Understanding the UK Low Carbon Energy Innovation System

A working paper prepared for the ETI by Brian Titley and Ken Warwick

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The analysis and views expressed in this working paper, unless otherwise attributed, are those of Brian Titley Consulting Ltd and Warwick Economics

Contents

1. Background

The innovation challenge

1.1 Meeting the challenge of delivering safe, secure and affordable energy combined with substantial reductions in emissions of greenhouse gases will require significant innovation in new, low carbon technologies over the coming decades. Innovation will be required in the way our energy is generated and delivered and the way in which it is used in our homes, transport systems, industries and places of work.

1.2 It will be easier to achieve this transition, at the scale and pace required, if there is a shared understanding of the drivers of new low carbon energy technologies, the barriers that can impede their development and the key interactions required to unlock opportunities in the UK.

1.3 To this end, a model of the UK innovation system has been developed to provide an accessible and consistent framework for engaging in dialogue on these issues and to help identify accelerated pathways for innovation.

1.4 The structure of the high-level model is necessarily stylised and generic. However, its application to the UK energy system and/or to specific low carbon technologies can reveal distinctive features of the innovation challenge and the specific issues that need to be addressed.

1.5 The issues include the need for radical innovation, requiring significant investment in both R&D and infrastructure; extended lead times; and the risks of locking-in to sub-optimal technological pathways. These problems are compounded by perceptions of a lack of stability in the policy environment and market signals that are often volatile or unclear. There are also questions about public and consumer acceptance of new technologies. Because of all these factors, new promising technologies will often appear economically inferior to incumbents for long periods.

Project requirement

1.6 In light of the innovation challenge, the aims of the Energy Technologies Institute (ETI) for this project are as follows[1]:

- To identify and build a common understanding among its stakeholders of the key factors required for the successful deployment of new low carbon energy technologies commercially and at scale.

- To develop a framework for the successful commercial exploitation of low carbon energy technologies that it hopes can be widely socialised and subsequently used by those organisations involved in the development, financing and delivery of resilient and affordable low carbon energy solutions in the UK.

- To provide an initial, high level 'model' of the UK low carbon innovation system, including its key stages, barriers, drivers and stakeholders, to provide a suitable

[1] Consultancy agreement reference: GAT/Titley(Warwick)/UK Energy Innovation System/1114, 10 December 2014

structure for testing and socialisation with industry, finance and government stakeholders engaged in energy and other low carbon innovations.

1.7 Ultimately ETI wishes to use this model to identify, understand and influence the key mechanisms and stakeholders required to accelerate the diffusion, deployment and commercialisation of low carbon technologies it has helped to develop.

Purpose

1.8 The purpose of this working paper is therefore twofold:

- to report on the findings from a short review of the existing innovation literature undertaken to identify whether there are any existing models of innovation that could be applied to or adapted for the UK energy system; and
- to present an initial conceptual 'map' or model of the UK energy and low carbon innovation system informed by relevant literature and identifying (without limitation) the key barriers, drivers and organisations involved.

Our approach

1.9 There is an extensive literature on theories of innovation and models, both generic and sector specific, offering a variety of perspectives on innovation processes and mechanisms of impact. Theories of the innovation process have changed quite considerably over time. Our search for applicable models has therefore focused on the most recent literature and in particular on those models specific to low carbon innovation in the UK energy sector. From the literature we have identified and classified models according to:

- broad types of model, based on the classification originally used by Rothwell (1992) and subsequently extended by Marinova and Phillimore (2003): linear or non-linear; push vs pull; system models, etc.;
- common elements or components: scientific/technical; financial; skills; organisation/product/market oriented, etc., drawing principally on a review of literature undertaken by Maldonado (2011).

These are discussed in more detail in Annex A while model applications to energy and low carbon technologies are examined in Annex B. Based on our review and analysis of the literature we develop an initial model of innovation that can be applied to the UK energy and low carbon innovation system.

2. A Conceptual Model of the UK Innovation System in Energy and Low Carbon

Models of innovation

2.1 It is now widely accepted in the innovation literature that successful innovation systems involve open and iterative processes from which both incremental innovations and large-scale "disruptive" technologies can emerge. These processes are often complex and non-linear, seldom involving a straightforward progression from basic research through to deployment. The key conclusions we draw from the extensive literature on non-linear models are:

- Successful innovation requires multiple interactions between different actors (individuals and organisations), to facilitate knowledge transfer and learning across science and industry.
- Collaboration is particularly important as few organisations will have sufficient internal resources - whether technical skills, financial or other - to develop and take an innovation from concept through to full commercialisation without external help.
- There is a key role for trial and error, whereby emerging technologies are assessed, rejected or refined and may be diffused at any stage. The process adds to the stock of knowledge, which in turn drives further innovation activity.
- It takes time for innovation systems, networks, relationships and expectations to form and mature and therefore for new technologies to be developed and deployed, especially more radical disruptive technologies.

2.2 Nevertheless, linear or sequential models of innovation can be useful as a means:

- to analyse the key drivers of innovation, whether science-led (technology push) or demand-led (market pull);
- to chart and monitor the progression or life-cycle of a new technology from initial concept through to full commercialisation and market maturity;
- to identify gaps or barriers that can impede the movement of emerging technologies along the innovation chain and prevent their successful commercialisation; and
- to assist the design of policy to plug these gaps, for example, through financial support, knowledge sharing and the creation of appropriate market signals.

2.3 We have attempted to capture and synthesise core elements from the existing literature to build an initial conceptual model of the energy and low carbon innovation system in the UK. This is represented in the diagram labelled Figure 1 below and described in Table 1. It borrows heavily from representations of low carbon innovation systems developed by Grubb (2004) and the OECD (2011) and the more generic framework of Crafts and Hughes (2013) among others.

Figure 1: A conceptual model of the UK energy/low carbon innovation system (high-level schematic)

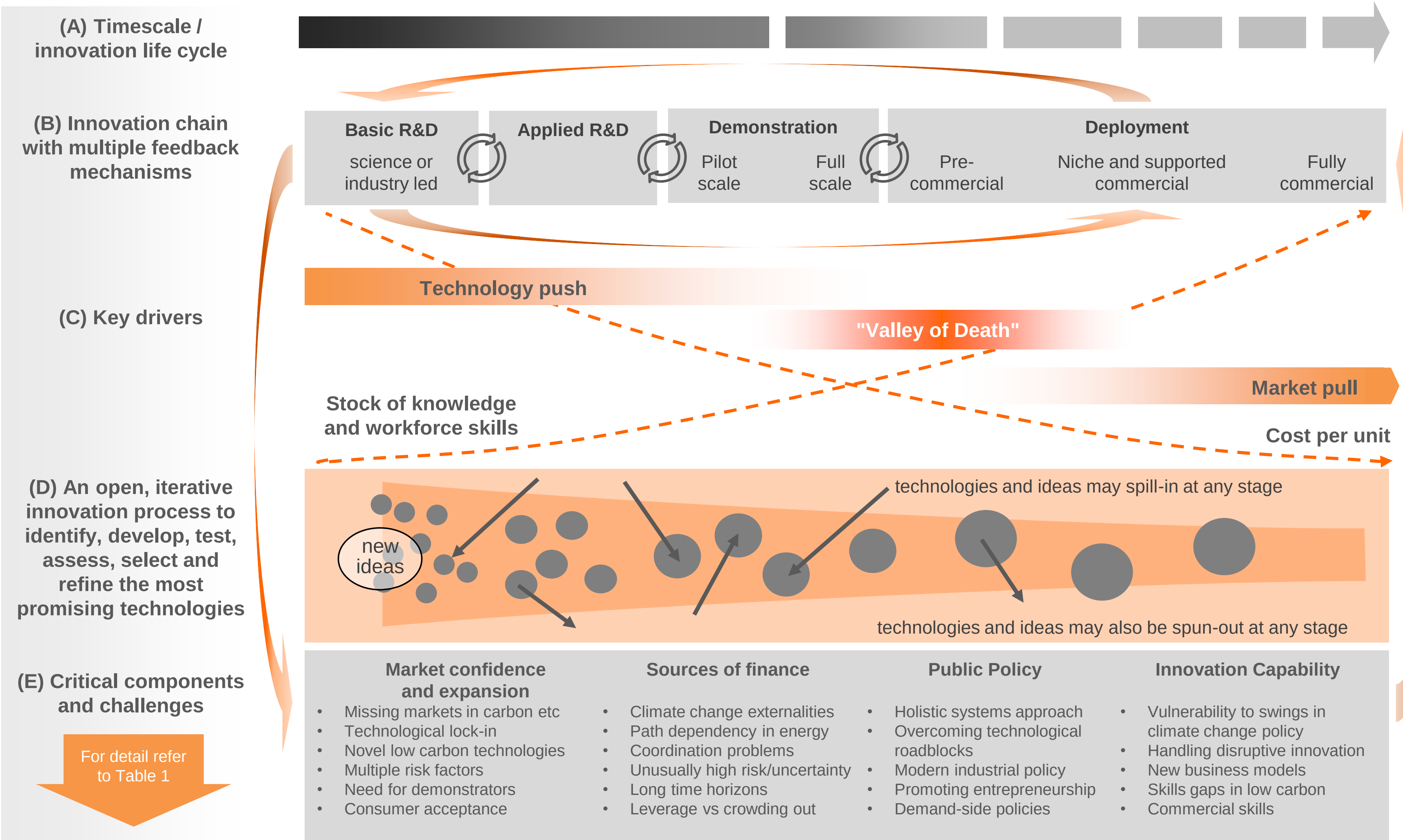


Table 1: Model UK energy/low carbon innovation system (underpinning conceptual framework)

Key element	Description
(A) Timescale / innovation life cycle	• It takes time for an innovation system, networks, relationships and expectations to form and mature and therefore for new technologies to be developed and deployed, especially more radical disruptive technologies. • Weak or immature innovation systems may delay the progress of an innovation, or decrease the likelihood of its success. • Risk of lock-in to sub-optimal technological pathways can lengthen timescales.
(B) Innovation chain with multiple feedback mechanisms: The "technology journey"	• While a new technology can be observed to pass through distinct stages in its evolution - from concept (basic research) to commercialisation (deployment) - the process of innovation is seldom linear. It will involve both forward and backward multi-disciplinary interactions across science, business/commerce and government to facilitate knowledge transfer and learning. Innovation may therefore occur at any stage in the process and need not involve all stages. • Innovation may result in competing technologies and networks. Each network will try to make the case and build political legitimacy for its particular technology. This in turn can create or increase entry barriers for alternative technologies.
(C) Key drivers	• Innovations may be idea-led and/or demand-led. The forces of technology push and market pull combine to provide continuous challenge to the innovation system to develop and demonstrate safe and cost-effective low carbon technologies (in terms of levelised cost per unit of energy produced and/or product unit cost). The strength of market-pull is critically dependent on the price of carbon and the stance of environmental policy. • Promising power generation and other low carbon technologies may fail to attract sufficient risk capital and other resources necessary to support full-scale demonstration and cost reduction to make it across a "valley of death" between applied research and commercial deployment due to significant market uncertainty. • Successful innovation must therefore involve collaboration and networking between different actors. Very few in isolation will have access to the knowledge, skills, finance and other resources required to develop and move a new technology from initial concept through to commercialisation. Coordination may however be difficult, nationally and internationally. • The stock of knowledge and workforce skills is increased through innovative activity and interactions. Knowledge can be fed back into the innovation process at any stage to stimulate further discovery and innovation.
(D) An open, iterative innovation process to identify, develop, test, assess, select and refine the most promising technologies	• Innovation involves 'trial and error'. Emerging technologies are continually assessed, refined or rejected and may be diffused at any stage. Failures nevertheless create useful knowledge able to stimulate further innovation. • Firms will import useful technologies as well as developing their own ideas throughout the innovation process, and will use different pathways to market, both internal and external, in an attempt to advance their technologies.
(E) Critical components and key challenges	• The development and deployment of new, low carbon technologies critically requires access to **markets** and **sources of finance**, a supportive **public policy** environment and widespread **innovation capabilities**. Socio-economic barriers can prevent these. • The probability of failure along the innovation chain and the cost of activities at different stages are fundamental risk factors for developing technologies. Low carbon technologies are also exposed to policy risks. • The innovation process must de-risk technologies over time to build investor, industry and user confidence. Equally, governments need to use their available policy levers at different stages in the innovation process to manage industry and public expectations and the transition to new low carbon technologies.

Key features of the model

2.4 The conceptual model contains the following key elements:

(A) The timescale over which an innovation system develops and different technologies emerge and mature;

(B) An illustrative innovation chain (the "technology journey") consisting of the key stages through which a technology will generally need to progress to reach full commercialisation;

(C) The combined forces of technology-push and market-pull that drive forward innovations to develop and demonstrate safe and cost-effective low carbon solutions;

(D) An open, collaborative and iterative innovation process in which firms exchange and refine ideas and pursue multiple pathways to advance their technologies;

(E) A sustainable innovation process with critical components involving routes to market, sources of finance, a supportive policy environment and widespread innovation capabilities within UK firms and the innovation system more generally (see Section 3).

What's different about innovation in energy and low carbon?

2.5 Many of the above features will need to be present for an innovation system to work effectively for any sector or technology. However, innovation in new energy and low carbon technologies is particularly challenging compared to other sectors because of specific characteristics of the market including the capital intensive nature of the energy sector, the longevity of its capital stock and its vulnerability to instability in the policy environment.

2.7 Lead times for the development and deployment of new energy technologies are especially long and there is considerable risk and uncertainty, more so than for other areas of innovation, making it hard to attract the required level of private finance.

2.8 The risk of lock-in to sub-optimal technologies is also especially high because the energy system is dependent on past investments in infrastructure, with long lifetimes, creating inertia and taking it difficult for alternative disruptive technologies to succeed.

2.9 The capital intensity of the energy sector combined with a highly concentrated supply-side means that incumbents have a vested interest in maintaining the status quo, to avoid the risk of their assets becoming stranded and being written down prematurely due to changes in policy and technologies. Instability in environmental policymaking adds materially to uncertainty in the sector as policies tend to vary with the electoral cycle and with changes in the national and world economy.

2.10 Above all other characteristics, however, the significant global externality of climate change makes it extremely challenging to create large-scale markets for low carbon technologies. Although domestic carbon markets have been spreading and linking around the world the burgeoning global carbon market is "characterized by dramatic changes in supply, demand, price, and public confidence" (Jones et al, 2013). So, while the UK has set very clear, comprehensive and challenging targets for long-term emission reductions consistent with international climate change goals, the current volatility in the global carbon price provides a poor basis for planning and making long-lived investments in new technologies.

2.11 In the absence of a credible carbon price, firms must be incentivised in other ways to take decisions that reflect environmental externalities. For example, Ofgem's regulatory framework for UK energy networks aims to encourage the investment in smarter and more innovative networks that will be required to reflect new patterns of demand and generation in a low carbon future. RIIO2 is an incentive-based framework that links the revenue network companies can earn from customers to performance in terms of delivering a sustainable energy sector and long-term value for money. The focus on delivering more sustainable energy changes the timescales that network companies need to consider. However, those able to demonstrate outputs, innovation and associated lower costs have the potential to earn above normal returns.

2.12 The need to deliver multiple outputs can increase complexity. Long-term planning in the UK energy sector may be further impeded by coordination failures due to the large number of decision-makers involved, each with different objectives and priorities. The political response to the challenge of meeting climate change targets has spawned multiple funding bodies, research centres and agencies spread across central, local and devolved government whose incentives and interests may not align. In turn, misalignment can occur with and between the many commercial organisations involved, whether developers, financiers or users of new, low carbon technologies in different sectors of the UK economy.

2.13 Successful innovation in new energy and low carbon technologies therefore requires the creation of new markets, the development of viable businesses and an appropriate regulatory framework. The following section describes in more detail the role that can be played by:

- measures to support commercialisation and the expansion of the market;
- access to finance and the removal of other market barriers; supportive policy and regulation; and development of relevant innovation capabilities including skills and new business models.

3. Innovation Journeys

Charting the critical components and challenges of the UK energy / low carbon innovation system

3.1 Many low carbon technologies will have to travel a long, expensive and risky innovation journey to get from initial idea to market. The conceptual model provides a framework that can be adapted for different technologies and the innovation pathways or "journeys" they may follow. These journeys can be viewed from the perspective of the innovator, investor, policy maker or end user and the framework can be used to identify the different barriers or issues those stakeholders will face and the interactions that must take place at the different stages of the innovation chain.

3.2 In addition to the technology journey illustrated in Figure 1, the Carbon Trust (2009) developed further journeys illustrating how companies, markets and regulatory frameworks evolve over time in line with the progress along the innovation chain (see Annex B). We have adapted and expanded on the Carbon Trust approach for the components we have identified as critical to an effective innovation system in energy and low carbon technologies, namely: market confidence and expansion, sources of finance, a supportive public policy environment and widespread innovation capabilities within UK firms and institutions.

3.3 Our four stylised journeys are as follows:

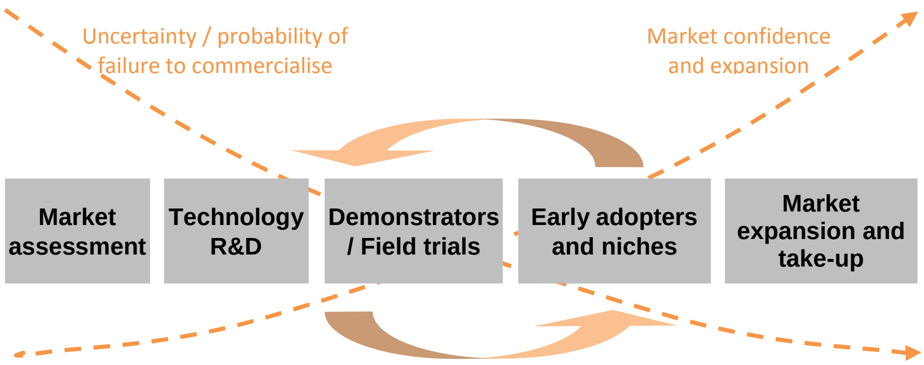
- The market journey charts the key stages involved in opening and expanding of markets for new low carbon technologies. It starts with an assessment of market needs to identify gaps in current provision that could be met through the development, de-risking and demonstration of new, cost-effective technologies.

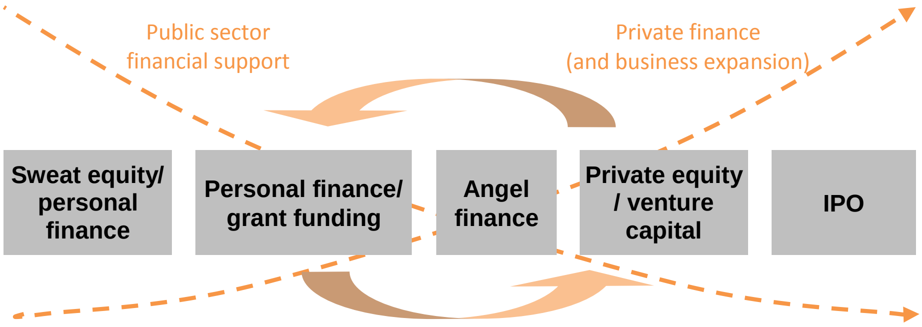
- The finance journey illustrates the different types and sources of finance that may be required as a company attempts to expand its scale and resources in order to support the development and deployment of its technology. Public finance may be especially important during the early stages of the journey, with private sources playing a greater role as investor confidence in technologies and their market potential grows.

- The policy journey evolves with the technology journey requiring the use of a mix of policy instruments to support technological advance and to enhance market signals, as well as policies to promote consumer and public acceptance.

- The capability journey reflects the need for new skills and business models to be deployed within organisations over time as they seek to finance, develop, sell and/or utilise new technologies.

3.4 Although highly simplified, each journey provides a potentially useful checklist and framework for analysis for the incentives, interactions and barriers at each stage of the innovation life cycle of a new energy or low carbon technology. Each journey views the innovation process through a different lens but the journeys are not mutually exclusive. All will apply to a greater or lesser extent to every technology. Many of the key stakeholders involved are common to all four journeys. Similarly, many of the key challenges are overlapping and reinforcing across the journeys. Charting more than one journey through the innovation system can therefore generate key insights into the characteristics of the system as a whole and its effectiveness.

Critical component	Market confidence and expansion
Innovation chain "Market journey"	
Key stakeholders	• Public sector funders (see Sources of Finance), who have a key role in providing finance in early stages when uncertainty is high, and returns less appropriable. • Potential private sector investors (see Sources of Finance) who have a key role in investment appraisal and whose engagement is crucial to securing sustainable expansion. • Policymakers (see Public Policy) and regulators whose decisions can shape the development of the market or in some cases create a new market and can themselves be a source of instability. • Incumbents who have a vested interest in resisting new technology, particularly disruptive technology. • Manufacturers, energy companies and service providers who need to provide facilities, establish supply chains and become engaged in the commercialisation process. • Final consumers and other users, whose needs must be understood and met and whose acceptance of new products and technology is a prerequisite for successful commercialisation. • Opinion formers (politicians, scientists, media and others) who can provide thought leadership and influence public attitudes towards the acceptance and adoption of new technology.
Key challenges	*"Overall, the maturity or deployment of a given technology appears to be the dominant intrinsic factors that define the overall risk perception for that technology. Furthermore, all low-carbon technologies are exposed to policy risk, to such an extent that several survey participants responded to the effect that they were unable to rank risk factors due to the uncertainty surrounding future energy policy".* (OXERA, 2011) • **Missing markets** for new low carbon technologies and uncertainty over the future price of carbon. • **Technological lock-in** the challenge of breaking away from existing energy models and building critical mass for disruptive technologies, while avoiding lock-in to sub-optimal pathways. • **Novel low carbon technologies** without a track record need successful pilot testing at scale. • **Multiple risk factors** include price levels and volatility (wholesale electricity; carbon); energy demand; government policy; value of subsidies; public acceptance/perceptions; capex and opex; construction lead times; availability of technical skills; maturity of technologies; etc. • **Need for demonstrators** bridging the valley of death before market/investor confidence established. • Need to win **public and consumer acceptance** of novel low carbon technologies.

<table>
<tr><th>Critical component</th><th colspan="2">Sources of finance</th></tr>
<tr><td>Innovation chain "finance journey"</td><td colspan="2">

Financial /company journeys may differ, often depending on the type of technology. The journey shown is stylised to illustrate potential sources of finance available.</td></tr>
<tr><td>Key stakeholders</td><td>Public sector sources:
• Research Councils
• Innovate UK & Catapults
• Carbon Trust
• DECC and other Central and Local Government Direct Support
• Office for Renewable Energy Development (ORED)
• Tax credits (R&D, Patent Box)
• Ofgem (Network Innovation Allowance and Competition)
• Green Investment Bank
• Public procurement programmes
• EC Framework Research & Technology
• EU-Emissions Trading Scheme</td><td>Private sector sources/representatives:
• Energy and Clean-Tech Venture Capital organisations (e.g. Low Carbon Accelerator, Oxford Capital Partners, Environmental Tech Fund, Good Energies)
• UK Business Angel Association
• British Private Equity and Venture Capital Association (BVCA)
• Major Corporates (as R&D investors)
• Major Corporates (as tech users)
• Low Carbon Innovation Fund
• 'Brokers', for example, Green Industry Business Network, Greenbackers</td></tr>
<tr><td>Key challenges</td><td colspan="2">"The iterative evolutionary process from research to economic impacts and the open innovation funnel will typically involve multiple investments beyond the original public and private sector research investments. The transition from early stage activities funded by the public sector to final commercialisation will, in particular, require private sector investments which are usually many multiples of the original science base investment". (Crafts and Hughes, 2013)
• Climate change externalities: make it more difficult for firms to fully appropriate the returns from their investments, which typically results in under-investment in innovation.
• Path dependency in energy systems and long lead times of many energy /low carbon technologies create significant uncertainty: investors cannot quantify the likelihood of successful investment. Coordination problems and network failures are also pervasive.
• Unusually high risk and uncertainty: financial risk in part reflects lack of experience and lack of understanding of specific risk return characteristics of low carbon investments. Funding also particularly challenging for technologies transitioning from R&D across to deployment – referred to as 'the valley of death'.
• Long-time horizons: risks at early development stages are exacerbated for renewable energy technologies due to their long timeframes to deployment and requirements for CAPEX intensive investment - especially challenging for VC funds.
• Leverage vs crowding out: does public funding crowd in or crowd out private investment? How best to structure public funding to leverage the (i) the ability of VC firms to successfully screen, develop and commercialise companies; and (ii) the ability of corporates to invest to longer timeframes based on strategic motives, using their significant internal resources and engineering ability?</td></tr>
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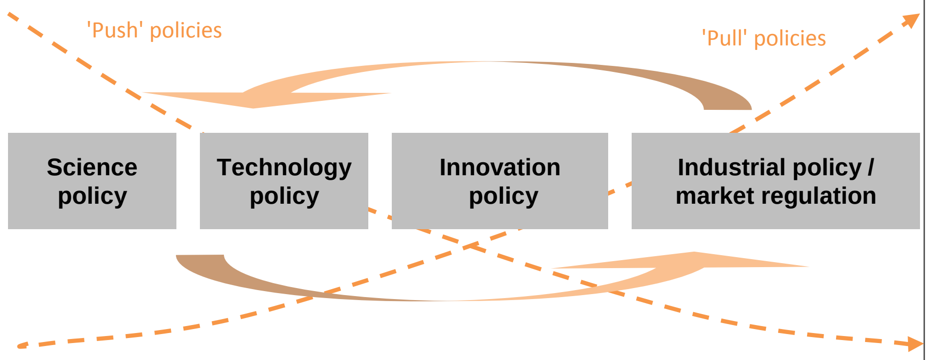
Critical component	Public policy

Innovation chain "policy journey"



Key stakeholders

- Department of Energy and Climate Change (+ DEFRA, DCLG)
- Department for Business Innovation and Skills
- GO-Science and Research Councils
- Council for Science and Technology
- Ofgem
- Local and Devolved Administrations
- European Union

Key challenges

"Just as no single technology can be considered entirely in isolation, no single support mechanism or programme could provide the range of support needed to deliver the diversity and scale of technology innovation required across the system. Government support needs to follow the same systems approach and should be provided in a range of ways by a range of bodies." (LCICG, 2014)

Science Policy
Focus: Production of scientific knowledge
Instruments:
- Public research funds granted in competition
- (Semi-) public research institutions (eg laboratories, universities, research centres...)
- Tax incentives to firms
- Higher education
- Intellectual property rights

Technology policy
Focus: Advancement and commercialisation of sectoral technical knowledge
Instruments:
- Public procurement
- Public aid to strategic sectors
- Bridging institutions (between research world and industry)
- Labour force training and improvement of technical skills
- Standardisation
- Technology road-mapping
- Benchmarking industrial sectors

Innovation Policy
Focus: Overall innovative performance of the economy
Instruments:
- Improving industrial skills and learning abilities (through general education system and labour training)
- Improving organisational performance and learning (e.g. ISO 9000 standards, quality control, etc.)
- Improving access to information: Information Society
- Environmental regulation
- Bioethical regulation
- Corporate law
- Competition regulations
- Consumer protection
- Improving social capital for regional development: clusters and industrial districts
- Intellectual benchmarking
- Intelligent, reflexive and democratic forecasting

Source : Based on Lundvall & Borrás (2005)

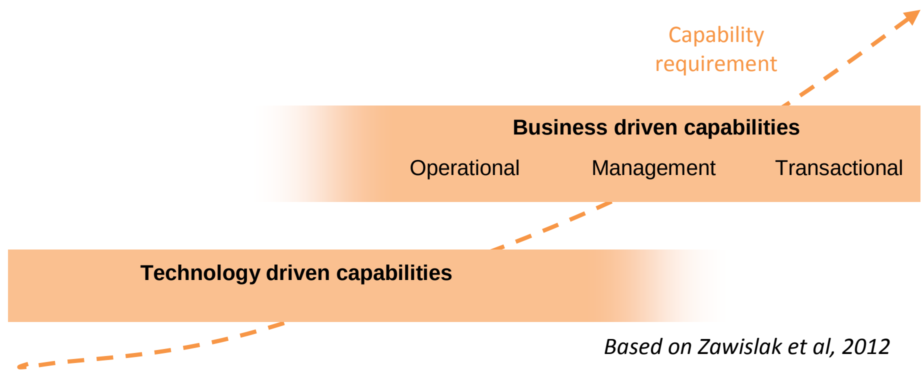
Key challenges (continued)

- **Holistic systems approach:** there are inherent policy conflicts in addressing the energy trilemma: security, affordability and low carbon. Overriding importance of stable environmental policy framework and an integrated, holistic approach - investors require stable, long-term policy frameworks and markets.
- **Overcoming technological roadblocks:** governments need to use their available policy levers to overcome technological lock-in, build innovation capability and facilitate the transition to new low carbon technologies.
- **Modern industrial policy** requires strategic collaboration between the private sector and Government (Rodrik, 2006). Industry and Government should work together to set strategic priorities, deal with coordination problems, allow for experimentation, avoid capture by vested interests and improve innovation performance.
- **Promoting entrepreneurship:** SMEs in the green economy need help to link to knowledge networks, access finance, develop skills and overcome regulatory barriers.
- **Demand-side policies:** including the use of market-based instruments, standards and public procurement, as well as policies to promote consumer and public acceptance.

Possible policies to foster green innovation

Policy challenge	Policy options
Insufficient demand for green innovation	Taxes and market-based instruments to price externalities and enhance incentives Demand side policies, such as procurement, standards and regulations, in specific markets and circumstances
Lack of innovation capability	Broad based policies to strengthen innovation
Technological roadblocks and lack of radical innovation	Investment in relevant R&D, including thematic and mission-oriented research International cooperation
Research and investment biases to incumbent technology	R&D support, tax incentives Adoption incentives/subsidies Technology prizes
Lack of finance	Co-investment funds Market development
Regulatory barriers to new firms	Regulatory reform Competition policy Front-runner approaches
Lack of capabilities in SMEs to adopt green innovation	Access to finance Skills development Liking SMEs to knowledge networks Improving information supply Reducing regulatory burdens
Non-technological innovation	City and transport planning Regulatory reform

Source: Based on “Fostering Innovation for Green Growth: Policy Considerations”, OECD (2011)

Critical component	Innovation capability
Innovation chain "capability journey"	
Key stakeholders	• Department for Business Innovation and Skills • Department of Energy and Climate Change (incl. ORED) • Office for Nuclear Development • Devolved Administrations • Confederation of British Industry • Energy and Utility Skills Group • Sector Skills Councils and Bodies / Fed. of Industry Sector Skills and Standards
Key challenges	*"Achieving innovation requires the coordinated efforts of many different actors and the integration of activities across specialist functions, knowledge domains and contexts of application. Thus, organizational creation is fundamental to the process of innovation."* (Van de Ven et al 1999) *"The ability of an organization to innovate is a pre-condition for the successful utilization of inventive resources and new technologies."* (Lam, 2010) • **Vulnerability to policy swings:** environmental markets are almost entirely driven by public policy which, in turn, will affect the willingness to invest in low carbon skills in the UK. • **Handling disruptive innovation:** many large corporations fail to develop disruptive innovations... basic constraints to creating successful disruptive innovation stem in large part from several inhibiting factors: the inability to unlearn obsolete mental models, a successful dominant design or business concept, a risk averse corporate climate, innovation process mismanagement, lack of adequate follow through competencies and the inability to develop mandatory internal or external infrastructure. (Assink, 2006) • **New business models:** many innovative firms lack the business models that enable them to capture value.As a result, they have lower growth and profits and therefore lower returns, reducing the incentives to invest in the UK innovation system despite its ability to create value. (Coad et al, 2014) • **Skills gap?** Some take the view that the UK does not have the necessary skills to make the transition to a low-carbon economy at the pace required to meet mandatory targets - or the training arrangements in place to fill the gap. (Aldersgate Group, 2009) Developing the skills... necessary for the transition to the low carbon economy have wider environmental, economic and technological benefits which are not captured by employers or employees participating in the training... This can result in widespread underinvestment in the generic skills required to make the transition. (BIS, 2009) • **Commercialisation skills:** overall, the UK energy sector is better at accessing and building innovation than commercialising it. (NESTA, 2009)

4. Using the Conceptual Model

Developing a strategic narrative and case studies

4.1 While the diagram at Figure 1 cannot fully represent the complexity of the underlying conceptual model, it is intended to provide ETI with a stakeholder engagement tool which can be used:

- to identify and build stakeholder networks around individual technologies or programmes to facilitate interaction, joint learning and the exchange and exploitation of accumulated knowledge; and
- to develop a "strategic narrative" to help those involved to better define and understand their role in the low carbon innovation system and the transition to a low carbon economy.

4.2 The model can be used as an evaluation tool, for example as a framework to develop accessible and compelling innovation case studies or "stories", aimed at promoting further interactions amongst stakeholders or inspiring innovation in related areas; or it can be used in appraisal mode, as a tool aimed at identifying and addressing specific innovation challenges. However it is used, there are likely to be significant differences according to the scale and complexity of the chosen technologies, the time required to progress them through each phase in their development and the number of different stakeholders, skills and capabilities required at each stage.

4.3 The model has been tested and promoted through interviews, a workshop and a UKERC-hosted webinar involving a number stakeholders drawn from industry, the research base and government. While the interviews focused on the structure and validity of the model, its coverage of relevant innovation literature and its potential value as an engagement tool within the sector, the primary aim of the workshop was to test its application on a number of low carbon technologies. The webinar also provided the opportunity to share the findings with a wider group of experts. Feedback from these activities helped to refine the initial model and journeys, prioritise key challenges and develop a number of specific case studies. The case studies summarised at pages 17-19 below are

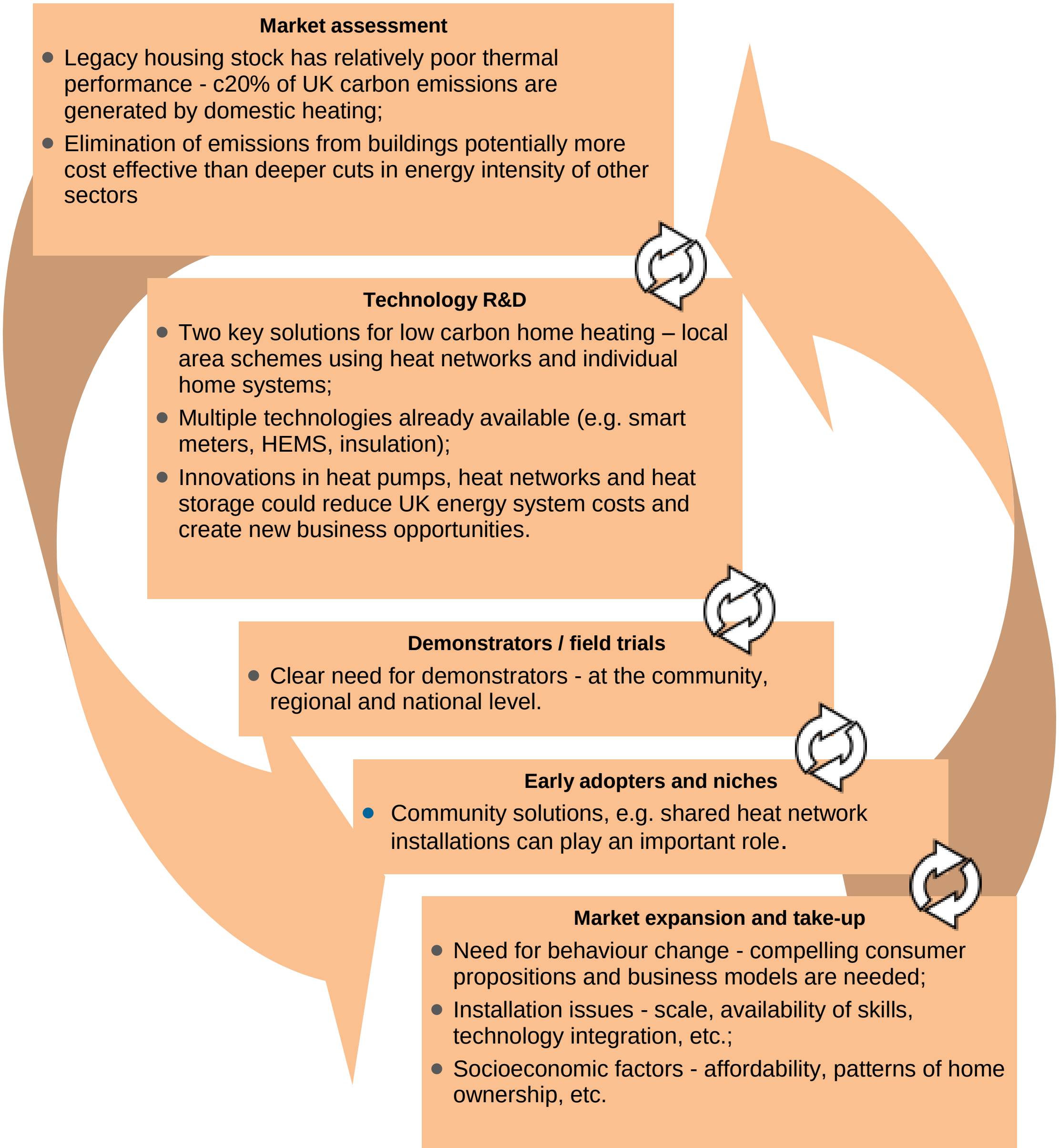
(1) Carbon capture and storage (CCS);

(2) Hydrogen fuel cell micro CHP (combined heat and power) boilers;

(3) Low carbon heat.

4.4 Each of the case studies captures and presents key elements of the various innovation journeys set out in this paper (see Section 3). For example, the challenges of the market journey provided the initial focus in the workshop discussion on low carbon domestic heating (see Figure 2 below) before connections to other critical components and challenges were assessed. The capability journey is also of crucial importance for the development of low carbon heat. In contrast, the policy journey was thought to be the most critical to the development, demonstration and deployment of large scale CCS in the UK and provided the primary stimulus and perspective for the case study application.

Figure 2: Stylised "market journey" for low carbon heat (Case Study 3)



4.5 Despite the limitations of time and scope, the conceptual model has proved to be a suitable framework to act as a catalyst discussion at the workshop and to help develop preliminary case studies in three quite different areas. It could be applied to other technologies or used more intensively to develop a more detailed innovation strategy for the technologies in the three case studies. In each case the different components and journey stages can provide a useful checklist to identify and prioritise issues that will need to be addressed to support the innovation process and the development and deployment of the most promising new energy and low carbon technologies.

Case study 1: carbon capture and storage (CCS)

CCS offers the potential for near-zero greenhouse gas emissions from continued fossil fuel combustion. However, the UK innovation system for CCS is relatively immature. Investment costs are high and market appetite is low.

Timescale: Energy system modelling suggests that electricity generation with CCS could deliver c.10-35% of total generation by 2050. However, considerable work remains to demonstrate CCS at large scale and across the entire chain (capture-transport-sequester-secure). Deployment prior to 2020 is, therefore, considered unlikely.

Basic and Applied R&D

Proven technology in oil and gas sector but not at scale in power generation

Demonstration

Mapping of UK CO2 storage capacity and demonstration of key components at commercial scale

UK publicly funded full-scale 'source-to-sink' demonstrators are now underway

Deployment

Significant market and public concerns over infrastructure and generation costs and safety. Assurance of long-term CO2 storage with a high degree of certainty is still unproven.

Key drivers: 'challenge led' technology… …but market pull is currently weak

CCS relate industry could contribute £3-16bn to UK GDP up to 2050 (LCICG, 2012)

Innovation has the potential to drive down the costs (ignoring fuel) of conversion with capture by 15% by 2025 and 40% by 2050 (LCICG, 2012)

Innovation funnel:
There are a number of competing technologies – pre-, post- and/or oxy-fuel combustion and inherent separation.
The UK also has specific R&D needs in transport, deep-sea storage and risk mitigation and remediation (M&R) technologies.

Key challenges:

Market confidence and expansion

- CCS requires a clear carbon price to be viable;
- Companies lack confidence in ability to generate or capture investment returns due to significant uncertainty, long lead times and spillover risks.

Sources of finance

- Uncertainty regarding infrastructure availability and cost;
- Long-term storage liabilities are difficult to insure against.

Public Policy

- Public policy needed to address uncertainty of demand, infrastructure needs, difficult to insure liabilities, uncertain regulatory regime;
- Rules regarding storage site approval are also unclear.

Innovation Capability

- Many CCS component technologies are generic – other countries are driving innovation;
- Innovation in following areas offers highest potential benefit to UK: storage; measuring, monitoring & verification; and M&R esp.offshore (LCICG, 2012)

Case study 2: hydrogen fuel cell – micro-CHP

Micro-CHP (combined heat and power) technology generates heat and electricity simultaneously, from the same energy source, in individual homes or buildings. Electricity generated within the building is not subject to the substantial transmission loss which accompanies centralised mains generation. Micro-CHP therefore offers potentially significant benefits to consumers and to society in terms of reduced CO2 emissions, reduced primary energy consumption and the avoidance of central plant and network construction.

Timescale: Micro-CHP is already near to market but key issue is what type of network the UK wants/needs in 10-30 years from now?

Basic and Applied R&D

Fuel cell CHP technology still at developmental stage

Demonstration

Pilot scale demonstration required – local community solutions, business parks, etc.

Deployment

Hydrogen in gas system can supply up to 15% of energy supply without need to change grid infrastructure – but higher content in mix will require new gas pipework, burners and turbines.

Key drivers: fuel cells are a proven technology already used for primary and back-up power in many applications…

…micro-CHP has become more cost effective due to rising energy costs but cannot sell at volume at present

New business models are required to build scale and consumer/market confidence and…

…to reduce installation costs for domestic consumers, e.g. through 'power by the hour' type contracts.

Innovation funnel:
Different types of fuel cell at different stages of development and deployment but no one type is cheap or efficient enough at present to widely replace traditional ways of generating power.

Key challenges:

Market confidence and expansion

- Barriers to take-up of microgeneration include high front end costs and the level of consumer awareness;
- Take-up could be accelerated through changes to building regulations/requirements

Sources of finance

- Commercialisation is dependent on achieving production and whole life costs close to those of existing gas boilers;
- Key issue is how to manage the costs of transition to a new network.

Public Policy

- Domestic microgeneration at scale requires a decentralised approach to energy planning and policy;
- New standards likely to be required for connections to distribution network.

Innovation Capability

- Few experienced installers at present in UK;
- Also an increased need for experts in microgeneration to advise consumers, communities and local planners.

Case study 3: low carbon heat

Heat accounts for over 40% of the UK's demand for energy, with domestic heating accounting for almost 20% of the UK's CO2 emissions. Near total elimination of carbon emissions from existing homes required by 2050 to meet UK emissions targets. Challenge of displacing gas boiler heating – will be bottom up not top down like conversion from coal to natural gas and so will take longer.

Timescale: By 2050 around 26 million homes will require new low carbon installations. ETI envisage a preparedness and confidence building phase to early 2020s followed by 25-year demonstration and upgrading programme.

Basic and Applied R&D

Most of the required technologies (for example heat pumps, smart meters, HEMS, insulation) already available.

Demonstration

Need to incentivise early adopters and develop demonstrators to show potential – at community, regional and national levels.

Deployment

Need to develop mass market deployment – customer proposition issue. Community solutions can play an important role.

Key drivers: challenge led – dominance of gas boilers will decline as new networks and heat pumps are introduced… …real challenges are not so much technology based, more about gaining public consensus and trust

Systems approach – integrate existing technologies, decarbonise energy supply and improve efficiency in domestic heating.

Development of consumer products and system design tools to support the transition.

Innovation funnel:
Innovation needed is incremental – will involve integration of existing technologies, new business models, new consumer products and behaviour change.

Key challenges:

Market confidence and expansion

- Challenge is to build social and political momentum necessary for new local energy production and distribution – shared heat network installations;
- Behaviour change and consumer acceptance will be required;
- In less densely populated areas, solutions more focussed on heating and efficiency solutions for individual properties – how to incentivise this?

Sources of finance

- Substantial financial implications for national infrastructure, local authorities and individual home owners;
- Novel sources of finance – community sources, peer-to-peer, etc.

Public Policy

- Local planning procedures need to be adapted to incorporate a strategic approach to local asset infrastructure requirements;
- Strong leadership needed from national government;
- Also need effective community decision making and governance;
- Socio-economic factors important – inequalities, patterns of home ownership.

Innovation Capability

- New innovative business models, e.g. buying level of comfort, selling back to grid, maybe required;
- Significant capability requirements – substantial extension of the existing workforce and development of new skills, e.g. in integration.

Annex A: Generic Innovation Models

Linear models of innovation: 'technology push' and 'market pull'

A.1 Innovation can be defined as all the scientific, technological, organizational, financial, and commercial activities necessary to create, implement, and market new or improved products or processes (OECD, 1997). In this annex we identify, review and summarise different theories or models of innovation from the research literature according to their broad type (for example, linear or non-linear) and common components.

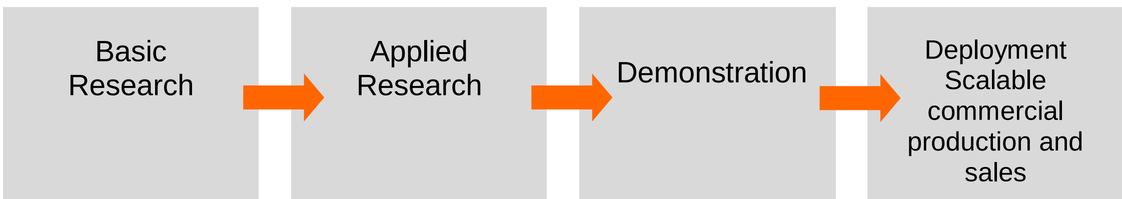
A.2 The field of innovation studies is relatively recent and in part traceable back to the economist Schumpeter (1942) who identified innovation as the critical dimension of economic change. He argued that economic change involved continuous innovation and "creative destruction" through the creation of temporary monopolies. Technological innovation, he argued, gave firms market power providing them with a profit incentive necessary to develop new products and processes. It was, therefore, a root cause of both cyclical instability and economic growth, with the direction of causality moving from fluctuations in innovation to fluctuations in investment and from these to cycles in economic activity and growth.

A.3 Following this during the 1950s and 1960s the concept of a ' **linear model**' of innovation leading from science and invention to wealth production was widely applied: the so called **'technology push' model of innovation**. In this model, innovation is seen as being 'pushed' through a pipeline of sequential phases from basic R&D to the commercial application phase in a unidirectional manner. Advances in scientific understanding therefore determine the rate and direction of innovation.

A.4 These simple, linear 'technology push' models vary in the number and shape of steps or phases in the innovation process but in general the key steps are:

- the idea or invention of a new (product or process) technology, for example, from basic and applied research
- the development and demonstration of the new technology
- the deployment, diffusion and/or commercialisation of the new technology

Figure A1: Simple linear, unidirectional 'push' model of innovation



A.5 The technology push model further suggests that innovation originates from individual entrepreneurs or firms that are prepared to take financial risks with radically new product and/or process innovations. It therefore has two important implications which have proved influential in public policy:

- there will be underinvestment in the development of new technologies unless individual entrepreneurs or firms can protect their inventions (and therefore the profits from their inventions) from being imitated or copied;
- there is a need for Government to support investments in the development of new technologies, through the protection of intellectual property and/or with financial assistance, either direct RD&D funding for emerging technologies or indirect support for inventive firms through tax credits.

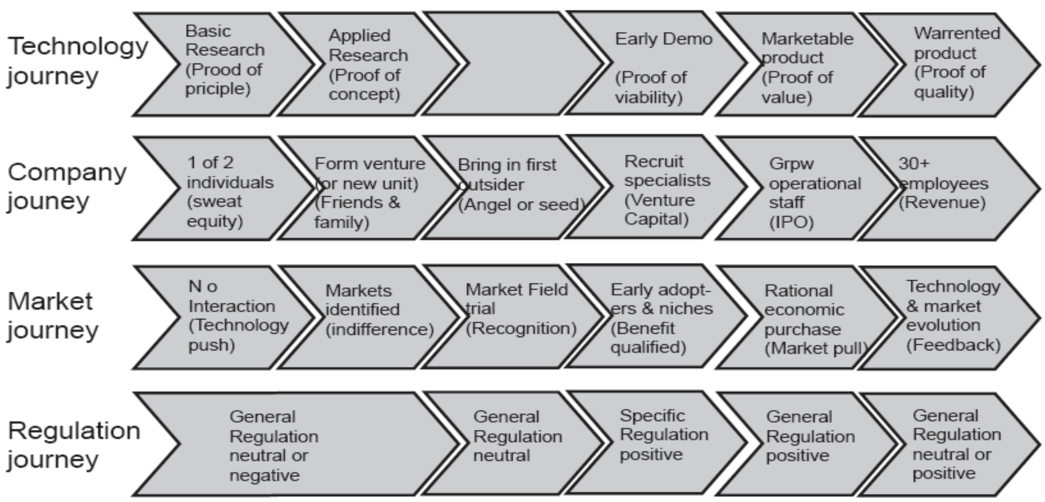
A.6 Collins (2006) describes an "**innovation funnel**" in which an organisation 'pours' a host of ideas at the top and from which, following further research, development and demonstration, a filtered set of the most useful innovations emerges at the bottom.

A.7 During the 1960s, academic studies increasingly argued that demand was the more significant driver of the rate and direction of innovation than technology. Although the model they described remained linear, the needs of the consumer or end user drives the requirements of the technology. Changes in market conditions therefore create the necessary stimulus for firms to "pull" knowledge out of scientific research to satisfy new and unmet needs: the so called **'market pull' model of innovation**. In this way, Rosenberg (1969) suggests that consumer demand signals which technical problems firms should focus their RD&D effort on.

A.8 From a public policy perspective, the model implies that demand-pull policies can help to reduce the financial uncertainty of R&D investments via the creation of markets. These policies may include new regulations including standard setting, taxes on competing technologies, public procurements, tax credits and rebates for consumers who adopt the new technologies and, in the case of new energy technologies, through tradable permits and feed-in tariffs.

A.9 The Carbon Trust (2009) usefully extends the linear framework to identify barriers that different organisations must overcome and the transformations they must undergo, whether inventor, investor, user or regulator, to move a low carbon technology from concept through to commercialisation. It explains these in terms of four related "journeys" - technology, company, market and regulatory.

Figure A2: The "four journeys" of innovation



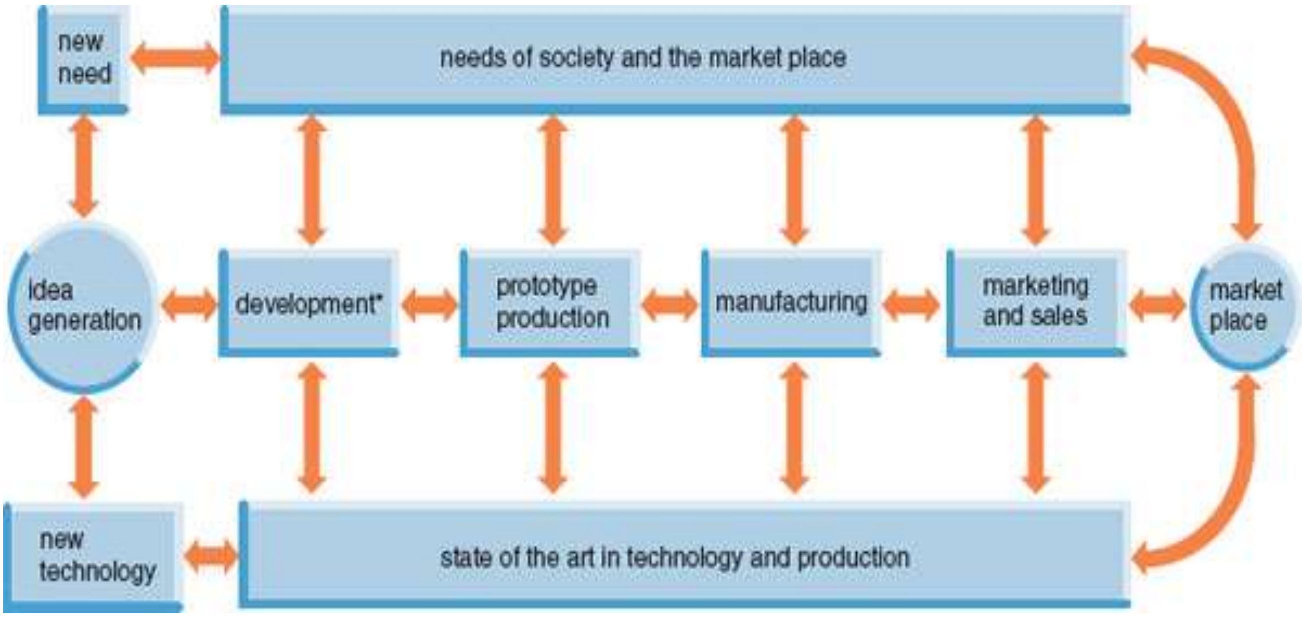
Source: Carbon Trust (2009)

Non-linear, interactive models: coupling and chain linked models

A.10 A key weakness of push and pull linear models is their failure to conceptualise the relationships between successive stages of innovation. They also focus solely on the relationship between **new** knowledge creation and innovation.

A.11 Mowery and Rosenberg (1979) sought to combine push and pull mechanisms into a single model of innovation by stressing the importance of **coupling** between science, technology and the marketplace via technological development, production, marketing and sales as depicted in Figure A3 below. It shows, for example, how an initial product offering may have been pushed to market following the linear 'push' model but following this the preferences of the end user assumes greater importance for subsequent incremental innovation.

Figure A3: Non-linear, coupling model of innovation



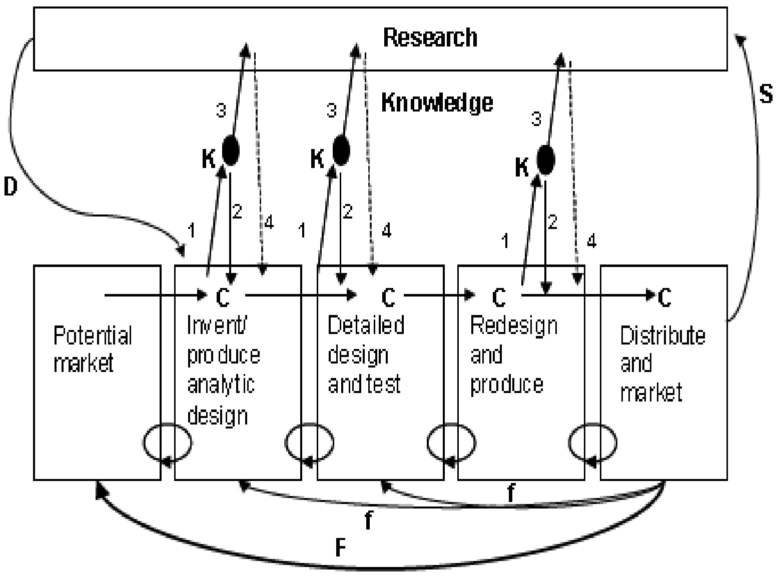
Source: Rothwell (1994)

A.12 An important development in the coupling and similar models of innovation was recognition that the creation of new knowledge and ideas often depends critically upon the **stock of existing knowledge** and/or the creation of complementary knowledge.

A.13 Kline and Rosenberg (1986), for example, developed the concept of an integrated **chain-linked model** with in-built continuous feedback and improvement (see figure A4). Scientific knowledge, old or new, could feed into any stage of the process resulting in innovation outputs which in turn could further new scientific developments.

A.14 Similarly, Beije (1998) stresses that innovation is no longer the end product of a final stage in an innovation process but can occur at any stage throughout. That is, the innovation process can be circular / iterative rather than sequential.

Figure A4: Non-linear, chain linked model of innovation



C = central chain of innovation

f = feedback loops (F- most important)

K-R = knowledge to / from research

D = direct link to/ from research in invention and design

I = support if scientific research by instruments, machines, tools and technical procedures

S = support of research in sciences underlying product area to gain information and by monitoring external work

Source: Adapted from Kline and Rosenberg (1986)

Non-linear system models: networked and open innovation models

A.15 Non-linear interactive models incorporating continuous feedback and use of the existing stock of knowledge underpinned the emergence of systems thinking in innovation studies. If the stock of existing knowledge is an important input to the innovation process then it follows that successful innovation will depend on:

- the extent to which relevant knowledge is available and transferable, including from external sources;
- the ability of individuals or organisations to use and learn from existing knowledge and from each other.

A.16 In contrast to neoclassical economics, evolutionary economics argues individual actors do not have perfect rationality or access to all relevant information. In modern models therefore, successful innovation must involve collaboration and networking between individuals and organisations, including suppliers and customers, to facilitate **knowledge transfer and learning**. This will be especially important for firms that lack the resources - human, technical and financial - to develop innovations in-house.

A.17 The term **open innovation** is often used to describe such models, in which different organisational cultures and strategies can now have an impact, both positive and negative, on the innovation process. According to Chesbrough (2003)

"Open innovation is a paradigm that assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market, as the firms look to advance their technology".

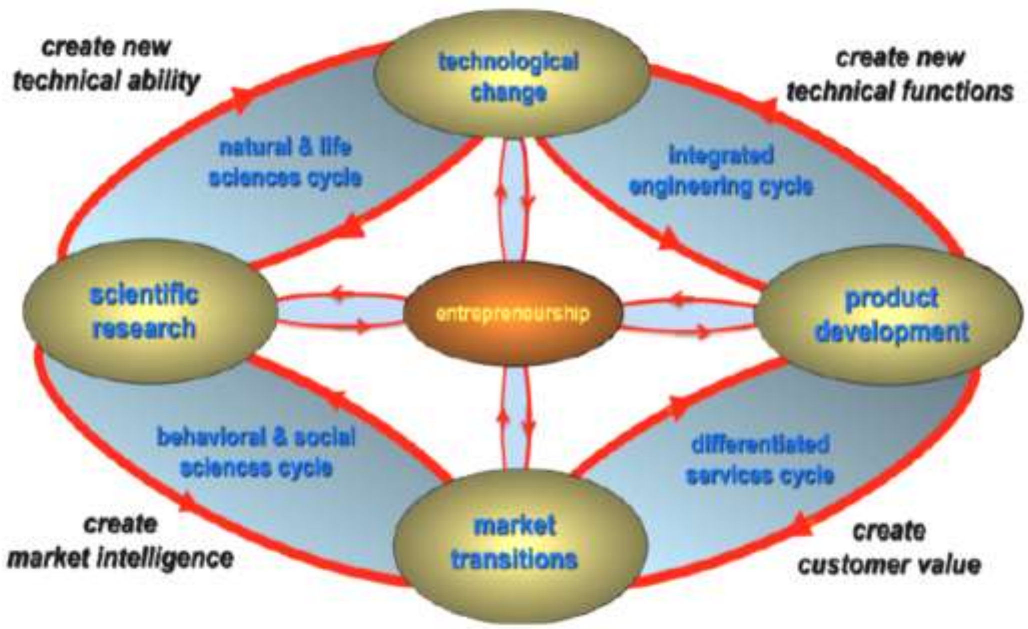
A.18 Collins (2006) describes the innovation funnel in an open innovation model as porous. Useful technologies can both flow in and out of an organisation at any stage either through collaborations or from being sold off, spun out or licensed to others. In addition, product innovations can also provide the catalyst for advanced service innovations.

Systems models of innovation: spatial, sectoral and technological

A.19 A number of more recent papers argue that the innovation process is best viewed as a system rather than a pipeline (for example, Berkhout, 2000). Complex interactions between new technological capabilities and emerging markets are a vital part of any innovation process, but are underemphasised in earlier models which also failed to capture the role of the entrepreneur.

A.20 In Berkhout's **cyclic innovation model**, the forces of push and pull continually challenge each other creating an innovation-driven society characterised by coupled cycles with each cycle representing a network of forward and backward interaction processes across science and industry.

Figure A5: Cyclic 'multi-channel' innovation model



Source: Berkhout (2000)

A.21 In Berkhout's innovation system, small incremental innovations can occur that do not involve all the stages in the innovation process. Instead, multichannel pathways link together changes in scientific insights, technological capabilities, products, production processes and market demand. In each pathway, one field of knowledge can contribute to many application sectors (a "one to many distribution process") or multiple fields can contribute to one application (a "many to one collection process").

A.22 ‘Innovation system’ is the term used to describe emerging scientific and technological structures and processes that influence economic development. The most well-known systems model is the so called **national systems of innovation**. Among frequently cited examples are Freeman (1987), Lundvall (1992), Nelson (1993) and Patel and Pavitt (1994). These stress the importance of flows of technology and information between firms, universities, other education and training institutions, and governments to the innovation process. Together they form a subsystem of the national economy where innovation and technology development are the result of their complex, multi-disciplinary interactions.

A.23 For policy-makers, an understanding of the national innovation system can therefore help to identify leverage points for enhancing innovative performance and overall competitiveness. However, Berkhout (2000) and others, caution governments against designing detailed roadmaps for boosting of innovation given the immense complexity of modern innovation. Instead, policies which seek to improve networking among the various actors and institutions in the system and which aim at enhancing intangible investments in workforce skills and the innovative capacity of firms, particularly their ability to identify and absorb technologies, will be most valuable.

A.24 The systems approach has also been applied to different

- spatial levels (**regional or local systems of innovation** including **industrial clusters**). For example, according to Longhi and Keeble (2000) the "*innovation process is not ‘spaceless’. On the contrary, innovation seems to be an intrinsically territorial, localised phenomenon, which is highly dependent on resources which are location specific, linked to specific places and impossible to reproduce elsewhere*".
- industrial sectors (**sectoral systems of innovation**). These include innovation chains linking major firms with their suppliers and distributors and innovation complexes or strategic networks that link together other organisations for the purpose of sharing risks (e.g. with publicly funded research institutions) and rewards (through joint ventures or other risk and profit sharing arrangements with private sector organisations). According to Fagerberg (2003) these sectoral systems of innovation represent a significant advance in understanding the often large and persistent differences across industries and sectors in the ways that innovation and knowledge diffusion takes place.
- technologies (**technological innovation systems**, TIS). A TIS can be defined as "*a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology*" (Carlsson and Stankiewicz, 1991). A recurrent theme within TIS models is the idea that there is cumulative causation between different systems **functions** – market formation, entrepreneurial experimentation, influence on the direction of search, resource mobilisation, knowledge development and legitimation.

  TIS models therefore focus on internal system dynamics and especially the potential for positive feedback. Healthy feedback can however be impeded by 'blocking mechanisms' including uncertainties of needs among potential customers, inadequate knowledge of relations between investments and benefits, lack of capability and poor articulation of demand, lack of standards, weak promotion, etc. Exploitation of knowledge to create new business opportunities is therefore central to TIS models.

A.25 The systems approach incorporates the idea of an **innovation life cycle**. It takes time for an innovation system to develop and mature, particularly for radical innovations whose initial development typically takes place over decades. Weak or immature innovation systems may delay the progress of an innovation, or decrease the likelihood of its success (van De Ven, 1993). However, for new technologies that are incremental improvements to existing ones, innovation systems will already be in place.

A.26 The systems approach therefore provides a broad conceptual framework that can be applied to different sectors or regions of an economy, nationally or internationally. However, it cannot explain how networks form, how long they will take to mature, how relationships are coordinated and how cooperation and competition can co-exist within networks. Public policies and regulatory frameworks that can encourage cooperation are desirable but the systems approach offers few clues as to their optimal design and likely effectiveness.

Evolutionary models of innovation

A.27 **Evolutionary models** have 'evolved' alongside other forms. Like system models they attempt to analyse actors in the innovation process and their relationships with each other. However, while system models focus on the system of these relationships and on the factors driving the development of the overall system, evolutionary models instead concentrate on the interactions between different actors, their diversity and different knowledge, motivations and behaviours.

A.28 In evolutionary models, firms are learning entities shaped by their external environment (see also paragraph A.22). This covers the socioeconomic, including regulatory, environment in which firms develop technologies and compete to survive. It is determined by mechanisms such as patent regimes, market structures, standards, regulations, cultural norms and, in the case of low carbon and green technologies, it also includes the natural environment.

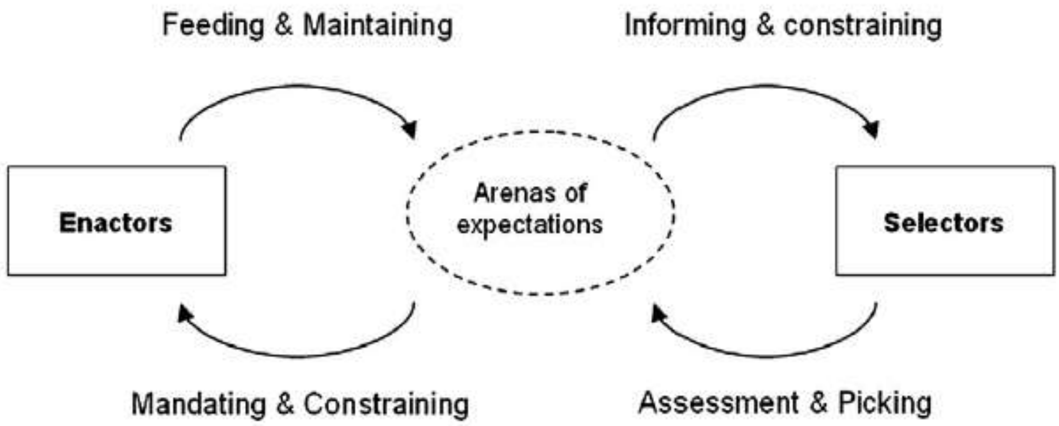
A.29 Innovations therefore evolve from historical context, social conventions and relationships according to Metcalfe (1995). Imperfections are therefore necessary conditions for technical change to occur in a market economy. Not all innovations will be successful while others "*...may fail to be selected because (the) surrounding environment at the time of (their) occurrence is unfavourable*" (Tidsdell, 1995).

A.30 In evolutionary models, therefore, the process of innovation (by trial and error) is as important, if not more so, than the result of RD&D. Their implication for public policy is that governments should focus more on creating the conditions necessary to create more innovative firms and to encourage relationships and learning, rather than correcting market failures and funding selected emerging technologies ('picking winners').

A.31 Bakker et al (2011) introduce the concept of "**arenas of expectations**" in which "**enactors**" (entrepreneurs or firms) of particular innovations create and maintain expectations while "**selectors**" (decision makers) will compare and assess their competing claims. As a direct consequence, the claims made by enactors for their competing innovations are continually constrained and revised by the financial risk aversion of the selectors (see figure A6 below).

A.32 Expectations are therefore of particular interest in the pre-market phase of innovation, when performance, cost and other market criteria are less certain. As a consequence, assessment and selection criteria will be influenced by the needs of the different actors, their vested interests, lobbying and learning processes. There is not one best technological solution to a single problem; for different actors, different technologies will fit better than others. As a result, actor-networks will form and they will try to build a case for a particular technology by building political legitimacy through "*...the enrolling, aligning and coordinating of other enactors and resources*" (van Lente, 2012; Alkemade and Suurs, 2012). In turn, these can create or increase entry barriers for alternative technologies and competitors.

Figure A6: Arenas of expectation in technology development and selection



Source: Bakker, van Lente and Meeus (2011)

A.33 Building strong positive expectations can therefore help to create, maintain and protect "technological niches" and as such, strong expectations may ensure that an emerging technology is more positively evaluated. For example, according to Hacking (2013)

"Shared, or aligned, expectations can reduce the financial uncertainty perceived by the technology selectors. This guides the process of technological change in ways that have been formalized in the private and public sectors of many economies via technological foresight/vision reports - or roadmaps - which have become a standard policy tool".

A.34 The **multi-level perspective** approach advanced by Kemp (1994) and Geels (2002, 2004) among others, draws particular attention to the role of technological niches in fostering **sustainable innovation** and the dynamics of competition between emerging niches and incumbent technologies. Kemp (1994), for example, recognises that **socio-technical barriers** need to be overcome in order to bring about the kind of **transitions** from one technology to another that policymakers seek to achieve with more sustainable economic development.

A.35 Governments therefore need to use their available policy levers to both to manage expectations and transitions and to avoid transition failures. This, it is argued, can only be achieved via joint decision-making and network management where visions and roadmaps hold together networks of stakeholders in a particular technology. Portfolio management overcomes the 'picking winners' problem in the provision of technology support.

Common components in innovation models

A.36 There have been a number of reviews of innovation models, both conceptual and applied, that have sought to identify their key or common components or elements. For example, Maldonado (2011) cites a review of generic national systems approaches undertaken by Edquist (1997) who concludes:

- innovation is a key element of analysis in all approaches and is linked to learning processes;
- systems models provide a holistic and an interdisciplinary approach, since they try to understand the object study as a whole, dependent not only on economic factors but also on institutional, organizational, social and political factors;

- they are all path-dependent, which means that developing innovations is usually a long-term process;
- they all emphasise interdependency and non-linearities;
- their common constituents can be defined as "**components, relationships and attributes**", where the "components of an innovation system" are the organisations and institutions which play a central role.

Components		Relationships	Attributes
Organisations	Institutions		
"*...formal structures that are consciously created and have an explicit purpose*". Organisations are therefore the 'actors' in an innovation system and include firms, universities, venture capital organizations and public agencies responsible for innovation policy.	*"...sets of common habits, norms, routines, established practices, rules or laws that regulate the relations and interactions between individuals, groups and organizations".* Examples of institutions include patent laws as well as rules and norms influencing the relations between universities and firms or traditions and social norms.	The links between the components. Relationships produce feedback mechanisms that make an innovation system dynamic. As a result of feedback mechanisms among the components, their properties / characteristics may change over time and therefore the whole configuration of the innovation system.	"*properties of the components and the relationships between them"* They are related to the function or purpose of the system, so if an innovation system's purpose is "to develop, diffuse and use innovations", then the attributes would be the capabilities of the actors to develop, diffuse and use innovations.

Based on Maldonado (2011) and Edquist (2005)

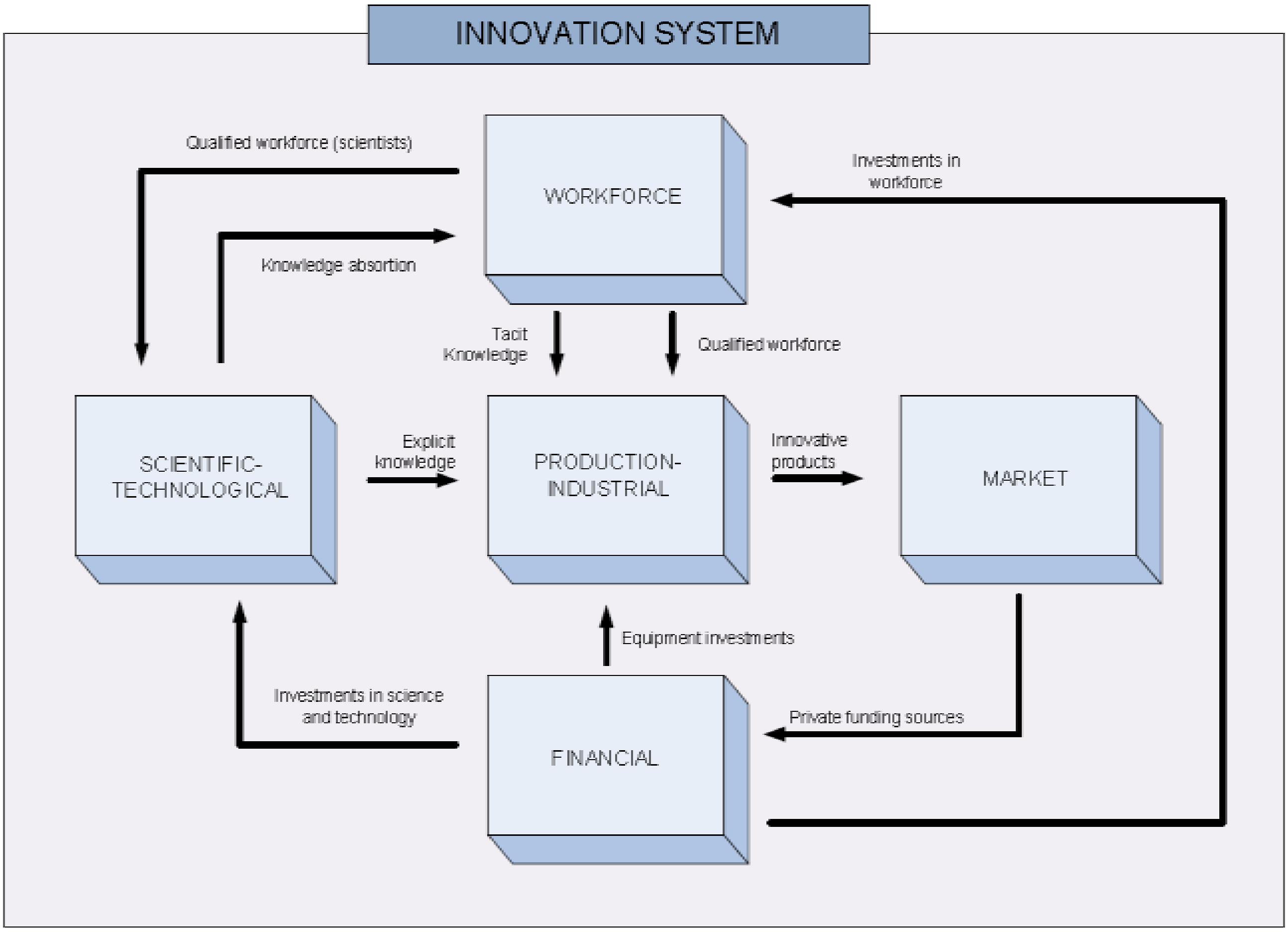
A.37 Maldonado's own "systematic review" covers 26 research papers on innovation systems including national, regional, sector and technology specific applications. Although he concludes there was no agreement in the papers in terms of how to represent innovation systems he does identify a number of their common elements or components:

- ***Financial Component*****:** this is vital for any innovation system and has as its objective the promotion of capital flows among the actors. It is also responsible for supporting public and private expenditure on RD&D, whether at the initial stages of research or at the final ones;
- ***Scientific-Technological Component:*** the main aim of this component is to produce and store knowledge as a product of allocating financial and human resources;
- ***Production-Industrial Component:*** this component uses the knowledge created in the scientific-technological component to produce innovations;
- ***Market Component:*** innovations from the production-industrial component are designed to generate profit;
- ***Workforce Component:*** according to Maldonado, this component receives investments from the financial component, offers workforce to the scientific-technological and

production-industrial components and absorbs knowledge from the scientific-technological component.

A.38 From these, Maldonova proposes a combined theory or meta-model of innovation linking the five major components. The model, he argues, is able to represent any type of innovation system whether national, regional, sectoral or technological, at the macro level. His schematic is repoduced below.

Figure A7: Maldonova's "meta-model" of the innovation system



Source: Maldonado (2011)

A.39 Maldonova's meta-model of the innovation system based on common components is a useful concept, but it appears to exclude the socio-economic environment and underplay the role of the market. As such, it provides little insight into the motivations of different actors, how learning takes place and how relationships and expectations are formed and managed in the system.

A.40 In contrast, Hacking (2013) reviews the full spectrum of theoretical and methodological approaches to innovation, with the aim of providing:

- insights for policy regarding the promotion and development of a low carbon economy (see table A1 below);
- a robust evidence base to underpin the sustainable innovation, knowledge transfer and rapid commercialisation of hydrogen and fuel cell technologies.

Table A1: Theoretical approaches to innovation and associated policy measures

Theoretical Approach	Associated Policy Measure
Technology Push	Public R&D funding, tax credits for companies investing in R&D, enhancing the capacity for knowledge exchange, support for education and training, and funding demonstration projects.
Market Pull	Tradable permits, feed-in tariffs, intellectual property protection, tax credits and rebates for consumers of new technologies, government procurement, technology mandates, taxes on competing technologies and command and control regulation inducing demand through standard setting.
National Systems of Innovation	Investments in technological learning activities by institutions, the links amongst them as well as incentive structures and competencies avoiding low corporate R&D spending and low spending in terms of workforce skills.
Regional Systems of Innovation	Incentives and support schemes need to fit the functionality of the system as well as its phase of development (formative or growth phase). Recommendations include: support advocacy coalitions to overcome a weak legitimacy; create visions and strategies to guide the directions of search; support experiments and demonstration projects to create and diffuse new knowledge and reduce the risk of entrepreneurial experimentation. Other measures include: attractive regional tax and welfare arrangements and general economic development policies.
Sectoral Systems of Innovation	Invest generically and thematically in basic science and R&D. Foster application of knowledge. Improve science education and the stock of qualified scientists and engineers. Invest in technological product and process and non-technological innovation. Support improved innovation management skills. Promote innovation culture and the networking of firms in clusters.
Technological Innovation Systems	Support firms to increase and diffuse knowledge. Support experiments with new applications. Develop standards. Develop research and education policies. Supporting advocacy coalitions.
Multi-level Perspective	Employ joint decision-making and network management via visions and roadmaps. Use problem structuring methods to deconflict alternate frames of reference. Use portfolio management, risk assessment, technology assessment and monitoring of effects to reduce uncertainties associated with long-term system effects of a technology. Also use flexible designs, adaptive management and the use of capital-extensive solutions with relatively short life times.
Expectations / Enactors and Selectors	Policymakers should be aware of expectations but remain open to different options and progressively drop failing applications/technologies instead of picking winners.

Source: adapted from Hacking (2013)

A.41 Hacking's objective is to develop a framework that can be used for case-study led analysis. He recommends the development of a "*co-evolutionary, enacted, relational, and interactional view of the nature of innovation*" by combining the following approaches:

- technological innovation systems (TIS)
- functions of innovation systems
- expectations

From this he concludes that innovation is best described and analysed as a quasi-evolutionary process centred on the learning that takes place inside and between institutions.

Annex B: Some Examples of Applied Innovation Models in Energy and Low Carbon

B.1 Theoretical and empirical applications of innovation models to the energy sector and low carbon technologies are increasing. Over time applications have, unsurprisingly, followed the evolution of generic models from linear to non-linear (systems and evolutionary) forms. There is now broad agreement that the innovation process or system in energy and low carbon technologies is decidedly complex and non-linear.

In this annex we therefore identify and summarise a small sample of applications of more recent models to the UK low carbon innovation system. National and technological systems and evolutionary models of innovation are being more widely adopted in the policy domain (see, for example, DECC 2012 and LCICG 2014). However, these complex, interactive models give rise to a number of data and methodological issues that make them more difficult to test empirically.

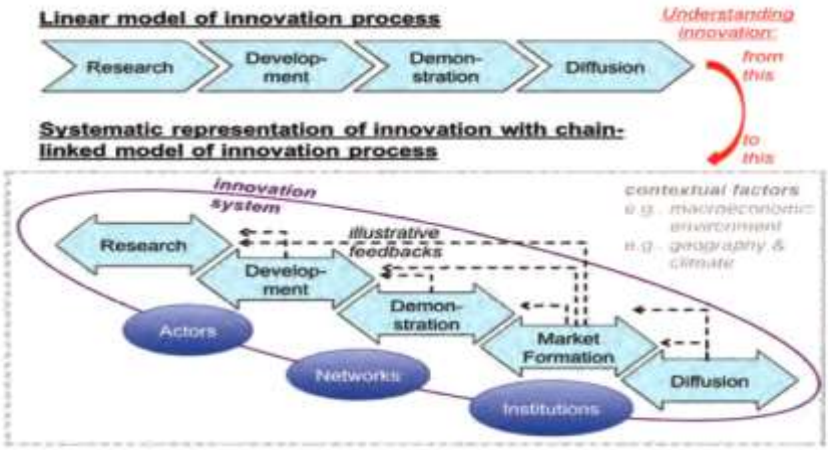
B.2 Grubler et al (2012) report that studying innovation from a systemic perspective in the energy domain is a "*relatively young endeavour*" that is weak on the feedback between the various components and demonstrates "*an empirical bias toward national and supply-side energy technologies*" despite the accumulating evidence on market-based technology learning. A systemic perspective necessitates more integrated analysis: from large-scale supply-side technologies to dispersed end-use technologies within the energy system and from early stage R&D through market formation to diffusion activities. In contrast, according to Grubler et al, conventional data collection and analysis has tended to focus on only one piece of the puzzle at a time.

B.3 For Grubler et al, innovation in energy is best understood as an interactive process involving a network of firms and other economic agents that, together with the institutions and policies that influence their innovative behavior and performance, bring new products, processes, and forms of organization into economic use.

B.4 Their **Energy Techonology Innovation Systems** (ETIS) approach therefore integrates current understanding of innovation processes within the energy system, their interlinkages, and the roles and influence of different actors and institutions including public policy.

B.5 To illustrate the evolution of their ETIS approach, the authors use a schematic contrasting a generic linear model with a **chain-linked model with multiple feedback mechanisms** (see figure B1). They then apply the ETIS framework to a number of energy demand-side and supply-side technologies to produce a series of case studies or "innovation histories" (see table B1).

Figure B1: Evolution of Technology Innovation Systems Approach



Source: Grubler et al, IIASA (2012)

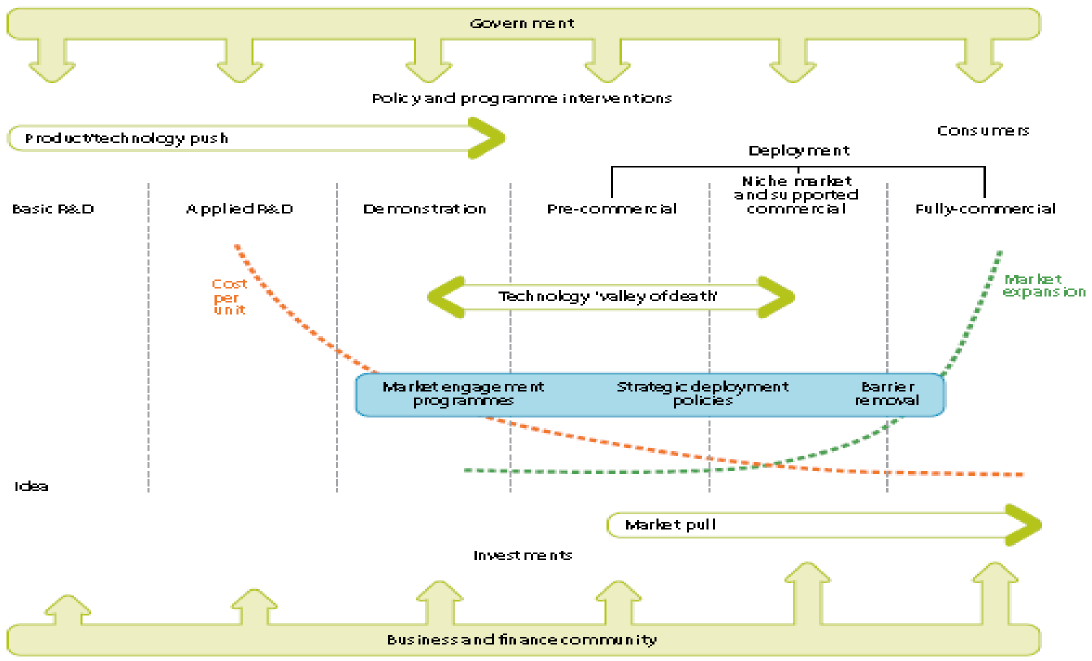
Table B1: Case studies ("innovation histories") of energy/low carbon technologies

Demand-side	**Summary Description**	**Example of relevance for ETIS**
Hybrid cars	Development of hybrid electric vehicles in Japan, US and China, emphasizing the role of public policy	Importance of policy alignment and consistency. Role of market demand and end-user preferences.
Solar water heaters	Early success and later failure of the solar water heater industry, particularly in the US.	Lasting legacies of industry failure, including knowledge depreciation. Alignment of innovation system actors.
Heat pumps	Different stages of heat pump diffusion in Sweden and Switzerland, emphasizing the role of public policy.	Interactions between supply of, and demand for, innovation. Importance of policy stability and consistency.
US vehicle efficiency	The 'CAFE' standard for vehicle efficiency in the United States, and its influence on technological change.	Interaction between policy standards and changing market characteristics, including prices.
Japanese efficiency	The 'top runner' program to improve end-use efficiencies in Japan, and the role of dynamic incentives.	Flexible policies creating dynamic incentives within a clear overall strategic direction.
Supply-side	**Summary Description**	**Example of relevance for ETIS**
Wind power	Evolution of innovation stages and strategies in different wind power markets worldwide	Need to integrate RD&D support with market formation. Interaction and feedback between innovation actors.
Solar PV	Development of solar PV in different markets worldwide, focusing on drivers of cost reduction.	Long-term R&D support complemented by market formation activities to stimulate commercial learning.
Solar thermal	Early experience of solar thermal electricity in the US, and spillovers to later stage production.	Codification of knowledge. Interaction between R&D and learning to support cost reductions.
US syn-fuels	History of US government investment in synthetic fuel production as oil substitute, and ultimate innovation system 'failure.'	Over-exuberant expectations in the context of changing market conditions. Public/private roles in innovation system.
French nuclear	Review of pressurised water reactor (PWR) programme in France, including cost escalation.	Interaction between learning effects and institutions, including standards and regulatory stability. Limitations of learning paradigm in technology cost reductions.
Brazilian ethanol	History of ethanol production and envelopment's in automotive technologies in Brazil, focusing on supporting role of policy.	Coalitions and shared expectations among innovation system actors, and interactions between related technologies.

B.6 Grubb (2004) reviews evidence on innovation processes relevant to the energy sector and particularly implications for national and international policy responses to climate change. His core finding is that the complex innovation processes at work in the sector are not well understood by policy makers.

B.7 While his useful schematic representation of the energy/low carbon innovation system (figure B2) appears linear, his underlying model is very clearly a complex and non-linear system "*in which feedbacks from the different stages of the innovation chain and the ability to learn from experience are crucial*." As such, policies that are aimed at either ends of the innovation chain are unable to address core "**technology valley of death**" problems in the central stages where volumes remain low and costs high.

Figure B2: Activities for spanning the innovation chain



Source: Grubb (2004) as adapted by and reproduced from the UK Committee on Climate Change (2010)

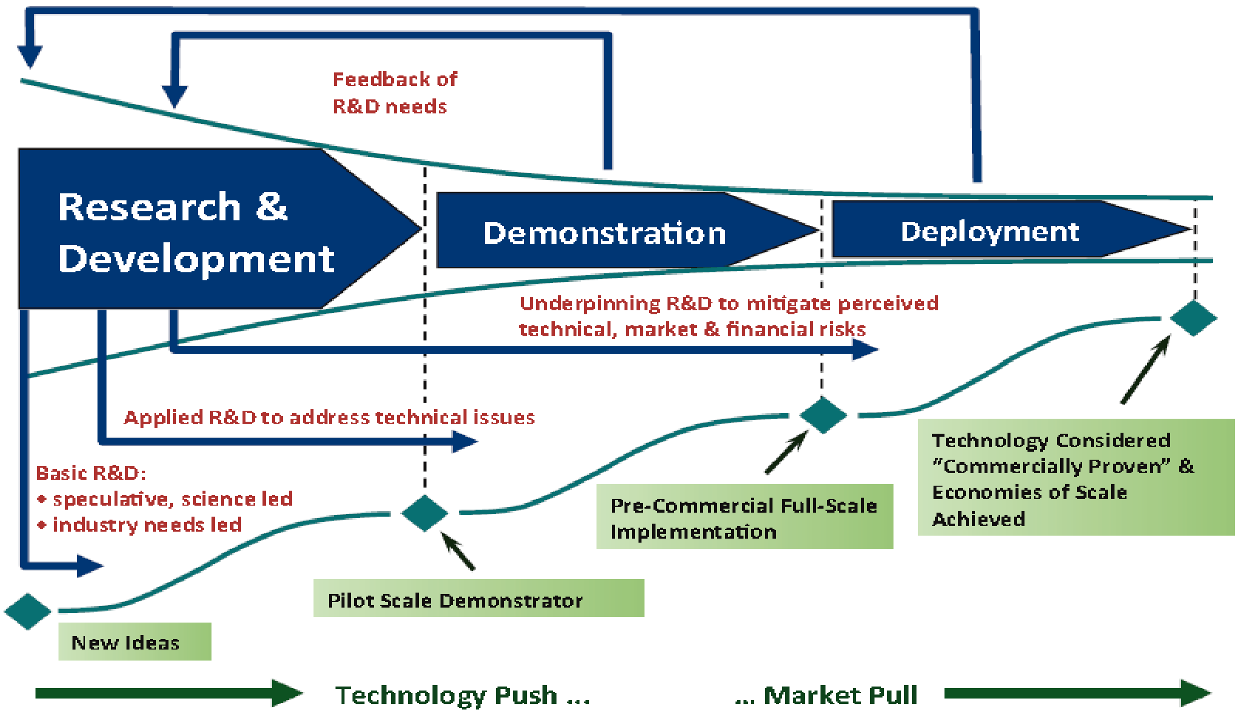
B.8 Grubb argues that public RD&D is primarily focused on achieving technological breakthroughs but this alone is unable drive commercial uptake. Similarly, at the other end of the innovation chain, emissions controls do not provide sufficient, long term security for investors. Instead, therefore, he recommends greater emphasis is given to market engagement and strategic deployment policies to build market scale and reduce the cost of technologies, and in so doing bridge the valley of death.

B.9 While Grubb's underlying model of innovation is non-linear the concept of a **linear innovation chain** or sequence continues to be important he argues, to identify gaps or barriers that impede the movement of technologies along the chain and prevent their successful commercialisation. The same argument is made by Foxon et al (2005) among others. DECC (2012), for example, characterises its support for energy innovation as either technology-push, market-pull or barrier removal.

B.10 The Research Councils UK (2013) similarly recommend applying the linear TRL (Technology Readiness Level) framework with "more rigour to emerging energy technologies", arguing that while some basic research challenges are of a ‘blue skies’ or breakthrough nature, many more may be defined by problems identified at later stages in the innovation process, for example in pilot plants, demonstration or deployment.

B.11 However, the RCUK also observes that the innovation system seldom proceeds in a linear fashion from basic research through to deployment and therefore recommends the need for a "fully integrated roadmap of research targets". While diverse energy applications are connected by the same underlying research skills, feedback from the demonstration and deployment of energy technologies can stimulate many research challenges which it distinguishes as either ‘science-inspired’ and ‘application-inspired’. To illustrate these points it uses the following schematic of the energy innovation process which also usefully captures notions of an **innovation funnel** and **life-cycle**.

Figure B3 : Energy Innovation Process

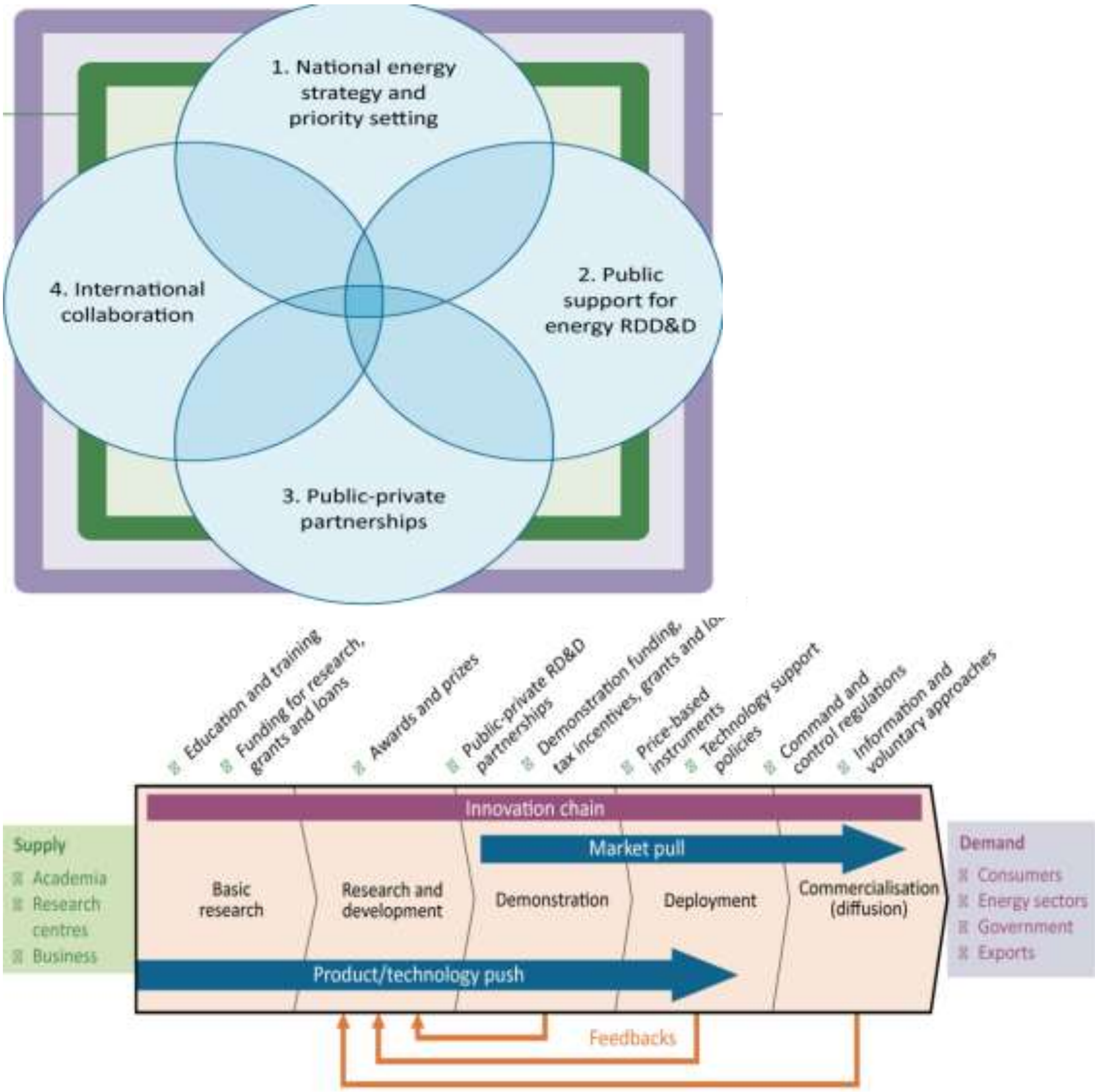


Source: Research Councils UK (2013) reproduced from Energy Research Partnership (2007)

B.12 The ERP diagram is also used by the Committee on Climate Change CCC (2010) and LCICG (2014) to provide a framework for policy formulation, with both organisations also stressing the importance of expectations and institutional structures to the progress or otherwise of low carbon technologies through the various stages in the innovation cycle.

B.13 The same broad innovation systems framework also underpins the policy recommendations of the International Energy Agency (2012). For the IEA the scale and complexity of the energy innovation system justifies governments to adopt a top-down, national 'systems' approach to strategy formulation and the identification of priorities, and the use of multiple, integrated instruments to support early deployment and drive private investment (see figure B4).

Figure B4: IEA policy framework and recommendations



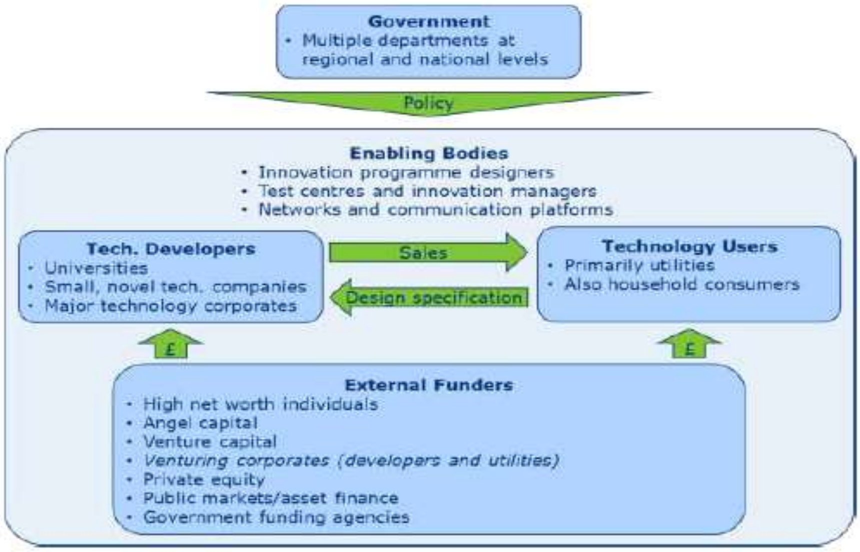
Source: International Energy Agency (2014)

B.14 However, while the complexity of the innovation system underlying the development and diffusion of energy and low carbon technologies is now widely accepted and influential, it remains challenging for policy design especially given the number of actors and interactions involved.

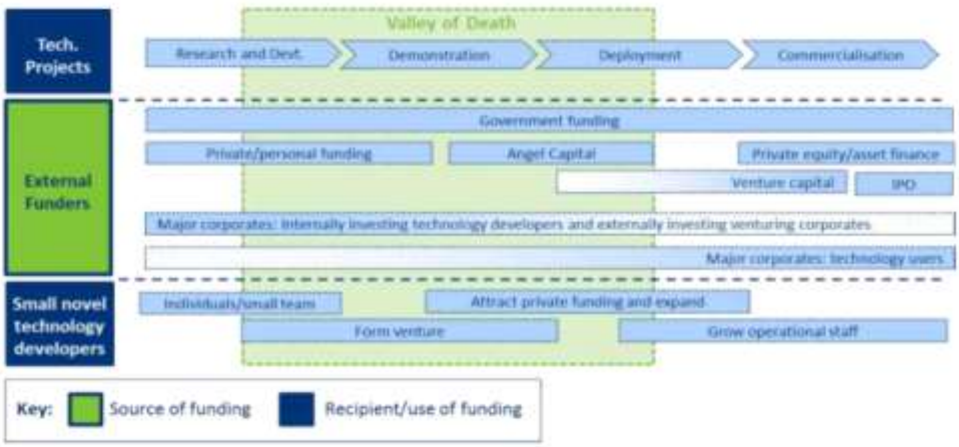
B.15 The Carbon Trust (2014), for example, categorises and maps stakeholders and their interactions according to their goals from innovation (see figure B5). Within this framework, it distinguishes between public funding agencies and the growth of public sector enabling bodies, with particular reference to the Technology Strategy Board (Innovate UK), the Energy Technologies Institute, the Energy Savings Trust and itself as examples of 'enabling' organisations developed and deployed in the UK to support emerging technologies at different stages of the innovation chain.

Figure B5: Carbon Trust framework - emerging renewable energy technologies

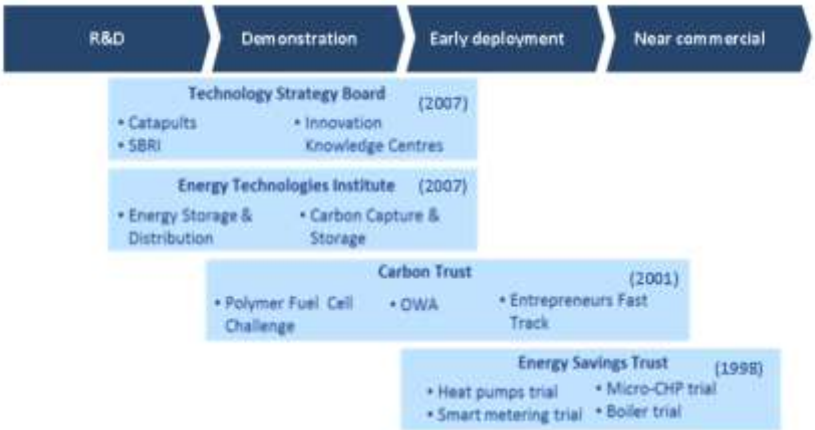
Stakeholder interactions:



Tech Funders:



Selected tech enablers:

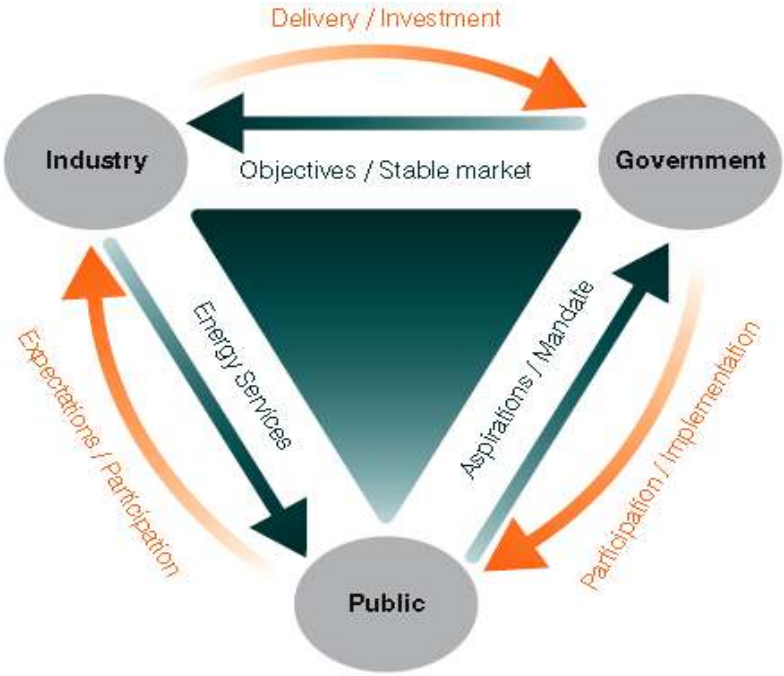


Source: Carbon Trust/IEA (2014)

B.17 The influence of more complex, interactive and **open innovation models** on government policy in the UK is in part further evidenced by the formation of the Energy Research Partnership (ERP) in 2005 and Energies Technologies Institute (ETI) in 2007. The aim of the former is to bring together key funders of energy research, development, demonstration and deployment in Government, industry and academia, plus other interested bodies, "*to provide high-level leadership for, and to enhance the coherence of, energy research and innovation activities in the UK, set within an international context*" (ERP, 2005).

B.18 The ERP has mapped interactions between key stakeholders in the energy domain (figure B6). The importance of forming, influencing and managing expectations is clearly highlighted in the diagram, reflecting the **expectations led models** that developed in the literature during the 1990s and early 2000s (see Annex A).

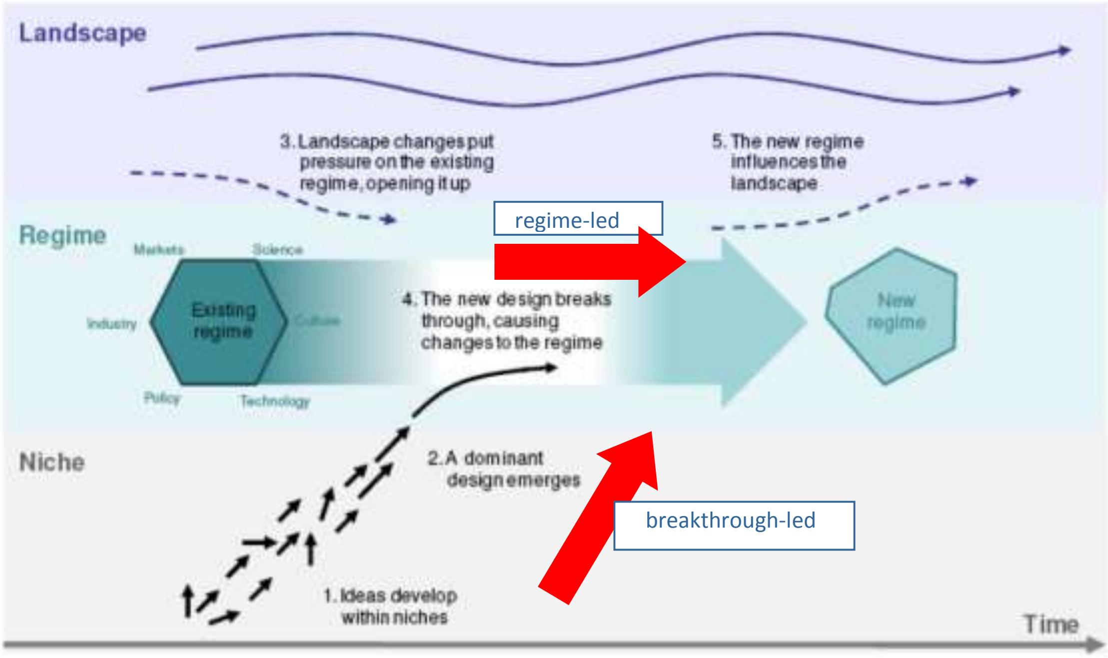
Figure B6: Energy stakeholder interactions highlighting requirements and expectations



Source: Energy Research Partnership (2014)

B.19 In contrast, Winskel and Radcliffe (2014) argue that it is energy innovation theory that has failed to keep up with changes in research practice/policy. In their review of UK energy innovation policy for the UK Energy Research Centre, they identify a shift in policy over time away from a top-down, breakthrough-led approach (of the type needed to develop large-scale generation technologies over long periods such as carbon capture and storage), towards a "regime-led" approach further to the right hand side of the innovation chain (see figure B7). This involves a greater reliance on the private sector and public-private partnerships to achieve what they term "**accelerated energy innovation**" focused on rapidly reducing the cost of new technologies and the attainment of short term carbon reduction targets.

Figure B7: From breakthrough-led to regime-led (energy technology) policy approaches



Source: Reproduced from Winskel and Radcliffe (2014)

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