency potential could be accelerated.

2. Provide support through market creation policies and investment to help technologies go from early deployment to widespread commercialisation

The support of market creation policies was crucial to success. Such policies, from the early voluntary power purchase agreements in Denmark, through to feed in tariffs in numerous countries including the UK's Contract for Difference auctions, are crucial to help support technologies in early or pre-commercialisation stages (Jones and Bouamane, 2011).

Investment support from governments or government-supported funding agencies has also been important in providing loan capital or loans to invest in projects where the market was not yet sufficiently confident due to the new technologies involved. The UK Green Investment Bank (now known as the Green Investment Group) has invested £1.6bn in the offshore wind sector, across nine projects with a combined total capacity of 3.2 GW. It has also set up and manages the UK Green Investment Offshore Wind Fund, which has a portfolio of six projects with a combined capacity of 1.45 GW (GIG, 2018). There is strong evidence that the GIB and European Investment Bank (EIB) provided important support to offshore wind deployment. They did so by: absorbing early deployment and technology risk and filling investment gaps, allowing the private sector to invest; buying equity stakes in existing offshore wind farms, allowing developers to 'recycle and reinvest capital in new projects'; and using their investments to support the development of innovative financial products such as portfolio aggregation, which attracted new investors to the sector (Vivid Economics, 2018).

Valuable policy lessons can be learnt from the investment certainty provided by market creation policies in the renewables sector. Evidence shows that the long-term confidence which this kind of support generates is crucial for encouraging businesses to invest their own money in research and development for further innovation. This in turn drives down future costs, as businesses have greater confidence in the future revenue stream that will reward such investments. Governments can also play useful roles in helping to secure the financial backing for projects, for example through state investment banks.

3. Develop innovation policy that builds on the UK's existing and potential comparative advantages and unlocks export opportunities

International dynamics contributed to the take-off of the industry. California provided early additional markets for Danish manufacturers, and the UK sector is now populated with a range of international companies (Wieczorek et al., 2015, 2013).

It is important to make the UK an attractive place in which to innovate. Inevitably, there are some technologies where the UK is not a first mover and this may limit its ability to develop domestic industries in which large international players already exist. However, by making the UK an attractive place not only to invest but also in which to innovate (e.g. because of institutions such as the OWA), there is a greater chance of international companies choosing to locate more of their supply chains in the UK, with ensuing benefits for the UK economy.

Priority should be given to technologies that are likely to help the UK capture export markets in low-carbon products and services. Areas of expertise in the domestic market provide a strong basis to export a range of low-carbon products and services. For low-carbon products, these include industrial technologies, offshore wind, building design, and smart grid technologies (including smart charging). There are a set of low-carbon services where the UK has a concentration of experience, such as smart charging for EVs and smart systems for homes. Section 3.2 sets out a deeper assessment of UK priorities within low-carbon products[1].

[1] The forthcoming Energy Innovations Needs Assessments (due to be published by BEIS in mid-2019) will provide further detail as to the areas of unique competence and where the export markets are strongest.

2.4 Steel in South Korea

Table 5: Key features of case study

Invention	Steel in South Korea
Invention definition	Steel production, primarily the basic oxygen furnace (BOF) and continuous casting (CC) processes. This was an industrial sector innovation, supported by strong government backing within a top-down economic strategy. Rather than innovation taking place in South Korea, it is a 'late-follower' strategy, with South Korea making a success of technologies developed in Austria and Japan. Later in the period under study, South Korea also began to make investments in its own innovation capacity.
Market need	There was a growing domestic demand for steel for reconstruction following the Korean War (1950–53) (Lee and Ki, 2017). However, contemporary assessments that were made at the time by the US AID and the World Bank regarding the financial viability of loaning to a steel mill project appeared to find the direct market need for steel production in South Korea unconvincing (D'Costa, 1994). Nonetheless, the drive to establish a steel industry in South Korea was part of the overall economic plan of the authoritarian President Park Chung-Hee, who had seized power in 1961 in a military coup, became President in 1963, and remained so until his assassination in 1979. Park pursued a strategy of development through industrialisation and export substitution, and establishing a modern steel industry was a major objective of this plan (D'Costa, 1994).
Scope of study	South Korea, 1949–2017
Link to UK innovation needs	The UK needs to pursue innovation in industrial sectors. It also needs to make strategic choices about the balance between acting as a late follower, building on innovations developed elsewhere, and being a first mover with its own domestically produced innovations.
Year of invention	In 1949, the basic oxygen furnace (BOF) method was developed by Austrian firm Linz-Donawitz (Oster, 1982). BOF was first commercially deployed in Austria in 1952, and subsequently rapidly adopted by Japanese firms. This adoption was an important factor behind Japan's rapid catching up with, and eventual overtaking of, the US in steel production, as US firms were slower to switch to the new technology from the traditional open-hearth furnace (OHF) (Lee & Ki, 2017; Oster, 1982). Continuous casting was developed from the 1950s onwards (Harter, 1951), and also rapidly adopted by Japanese firms (Lee & Ki, 2017).
Year of market entry	The year of market entry is defined as 1972, marking the entry of South Korea into steel production at scale. The construction of the first phase of the South Korean Pohang Iron and Steel Company (POSCO) was undertaken between 1970 and 1973 (D'Costa, 1994), and production commenced in 1972.
Year of market commercialisation	The market commercialisation year is taken as 1986. In this case, the 20% penetration rule is applied to output, not capacity. In 2017, total annual crude steel production in South Korea was 71,081 kt (World Steel Association, 2018). Twenty percent of this was surpassed in 1986, when annual production was 14,555 kt (International Iron and Steel Institute, 1990).

Steel in South Korea

DEVELOPMENT STAGE

1949
Basic oxygen furnace (BOF) process developed in Austria

1958
South Korean government begins to seek funding for an integrated steelworks

1960
BOF is 15% of non-electric steel production in Japan; 4% in US

1961
In South Korea, Park Chung-Hee seizes power in military coup

1963
Park Chung-Hee becomes President of South Korea

1968
Pohang Iron and Steel Company (POSCO) established with 60% of capital supplied by Japanese sources, supported by South Korean government loan guarantees

1970
BOF is 90% of non-electric steel production in Japan; 56% in US. Construction of first phase of POSCO steel mill begins, guided by Japanese teams and using Japanese built facilities. South Korean government introduces Steel Industry Promotion Law.

MARKET FORMATION STAGE

1972
Production of steel at POSCO begins

1973
Oil crisis, downturn in steel industry, steel manufacturers look to export equipment. POSCO exploits competition to drive down costs of new imported equipment as it expands.

1978
51% of Japanese steel production adopts continuous casting

1979
Second oil crisis, another downturn in global steel industry. Again, POSCO in strong position to acquire state of the art technologies at lower cost.

1984
Second mill at Gwangyang, South Korea constructed using state of the art imported technologies, including pulverised coal injection and continuous casting

1985
51% of POSCO's production uses continuous casting. Plaza Accord leads to rising value of yen, affecting exporting ability of Japan.

COMMERCIALISATION STAGE

1986
The Pohang University of Science and Technology (POSTECH) established

1987
Research Institute of Industrial Science and Technology (RIST) established. Along with POSCO and POSTECH, forms the 'tripartite' system, covering fundamental research, development, demonstration and commercialisation. RIST undertakes 241 R&D projects during the year.

1992
98% of POSCO's production uses continuous casting

1993
RIST undertakes 713 R&D projects during the year

1998
POSCO's productivity surpasses that of Japanese firms

2002
POSCO privatised

2017
South Korea 6th largest steel producer in the world

Discussion

This was a relatively fast innovation process, taking place over 37 years (1949–1986) from invention to widespread commercialisation. The innovations in steel aligned with broader industrial advantages and spillovers, where innovation policy pushes a self-reinforcing dynamic of competitiveness and growth. The innovations in the steel sector and adoption of new methods relied on a clear strategy that was tied to economic development and reducing costs for downstream customers.

The innovations in steel aligned with broader industrial advantages and spillovers, where innovation policy pushes a self-reinforcing dynamic of competitiveness and growth. The innovations in the steel sector and adoption of new methods relied on a clear strategy that was tied to economic development and reducing costs for downstream customers.

Key lessons for UK policy to accelerate innovation include:

1. Setting a clear government strategy can help successfully develop complex and multi-faceted systemic innovations

Developing a steel industry in South Korea was part of a strategy to deliver economic growth. Low-cost steel was part of a strategy to reduce input costs of downstream industries. Over time, steel producers gradually moved towards producing higher value steel products and to deliver higher profits. As efficiencies lowered the cost of steel production, cost savings, instead of being captured by POSCO, were passed to manufacturers. This lower cost steel underpinned the further growth of these downstream industries. The state-owned position of POSCO may have contributed to pricing policies enacted with a more macro-economic view than might have been the case in a private company with strong market power (D'Costa, 1994). POSCO had a clear strategy: in the early 1970s, POSCO focussed on low-cost low-value steel, building up output steadily. In later phases, as it acquired technology and developed its own R&D capability, it was able to focus on higher value products (Lee and Ki, 2017).

Although the political system in South Korea during the late 1960s and 1970s was more state directed than the UK, there are general lessons about both the role of government and the importance of a well-integrated industrial strategy. The South Korean government provided important financial support to the steel industry in its early stages through fiscal policy and acting as guarantor for international loans. The government's economic programme also located the steel production sector within a wider industrial ecosystem and was focussed on maximising macroeconomic benefits. In the UK, a focus on areas where technology spillovers are likely to be high could drive additional productivity benefits. Several low-carbon technologies, including CCUS, wind, biofuels, and batteries, have high potential for economic benefits beyond simply the value of the good, such as a contribution to the economic productivity or local growth. These wider benefits can feed back into greater innovation investment overall.

2. Support for both R&D and market creation is essential to pull through innovations to commercial scale

South Korea supported both R&D and commercialisation activities. In the 1980s, the establishment of the Pohang University of Science and Technology (POSTECH) and the Research Institute of Industrial Science and Technology (RIST) were fundamental to the transition of POSCO from a late follower to a leading innovator. **These new institutions, along with POSCO itself, created a 'tripartite' system, covering fundamental research, development, demonstration, and commercialisation.** The close collaboration of these institutions enabled an effective feedback between each of these stages of the innovation chain. Under this system, RIST undertook 241 R&D projects in 1987, rising to 713 in 1993. The overall result was that POSCO was able to transition from its focus on low-value products, which had dominated its approach during the 1970s, to an increasing share of high-value products. One example of an innovation emerging from this system is the high-value product 'extra-deep drawing steel sheet' used for automobiles. By the late 1990s POSCO had effectively 'caught up' with Japanese firms such as Nippon Steel, having a comparable share of high-value products, and even surpassing them in terms of productivity (Lee and Ki, 2017).

New markets are required to pull innovations through to commercial scale. For example, to deliver a pipeline of CCUS projects, CfDs or a form of government tendering will likely be needed to secure investment. Government could consider an obligation and certificates scheme like the Renewables Obligation. For example, obligations or incentives for fossil fuel using industries to sequester their CO_2 emissions[2].

3. **Policy should encourage UK industry to capitalise on international innovation, particularly where the UK has a comparative advantage**

South Korea successfully developed a competitive steelmaking industry by harnessing innovations that were developed internationally. This is more likely to be successful where there is a latent comparative advantage. In South Korea, low-cost steelmaking was an advantage, and new innovations then developed this into an internationally competitive industry.

The UK should consider being a late follower in areas where innovation activity may be stronger internationally and domestic competitive advantages are yet to be developed. The priorities for innovation take place in an international context. Where there is a high comparative advantage but lower innovation activity, it may be possible to be a late follower, and harness international innovation. Potential areas of high comparative advantage in the UK include buildings, offshore wind and industrial technologies. Further work is required to determine the specific areas where innovations should be imported, rather than developed in the UK. It is also important to consider focussing effort where spillovers are potentially high, as is explored in section 3.2 below.

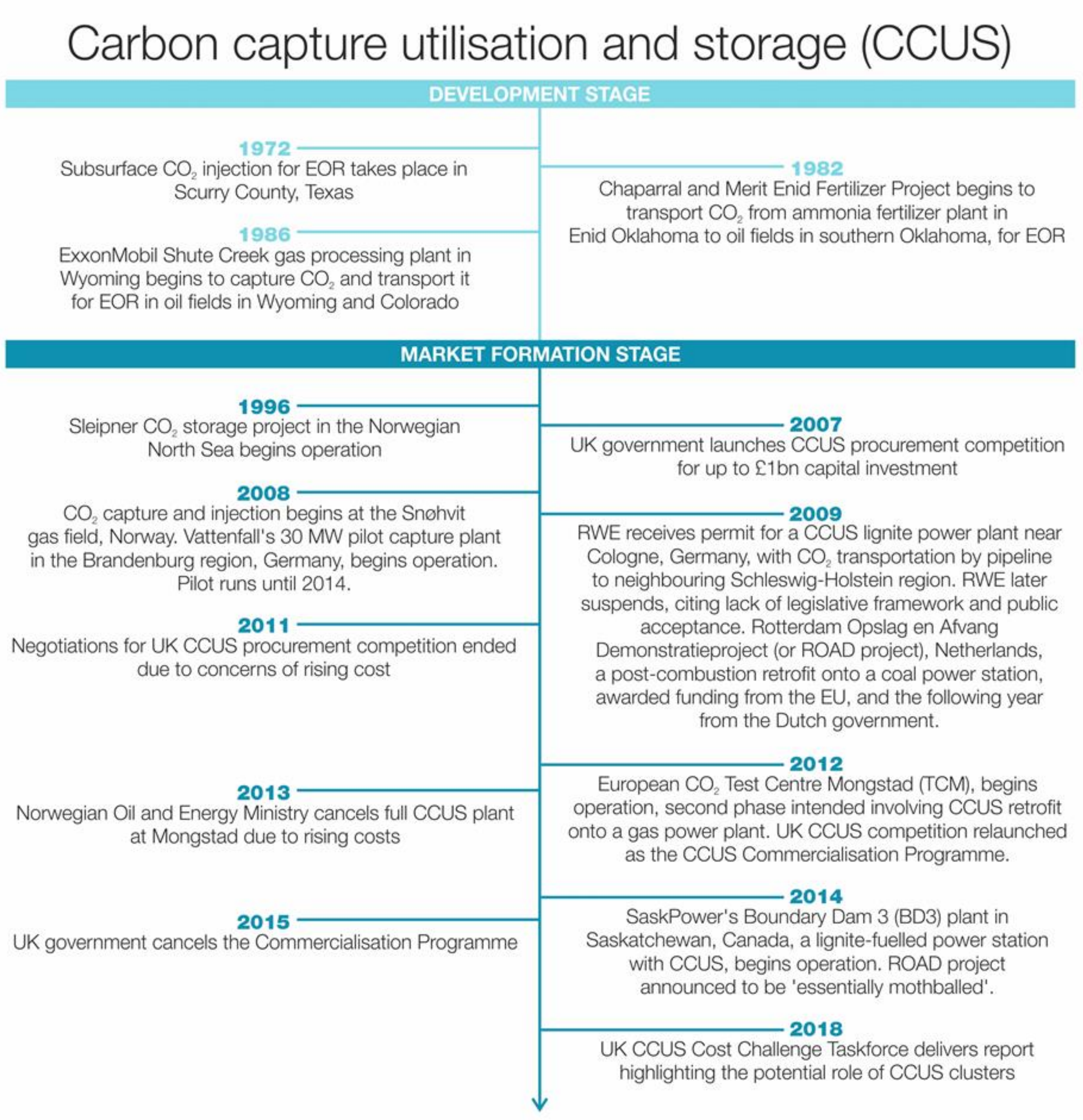
[2] A CCS obligation scheme is explored in more depth in Element Energy and Vivid Economics (2018) http://www.element-energy.co.uk/wordpress/wp-content/uploads/2018/05/Element-Energy-Vivid-Economics-Report-CCS-Market-Mechanisms.pdf

2.5 Carbon capture utilisation and storage (CCUS)

Table 6: Key features of case study

Invention	CCUS
Invention definition	Carbon capture utilisation and storage (CCUS) refers to the capturing or stripping out of carbon dioxide (CO_2) from the flue gas from the combustion of a fossil fuel, as a result of the processing of a fossil fuel, or from another industrial process; and the permanent sequestering of this CO_2 in a geological formation, underground reservoir, or subsea aquifer. In certain contexts, CO_2 is already being captured and sequestered successfully, and in some cases this activity has been happening for several decades. Nonetheless, the total global activity in CCUS must be acknowledged to be small in comparison to its envisaged contribution if it is to offer a serious contribution to decarbonisation. For example, it is prominent in the outputs of global integrated assessment models under scenarios consistent with a 2°C global temperature rise or lower, often combined with the use of biomass fuel to deliver 'negative emissions'. In the context of these ambitions, CCUS has not been delivered on the timescale which many had hoped for ten years ago. In this case study we consider examples both where CCUS is in operation and where it has not yet delivered on expectations. As such, the sub-heading structure of this case study departs from that used for the previous four.
Market need	There can be a market need for this, as CO_2 sequestered in this way can be used to bring about enhanced oil recovery (EOR), the revenues from which may in some cases be sufficient to support the activity without policy incentives. However, EOR cannot drive the need for CCUS in a net zero world and as yet there is no market for this technology as a major source of decarbonising energy processes, or achieving negative emissions. As a large-scale low-carbon technology, the driver to create a market for this technology must come from policy.
Scope of study	CCUS is undergoing demonstration and early commercialisation in various locations around the world. However, due to its large scale, installations tend to be limited to a small number per country. Hence it is harder in this instance to focus on a specific country's innovation system. Instead, a global perspective is taken, comparing different kinds of CCUS activities and policies in different countries. The timeframe begins in 1972, and is ongoing.
Link to UK innovation needs	On a global scale, CCUS is argued to be a crucial technology for decarbonisation, as integrated assessment models indicate that trying to meet targets of 1.5°C or 2°C without CCUS is usually considerably more expensive, or even in some cases infeasible (Edenhofer et al., 2014). Peters et al. (2017) comment that 'without large scale CCUS, most models cannot produce pathways consistent with the 2°C goal'. Furthermore, the UK is potentially in a favourable position to be at the forefront of developing the technology. It has favourable geology, existing infrastructure and expertise in related activities, through its history of hydrocarbon extraction in the North Sea. More generally, CCUS is a good example of a technology that requires policy support at different stages of the innovation and deployment chain, and thus may be more broadly instructive.
Year of invention	CO_2 capture technology has been in use since the 1920s for the purpose of removing it from natural gas (IEAGHG, 2013). However, 1972 is the year in which

	subsurface CO_2 injection, in this case for EOR, is believed to have first taken place, in Scurry County, Texas (Office of Fossil Energy, 2019).
Year of market entry	The year of market entry is defined as 1996, the first year of the Sleipner CO_2 storage project in the Norwegian North Sea, commonly referred to as the oldest large-scale CO_2 storage project.
Year of market commercialisation	There is no market commercialisation date in this case. The Global CCS Institute (2018) reports that in 2018 there were '23 large-scale CCUS facilities in operation or under construction, capturing almost 40 Mtpa of CO_2. A further 28 pilot and demonstration-scale facilities are in operation or under construction. Collectively, these capture more than 3 Mtpa of CO_2.' However, these quantities are a fraction of those that will ultimately be required if CCUS is to play a meaningful role in decarbonisation. For example, the IEA's '450 Scenario' – a global pathway to 2040 consistent with a 50% chance of keeping temperature rise to 2°C – has CCUS in power and industry capturing 5 Gt CO_2 per year by 2040, globally (IEA, 2015). As such, current rates of capture are just under 1% of those required in this scenario by 2040.



Discussion

Several large-scale power CCUS projects with government sponsorship have foundered due to spiralling costs. Commentators are increasingly arguing for alternative approaches to cost sharing and risk allocation, possibly with a state-backed delivery agency taking a key coordinating role (Oxburgh, 2016). CCUS is, however, working in specific cases where the incremental cost of adding CCUS is small relative to the existing process.

As a result, this complex infrastructure is not proceeding on the innovation pathway required to meet the IEA's Sustainable Development Scenario (2018). While incentives have been implemented in the US, UK, Canada, and Norway, projects have stalled or not translated into a pipeline of future projects. A common feature of these cases is a stop-start approach to demonstration, which has been ineffective in the context of promoting CCUS deployment.

Key lessons for the UK include:

1. **Demonstrate complex infrastructure including CCUS, BECCS and DACCS at scale**

Industrial clusters, in which adding CCUS may be relatively low-cost for some processes, are being considered a potentially better starting point for building up a shared CCUS infrastructure than large single power station projects (Poyry and Teesside Collective, 2017; CCUS Cost Challenge Taskforce, 2018). As noted in the case studies, activities such as natural gas processing, which already strip out CO_2, have comparatively low incremental costs for adding transportation and storage. Ammonia fertiliser production is another example of a process for which adding CCUS may also be relatively low-cost, and which could help to address emissions associated with agriculture. Shared infrastructure could reduce costs further.

Government should provide a clear strategy and institutional support for the development of shared CO_2 transportation and storage infrastructure. At scale, CCUS would involve the construction of a large-scale infrastructure which would be shared by numerous point sources and storage points. It is instructive that most comparable national level infrastructure systems have been constructed under the guidance of national level coordinating bodies, such as the Central Electricity Board in the case of the original electricity transmission network in the UK, and the Gas Council for the natural gas grid (as discussed earlier in section 2.3 of this report). Based on such precedents, the argument for a comparable organisation for the coordination of CCUS infrastructure is compelling. The recommendation of the Parliamentary advisory group on CCS for a new delivery body is one way to achieve this.

2. **Create new markets for complex and high capital cost technologies**

New markets for CO_2 capture and storage are required to enable commercialisation. Clarity on the development of long-term market creation measures, such as a power-CCUS CfD, or revenue for stored carbon for industrial CCUS, is essential to increase private sector appetite for investment in the innovation process. A clear view on the availability of future revenue streams gives a concrete indication to CCUS technology developers and consortiums that their investments would be rewarded if they succeeded in bringing the technology to market at scale.

3. **Commit to early, genuine, open and transparent public engagement**

CCUS is an unfamiliar technology and likely to elicit feelings of risk and uncertainty. It is crucial to avoid the perception that concerns are not being acknowledged, or that judgements have already been pre-decided. As discussed in the natural gas transition case study, a granular understanding of the various end-users underpinned the public communication strategy, and independent reports were important in building trust. More recent experience of public engagement on energy technologies has been mixed. In the case of large-scale renewable technologies, Devine-Wright finds, for example, that public engagement by government and developers has often followed a 'passive' model, which then fuels a perception of the public as having 'a deficit in factual knowledge and a surfeit of emotion'. This then results in attempts to marginalise them, through streamlined planning processes and one-way engagement mechanisms. Such approaches are likely to stir up greater resentment, such that so-called NIMBYism becomes a self-fulfilling cycle (Devine-Wright, 2011).

Early, genuinely open and transparent engagement, as well as clear communication of what is known and what remains uncertain, are vital. It should also be made clear that any project is contingent upon ongoing monitoring and feedback to consumers about the performance and reliability of technologies in practice.

3 Innovation priorities

Given an ambition of meeting a net zero emissions target by 2050, the deployment of low-carbon technologies must be accelerated. This is a diverse set of technologies that vary in terms of maturity and their potential contribution to rapid decarbonisation. A prioritisation of these technologies is therefore useful in creating innovation policies that are focused and systematic. Innovation priorities should be placed on technologies that provide significant abatement potential and wider economic benefits, yet face barriers to widespread deployment. At a global level, innovation priorities correspond to the importance of respective technologies in an ambitious decarbonisation pathway, such as a scenario aiming at limiting the increase in global average temperature to 1.5°C.

The focus of this section is to identify a list of technologies as innovation priorities. The innovation priorities identified below cover research and development and early market deployment.

3.1 International innovation priorities

Achieving a net zero future would require accelerated innovations that address climate change and broaden affordable energy access at the same time. A review of the existing literature identifies innovation priorities in three broad categories: (i) renewables and electrification, (ii) energy efficiency, and (iii) CCUS and negative emission technologies. While each category contains a diverse set of technologies, together they identify the key channels towards 95% of the cumulative emissions reductions as identified in the IEA's most ambitious scenario, the B2DS (Beyond 2°C Scenario), which corresponds to net zero emissions globally by 2060.

Renewables and electrification

The basis for rapid decarbonisation is the substitution of fossil fuels, which currently supply 81% of global primary energy demand, with renewables. The use of renewables and fuel-switching contribute up to 38% of cumulative emissions reductions by 2060 in the B2DS. Further innovations in biofuels and hydrogen in transport and industry are particularly important in achieving a more ambitious decarbonisation pathway. As the power sector becomes largely decarbonised, increased electrification across end-use sectors, such as through heat pumps, batteries and EVs, is critical. These technological innovations should be accompanied by systemic ones that span business models, market design, system operation, and enabling infrastructure (e.g. district heating systems that can utilise electricity generation at times of low demand and high supply).

Energy efficiency

Energy efficiency contributes up to another 38% of cumulative emissions reductions by 2060 in the B2DS, split in roughly equal magnitudes between buildings, transport, and industry. Many energy efficiency technologies are readily available, such as improved insulation and zero emissions buildings, fuel economy of vehicles, and electrical efficiency of industrial equipment. However, the deployment of some of these technologies remains limited due to a lack of financial incentives. Policies to support market creation and deployment is required to unlock these opportunities. **Further innovation is particularly required for low-carbon substitutes and alternative processes in industry.** Examples include low-carbon cement and bio-based feedstocks in chemicals production.

CCUS and negative emission methods

CCUS and negative emission methods are essential to meet a net zero target. The use of CCUS contributes up to 19% of cumulative emissions reductions by 2060 in the B2DS. Greater innovation is required to lower the cost of CCUS so that it can become commercially viable for the industry and power sector. The deployment of CCUS would also be sensitive to carbon prices. Innovations in CCUS extend to BECCS and DACCS for negative emissions.

Supporting infrastructure for the storage and transport of CO_2 must also be developed. Land use innovations and appropriate policy adjustments are needed to facilitate the deployment of a range of greenhouse gas removal (GGR) methods (Royal Society, 2018a).

3.2 UK innovation priorities

The UK Government has made clean growth a cross-cutting theme in the Industrial Strategy and brought attention to low-carbon missions across sectors, actors, and disciplines. This effort is accompanied by a public commitment to double energy innovation spend between 2015 and 2021. In 2018, a £20 million venture capital fund was announced by BEIS, with the aim to speed up the deployment of innovative clean technologies that reduce greenhouse gas emissions.

However, UK investment in R&D as a share of GDP is lower than other major economies (ONS, 2018; Royal Society, 2018b). R&D on energy-related technologies is also low by historical standards, at under 0.02 percent of GDP today, compared with around 0.1 percent in the early 1990s (Rydge et al., 2018). Although the UK is a strong performer in terms of venture capital investment in clean energy technologies (on a per capita basis), it has been argued that it is relatively weak in providing long-term patient finance (HM Treasury, 2017).

At a national level, three policy objectives can guide the prioritisation of innovations:

- *Secure a cost-effective transition:* This perspective prioritises the technologies that are the most valuable across the energy system (and therefore where lower-cost and higher-performing versions of these technologies would be most valuable). Technology value is estimated in the Energy System Modelling Environment (ESME), an energy system model developed by the UK's Energy System Catapult to estimate the value of different technologies to the system in 2050. Where ESME does not provide detailed results, other modelling frameworks were reviewed.
- *Increase productivity through spillovers:* Technologies that can generate the greatest spillover benefits in the economy are prioritised. Spillovers are defined as knowledge that is created in the process of invention by governments or firms, which could provide valuable information for other firms to improve economy-wide productivity. The fact that this process only happens at a suboptimal level in the market creates a case for government intervention. A recent study by the LSE Growth Commission (Rydge, Martin, & Valero, 2018) provides a basis for assessing spillover benefits of various technologies in the UK.
- *Capitalise on export competitiveness:* Innovations are prioritised based on their potential to make the UK more competitive in certain export markets. Although it is difficult to determine the extent to which stronger innovation in specific industries can promote UK exports, a useful starting point would be to consider the technologies where the UK currently enjoys a comparative advantage. This report draws on existing studies that assess both trade data and expert opinion from industries.

The rationale for selecting the UK's innovation priorities is summarised in Table 7.

Table 7: UK Innovation priorities

Innovation area	Rationale for selection
Buildings	Heat pumps are particularly high-value technologies in ESME. Buildings is also a high spillover sector, and the UK has a high comparative advantage.
CCUS, BECCS, DACCS	Decarbonising is double the cost without CCUS. DACCS is not explicitly modelled but assumed to be high value as it can achieve negative emissions. CCUS is also a high spillover sector.
Offshore wind and marine	Valuable to the energy system due to the high scope for rollout. Offshore wind is also a high spillover sector and the UK has a high comparative advantage. There remains scope for further innovation in offshore wind (through floating platforms and larger turbines) and in other forms of marine renewables.
Hydrogen	Production and use of hydrogen is highly valuable in ESME.
Smart grid technologies	Strbac. et al. (2016) estimate that the value could be £17-40 billion, cumulatively to 2050. Smart grid technologies also have a high comparative advantage.
Bioenergy	Production and use of bioenergy is highly valuable in ESME. Bioenergy is also a high-spillover sector.
Industrial technologies	The UK has a high comparative advantage in industrial technologies.

UK innovation priorities to secure a cost-effective transition

Key technologies are CCUS, BECCS, DACCS, bioenergy, insulation and heat pumps in buildings, hydrogen and offshore wind. There are several studies that conduct energy system modelling to assess priorities. A publicly available study of energy modelling prioritisation was performed by the ETI (2012, 2018)[3] using the ESME model and identifies several technology categories that are relatively important to the UK energy system. In the ETI's analysis, bioenergy, CCUS, buildings (both heat pumps and insulation), offshore wind and hydrogen internal combustion engine vehicles are found to have the largest opportunity costs (i.e. increase in the cost of delivering energy if they are not available). In other words, they are the most important technologies to the UK in securing a cost-effective transition towards a low-carbon economy.

Negative emission technologies are also highly important. This is because negative emissions serve to offset emissions from hard-to-abate sectors such as industry and agriculture. Restricting negative emissions in a net zero emissions scenario would certainly result in substantial costs in cutting the remaining emissions. In particular, BECCS and DACCS, both of which are critical to negative emissions in the UK, would require much more innovation to become cost-competitive and get deployed at scale (Royal Society, 2018a).

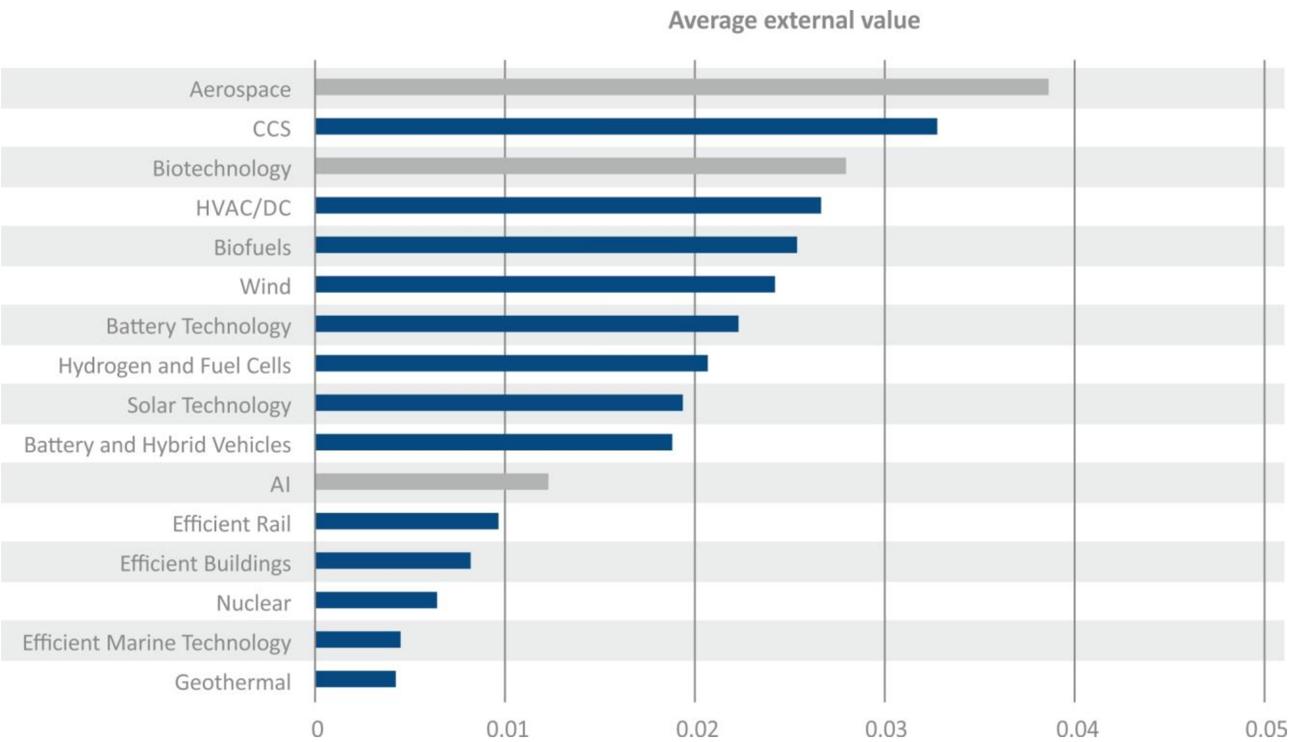
[3] Some of the assumptions from this 2012 ETI modelling are now out of date. While the 2012 analysis did not highlight offshore wind as a priority, a 2018 report with up to date cost assumptions suggests that it is a priority. A full presentation of innovation priorities, using the latest modelling assumptions, will be included in a forthcoming study by BEIS, on the Energy Innovation Needs Assessments.

Innovation priorities to increase productivity through spillovers

Priority can be given to technologies that generate the largest spillover benefits for UK productivity, notably: CCUS, Heating, ventilation and air conditioning (HVAC), biofuels, and wind. Innovation is a long-term driver of economic productivity and growth. In the private sector, this is propelled by firms investing in R&D as they compete to develop better products via more efficient means. However, the private sector systematically underinvests in innovation due to the existence of spillovers. This is a result of private companies incurring the costs of their R&D efforts but not the full benefits of them: valuable information diffuses across firms and sectors, leading to productivity gains in neighbouring industries. Consequently, **the social marginal returns to innovation are greater than the private marginal returns to innovation, disincentivising private businesses from innovating in the first place**. Recent studies have estimated social marginal returns from R&D at between 30 and 50 per cent, which can more than double private marginal rates of return (Hepburn et al., 2018).

UK innovation priorities should go where the spillovers are highest. The stronger the productivity spillover, the larger the gap between social and private marginal returns to innovation, and the greater the need for additional incentives to innovate. **There is further evidence that spillovers from low-carbon innovation may be significantly higher than from high-carbon technologies (Dechezleprêtre et al., 2013), justifying additional R&D spending**. Figure 3 below displays the extent of spillover benefits that various technologies generate in the UK. The results identify several low-carbon technologies that deliver strong spillover benefits, including CCUS, HVAC, biofuels, and wind.

Figure 3: Value of spillovers in the UK in different sectors



Note: Grey bars indicate technologies outside of the low-carbon economy inserted for comparison
Source: Rydge, Martin & Valero, 2018

Innovation priorities to capitalise on export competitiveness

Priority can be given to technologies that are likely to help the UK capture export markets, particularly in industrial technologies, offshore wind, building design, and smart grid technologies. The size of business opportunities from the low-carbon economy, sometimes called 'green growth opportunities', is potentially significant. Estimates suggest that the global market size for a broadly-defined group of low-carbon products could grow from £0.7-0.8 trillion in 2015 up to £10-18 trillion in 2050, of which £100-200 billion is captured by UK exports (Ricardo Energy & Environment, 2017).

Two factors can serve as a basis for prioritisation: current UK export competitiveness and the level of innovation taking place. Drawing on existing assessments and expert opinion, Table 8 below highlights a selection of technologies where the UK currently enjoys relatively strong export competitiveness and their corresponding potential. Building on the assessment from previous sections, this perspective on export competitiveness reinforces the case for prioritising innovations in industrial technologies, offshore wind, building design, and smart grid technologies.

Table 8: UK export strengths and future potential in low-carbon technologies

Current UK strengths	Potential to capture global market share
Bio-processing, membranes, and catalysts Power systems and transmissions	Medium to high
Batteries	
Industry (materials and manufacturing systems)	Medium
Offshore wind	
Advanced building design	
Smart grids	
Biofuels	Low to medium
Waste recycling techniques	

Source: Ricardo Energy & Environment (2017)

Based on securing a low-cost transition, maximising export potential and capturing spillovers, we have generated several priority areas of innovation for the UK. These include buildings, CCUS, BECCS, DACCS, offshore wind, hydrogen, smart grid, bioenergy and industrial technologies.

Where these priorities are sensible analogues for our case study assessment, lessons from the case studies can be applied, for example:

- The deployment of technologies and infrastructure at scale was integral to systemic transitions such as the roll-out of ATMs and the transition from town gas to natural gas. Similarly, commitment to projects at-scale is needed in the 2020s for CCUS (including in combination with bioenergy) and funding for demonstrations of Direct Air Capture.
- Once tested, Feed-In-Tariffs for wind projects were vital to move towards industrial scale deployment, and the South Korean government's strategy for steel created a new domestic market which then provided a basis from which local industry could exploit export opportunities. New markets for CCS and BECCS must now be created to move these emerging low-carbon technologies from at-scale demonstration towards a pipeline of projects.
- The transition towards central heating was a relatively rapid transition, in part because it provided a higher level of service and benefits to the consumer. There is a clear opportunity for digital technologies to increase flexibilty and accelerate customer take-up of energy efficiency, low-carbon heating and clean mobility solutions.
- Rapid consumer transitions have happened in the past (for example, an average conversion rate from town gas to natural gas of over 1 million users per year, during the late 1960s and 1970s). This was facilitated through trusted institutions that provided a strong combination of information, technical assistance and response to consumer concerns (e.g. around safety). To facilitate the low-carbon heating transition, setting up a reliable system of certification of heat pumps and hybrid systems will build trust.
- Innovations in the South Korean steel sector and adoption of new methods relied on a clear strategy that was tied to economic development and reducing costs for downstream customers. In the UK, a focus on areas where technology spillovers are likely to be high could drive additional productivity benefits. For example, one assessment suggests that several low-carbon technologies, including CCUS, wind, batteries and biofuels, have high potential for economic benefits beyond simply the value of the good, such as a contribution to the economic productivity or local growth.

Appendix: Further background information on case studies

1. Banking

Development stage (1964–1967)

What did government do?

One key action taken by the government during this stage was not intended as a direct stimulation of the cash dispenser innovation but was to provide important context for the systemic innovations undertaken by banks in subsequent years. This was the decision to proceed with decimalisation of the UK currency, agreed between Prime Minister Harold Wilson and Chancellor of the Exchequer Jim Callaghan, and announced to Parliament in 1966 (Freeman, 2011). The government had little other direct involvement in the innovation at this stage – however the National Physical Laboratory (NPL), a government-owned institute, was liaising with Midland Bank and Speytec on their dispenser design, including providing tests and trials on security aspects (Bátiz-Lazo and Reid, 2008).

What did business do?

The innovation was led by several banks that had identified the potential desirability of an automated cash dispensing technology. The idea was likely inspired by the emergence of other kinds of automatic dispensation during the 1950s and 1960s, including 'self-service gas stations, supermarkets, automated public-transportation ticketing, and candy dispensers' (Bátiz-Lazo, 2015), as well as photo booths and dry-cleaning (Bátiz-Lazo and Reid, 2008). It was also conceived as a means of enabling out-of-hours cash distribution, in response to 'increasing unionization and labour costs' (Bátiz-Lazo, 2015). Bank staff and unions were moving against Saturday opening of branches. Saturday morning openings began to decline from 1971 onwards, in response to progress with cash dispensers (Bátiz-Lazo and Reid, 2008). Having conceived of the idea, banks then began to set up partnerships with engineering firms – Barclays working with De La Rue Instruments, Westminster with Chubb & Sons Lock and Safe Company and Smith's Industries, and Midland with Speytec (Bátiz-Lazo, 2007, Bátiz-Lazo and Reid, 2008).

A significant preparatory activity was work undertaken by James Goodfellow, working within Kelvin Hughes, a branch of Smith's Industries, to develop a system for dispensing oil to tanker drivers at unattended loading areas. The driver would operate the automated delivery system using a punched card. Goodfellow developed the same principle for a card-operated cash dispenser in initial designs with Chubb, but crucially added the additional innovation that the card would be secured in combination with a private identification number (PIN). The patent for the whole system was filed in 1966 (Bátiz-Lazo and Reid, 2008). The Barclays and De La Rue Automatic Cash System (DACS), marketed as 'Barclaycash', also used a punched card and PIN system. De La Rue had previously developed machines for the automated counting of bank notes, and so brought their technology to this part of the system. Speytec, working with Midland, were developing a card with information carried in impregnated magnetic stripes (Bátiz-Lazo, 2007).

Was there an international dimension?

Parallel developments were occurring in Sweden and the US (Bátiz-Lazo, 2015). However, as far as the UK banks' activities were concerned, there was no international dimension at this stage.

What was the result?

Within a relatively short space of time, three banks had cash dispenser designs ready for use or initial trialling.

Market formation stage (1967–1986)

What did government do?

Once again, the government was not directly involved in the innovation processes associated with the cash dispenser in this stage. However, certain government strategies or policies created important context. Following its announcement in 1966, decimalisation was set for 1971. The build-up to this involved the gradual introduction of certain decimalised coins which could also stand in for existing units – such as the 5p and 10p coins which had the same size and value as existing one and two shilling coins – as well as information campaigns such as posters of conversion tables (Freeman, 2011). Banks also had to undergo considerable preparations for the change, which may have spurred the computerisation of accounting systems (Bátiz-Lazo, 2007). Further impetus to streamlining of transactions may have been provided by banking deregulation, beginning with abolition of exchange control in 1979, and the abolition in 1980 of a system known as 'the corset'. The latter was designed to curb the banks from overly aggressively competing for deposits by requiring them to hold non-interest bearing deposits at the Bank of England (Bátiz-Lazo, 2007; Buiter & Miller, 1981).

What did business do?

In 1967, the first ever cash machine was deployed, at a branch of Barclays Bank in Enfield, UK, using a design by De La Rue Instruments. Shortly afterwards, the Westminster Bank deployed a cash machine built by Chubb & Sons Lock and Safe Company in collaboration with Smith's Industries, at its Victoria branch in London. Nine more machines were installed over the next four months. In the same year the Bankomat was also launched in Sweden (Bátiz-Lazo, 2007, 2015; Bátiz-Lazo & Reid, 2008). In 1968, Midland launched 12 of its Speytec machines for field testing, at branches across the UK (Bátiz-Lazo and Reid, 2008). Other banks quickly adopted cash dispensers – by 1968 the Royal Bank of Scotland had dispensers in 25 branches in Scotland and London.

At this time, cash dispensers had no computerised link up to customers' accounts – the transactions still required manual processing and accounts were still held in an individual's local branch, not in a centralised computer database. For example, in the Chubb system, the customer's card was retained by the machine. After the transaction was processed by a bank employee, the card was posted back to the customer for future use, along with an updated statement of account (Bátiz-Lazo, 2007). In the Barclaycash system, customers were given vouchers with information in punched form. They would need to apply in advance for these vouchers, from retail branches during opening hours. The vouchers would be valid for 6 months from the date of issue. Barclaycash vouchers were non-returnable. – the voucher would be retrieved from the machine by bank staff and processed like a cheque during working hours (Bátiz-Lazo, 2007).

The move to 'online' cash dispensers – machines that processed the transaction and automatically debited it from the customer's account via an online computer system – was an important next step. It was strongly linked with related ongoing developments in the centralisation and computerisation of banking systems, for which the preparations for decimalisation provided a logical window of opportunity (Bátiz-Lazo, 2007).

In November 1970, after five years of development, Lloyds Bank moved customer accounting systems away from retail branches to a central computer (Bátiz-Lazo, 2007). Up to this point Lloyds had resisted launching a first-generation cash dispenser, indicating that 'we are ready for "on-line" versions but the machines are not here yet' (Bátiz-Lazo, 2007). Now it developed a partnership with IBM and ordered 500 machines. The first cashpoint began operation in December 1972. It was 'operated by a plastic card with a magnetic strip on the back (containing the customer's account number and the branch sorting code)' (Bátiz-Lazo, 2007). It was an online machine with a direct link to customers' accounts, offering the choice of variable amounts of cash up to a maximum of £50 at any one time.

This development marked the entrance of important new players – large computer mainframe developers and manufacturers were required to provide the IT systems. Not only the new generation of ATMs would depend on these systems; they would also underpin the broader digitalisation of banking which would increase processing efficiency and enable other innovations such as the Clearing House Automated Payments System (CHAPS) (Colwell, 1991).

IBM was the first such player, initially through its partnership with Lloyds, and became a dominant one during the 1970s. Its activities during this period had important long-term effects: 'throughout the 1970s, IBM engineers developed the rails, pipes, and standards on which other elements of the payments ecosystem (such as credit cards and point-of-sale terminals) would eventually depend' (Bátiz-Lazo, 2015). Other US computing firms also made important entries. NCR partnered with NatWest, to enable the launch of their first online machine in 1975 (Bátiz-Lazo, 2007); and Burroughs, which was already the supplier of computer equipment to Midland Bank, took over Speytec and its cash machine activity for the bank, with their first online machines launched in Belfast in 1974 (Bátiz-Lazo and Reid, 2008). By contrast, earlier pioneers such as Chubb and De La Rue began to leave the market, lacking the now important expertise in computing and electronic components (Bátiz-Lazo, 2015, Bátiz-Lazo and Reid, 2008).

The functionality of ATMs evolved rapidly during the early 1980s, with banks requesting features such as funds transfers, bill payments, audio feedback, multiple currencies, print outs, and data encryption (Bátiz-Lazo, 2007). Thus, ongoing development continued to refine and improve the original product well beyond the pre-market development stage. The early 1980s saw a major take off period for ATMs, with annual growth rates of installed units in the UK exceeding 40% in the first four years of the decade. This was due to the increasing functionality of the machines, as well as regulatory changes in the British banking system that removed controls on retail currency transactions (Bátiz-Lazo, 2007).

Whilst up to this point ATM networks had been proprietary, it became increasingly clear that there were mutual benefits in reciprocity agreements. The first of these came in 1983, when NatWest and Midland Bank agreed to let each other's customers use their machines to withdraw cash. Building societies and other smaller institutions entered the ATM market and soon realised the benefits to them of shared networks, establishing the LINK network in 1985 (Bátiz-Lazo, 2007).

Was there an international dimension?

The entrance of US computing firms such as IBM, NCR, and Burroughs were crucial in this stage in developing cash dispensers to the level of functionality that would enable their deployment to take off. Such firms already had partnerships with banks, as accounting systems were increasingly becoming computerised. The extension of their activities into ATMs was therefore logical and ensured that fully online ATMs developed as part of the overall computerisation and centralisation of banking systems.

What was the result?

At the start of this phase, cash dispensers offered small advantages to customers by allowing them to collect money from branches other than their local one, and in some cases allowing collection outside of bank opening hours. However, the still largely manual and paper-based processing arrangements that underpinned the transactions, meant that the overall gains in convenience and efficiency for banks and customers were minimal. By the end of this phase, cash machines were fully online, and linked up to a broader system of centralised and computerised banking, which brought substantial gains in convenience and efficiency for banks and customers.

Commercialisation stage (1986–2003)

What did government do?

There was no direct intervention from government during this stage. Key developments, including reciprocity arrangements, were driven by banks and partners.

What did business do?

Reciprocity networks continued to grow, with the LINK network being followed by the MATRIX network in 1986. Increasingly, large reciprocity networks became even larger as more institutions joined or networks combined, and public opinion came to see unfettered and charge-free access to cash via multiple institutions' cash points as the norm. This was such that in 1999 when Barclays, having recently joined the LINK network, attempted to impose charges, it was roundly criticised, and the move resisted by other LINK institutions. By 2000, all charges were dropped and there was effectively a single ATM network in the UK (Bátiz-Lazo, 2007).

Although IBM had come to dominate the market in the 1980s, a significant mistake was made when a new model – the IBM 4732 – was introduced, which was incompatible with previous ones, including the IBM 3624 which was now widely deployed. This forced obsolescence in both machines and software was resented by the banks and opened up the market to new manufacturers, including NCR and Dioebold, who introduced innovations into the design of the customer interface (Bátiz-Lazo, 2015). In 1990, IBM withdrew from ATM manufacture. NCR was now the main global designer and provider of ATMs (Bátiz-Lazo, 2007).

Further technological changes in supporting systems and software reduced costs and therefore continued to boost growth of ATMS in the late 1990s. Until this point, ATMs were still high capital cost investments, and required dedicated telephone lines for maintenance. This limited them to bank branches or high-volume locations such as busy train stations or airports. The advent of digital telephony and the Windows operating system removed these barriers, however. 'These two seemingly simple modifications transformed the ATM, enabling remote diagnostics and integration with credit card clearance networks. They also enabled the advent of the Independent ATM Deployer (IAD)—ATM vendors unaffiliated with a major financial institution —and renewed growth in the machine's deployment in the late 1990s' (Bátiz-Lazo, 2015).

Was there an international dimension?

The involvement of international – largely US-based – computing firms remained crucial, although IBM withdrew from the sector leaving NCR as the dominant player. The adoption of the internationally standard Windows operating system enabled further improvements to the technology.

What was the result?

An online computerised banking system with convenience and efficiency benefits including, but not limited to, ATMs. A pervasive and integrated ATM network largely charge-free, with machines provided not only by banks but also by independent ATM deployers. Gradually the out-of-hours convenience of the ATM had social impacts, allowing unplanned weekend expenditures, changing consumption patterns. It allowed banks to outsource teller activities and devote more staff time to high-value sales such as insurance, credit cards, and mortgages. It also led to staff losses and branch closures (Bátiz-Lazo, 2015).

Future developments are unclear. Mobile banking and remittances are increasingly common in developing countries and may obviate the need for ATMs at all. Trends may go towards a cashless society with mobile money and virtual crypto-currencies like Bitcoin (Wonglimpiyarat, 2016).

2. Gas and central heating

Development stage (1957–1966)

What did government do?

In the years leading up to the Second World War, the British gas industry was fragmented with many different undertakings and regional networks. As a whole, the industry was beginning to lose out to electricity, considered a more 'modern' form of energy. In 1948/49 the gas industry was nationalised, initiated by the Gas Act 1948. Reflecting moves in other industries, including electricity, nationalisation reflected an increasingly prevalent view that national industries with public service characteristics and natural monopoly infrastructure were best run in the public sector. The structure of the newly nationalised industry was similar to that adopted in the already nationalised electricity industry, with an overall Gas Council, and regional Area Boards (Pearson and Arapostathis, 2017).

The domestic coal fire was deeply integrated into domestic life. 'In 1942 more than 95% of working class dwellings used coal to heat the kitchen and sitting room' (Arapostathis et al., 2013). However, usually only a few rooms in the house were heated (Hanmer & Abram, 2017). In the post-war period the issue of heat in homes became increasingly a public health question. The 1961 Parker Morris report *Homes for Today and Tomorrow* presented guidelines as to the healthy internal temperatures of homes. In this context central heating became increasingly legitimated and desirable. The Gas Council and the Area Boards, as well as oil companies like Shell, began to promote central heating to attract customers (Arapostathis et al., 2013).

Another important background factor was the Clean Air Act 1956, which allowed local authorities to create smokeless zones. The largest contributor to the 1952 London smog disaster had been domestic burning of bituminous coal in open grate fires. The Act also provided grants to help people convert their heating appliances (Scarrow, 1972). Scarrow also notes that local authorities found significant levels of voluntary conversions before an area was due to become smokeless, suggesting that there was a growing consumer awareness of and demand for cleaner fuels (Hanmer and Abram, 2017).

However, the gas industry still faced challenges due to competition with other fuels, and because gas produced from coal was still a relatively costly feedstock. The Gas Council began to trial alternative sources or means of producing gas, such as the Lurgi coal gasification process, and new oil gasification processes. It also pursued imported LNG from Louisiana and Algeria, constructing an import terminal at Canvey Island and a pipeline for the delivery of regasified LNG to the Area Boards (Pearson and Arapostathis, 2017; Arapostathis et al., 2013). While the Lurgi process did not deliver cost reductions and remained a niche technology, oil gasification was more successful and became the dominant technology by the late 1960s (Arapostathis et al., 2013).

In the late 1950s LNG begun to be explored. This was largely driven by the boards around London, because of the uneconomic production of coal gas there, and the increasing pressure caused by growing demand and, in particular, growing peak demand, caused by a particularly wide diffusion of gas heating appliances there, more so than in the north of England (Arapostathis et al., 2013). In 1959 LNG from Louisiana began to be imported to Canvey Island (Falkus, 1988), and in 1961 the Gas Council decided to import LNG from Algeria (Arapostathis et al., 2013).

The aspiration was to integrate LNG into the gas system, and to develop a national gas grid following the example of electricity. The 'backbone' of this was to be a new large- capacity bulk-transmission gas pipeline. This was to consist of a main 18 inch diameter pipeline stretching from Canvey Island to near Leeds, with several 6 inch diameter branch pipelines linking to other Areas (Figure 4, Arapostathis et al., 2013). The new pipeline was constructed between 1962 and 1963 (Williams, 1981).

This LNG network provided the 'backbone system' for the establishment of the natural gas grid. It 'functioned as a hybrid technological system, which provided critical infrastructure… for the eventual development of the natural gas transmission system' (Arapostathis et al., 2013).

Figure 4: Route of the natural gas pipeline as proposed in 1962

Source: Arapostathis et al. (2013)

In 1953 the Gas Council, along with the BP Exploration Company, began searching for natural gas in Britain (Arapostathis et al., 2013). In 1959, the Slochteren gas field in Holland was discovered, prompting the Gas Council, as well as international oil companies, to focus on the North Sea (Arapostathis et al., 2013). Gas was first discovered in the North Sea in the West Sole Field, off the coast of East Anglia, in 1965 (Manson, 2006).

When North Sea gas was discovered, the Gas Council made what Pearson and Arapostathis (2017) call a 'bold' move to reorganise the industry around the discoveries. It constructed new terminals and a national gas grid, building on the LNG pipeline 'backbone' which had already been constructed (Pearson and Arapostathis, 2017).

The gas council and boards initially considered an option for converting the natural gas into a substitute gas, called GS gas, which would have fast burning properties similar to town gas, and thus be compatible with the old burners albeit with some level of modification. However, it was felt that this would be an intermediate measure and the whole conversion would have to be done eventually. The cost of converting in two or more stages would be more than doing it all at once (Arapostathis et al., 2013).

What did business do?

At the same time as the higher-level political developments in the nationalised industries, a number of different industries began to respond to the growing interest in central heating and alternative fuels prompted by both the Parker Morris report and by generally improving living standards. Many of the businesses involved were state-owned. There were technical developments that helped to promote the spread of central heating, especially the development of 'small bore' pressurised pipework systems with the water circulated by a small, silent pump. This made the technology easier to fit and more suitable for smaller homes than pre-existing large bore systems. Contemporary trade textbooks indicate a growing appreciation of such systems. The British Coal Utilisation Research Association (BCURA) was a subscription-based industry research association, credited with developing the small-bore hot water heating system. Information Circulars published by BCURA in 1957 suggested the technology could bring the cost of a central heating system 'within the reach of a much larger section of the population, and at the same time… produce a system with an improved efficiency of operation'. BCURA was also working on improving system control, such as with room thermostats. BCURA 'acted as an industry "translation hub", making links among equipment manufacturers and heating system designers and pulling together people, equipment and texts in support of this new way of designing central heating' (Hanmer and Abram, 2017).

In the late 1950s and early 1960s, as domestic consumers' interest in central heating was growing, there were still choices about which fuel to base the system on. Coal boilers remained dominant in the early 1960s, with gas, oil, and electricity systems still emerging. Advertisements from the period suggest that heating systems were increasingly being marketed on the basis of reduced effort to refuel them. Here, solid coal boilers were to lose ground to the advantages of the automatic fuelling of gas and electric systems – by the mid-1960s sales of gas- and electric-based central heating systems had increased to be on a par with coal- or coke-based ones (Hanmer and Abram, 2017).

Was there an international dimension?

The Gas Council was pursuing a strategy of securing LNG supplies, initially from Louisiana, US, and then from Algeria. However, the discovery of North Sea oil and gas radically altered this strategy.

What was the result?

In 1965 the discovery of North Sea gas completely changed the Gas Council's strategy, and it rapidly made the decision to commit to a nationwide conversion programme.

Market formation stage (1966–1971)

What did government do?

As the Gas Council committed to the conversion programme, it took a further institutional step in 1966 of setting up a specific Conversion Executive to provide nationwide coordination (Hanmer and Abram, 2017).

There were significant challenges given the highly distributed nature of the problem. The 10-year conversion required converting the appliances of 14 million consumers. Every gas-burning appliance had to be modified due to the different calorific value of natural gas relative to town gas. This was achieved in part through working with the private sector, training teams to go into homes, businesses, and factories to modify appliances (Pearson and Arapostathis, 2017). Domestic customers might have to be visited as many as 5 times (Hanmer and Abram, 2017). The education of technicians was key. Training programmes were 'coordinated by the Gas Council and organized by Boards or private contractors' (Arapostathis et al., 2013).

Some appliances were harder to convert than others – fish fryers and older appliances proving particularly resistant to the upgrade. In some cases, appliances could not be converted and thus were rendered obsolete, leaving some customers resentful. For many customers and engineers the changeover was not smooth, and there were many complaints (Hanmer and Abram, 2017).

Marketing strategies were organised. The Conversion Executive was established as a mediator between the Gas Council, the Area Boards, and the Society of British Gas Industries (representing manufacturers and contractors). A public relations strategy, the Conversion Handbook, was published. There were targeted campaigns for different building types and social groups. The conversion of Buckingham Palace, Parliament, the Bank of England, and Westminster Abbey had symbolic status (Arapostathis et al., 2013).

Pilot conversion schemes, like Canvey Island, were undertaken to both habituate experts and the public to the fuel and build confidence.

There were safety concerns, especially following the Ronan Point explosion at Canning Town in 1968 (Arapostathis et al., 2013). However, the Morton Report in 1970 confirmed that natural gas was at least as safe as town gas (Pearson and Arapostathis, 2017), and would lead to a reduction in accidents and poisoning (Arapostathis et al., 2013).

What did business do?

Gas board staff were also tasked with increasing sales of gas, reflecting the now abundant supply from the North Sea. Central heating was an obvious option for this, and there was a rapid rise in central heating installation in the late 1960s and early

1970s. Publicity campaigns such as the 'Guaranteed Warmth' campaign aimed at securing existing gas customers and converting coal ones. Hanmer and Abram report that the Director of Sales for NW Gas described the campaign as "in my opinion the greatest single event to influence the development of central heating since its inceptions" (Hanmer and Abram, 2017). Additionally, it has been suggested that the packaging together of components such as the boiler, radiators, pipes, and installation with guarantees for workmanship, materials, and the temperature achieved, into a whole system with a standardised price based on the volume of the house, was effective in cutting out the complexity. Customers could view the system in terms of its benefits and performance, without having to delve into its inner workings (Hanmer and Abram, 2017).

Was there an international dimension?

The discovery of domestic oil and natural gas supplies in the North Sea meant that there was less international focus on securing LNG supplies from other countries.

What was the result?

Natural gas had grown from accounting for less than 1% of total gas consumption in 1962, to more than 50% in 1971.

Commercialisation stage (1971–1978)

What did government do?

The Gas Act 1972 led to the formation of the British Gas Corporation, an organisation with responsibility for the gas supply across the whole country (Hanmer and Abram, 2017).

What did business do?

By the early 1970s, the plethora of technical options for central heating systems that had been presented in the 1960s, had been narrowed down, as contemporary advertisements show. The system of gas boilers with radiators had become the default option (Hanmer and Abram, 2017). Natural gas was becoming established as a cheap, convenient, and abundant fuel, thereby exhibiting notable advantages over competing coal, oil, and electric systems. Due to the efforts of the Gas Council and the Conversion Executive, the system was also backed up by trained fitters and secure supply chains, As Hanmer and Abram observe, 'for the 92% of the UK population with a gas grid connection, the fuel, heating system and building were so strongly aligned that other options were very rarely considered' (Hanmer and Abram, 2017).

Was there an international dimension?

The increasing self-reliance of the UK for its gas and oil supplies meant that there was very little international dimension in this phase of the transition.

What was the result?

Forty million appliances from 14 million users had to be converted, modified, or replaced. Six million users had been converted by 1972, and the whole programme complete by 1977 (Arapostathis et al., 2013).

3. Wind in Denmark and the UK

Development stage (1957–1979)

What did government do?

In the earliest developmental stages of wind power, government actions were more likely to hinder than assist the technology. The early boom in the wind turbine industry, largely for rural off-grid areas in Denmark and the US, came into competition with government electrification programmes towards the middle of the twentieth century, and interest in wind tailed off in the post-war period with the growth in transmission grids and large-scale centralised generation (Jones and Bouamane, 2011). The industry began to revive in Denmark in the late 1950s, following the construction of the Gedser turbine (see below). However, this prototype turbine was expensive, and Danish government funds were directed towards nuclear, with the nuclear test plant at Risø inaugurated in 1958 (Jones and Bouamane, 2011). Government policy again threatened to undermine the case for wind, when in 1976 the Danish government launched an energy transition plan which included a proposal to build 6 new nuclear plants by the end of the century (Jones and Bouamane, 2011). Nonetheless, in a broader social context of rising environmental consciousness and opposition to nuclear power, these actions may have indirectly spurred on the development of wind power, by galvanising opposition to nuclear power which coalesced around the entrepreneurial development of alternative energy technologies, including wind power.

By the late 1970s, however, as Danish entrepreneurs and civil society groups were becoming increasingly active in the development of the technology (see below), the government undertook some important actions in support of wind power. The Danish Wind Turbine Test Station was founded in 1978 when the government's Risø test laboratory, which had been established in 1958 primarily as a nuclear power testing centre, now moved into wind turbine testing (Garud and Karnøe, 2003). Shortly afterwards the government required that turbines had to be certified before owners could access subsidies, and the test station began establishing the testing criteria (Jones and Bouamane, 2011).

The Risø laboratory made a significant contribution in its sponsoring and acquisition of knowledge about early turbine designs, which then became a public asset. It conducted rigorous and independent tests, the results of which were made public for private actors in the Danish wind industry to benefit from. This meant that the most successful designs were proliferated much more quickly than would have been the case with individual companies working alone, meaning that the Danish industry as a whole moved quickly ahead of other national industries (Grubb et al., 2014, Maegaard et al., 2013).

Government activity was significant also in the US. Following the 1973/74 oil crisis, federal funding began to be directed towards alternative energy programmes, including wind power (Jones and Bouamane, 2011). In 1975, the Gedser turbine was refurbished at request of NASA, in order to generate measurement results for the US wind energy programme (Danish Wind Industry Association, 2003a). In 1978, the Public Utility Regulatory Policies Act (PURPA) opened the door to feed in tariffs, and the Energy Tax Act offered tax credits for renewables. These measures began to create a significant new market for Danish wind turbine manufacturers (Jones and Bouamane, 2011).

What did business do?

In this case study, the invention point is taken as 1957, with the construction of the Gedser turbine. However, if it is asked why this important event took place in Denmark, it becomes clear that the roots of this invention go further back. The first windmills used to generate electricity were built in the 1880s, and during the first half of the twentieth century entrepreneurs and businesses produced substantial quantities of wind turbines, often driven by the desires of rural communities to access electricity, especially in Denmark and the US. One of the earliest Danish wind energy innovators at the turn of the century had been Poul La Cour, who also ran engineering courses on the subject, one of which was attended in 1903 by Johannes Juul (Jones and Bouamane, 2011). Towards the end of his career Juul took up his interest again, and, drawing on his knowledge from La Cour's course, constructed his Gedster turbine in 1957 (Danish Wind Industry Association, 2003a). The design was 'fairly similar to Poul La Cour's wind turbine... Juul's key invention - emergency aerodynamic tip breaks - remains in use in turbines today' (Jones and Bouamane, 2011). The turbine ran until 1967.

After a mid-century decline in demand for wind turbines due to the increasing reach of centralised generation through power grids, interest in alternative energy sources was renewed in the early 1970s, with the oil crises and the rise of environmental consciousness. The Danish government initially pursued policies to develop nuclear power (see above). This provoked opposition, which coalesced with the forming of the Organisation for Renewable Energy (OVE) in 1976, a membership-based non-profit organisation, to oppose the government's nuclear plans and promote alternatives.

A member of OVE, Erik Grove-Nielson, founded a turbine manufacturing company, Økær Vin Energi, in 1977, developing and refining blade design, and selling blades to self-builders; Grove-Nielson's business was supported by OVE (Jones and Bouamane, 2011). Another pioneer, Christian Riisage, a Jutland carpenter, created a 7 kW turbine using wood and truck gears, based on Juul's design (Jones and Bouamane, 2011). Jorgensen, a mechanic, improved on Riisager's design, adding an active yaw mechanism, for keeping the rotor turned perpendicular to the wind (Danish Wind Industry Association, 2003b), and adopting Grove-Nielsen's fibreglass blades (Garud and Karnøe, 2003).

The growing number of wind energy entrepreneurs began to coalesce into formal and informal groups and organisations, sharing knowledge and building capacity. From 1976, firms began to meet each other at *Windmeetings*, during which firms exchanged learning from their trial and error experiences. These meetings culminated in the forming of the Windmill Manufacturers Association in 1978 (Garud and Karnøe, 2003). In the same year, the Danish Wind Turbine Owners Association was founded, which began to lobby electricity boards and disseminate information about wind (Jones and Bouamane, 2011). This association also provided feedback to manufacturers, as its members sought design features that would enhance the safety and reliability of wind turbines (Garud and Karnøe, 2003).

Was there an international dimension?

Policy developments in the US were beginning to set up the opportunities for the expansion of Danish manufacturers into US markets in the next stage. However, during this one there was little direct international influence on the Danish system, which was steadily refining turbine designs through practical trial and error approaches, enhanced by fluid communication between and amongst manufacturers, end-users, and lobby groups.

What was the result?

The first commercial wind turbine was built in Denmark in 1979 (Ministry of Foreign Affairs of Denmark, 2018).

Market formation stage (1979–1998)

What did government do?

After the second oil crisis, and no doubt influenced by the impressive levels of activity in the technology amongst entrepreneurs and civil society, public policy in Denmark became more supportive of wind energy. In 1979 a 30% investment subsidy towards the purchase cost of wind turbines was instituted, which after having little effect, later rose to 50% (Jones and Bouamane, 2011).

The voluntary power purchase agreements between utilities, manufacturers, and turbine owners (discussed below), seem to have been more effective in bringing about deployment. However, when these broke down, in 1992 the government introduced a feed in tariff. In 1994 the government required municipalities to plan for future wind turbines, and to provide subsidies for the substitution of older, inefficient, and noisy machines with newer ones (Jones and Bouamane, 2011).

Policy measures were also significant in the US, and had a considerable benefit for Danish companies, which were able to expand into a rapidly growing market, particularly in California. In 1983, California built on the federal PURPA legislation, launching the Interim Standard Offer 4 (ISO4) – wind energy feed in tariff contracts with ten-year fixed-price components, followed by twenty-year floating prices (Jones and Bouamane, 2011).

What did business do?

Danish agricultural equipment manufacturers, in the wake of the post-1979 recession, were looking for other products and began to expand into wind turbines. One of these small companies was Vestas. These companies purchased blades from existing designers, including Økær Vin Energi, and went on to develop them (Jones and Bouamane, 2011). Vestas licensed a turbine design by Jorgensen, which used Grove-Nielsen's fibreglass blades, in 1979 (Garud and Karnøe, 2003).

From 1979, utilities and associations of wind turbine manufacturers began to agree voluntary power purchase agreements, which gave a guaranteed minimum price, and shared the costs of grid connection. These have been argued to have been more significant than the government purchase subsidies discussed above (Jones and Bouamane, 2011).

In 1980 the first Wind Turbine Guild was established near Aarhus in Jutland. 'This was a partnership for tax reasons, but functioned as a co-operative'. (Jones and Bouamane, 2011).

The Danish industry was characterised by small geographical clusters of firms working on incremental innovation derived from practical knowledge. This reflected the traditional industry structure in Denmark, characterised by small medium firms and collaborative learning networks. The small size of the country meant that manufacturers like Vestas would directly service their own turbines, which was another source of learning. The wind turbine owners' association was important in improving technological performance, as it published data on reliability and performance. The Danish market reached 50 MW in 1985 (Jones and Bouamane, 2011).

During the 1980s, policy incentives in California opened up the market to foreign firms, and Danish firms became active there, with Vestas, for example, opening an assembly facility. Danish firms favoured a 3-bladed design, derived from the Gedser turbine, but now with fibreglass blades. Certification from the Risø test centre showed these to be more reliable than their US counterparts. In 1987, while the largest producer of turbines in California was US Windpower, the next five firms were Danish. Between 1980 and 1988, 97% of wind power installations in the world were in California (Jones and Bouamane, 2011).

Was there an international dimension?

The most critical international dimension in this phase was the development of deployment support policies in the US, and in particular in California. The US was also investing in R&D support for its domestic industry, and the company US Windpower, in particular, performed strongly. However, the deployment support policies were open to international competition, and provided an opportunity which Danish companies seized effectively. The results of a decade of refinement of Juul's basic design were bearing fruit, and crucially this could be verified by certification from the Danish Wind Turbine Test Station.

What was the result?

In 1998, total installed capacity in Denmark (onshore and offshore) was 1.44 GW. This was 23% of what would be the installed capacity in

November 2018 (Danish Energy Agency, 2018). Twelve percent of Danish electricity came from wind in 2000 (Jones and Bouamane, 2011).

Commercialisation stage (1998–2018)

What did government do?

The UK was not at the forefront of the early development of onshore wind turbines. However, it has played a significant role especially in promoting the deployment of offshore wind turbines and pushing forward their innovation. A key part of this is the contracts for difference (CfD) subsidy regime, introduced by the Energy Act 2013, which guarantees a price per unit of energy to developers for an agreed contract period, and provides a strong market pull for offshore wind developers. In 2014, the first CfDs were awarded to 8 renewable energy projects including 5 offshore wind ones. The contract prices were set administratively, at £140-150 / MWh, several times the average price of electricity at the time. However, the introduction of an auction mechanism for allocating CfDs saw costs falling quite substantially. In 2015 the first competitive CfD auction awarded contracts for offshore wind projects at £120 and £114 / MWh. CfD auctions in 2017 delivered contract prices for offshore wind projects scheduled to start in the early 2020s, at £74.50 and £57.50 / MWh, which would be much closer to the average price of electricity expected at that time. Onshore wind was excluded from this auction.

Thus, some degree of policy learning in respect of market-pull subsidies has taken place. This has also been supported by coordination activity supporting and promoting learning and innovation amongst firms active in the industry.

In 2008 the UK body the Carbon Trust set up the Offshore Wind Accelerator (OWA). This brought together the major offshore wind project developers with the initial aim of reducing the costs of offshore wind by 10%. The process focussed on a range of aspects of the supply chain, including the designs of foundations and site access systems. These were products and services that all the convened project developers used but did not provide themselves – hence, all the convened developers were not competing on the technologies under discussion. Rather, the companies in the group were able to clarify their needs to other potential providers, with each participant leveraging their own investment by many times due to the contributions of the other participants, and to establish a clear market demand for the products required, at a desired cost (Grubb et al., 2014).

In its current phase the core public funding of the OWA is provided by the Scottish Government, with the remaining funding coming from industry. The OWA's nine industrial partners are: EnBW, E.ON, Innogy SE, Ørsted, Scottish Power Renewables/Iberdrola, Shell, SSE Renewables, Equinor, and Vattenfall Wind Power (Carbon Trust, 2019). This is evidently a highly international group of partners.

The UK's "Catapult" centres are intended to be 'a network of world-leading centres designed to transform the UK's capability for innovation in specific areas and help drive future economic growth' (Catapult, 2019a). The funding model is one third business-funded R&D contracts won competitively; one third collaborative R&D projects jointly funded by the private and public sectors, also won competitively; and one third core public funding (Catapult, 2019b). This is a similar model to those used in other national research institutes, such as Germany's Fraunhofer institutes (Fraunhofer ISE, 2018). The Offshore Renewable Energy Catapult was established in 2013. It is undertaking projects on testing and validation, research and innovation, and operation and performance, frequently collaborating with different commercial companies and across national boundaries (OREC, 2019).

An independent review of the Catapult network was conducted by Ernst and Young (E&Y, 2017). It found that the concept of the Catapult network, as a means to bridge the gap between research and commercialisation, was sound, and that it has 'the potential to drive innovation and economic benefit to the UK'. However, some criticisms were made, including a lack of robust governance, performance management, clarity of purpose, and measurement of outcomes. It also reported that catapults have not achieved the intended split between public and private funding, and 'remain overwhelmingly reliant' on the former. It suggested that further core funding should be dependent upon 'measurable milestone plans that will lead to economic benefits for the UK economy through addressing clearly articulated market failures' (E&Y, 2017). Demonstrating economic benefit for the UK economy may not be straightforward, however, in the case of offshore wind. This is both due to both the complexities inherent in measuring the net increases or decreases in jobs resulting from the substitution of one power technology with another, and the fact that the international nature of the UK's offshore wind supply chain could further complicate assessment of how much of any wider economic benefit is retained in the UK. This raises the question: is investment in innovation for the low-carbon transition to be justified only if it also causes measurable economic benefits within the UK, or is low-carbon innovation to be justified on its own terms, even if the international firms that form the UK's supply chain capture these benefits?

Financial support has also played a role. The Green Investment Bank was a non-departmental public body of BIS (now BEIS) launched by the UK government in 2012. In 2017, however, it was sold to the private sector and is now owned by Macquarie Group Ltd and known as the Green Investment Group (GIG) (UK Government, 2019). It continues to invest in green infrastructure projects on commercial terms, as well as offering financial services and products, project delivery and portfolio services, and other services. It has invested £1.6bn in the offshore wind sector, across nine projects with a combined total capacity of 3.2 GW. It has also set up and manages the UK Green Investment Offshore Wind Fund, which has a portfolio of six projects with a combined capacity of 1.45 GW. The GIG also provides finance for onshore wind projects, noting that 'the potential for this sector is significant, but there is currently a market failure in the provision of finance to these projects' (GIG, 2018).

There is strong evidence that the GIB and European Investment Bank (EIB) provided important support to offshore wind deployment. They did so by: absorbing early deployment and technology risk and filling investment gaps, allowing private sector investment; buying equity stakes in existing offshore wind farms, allowing developers to 'recycle and reinvest capital in new projects'; using their investments to support the development of innovative financial products, such as portfolio aggregation, which attracted new investors to the sector (Vivid Economics, 2018).

What did business do?

The growing familiarity with the long-term contract or feed in tariff type of policy mechanism has gradually increased the confidence of investors and project developers in respect of wind projects. This has led to a gradual learning effect, bringing about cost reductions. The effect of the economies of scale of larger turbines is also significant, especially for offshore wind. Larger turbines deliver greater capacity factors, which in turn increase output and return on investment. IRENA data shows the capacity factors of offshore wind turbines have been increasing steadily, reaching a global average of 42% in 2017 (IRENA, 2018b, p.102). In the final quarter of 2016 and the first quarter of 2017, all offshore turbines ordered were in the 7-9 MW range (Wind Europe, 2017, p. 40, fig 29). Larger turbines also mean fewer towers have to be built per unit of energy output, reducing material and construction costs. Improvements to turbines and blades are also increasing load factors, and cost savings have also been found in the design of foundations and in cable capacity. Bids being made now may be taking into account expected future gains from larger capacity and higher efficiency turbines. Ørsted expects 13-15 MW turbines to be available in 2024. Furthermore, economies of scale can apply to the project as a whole, as there are significant fixed costs, such as cables and installation vessels (NERA, 2017).

Was there an international dimension?

The UK is world-leading in its deployment of offshore wind. However, this has been delivered by an extremely international supply chain. Wieczorek et al (2013) observed that 'the United Kingdom does not have such a strong national industry and is very dependent on foreign actors to fulfil their national ambitions.' The importance of international actors in the sector remains large, as is evidenced by the industrial partners in the OWA – all of the companies are headquartered outside the UK, with the possible exception of SSE. However, even in this case, while the parent company SSE is headquartered in Perth, Scotland, its subsidiary SSE Renewables, which is the entity involved in the OWA, is headquartered in Dublin. The extent to which this should be considered problematic for the UK is perhaps open to question. Wieczorek et al (2013) suggest that 'a too strong dependence on foreign actors may result in a loss of legitimacy and political support, as domestic incentives for offshore wind primarily lead to the building up of an offshore wind industry abroad.' On the other hand, activities of firms headquartered outside the UK may still create economic activity in the UK, as, 'by using the domestic market and wind potential of the United Kingdom, foreign companies provide the domestic innovation system with access to foreign knowledge and skilled personnel… and contribute to national employment creation' (Wieczorek et al., 2015).

What was the result?

Fairly successful cost reduction, a strong and growing offshore wind sector in the UK, with strong international involvement.

4. Steel in South Korea

Development stage (1949–1972)

What did government do?

In South Korea there was increasing demand for steel products during the reconstruction period after the Korean War of 1950-1953. However, perhaps an even stronger driver was the importance of establishing a national steel industry in the overall economic plan of President Park Chung-Hee, based around a strategy of development through industrialisation and export substitution (D'Costa, 1994). Numerous attempts by the Korean government to construct an integrated steel mill between 1958 and 1968 were unsuccessful due to lack of financing. The World Bank and the US Agency for International Development refused to provide loans, doubting the country's credit-worthiness, whether a large capacity steel mill was needed in a small developing country, and whether South Korea could ever 'master the technology'. (Lee and Ki, 2017; D'Costa, 1994).

In 1967, a small amount of production, around 300,000 tonnes per year, existed in South Korea, mainly using OHF (Hogan, 1994). However, in 1968 the Korean government established POSCO (Pohang Iron and Steel Company) with 60% of the capital supplied by Japanese sources, and the remainder from other international lenders and domestic sources. The government took an active role, providing guarantees to lenders of the loan payments from POSCO. It also enacted the Steel Industry Promotion Law in 1970, which enabled reductions in electricity, gas, and water rates, and of rail transport and port dues for the industry. POSCO also received exemptions from corporate taxes, and an 80% reduction in import tariffs (Lee and Ki, 2017).

What did business do?

In the first half of the twentieth century the US was the world's dominant steel producer, using the open-hearth furnace (OHF) method. In 1945, the US accounted for 64% of global steel production. Japan's steel industry began to grow from the early 1950s onwards, in part driven by demand caused by the Korean War. During the 1960s, Japan rapidly caught up with the US in steel production, eventually overtaking it in 1980. A significant factor was Japan's rapid adoption of new steel production technologies; the basic oxygen furnace (BOF), which had been developed in Austria, and continuous casting (CC). These new technologies had considerable advantages. For example, the BOF refining process was 10 times faster than OHF; constructing BOFs was 50% cheaper; and BOFs had lower operating costs (Lee and Ki, 2017).

Japan was the crucial conduit of learning for POSCO when it was set up. Through an agreement with Nippon Steel, guidance was provided on technical details and where to purchase equipment. Japanese firms built the main facilities and administered business deals and projects. The technology that was being transferred in this way was relatively outdated and small scale, however. Korean workers were also trained in Japan, and they then returned to train others. Retired Japanese technical experts also provided knowledge (Lee and Ki, 2017).

Was there an international dimension?

The international dimension was crucial for South Korea to gain access to the required technology. Initially the main conduit for this was Japan, a near neighbour that had been innovating rapidly in steel production, with whom relations had been recently normalised in a treaty of 1965, one of the conditions of which was the payment of war reparations to South Korea. These were partly directed towards the steel project.

What was the result?

From a starting point having negligible steel production capacity, South Korea was ready to start producing it in an integrated steel mill using well-established – albeit not cutting edge – Japanese technologies, with the support of training and guidance from Japanese teams.

Market formation stage (1972–1986)

What did government do?

As POSCO was a state-owned company until 2002, the questions of what government did, as opposed to what businesses did, are not as distinct in this case study as they might be in others. The section below deals with the business strategy of POSCO. However, during this period of rapid scaling-up the effect of the political context is important to consider. As previously noted, establishing a steel industry was a central plank of President Park's strategy, which gave it strong political support. POSCO's Chairman, Park Tae Joon also came directly from the military, and was vested with similarly strong decision-making powers over the company as the President assumed over the country. State support reduced costs of international loans (D'Costa, 1994).

In both integrated steel mills, first at Pohang, then at Kwandyang, every stage of construction was completed ahead of schedule. As well as enabling rapid expansion, this reduced the interest on loan payments. However, the political and social conditions under which these results were achieved are salient. 'Thousands of non-union construction workers at or near subsistence wages were mobilised and worked around the clock' (D'Costa, 1994). For much of the period under discussion, there was considerable state control of workers' representation. The Federation of Korean Trade Unions was established by the state to consolidate all unions, but its leaders were selected by the Korean Central Intelligence Agency. POSCO's workers were unable to join a union at all until 1988 (D'Costa, 1994).

What did business do?

As POSCO began to expand in the early 1970s, it was helped by the effects of the 1973 oil crisis. These included a downturn in global steel demand which meant that steel industries in developed countries had overcapacity problems. As a result, steel manufacturing equipment suppliers were looking to export to other countries. POSCO was able to exploit the resulting competition between suppliers to drive down costs of equipment and maintenance during this period of its expansion. This has been contrasted with countries such as Brazil and India that were trying to expand their steel production during boom times (Lee and Ki, 2017).

Nonetheless, due to global competition, during the 1970s and through much of the 1980s POSCO focussed on low-end steel products, such as hot-rolled coil and thick plates, rather than higher value products such as coated sheet and alloy steel. Although initially built up around imported, mainly Japanese technologies, during the 1970s POSCO began to develop its own technological capabilities (Lee and Ki, 2017).

In the 1980s, POSCO moved from being an 'imitator' to a 'fast-follower'. Once again, the timing of global economic events was in their favour. In the early 1980s POSCO decided to build a second integrated steel mill and called for bids. At this time the steel industry was again in recession due to the second oil crisis of 1979, so once again competition was created amongst steel mill equipment suppliers and POSCO was able to drive costs down. Due to this, POSCO was also able to adopt state-of-the-art technologies, including pulverised coal-injection technology, which delivers energy saving benefits in operation. The new mill also adopted continuous casting (CC). The share of CC in POSCO's activities reached 51.3% in 1985 (Lee and Ki, 2017). Construction of the new integrated mill began in 1985 (Hogan, 1994).

Thus, POSCO was now able to focus on narrowing the gap between it and the leading companies, as a result of acquiring the latest technologies.

Was there an international dimension?

In part through fortunate timing of global events, but also through effective negotiation, POSCO was able to acquire increasingly state-of-the-art technology from international companies at favourable prices.

What was the result?

South Korea's crude steel production had risen from negligible levels to around 15 Mt, or around 15% of the production of the world leader, Japan (International Iron and Steel Institute, 1990).

Commercialisation stage (1986–2017)

What did government do?

Further organisational changes increased the capacity for internal research and development. The Pohang University of Science and Technology (POSTECH) was established in 1986, and the Research Institute of Industrial Science and Technology (RIST) in 1987. These new institutions, along with POSCO itself, created a 'tripartite' system, covering fundamental research, development, demonstration and commercialisation. Under this system RIST undertook 241 R&D projects in 1987, rising to 713 in 1993. The overall result was that POSCO was able to transition from its focus on low-value products which had dominated its approach during the 1970s, to an increasing share of high-value ones. One example of an innovation emerging from this system is the high-value product 'extra-deep drawing steel sheet' used for automobiles. By the late 1990s POSCO had effectively 'caught up' with Japanese firms such as Nippon Steel, having a comparable share of high-value products, and even surpassing them in terms of productivity (Lee and Ki, 2017).

D'Costa suggests that the state-owned position of POSCO may have contributed to pricing policies enacted with a more macro-economic view than might have been the case in a private company with strong market power: 'POSCO's cost competitiveness was passed on to steel-using industries in the form of lower prices… Low prices for steel have helped downstream activities… What is salient is that POSCO, despite being a monopoly, has not behaved like a rentier. When demand for steel was growing rapidly the government ensured adequate supplies without raising prices. POSCO has not pursued profits like a private sector firm, rather it has maintained its technical efficiency for competitiveness' (D'Costa, 1994).

What did business do?

During the 1980s, a group of minimills emerged in the country using electric arc furnaces (Hogan, 1994). By 1992 there were ten minimills in the country with capacities ranging from 150,000 tonnes to 2.8 Mt per year. The combined capacity of the minimills was 11-12 million tonnes (Hogan, 1994). Total production in South Korea in 1992 was 28,054 kt (International Iron and Steel Institute, 1993), which meant that the minimills could have accounted for as much as 40% of output.

D'Costa reports that the minimills are important to providing steel products which are used by South Korea's downstream industries: 'Since many steel-intensive products are also exported by South Korea, POSCO has contributed to the general competitiveness of Korean industries. Using mini-mills, which further process steel products, POSCO has been able to supply low cost, high quality steel to steel-consuming industries'(D'Costa, 1994).

The Korea Iron and Steel Association lists 22 companies as 'major producers', including POSCO (KOSA, 2010).

The share of CC in POSCO's activities reached 97.8% in 1992 (Lee and Ki, 2017).

In 1997, the privatisation of POSCO was proposed by the South Korean government. In 1998 the government reduced its share ownership in the company to 20%. POSCO remained a dominant player. In 2002 63% of the country's crude steel output came from POSCO (Wichert, 2002).

Was there an international dimension?

In the 1980s POSCO began to invest in other countries. In 1986 it signed a joint venture agreement with US Steel in Pittsburgh for a 50-50 shared $500 million investment in a plant which opened in 1989 (Hogan, 1994; UPI, 2019).

What was the result?

From having a virtually non-existent steel industry in 1968, South Korea had almost caught up with the US and Japan in terms of production output by the early 21st century. In 2017 it had the 6th largest crude steel production in the word – behind China, Japan, India, the US, and Russia (World Steel Association, 2018).

5. Carbon capture (utilisation) and storage (CCS / CCUS)

This case study is approached differently as the innovation is not complete yet. Rather than analyse the three stages, we conduct a summary of key attempts at innovation around the world.

UK

The UK government's first engagement with CCS was in 2005. Funding could not be agreed, however, and BP withdrew its project proposal. BP-SSE had proposed a post-combustion retrofit of the Peterhead gas fuelled power plant, with CO_2 storage offshore via an existing pipeline to a depleted oilfield.

In 2007 the UK government launched a CCS procurement competition; however, the programme was terminated. Funding was for up to £1bn capital investment, with the aim of delivering a CCS power project by 2014. However, negotiations were ended in 2011, due to concerns that the project could not be funded within the £1 billion limit.

A programme was re-launched in 2012 as the CCS Commercialisation Programme, and contracts were awarded to two preferred bidders: Capture Power (led by Alstom), for its White Rose project in Yorkshire, and Shell and SSE for the Peterhead project in Aberdeenshire. £1 billion was still available in capital funding, and further support for increased operational expenditure would be made available through the creation of a CCS CfD (ECCC, 2015). However, on 25th November 2015, the government unexpectedly announced that the funding for the Commercialisation Programme was terminated. A UK National Audit Office (NAO, 2017) inspection stated that £100M of public money had been spent, but that a fundamental flaw was the lack of agreement by Treasury to support any CCS project.

Norway

In Norway, CO_2 capture and sequestration has been practised in the natural gas extraction and processing sector for many years. The Sleipner CO_2 storage project is the oldest of these. It has been capturing CO_2 since 1996, at the rate of approximately 0.9 Mtpa. A carbon tax (introduced in 1994) provided sufficient incentive for the company to re-inject the captured CO_2 into a sandstone reservoir above the Sleipner East field, in order to avoid the tax (GCCSI, 2015b). CO_2 capture and injection has also been undertaken at the Snøhvit gas field since 2008, at the rate of approximately 0.7 Mtpa. Additionally in this case, the application of CCS was mandated by the government as a condition of the original licence to operate (GCCSI, 2015c).

Beyond natural gas, the Norwegian Government has had poorer outcomes. A test centre for capture technologies, the European CO_2 Test Centre Mongstad (TCM), began operating in 2012. This is a joint venture between the Norwegian Government, Statoil, Shell, and Sasol. It was intended that the project would have a second phase, involving a full CCS retrofit onto a gas power plant (Bugge & Ueland, 2011; MIT, 2016c). However, in 2013 the Norwegian Oil and Energy Ministry announced it was cancelling the full CCS plant due to rising costs (Holter, 2013; MIT, 2016c).

Canada

SaskPower's Boundary Dam 3 (BD3) plant in Saskatchewan, Canada, is a lignite-fuelled power station with CCUS, which began operating in 2014. As such it has claims to be the world's first operational large-scale CCUS project in the power sector (Banks & Boersma, 2015; GCCSI, 2018).

A crucial driver for this project was the threat of closure. The existing BD3 plant would have had to close as a result of Canadian government emissions standards, which required plants to achieve a CO_2 emissions intensity of 420 tonnes / GWh – approximately equivalent to current high-efficiency combined cycle gas plants (SaskPower, 2016) – or face limited operating hours. Although the company could have met the emissions standard with a new gas-fired plant, the plant is located in an area rich in coal but with limited access to natural gas supplies.

Nearby opportunities for CO_2-EOR aided the project's success (Banks and Boersma, 2015). There is some storage of CO_2 from the project in a deep saline aquifer 2km from the plant. However, most of the CO_2 is transported by pipeline to the Weyburn oil field where it used for enhanced oil recovery (EOR), which creates considerable revenues (Banks and Boersma, 2015). $CAN240 million of the total $CAN1.5 billion investment cost of the project was provided by the Canadian government in subsidies (Banks & Boersma, 2015; IEAGHG, 2015). SaskPower itself is a Crown electricity company that has a near monopoly position in Saskatchewan.

Germany

Germany's 2010 Energy Strategy indicated the potential role of CCS in contributing to its climate change targets, planning for two new demonstration projects to be built by 2020.

A 30 MW oxycombustion pilot capture plant was constructed by Vattenfall at Schwarze Pumpe in the Brandenburg region and operated from 2008 to 2014. Between 2008-2013, the CO_2 was transported by road trucks to an injection and storage site at Ketzin, near Berlin, during which time the subsurface was monitored (MIT, 2016a). The project was funded by German federal research, German industry and research institutes, and Norway CLIMIT.

In 2009 RWE received a permit for a CCS lignite power plant near Cologne, however it was suspended. The CO_2 from the plant was to be transported by a 600km pipeline to an underground storage site in the Schleswig-Holstein region. When the pipeline and storage plans became known, they were the subject of considerable public objections and protests, with the government of Schleswig-Holstein also being persuaded to oppose the plans. RWE suspended the project, citing the lack of both a legislative framework and of public acceptance of transportation and storage of CO_2.

Krämer (2011) lists a range of concerns in Schleswig-Holstein in relation to the RWE project. These include: potential for CO_2 leakage and its effects on health and safety, the environment, and contamination of ground water; the land-take of the pipeline; the image of Schleswig-Holstein as a tourist region; the idea that pursuing CCS results in a lack of investment in renewables; and the perception of being a waste-depository for the activities of coal power plants being built elsewhere in Germany. Krämer further suggests that 'generally, political parties, be it at the regional or the national level, which favour nuclear or CCS technologies – and these two technologies are often put on the same level in public discussions – run a strong risk of losing votes or even elections' (Krämer, 2011).

Netherlands

In the Netherlands the main CCS activity concerns the proposed Rotterdam Opslag en Afvang Demonstratieproject (or ROAD project). This is a planned post-combustion retrofit onto a new coal-fuelled power station near Rotterdam, with the CO_2 to be transported to an offshore depleted gas reservoir. The project received €180 million in 2009 from the EU's European Energy Programme for Recovery (EEPR), and a further €150 million for 2010-2020 from the Dutch government (MIT, 2016b).

The project has stalled due to lack of funding. A full storage permit was granted for a depleted gas field 20km offshore. Reiner (2016) comments that the project 'remains the most advanced CCS project in Europe', but that it has been 'stalled because of a funding shortfall'.

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