On order and complexity in innovations systems:

Conceptual frameworks for policy mixes in sustainability transitions

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'New perspectives on analyzing policy mixes for sustainability transitions'

Contents

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ABSTRACT

The sheer complexity of sustainability transitions makes it vital to develop simplifying conceptual frameworks. Starting from the contrast between the mainstream innovation-economics and systems-innovation/evolutionary literatures, this paper begins by summarising the "Three Domains" framework, which relates technology innovation and adoption choices to different domains of socio-economic decision-making, at successfully larger scale of time and social structures. We note the high-level implications for policy packages and illustrate the main themes through three electricity technology examples (lighting, fossil fuel generation, and low carbon power systems), and use these also to show that the relative importance of different policy pillars may differ substantially according to the technology and context. We then relate this to the "innovation chain" (another simplifying framework) approach to vertical innovation and show how this can help to explain radical differences in innovation intensities between different sectors. We then expand the innovation chain framework from technology to the multiple journeys required for successful innovation, ordered according to levels of decision-making and hence domains. We conclude by indicating how this can help identify key blockages in energy transformations, and potentially help to reconcile the classical innovation-economics with systems innovation / evolutionary perspectives, and explain their currently divergent policy recommendations.

1. Introduction

In Autumn 2015, the UK hosted two major international conferences on theories of innovation within an hour's travel of each other, just a few days apart. Participants travelled from around the world to attend. The most striking feature, however, was the almost complete lack of interaction: only one name appeared on the participation list of both meetings. One conference was on the economics of innovation; the other, a meeting of innovation systems researchers. They represented different worlds.

This paper concerns that gulf. The two communities tend to different forms of analysis and reach different policy prescriptions, and the disconnect between mainstream economics of innovation on the one hand, and systems innovation/evolutionary perspectives on the other, is an important obstacle to effective innovation policy. We summarise the underlying conceptual differences and argue that bridging these perspectives is crucial to effective innovation policy and the development of policy mixes, illustrated throughout with particular reference to the nature of, lessons from, and policy challenges facing the transformation of the energy sector.

Against this background this paper has the following specific objectives.

Our *conceptual* aim is to offer a broad framework for and categorisation of the processes involved in transforming complex systems, within which to locate both the mainstream innovation-economics, and innovation systems/evolutionary perspectives and literatures; this allows us to illustrate how the different approaches focus on different aspects of the overall challenge. Thus we develop a relatively simple set of conceptual tools that bridge the economics and systems literatures, drawing on insights from both. Through this we aim to narrow – or at least explain - the intellectual gulf between these approaches, and offer a wide but conceptually simple map of transformation processes (which necessarily combine innovation and diffusion), particularly relating to lessons from the energy sector and current debates about energy transformation.

Our second objective concerns policy. We offer both data and explanations to suggest that energy systems display particular characteristics which make transformation unusually challenging, with theoretical divergences further impeding effective policy. Policies to transform energy systems have been strongly contested politically, in part because of the different world-views of the innovation-economics compared to the systems innovation / evolutionary literatures. An obvious example is the scorn that many economists expressed for renewable energy targets, and German PV supports in particular, commonly arguing for policy beyond R&D to be 'technology neutral' (eg. a single emissions target, not multiple targets, and main emphasis on carbon pricing).[2] Whilst many energy economists have in the past decade nuanced their views and paid more attention to learning-by-doing, a clear gulf remains as we indicate later. In contrast, systems innovation theorists and evolutionary perspectives have tended to emphasise cultivation of niche and growing markets for the most potentially important

[2] Eg: as late as 2014, The Economist wrote that "solar power is by far the most expensive way of reducing carbon emissions …. the carbon price would have to rise to $185 a tonne before solar power shows a net benefit. … governments should target emissions reductions from any source rather than focus on boosting certain kinds of renewable energy." Their article was based on a report by Frank (2014) – which only reflected a long-standing view of many economists, taking an equilibrium view of minimising abatement costs, and decried in particular Germany's approach to solar PV – and the EU's inclusion of a renewables target in its 2020 package - as economic madness (e.g. Boehringer and Rosendahl, 2011; Helm, 2009).

technologies, even at high unit costs, using a wide range of policy actions, sometimes with less pronounced attention to issues of cost and economic incentives.

The policy community often relies on relatively simple views of innovation based on traditional perspectives. Systems views sometimes struggle to get traction in high-level policy debates, hindered by unfamiliarity, complexity, and the difficulty of drawing clear policy conclusions. Despite increasing prominence of systems approaches in informing innovation policies design, in high-level forums innovation policy is often equated with just R&D funding. Our policy aim is thus to present a framework that makes clearer to policymakers how to understand and engage with the co-evolutionary dynamics presented in the systems literature.

Consequently, by developing a wider framework and classification of different processes and theories, and showing a certain complementarity in their roles, we aim as a third objective to shed new light on the rationales and multiple roles of policy packages, and thereby help to narrow policy differences and identify gaps that still impede the energy transition.

Whilst seeking to build on the existing literatures, this paper also has a very practical origin. Alongside academic roles,[3] the lead author has been Chief Economist at the Carbon Trust – established in 2001 as the UK's main body working with industry to commercialise low carbon technologies – and then Senior Advisor to the UK energy regulator, Ofgem. This paper offers an approach that reflects this practical experience, and thus whilst seeking to locate and build upon the academic literature, is not constrained by it.

The paper is organized as follows. Following a brief review of the literatures most directly relevant to the main themes and classification of systems innovation theories (2), in section 3 we summarise the high-level 'Three Domains' framework of Grubb, Hourcade and Neuhoff (2014, 2015: hereafter the GHK framework). This organizes the main processes in terms of *behavioural and organizational characteristics* ('satisficing') that impede adoption of seemingly cost-effective technologies; the *optimizing* behaviours that underpin the mainstream economics literatures and provide the central theoretical basis for markets and cost-reflective pricing ('optimising'); and the *evolutionary and institutional* characteristics of large-scale (non-marginal) changes in technologies, systems, and industrial and institutional structures ('transforming'). We show how these operate a different scales and have clear and complementary roles in the space defined by the relationship of resource inputs to economic outputs.

From this basis, the subsequent section (4) summarizes briefly how this underpins three high-level categories of policy instruments and explains their relationship to transformation processes, and in particular to the classical economic policy distinction between *horizontal* and *vertical* innovation policies, and the increasingly influential discourse on *mission-oriented innovation*.

To illustrate the main concepts and provide some empirical basis, we then (section 5) chart the evolution of three categories of electricity technologies – lighting, fossil fuel generation, and renewable energy technologies and associated features of overall electricity systems – across the high-level map of resource inputs and economic outputs.

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[3] Part time academic appointments at the Faculty of Economics, Cambridge University, and subsequently Professor of International Energy and Climate Change Policy at UCL. Running alongside roles as Associated Director of Policy (2001-4), and subsequently Chief Economist (2004-2009) at the UK Carbon Trust; and at Ofgem as Senior Advisor, Sustainable Energy Policy (2011-15), and Improving Regulation (2015-16). Outside academia, Grubb now chairs the UK government Panel of Technical Experts on Electricity Market Reform.

To move the paper towards the more specific stages of innovation processes, section 6 then revisits some concepts and literature around the 'innovation chain'. Though sometimes criticized as a re-invention of a simplistic and long-refuted linear model, we argue that when properly understood it in fact offers a compelling way of explaining the relationship between 'technology push' and 'demand pull', within a wider system context which can in turn be linked back to the Three Domains framework. We show that this can also help to explain major differences in innovation intensity between sectors and argue why this is crucial to understanding the needs of innovation policy particularly with respect to energy-related sustainability concerns.

In the final section we expand the innovation chain framework to show in fact it can accommodate several layers of complexity relevant to policymaking particularly for 'vertical' innovation policy with sector-specific technologies. Finally, we use our approach to suggest that many of the differing outlooks between the two communities noted arises from inadequate attention to the multiple domains of real-world decision-processes.

2. Context and links to existing literature

Innovation is complex, and as our understanding of it has improved the field of innovation studies has also increased in its complexity. This trend appears also to have increased the gulf between mainstream economic thought and systems innovation theories, which have evolved through largely different communities. Yet the divergence dates back even to historical approaches to problems with multiple goals (contrast the famous Tinbergen rule (1952; 1956) of one instrument for each goal, with Lindblom's (1958) critique); the gulf has merely taken on somewhat different forms in the context of modern economic treatments of endogenous technical change (eg. The extensive modeling studies in the Innovation Modelling Comparison Project (Edenhofer *et al*, 2006), still had little reference to the systems innovation literature).

The different schools moreover frequently produce different policy recommendations. The economics community tends to emphasise the role of pricing and R&D (eg. Acemoglu et al 2012), justified with specific reference to identifying where the market barriers may lie (eg. Jaffe, Newell and Stavins 2005), and with patents as the main index of innovation (eg. Dechezleprêtre *et al* 2011). They emphasise classic economic concerns: expected profitability and return on investment, prices, and so on. There is much less emphasis on intangible aspects (norms, cognitive routines, the visions that motivate and align innovators), or on the co-evolution of technology with institutions and politics.

The systems innovation community uses different language and emphasizes far more the dynamic, complex, interdependent and evolutionary nature of innovation, with strong emphasis also upon the learning-by-doing, infrastructure, and institutions associated with deployment (eg. Nelson and Winter 1982; Geels and Schot 2005). In contrast to the economics of innovation literature, this literature pays much less attention to prices and cost trajectories.

Both schools recognise the need for multiple policy instruments (which may be defined as a tool or technique used by government in order to achieve a policy goal (Howlett, 2005)), to be combined into a policy instrument mix to achieve (single or multiple) policy objectives. For example, from the economics perspective, Jaffe, Newell and Stavins (2005) conclude that the interaction of market failures associated with environmental pollution and with innovation and diffusion of new technologies provide a strong rationale for a portfolio of instruments that foster emissions reduction alongside the development and adoption of environmentally beneficial technology. Lehman (2010) supports this rationale, and indicates that a policy mix is also justified if the implementation of individual first-best instruments produces high transaction costs (although as Costantini *et al* (2017) highlights, care must be taken not to introduce an indiscriminate number of instruments, which may prove counterproductive).

From the systems innovation perspective, Nill and Kemp (2009) argue that multiple instruments are required in order to overcome practical constraints provided by technical, institutional, political, and economic realities and uncertainties, and their dynamic co-evolution. In turn, the dynamic influences and effects of instruments themselves are important.

Various typologies of *environmental* policy instruments may be found in the literature (see Jordan, Wurzel and Zito (2013, p.26) for a recent overview), although attempts to combine *environmental* and *innovation* policy instrument typologies are relatively new (e.g. Nauwelaers *et al*, 2009). In such typologies, categories are commonly defined by the primary purpose of the instrument, or their main *modus operandi*. Rogge and Reichardt (2016) employ both elements to elaborate a 3x3 'type-purpose' matrix typology, drawing on previous literature (with '*type*' defined as 'economic instruments', 'regulation' and 'information', and '*purpose'* defined as 'technology push', 'demand pull' and 'systemic'). Few typologies explicitly base their instrument categories on the underlying economic and decision-making processes upon which instruments operate.

Although often synonymous in the literature (as evidenced by the definitions provided by Rogge and Reichardt (2016, p.1612)), a 'policy instrument mix' must be distinguished from the broader concept of a 'policy mix'. Rogge and Reichardt (2016) outline three building blocks in their extended definition of a policy mix for sustainability transitions – '*elements*' (i.e. the policy instruments themselves, and associated objectives), '*policy processes'* (i.e. the processes by which the 'elements' in the mix are arrived at), and '*characteristics*' (consistency of 'elements', 'coherence' of processes, 'credibility' and 'comprehensiveness').

This paper complements the existing literature by proposing a simplifying framework that gives clear and complementary spaces to the insights from mainstream innovation-economics and systems innovation perspectives. In turn, this may be used to evaluate the characteristics of policy and policy instrument mixes for innovation for sustainable transitions, and inform their future development.

The benefit of conceptual simplification is not necessarily to aid centralized coordination. As Flanagan, Uyarra and Laranja (2011) persuasively argued, centralized policy coordination may to a large extent be a chimera. As emphasized by broadly *evolutionary* approaches (e.g. Cooke, Uranga and Etxebarria, 1998; Geels, 2002; Iammarino, 2005), and as our understanding of the sheer complexity of policy processes also deepens towards an evolutionary perspective (e.g. John, 2003; Metcalfe, 1993), the challenge of central coordination becomes ever more problematic. Indeed, one of the 'four dangers' in innovation policy studies proposed by Flanagan and Uyarra (2016) is excessive faith in rational design and co-ordination of policy mixes.

Another danger highlighted by Flanagan and Uyarra (2016) is the treatment of policy instruments simply as tools to be selected from a toolbox. An individual instrument, much less a mix, exhibits a high degree of interpretive flexibility – their definition, objectives, implementation and outcomes may vary spatially and temporally, and across different types and levels of actors (del Rio and Howlett, 2013; Flanagan, Uyarra and Lrannja, 2011). As such, no conceptual framework may be predictive or prescriptive regarding specific policy instruments to introduce, and their effects, as a universally applicable rule.

Rather, we argue, simpler conceptual frameworks can offer a more useful map of the components that comprise a broader and more complex innovation ecosystem. These include the interactive role of different actors, economic processes, and policies that can accelerate (or hinder) the transition to an environmentally sustainable techno-economic system. Coordination can then better emerge from the system, much in the way that natural ecosystems reflect apparently extraordinary degrees of coordination without any central planner.

3. The Three Domains

We approach this task starting with one simple framework, namely the 'Three Domains' of socio-economic decision-making advanced by Grubb, Hourcade and Neuhoff (2014, 2015), hereafter GHN (2014).

The **first Domain** concerns the behavioural, social and contractual characteristics that influence (and frequently impede) the adoption even of existing, cost-effective technologies. Component concepts include behavioural economics, with its emphasis on risk aversion, habits, myopia and vicarious learning (eg. Kahneman 2012), much of which corresponds in large measure to what economics has termed '*satisficing'* behavior – the term used to reflect situation in which people appear to be 'satisfied enough' not to change demonstrably sub-optimal conditions. It also encompasses many strands of organizational theory (eg. principal-agent effects), transactional analysis, contract theory including incomplete and missing contracts (eg. tenant-landlord relationships), etc. Together these form what GHN (2014) term '*First Domain*' characteristics. It has a close relationship to concepts of 'bounded rationality', though extends substantially beyond this specific idea. For a recent analysis with reference to climate policy modelling see Safarzyńska (2017).

Though GHN (2014) focus examples of this with respect to the energy efficiency gap, in reality it has a far broader interpretation; it encompasses many of the processes of (and impediments to) the diffusion of technologies, beyond the purely cost/market-driven. First Domain analysis is intrinsic to innovation studies insofar as it can shed light on the challenges and timescales of technology diffusion.

The **second Domain** characterizes optimizing behavior. This is the world in which agents – consumers, firms and others – act according to the principles of neoclassical economics, with behavior approximating to the implications of conscious, evaluated decisions to minimize costs and maximize personal or organizational benefits. The underlying assumptions (acknowledged or not) are well mapped out by (Staub-Kaminski *et al* 2014), who from this offer a more detailed typology of 'market failures' with a clear mapping on the Three Domains framework (Grubb, Hourcade and Neuhoff 2015).

In second Domain processes, Innovating activity and investments occur but mostly within an acknowledged 'innovation possibilities frontier', as also constrained by existing infrastructures and institutions. Policy prescriptions emerging from this Domain tend to relate most to markets and relative prices, with interventions justified with reference to market failures and direct externalities.

The **third Domain** encompasses evolutionary and institutional processes. This embodies more explicit theories of innovation *systems* and transformation, taking into account the role not only of innovation in discrete technologies, but also the roles of infrastructure, institutions, network effects, learning-by-doing and path-dependencies, amongst other factors. For a recent extensive review in relation to sustainability transitions see Rogge and Reichardt (2016).

The distinction between the different domains – and the fundamental reasons why an approach framed in terms of the role of technologies in transforming resources into economic outputs has only three- can be readily illustrated as in Figure 1. The left hand panel shows the simple concept of what we can call the 'best practice frontier' – reflecting the leading *commercially available* ways to produce a given output (service or welfare) (horizontal axis) for a given use of key resource inputs or pollution outputs (the vertical axis). Restricting the use of a resource (e.g. fossil fuels) or the generation of pollution (e.g. CO_2 emissions) comes at a cost to the services or welfare (i.e. the sum of producer and consumer surplus) provided by such activities, at least in the short term, because other factors (eg. more capital or labour, or some other more expensive resource) must be used – substituted - instead.

The frontier defines that trade-off. The curve is in practice fuzzy because of the scope for differing interpretations of what is 'commercially available', and the different discount rates, risk aversions or other criteria, that might be applied, in different contexts. Obviously, the idea can be generalised to any number of resources and associated dimensions. In the context of energy transitions, think of the vertical as representing energy use and associated emissions, whilst the horizontal axis is the service (value) provided per unit energy.[4] In section 5 we illustrate this more specifically with a few examples.

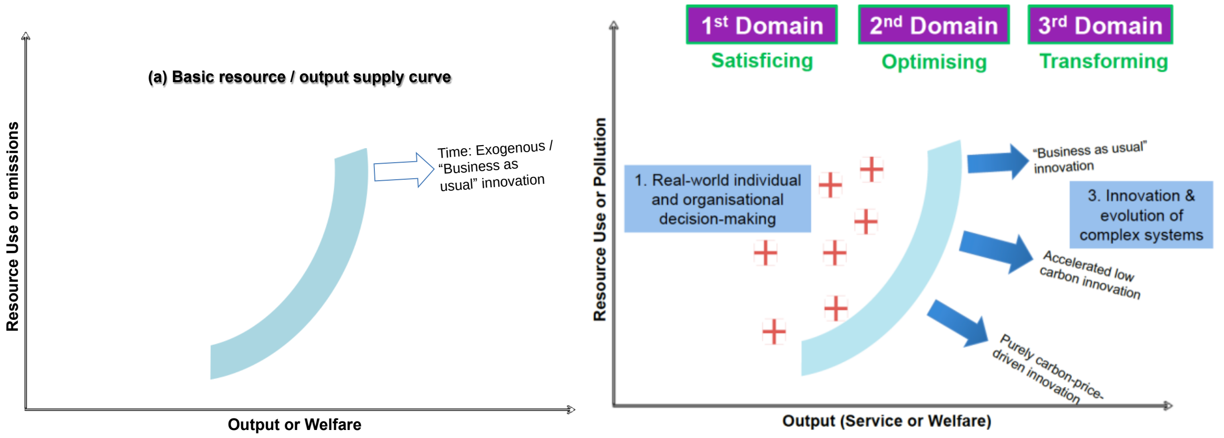
Any economy comprises thousands, or indeed millions, of curves associated with different resources, activities and services. Much of welfare economics is, fundamentally, about how economies can be designed to optimise the trade-offs defined by such curves, across the enormous range of resources available - largely as determined through market structures and relative prices, the prime mechanisms for transmitting information about the scarcity and value of the different resources available.

The simpler levels of analyses are time independent – hence the term 'equilibrium' economics. In this condition, given an assumption of optimising behaviour, no agents would be to the left of the line since they could improve welfare, without any greater use of resources, by moving to the line. In this sense the frontier embodies the classical economic concepts of supply curves.

Time then enters through movement of the curve itself – technical change, which increases the output available from use of a given resource, for example. The classical economics and modelling literature tends to make one of two simplifying assumption regarding such innovation. One is that this process is *autonomous* – it occurs from outside the frame of reference, like manna from heaven (or spillover from other sectors, or from R&D programmes that do not enter in the model). The other, more sophisticated, approach is to assume that such innovation is part of *optimising* processes - the product of economic agents maximising their benefits from innovations, and the product of accumulated investment in knowledge which then forms part of the economic production function.

[4] In this format the public policy objective can be interpreted as moving right (increase welfare), whilst reducing energy consumption and emissions (moving down). Note that the frontier in economics is often called the 'possibilities frontier', which is potentially confusing as soon as one brings innovation into consideration. Also economic textbooks would typically draw the curve as a straight line, and hardly ever show it bending backwards. However, there is such a thing as excessive energy consumption or emission levels, which would damage economic output – and indeed, plenty of evidence that this is not uncommon, in part through subsidies and the impacts of high oil price volatility on oil-dependent economies.

Figure 1: The technology 'best practice' frontier - (a) basic resource and supply curve and (b) resources and economic outputs in the Three Domains



In this illustration, the other two domains enter as illustrated in Figure 1 (b). Phenomena of the first Domain lie to the left of the line, producing less output than potentially available using 'best practice' for the same resource use. Clearly, this creates the *potential* for improvements apparently *without* any trade-offs.

The implied assumption of most economic theory is that self-interested individuals and organisations, given the freedom to do so, will naturally move to the 'frontier'. When reality differs from this ideal, neoclassical economics generally attributes this to various forms of market and institutional failures, transaction costs or other 'hidden' costs that are incompletely measured, and time lags in catching up with a moving target as innovation moves the best practice frontier. However as noted in the previous section, first Domain (or 'satisficing') behaviour implies that actually, most people fall well short of this. So do real organisations. It is principally the experimental evidence underpinning behavioural and managerial economics, which has revealed and explained this as a *systematic* feature of human psychology and organisation, rather than an anomaly that people or organisations will quickly and spontaneously deal with.[5]

On the other side of the line, the 'best practice frontier' defined by available technologies and systems moves over time: technologies and organisational structures improve to allow the same output with less input of resources. The third Domain is defined by the question not of *whether* the curve moves – whether there is innovation – but by *how* and *where* it moves – the pace and direction of innovation. The simplest workhorse assumption is innovation that is 'resource neutral' – it occurs equally across all inputs. This is obviously unrealistic. Nothing fundamental changes if the pace of innovation – in this case, the efficiency of using resources – is projected to vary for different resources.

Innovation economics gets far more interesting when it looks at how technology evolution may be channelled, accelerated and oriented eg. to reduce the use of more expensive or damaging inputs. As noted, this applies not only to innovation *per* se, but the development of infrastructure, rules and institutions associated with the use of major resources and associated technological systems. These possibilities help to define the third Domain, in which changes in technology, institutions, infrastructure and more can influence the whole direction in which systems develop. Over time this

[5] Note however that such behavioural and organisational theories only form part of the First Domain realities, which comprise all the factors which lead to societies operating far short of the frontier. See references in the introduction.

may fundamentally reshape the 'best practice' frontier, as per the direction of the movement of the curve in Figure 1b, and illustrated by the three different arrows of how the frontier might evolve.

The essential point emphasized in GHN (2014: Chapter 2) is that the different dsomains are not competing explanations of the same phenom`ena, nor is it simply that they have different relationships to the 'best practice frontier' of Figure 1. Rather, they describe different processes which occur at different scales: different social scales of decision-making, and different time horizons of those decisions and timescales over which consequences play out, as elaborated throughout GHN (2014).

4. The policy matrix and alignment with 'Mission-oriented' innovation

From this framework flows a natural approach to high-level mapping of policy mixes for sustainability transitions. Each of the domains corresponds to a different type of change that is needed if we are to move towards more secure and less carbon-intensive energy systems. For each of these, there are leading – though not exclusive – policy approaches (summarised in Figure 2 / Box 1).

Box 1: The Three Pillars of Policy

The Three Domains framework provides a natural policy mapping as illustrated in Figure 2:

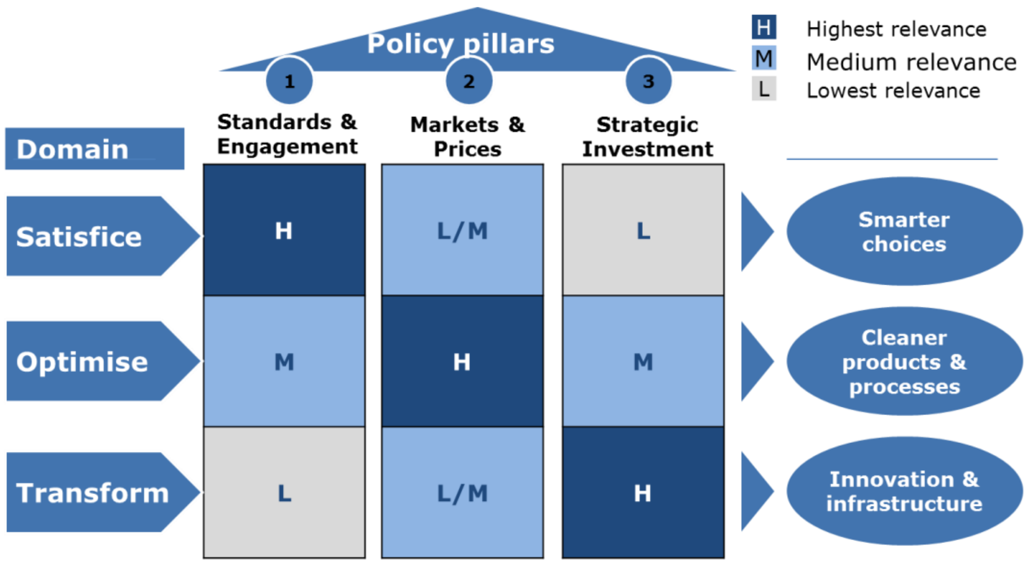


Figure 2: The policy matrix

As summarised in GHN (2014)

- *Smarter choices* can be fostered through appropriate standards and engagement. For example, energy efficiency regulation is typified by standards that ensure adequate insulation in buildings, remove inefficient products from the market, or require producers to display clear and unambiguous information to inform consumers. *Engagement* starts with such information and may build upon it in many ways to increase attention to, motivate, and facilitate, better choices.
- Most economic decisions to buy, sell or invest in *cleaner products and processes* depend on *markets and prices*. Measures that affect absolute and relative prices – including carbon

pricing - will tend to be the strongest and most relevant lever operating through market transactions. In practice their impact will also depend on *market structure* - many big energy sector investments are in sectors (like electricity), which if not directly conducted by state entities, are nevertheless strongly influenced by the rules and regulations that shape the market structure and related terms of investment.

- *Technology innovation and infrastructure* can be accelerated and guided in low-carbon directions partly by price incentives, but we illustrate in this paper the extent to which private investment in energy innovation is neither adequate in scale, nor likely to lead mainly in a low-carbon direction, unless there is either public involvement or other factors influencing strategic expectations. Infrastructure is also crucial. Hence, the key determinant will be *strategic investment* – investment in which the public returns exceed any conceivable returns to private investors, fostered by direct public support or other influences which, looking beyond short term private returns, support the evolution of more efficient and lower carbon energy systems.

Source: adapted from GHN (2014), Chapter 2.

END BOX ====================================

These form the three pillars of policy. They are illustrated in Figure 2 in a way that seeks to underline that each pillar has a prime focus of impact on the economics processes and opportunities in the respective Domain, but also influences the others. These interactions are, in fact, not peripheral, but central to the overall argument.

This is fundamentally because the domains themselves interact, and influence innovations. Thus for example markets and prices most centrally influence the decisions of economic actors seeking to optimize choices from existing products and processes, but may also raise awareness eg. of energy wastage (first Domain) and (along with R&D tax breaks) affect private sector *strategic judgements* around the costs and benefits of investments in energy innovations (third Domain).[6] As emphasized, classical economics recognizes the movement of the frontier, whether it is assumed to occur exogenously, or analysed as a function of R&D / knowledge accumulation and the incentives in competitive markets. The policy discourse is however framed in terms of identifying and fixing market failures. Thus for example in the context of climate change, the mainstream economics discourse emphasises competitive markets and carbon pricing, with technology spillovers the main justification for R&D expenditures and tax breaks.

The associated economics literature on innovation *policies* has long distinguished between such generic *horizontal* innovation policies, and more sector- or technology-specific *vertical* policies, which come closer to specific industrial policies.[7]

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[6] Even within second Domain reasoning one might consider the differentiation of R&D tax credits to acknowledge likely differences in the social return on R&D in different sectors (e.g. see Castellacci & Liu 2015), and argue that universally applicable R&D tax credits should be removed for innovation in activities likely to exacerbate ‘public bads’, on the basis of a lower expected social return.

[7] Horizontal innovation policies of course also move the frontier, introducing potential ambiguity into the terminology of the framework as displayed by Figure 1; however the authors suggest that *purely* horizontal

The main concern of this article is with *transformative* processes and associated policies. It follows from the above that all three policy pillars can be understood as having innovation effects, as all can influence the frontier, whether directly or indirectly. Pillar II policies are typically broadly horizontal, targeted at economy-wide policy goals rather than focused on specific technologies. For reasons outlined below, in energy at least they tend to induce innovation along incremental trajectories favoured by incumbent actors.

Pillar I policies are often sector-specific (rather than technology specific) and so fall somewhere between the horizontal and vertical dichotomy. Such policies, while aimed at driving adoption of already cost-effective technologies, can also result in movement of the technology frontier, through the mechanisms outlined by Porter & van der Linde (1995). Twenty years on, evidence for this 'Porter Hypothesis' – that environmental regulation could stimulate valuable innovation – has strengthened, (Ambec et al 2013), and refined to indicate that economic gains from such innovation are more likely when regulations stimulate process rather than end-of pipe innovations (Wagner 2003)).

The economic lens has tended to place the emphasis on horizontal policies, to enhance the innovative potential of many markets. The key characteristic is that such approaches embody a *neutrality* view of innovation; more may well be better, but the market – as influenced also by price signals to reflect externalities, and perhaps regulation justified by market failures – is the best vehicle for determining the direction of innovation (for a recent exposition, see Fischer, Newell and Preonas, 2013).

This contrasts sharply with the view that public policy should have a mission in supporting innovation with a public purpose – that it should influence the direction in which the frontier evolves in ways beyond the classical market prescriptions. That purpose may be simply to improve economic performance and competiveness in particular sectors, but the influential research of Mazzucato (2013) argues that the mission should often target other public goods, like health and environment. This implies a large role for vertical innovation policies, which correlate closely with the Pillar III policies of strategic investment in Figure 2. This article focuses particularly on such innovation in the energy sector, which aim not only to enhance innovation, but also to give it direction, to address the sector-specific concerns of the 'energy trilemma' (security, affordability, and sustainability).

Even though this approach highlights the importance of strategic investment in innovation, we emphasise that transformative processes are *not* confined to such Pillar III policies: indeed, this is a central point. Innovation may be promoted also by Pillar I policies, if for example standards are set aggressively close to the technology frontier (or even slightly beyond it), or if technology is linked with innovations in first Domain processes: behaviour, regulations, organisational routines and other ways of making better use of advancing technologies, and thus providing 'demand pull' for investment at or beyond the technology frontier – extending the mechanisms of the Porter Hypothesis.

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polices are best seen as fitting within the markets (second) Domain at least for as long as they are technology neutral. A review of the distinction and literature around horizontal vs vertical innovation policies is given by the OECD (Warwick 2013), which notes the close intellectual link between vertical innovation policy and the development of industrial policy initiatives in many countries, and suggests reasons for the rapid re-emergence of interest in industrial strategy in the OECD countries. Note that Crafts (2010) highlights three specific types of market failure, related to (i) infant-industry-related capital market failures; agglomeration externalities; and rent-switching via strategic trade policy. The first two have clear parallels with the analysis respectively of technology valley of death, and learning-by-doing, effects noted in this paper.

Moreover as already noted, innovation is also intrinsic to second Domain processes – indeed, their openness to innovation is one of the classical economic arguments for markets, in which private R&D may also be enhanced by 'horizontal' innovation policies (like generic R&D tax breaks on the grounds that markets tend to systematically underinvest in innovation), whilst prices (including taxes) obviously influence the direction of market incentives for innovation.

An effective policy mix for mission-oriented innovation can thus be understood as one which spans the bottom row of Figure 2, embracing and selecting tools from all three policy pillars. Which, as we now show, has indeed been the story behind major innovations already observed in the energy sector.

5. Applying the conceptual framework in practice - three examples

Before delving further into theory, we consider briefly some examples drawn from different electricity related technologies, to illustrate specific applications of the 'Frontier' diagram, and the way in which policies across all three pillars have – in different circumstances – influenced energy innovation. The three technologies examined – lighting, fossil fuel electricity generation and overall low-carbon electricity systems - are all of clear and significant relevance to the low-carbon energy transition, and are chosen to represent technologies and systems of different types (e.g. supply, end-use and network-dependent), and scales (small individual electricity-using units, large-scale centralized generation, and system level technologies).

(a) Lighting

Figure 3 illustrates the case of lighting technologies. Here, the key service involved is provision of light (measured in lumens); the relevant resource input (y-axis) is electricity inputs per lumen; the welfare-related output is lumens per $/€ expenditure. The graph shows three frontier curves approximating the commercial availability of lighting technologies up to approximately 1990, in the 2000s, and by 2015, respectively.

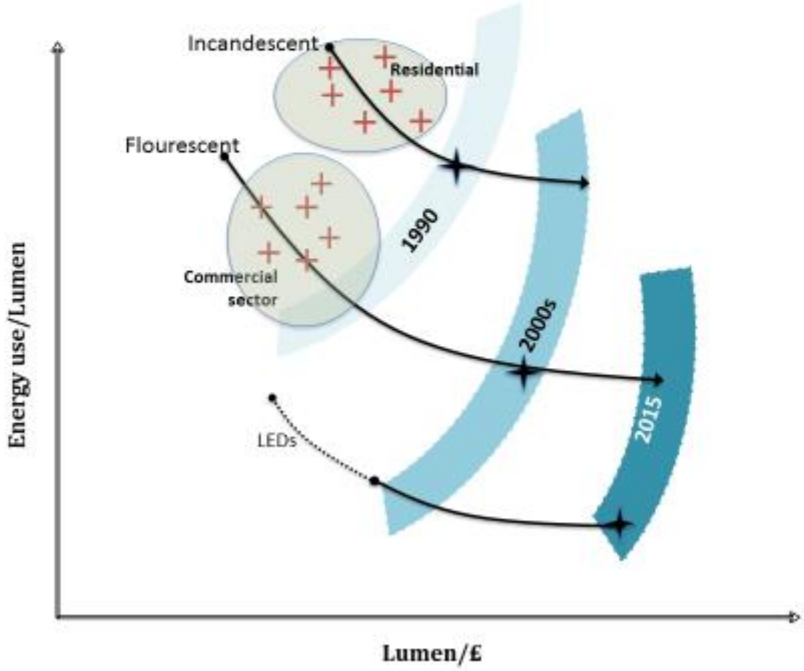

Figure 3: Technology frontier – evolution for lighting

The technology story can be largely told through the evolution of three technologies, and their use and status over these periods:

- By 1990, **incandescent bulbs** dominated domestic lighting and formed a mature industry, as typified by the ubiquitous 100W and 60W bulbs. The technical efficiency had improved only slightly over the previous three decades, producing a maximum below 25 lumens per watt (Glenny and Proctor, 1992) – the actual lamps *in situ* were frequently older and/or made to lesser standards and/or fittings, and hence far less efficient (as indicated by the area of "residential" crosses). The subsequent decade saw some cost reductions (but little efficiency improvement) in incandescent bulbs (Menanteaua and Lefebvreb, 2000), as illustrated by the upper line in Figure 3.
- The 'best practice' frontier up to 1990 also comprised various forms of **fluorescent tubes**, widely used in the commercial sector, with lighting up to four times the energy efficiency of incandescents, but they were typically more expensive and required a tube up to a meter long (Glenny and Proctor, 1992). However the technology was evolving rapidly into far more compact forms so that by 2000, **compact fluorescent bulbs** were commercially and competitively available for household fittings, reducing energy use per lumen several fold (Bladh and Krantz, 2008). This decade saw rapid cost reductions (the middle technology line) and they began to dominate the market.
- **Light Emitting Diodes (LEDs)** in 1990 were mostly known in the electronics industry but not commercially available for lighting; they intrinsically offer much higher efficiencies again, but initially were far too limited and costly. They only started to emerge for normal lighting applications, initially in quite specialized niches, around 2000. They then improved rapidly, offering far lower energy use at scale (being around ten times more efficient than incandescents) and ultimately lower all-round costs and (as the technologies evolved) better variety and controllability (the lowest line in Figure 3) (Almeida *et al* , 2014)

In terms of lighting productivity this is an extraordinary evolution. In the short term it has also led to a major reduction in the electricity use and environmental impact associated with lighting (though long-term technology studies have emphasized lighting as an emblematic example of rebound effects, with the transition from candles to kerosene lamps to incandescent bulbs being accompanied by an explosion of lumens, and more not less energy consumption (eg. Fouquet and Pearson 2006).

The lighting case exemplifies the diverse nature of innovation processes and policy drivers. The evolution of compact fluorescents was in part a simple commercial affair driven by the pursuit of improved service sector lighting products, but the clear potential to spill over in to domestic markets was then hugely stimulated by environmental pressures and government policies – many of which were essentially Pillar I policies (Mills and Schleich, 2014). In the early 1990s the EU introduced mandatory energy labelling on lightbulbs, along in many cases with forms of direct or indirect subsidies (eg. through 'white certificate' energy efficiency obligations on electricity suppliers). These helped to overcome persistent barriers, and evolved hand-in-hand with improved technologies.[8]

This experience also shook up the old incandescent industry, and made it more alive to the rapidly developing potential for LEDs. These initially were a spillover from an entirely different sector, but then become an object of dedicated government support and rapid promotion, not just with R&D but also through labelling, supplier obligations, and in some countries government procurement – targeted market development. Shortly after 2010, technology had advanced so far that numerous governments followed the Australian example of then simply banning incandescent bulbs (Howarth and Rosenow, 2014) – hence the cutoff of the third frontier line in Figure 3, of a technology that had become economically redundant as well as environmentally damaging - whose practical demise could be much hastened by simply outlawing their sale to those still inclined to follow the comforting 'first Domain' habit of buying filament bulbs.

(b) Fossil fuel power generation

Figure 4: Technology frontier – evolution for fossil fuel power generation

[8] Indeed it is interesting to read an evaluation from 1992: "The acceptance of compact fluorescent lamps in the very large domestic market is slow. A major obstacle is that it is very difficult for the domestic user to balance energy savings against higher lamp costs … as sales increase, the cost of compact fluorescents will fall, though their greater complexity and material requirements mean they can never be as cheap as filament lamps. At present they are bigger and heavier, and may not be suitable for some luminaires. Also some domestic users would prefer new lamps to look exactly like filament lamps.. another unfamiliar characteristics is the warm-up period to full light output. This has recently been reduced…. Some of the electricity supply companies have drawn attention to the 'power factor', a characteristic which will be improved in the next generation of lamps.' (Glenny and Proctor 1992, p.101). The barriers did not only apply to domestic CFLs: "High frequency developments may not obtain a share above about 10% in the batten market unless there is action by governments to favour the more energy efficient products."

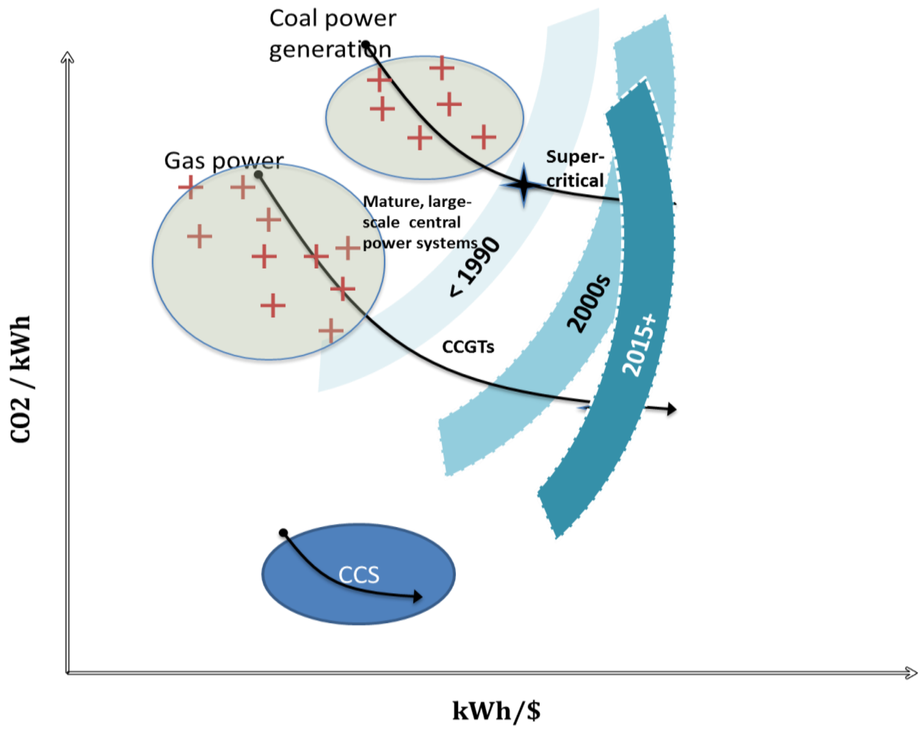

Figure 4 illustrates the evolution of the frontier diagram over the same period for fossil fuel power generation, this time with the resource input intensity being in terms of CO_2 per unit of kWh generation, and the output-welfare indicator being kWh/$. It shows the technology evolution for coal and gas generation respectively, each of which went through significant changes:

- In most systems, Coal dominated power generation around 1990, with large thermal stations reaching conversion efficiencies around 35% compared to the 20-25% efficiency typical of many older plant still in widespread use. As materials improved and the technology honed further, there were some further gains, particularly the higher efficiency of supercritical plant, which may reach around 47% (Hussy *et al*, 2014). But in cost terms, these were running up against the limits of scale economies, and increasingly offset by tougher environmental policy – which by raising the cost of emissions (with SO_2, mercury and NO_x controls preceeding the impact of carbon policies) has the economic effect of tilting the curve backwards, since gas is generally the cleaner fuel on most counts. Stripped of the impact of coal wholesale prices, the costs of coal power stagnated or rose, particularly where carbon prices began to be applied, as implied by the top end of the curve going backwards from around 2000 – but of course, remained in widespread use.
- Gas turbines for power generation were technically quite well developed already by 1990, drawing substantially on advances for initially military and then civil aviation. They had previously been largely confined to peaking roles, and entrenched models of state-run utilities tended to perpetuate this even though CCGTs already looked competitive on paper by 1990 in many regions (Buxton, 1992). The liberalization of power generation in much of Europe and the Americas combined with greater availability of natural gas and rising environmental pressures changed the dynamics. Whilst many old and less efficient installations remained, there followed rapid market growth, cost reductions and a leap in efficiency gains using combined cycle plants, as suggested by the curves (Hussy *et al*, 2014)

- CCS in principle offers much lower emissions and has long been held as 'demonstrated' – but only, as indicated, with a considerable cost penalty (Rubin *et al*, 2007) and with rather slow evolution.

The relative economics of coal and gas still depend on the combination of gas and coal prices with the nature and degree of environmental pressures, but in many systems *new* coal investment looks at best a dubious choice compared to gas, which is environmentally as well as often economically preferable (Lazard, 2017), as suggested by the almost vertical line for 2015.

In the case of these fossil fuel generating technologies, the innovation largely emerged from the combination of market pressures (including direct or implicit internalization of environmental costs) (Markard and Truffer, 2006), and spillovers from defence, aviation and materials sectors. Being large supply technologies, classical economic incentives dominated; and – beyond the generally high level of state involvement in all the sectors concerned - there was little need for direct state-led strategic investment to try and change the nature, pace or direction. It was thus classic 'Second Domain'-led innovation, embracing spillovers from other (often State-sponsored sectors), and learning-by-doing accelerated by market growth. Over time, the innovation was considerable, but it was also in the direction that suited and sustained the main interests and business models of the heavy engineering firms and utilities involved.

c) Renewables and low carbon electricity systems

Alongside these developments, more radical change was occurring most notably in renewable energy technologies. The developments have been well documented but are nonetheless striking, the strategically most important ones being with wind and PV. Both of these saw major improvements already during the 1980s which moved them from little more than curiosities to viable technologies with costs that had fallen by around 50% (wind) and 70% (PV) by 1990 during the decade (Lantz *et al*, 2012; REN21, 2013). This was followed with steady (for wind from 1990)[9] and more explosive (for PV from c. 2000) market growth with the latter eventually culminating with the 'solar surprise' as long-promised economies finally emerged to bring PV also within cost comparability to conventional power sources. (Lazard, 2017).

This was not however a simple story of technology innovation. There were technology spillovers (from semiconductor industries to PV; from aviation and materials to wind). There were focused R&D and development programmes to hone leading technology candidates and map the resources and interactions eg. of windfarms. Supply chains developed and industries grew. The major developments over the recent decades however were fostered mainly by subsidized markets – notably, feed-in tariffs (Johnstone *et al*, 2010). Klassen et al (2005) were amongst the first to try and disentangle effects of

[9] In the aftermath of the 1970s oil shocks, from 1980 to 1990 the unit size of commercially-available wind turbines grew from around 50 to 150kW, with hugely improved load factors and a halving of capital costs. These gains stemmed from R&D & development programmes combined with heavily subsidized deployment predominantly in Denmark and California. During the 1990s the industry professionalized around dominant designs, and grew with the entry of the major international engineering firms, and growing markets across Europe in particular. During the 2000s, typical unit sizes grew to over 1MW with energy costs halved from those of 1990, and started moving into offshore waters.

R&D from deployment in cost reductions, and a recent study by Bruegel underlines the complementarity of R&D and deployment in wind energy's development.[10]

As the technologies themselves became more plausible, there were institutional impediments (eg. with major struggles over planning permissions and grid connections) and questions about capacity and costs of balancing and backup on power systems – in the early years it was commonly asserted that grids could not cope with more than 5 or 10% input from such variable sources. More serious research at the time suggested it could be at least 20%, based on then-existing power system structures. But Germany has now surpassed 35% (BEE, 2017), and Denmark almost 50% (IEA, 2017). The emergence of better power electronics and control technologies (including responsive demand), smarter balancing markets, and interconnection, all played a role; dramatic developments in batteries open the prospect of significantly higher levels still, with the industry itself undergoing a more widespread revolution of both technologies and industry scales and structures.

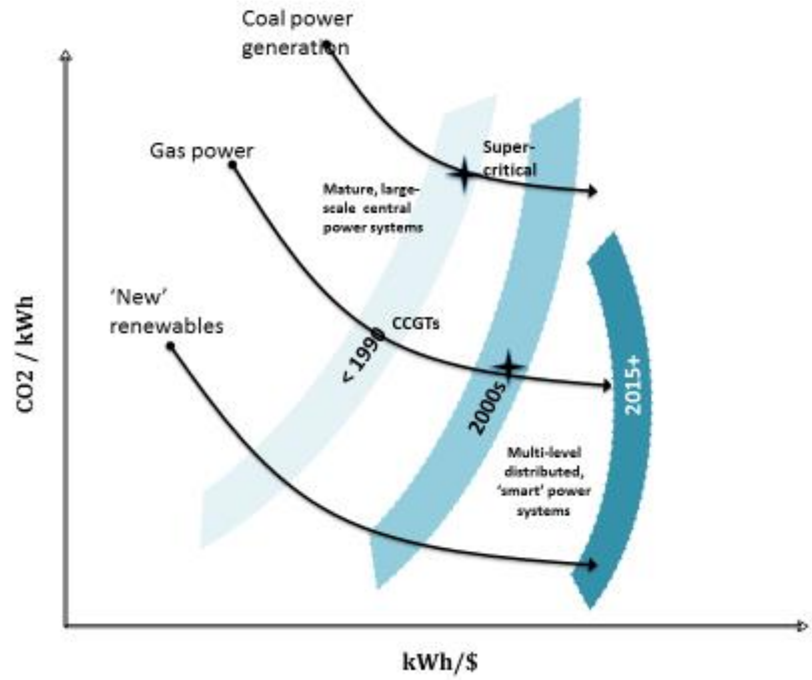

Figure 5: Technology frontier – overall low carbon systems

The net effect, in terms of the 'best practice frontier' for delivering low carbon electricity, is something like that displayed in Figure 5. It has enabled some governments to finally take the step analogous to the banning of incandescent bulbs, and ban new coal stations, with some having phased out coal generation altogether and others having set firm date by which to do so (including the UK, with a proposed phase-out date of 2025) (BEIS, 2016). By any reasonable measure the process is culminating as a technology revolution - one substantially driven by policy. The policies have drawn upon all three

[10] "Both deployment and RD&D coincide with increasing knowledge generation and the improved competitiveness of renewable energy technologies. We find that both support schemes together have a greater effect that they would individually, that RD&D support is unsurprisingly more effective in driving patents and that timing matters. Current wind deployment based on past wind RD&D spending coincides best with wind patenting. If we look into competitiveness we find a similar picture, with the greatest effect coming from deployment." (Zachmann, Serwaah and Peruzzi, 2014)

pillars, but with particular emphasis on deliberate strategic investment – major and interacting programmes of mission-oriented innovation.

However, the simple insight from these three examples is that innovation is not a simple product of 'strategic investment'. From the basic 'frontier' diagram it is apparent that the faster innovation proceeds, the more important the first and second domains may become – if the curve moves due to pure 'technology push' policies, then the faster it moves, the further consumers (and market structures) may otherwise get left behind. This of course would start to deter further innovation due to the lack of market demand. But the curve can also be pushed by demand – agents moving closer to the frontier, or market structures or relative prices moving demand towards different sections of the curve.

In terms of the associated policies, the relative mix of the different policy pillars and their interactions have differed radically between the three examples (chosen to emphasise the role of Pillars I, II and III respectively in the different technology evolutions). To a large degree, the apparently infinite complexities of innovation can be understood in terms of the relative mix and interactions of these components.

6. The innovation chain and cross-sector evidence

The policy pillars which flow from the Three Domains framework are themselves quite high-level abstractions. In starting to use the language of 'technology push' in relation to consumer or market demands, the links start to emerge with processes of technological development as viewed through the 'innovation chain'.

Despite the well-known limitations of a 'strong linear' model, as Balconi et al (2010) argued, a weakly linear framing of technological development—structured as phases of maturity from invention through to maturity—can be useful. It can be particularly relevant for understanding 'vertical' innovation processes associated with particular sets of technologies in a given sector, without forgetting that these are embedded within a broader inter-relationships, feedbacks, and multiple origins of and stimuli to technological innovation.[11] At minimum, it sets out stages of maturity which almost any technology needs to pass through, however many feedbacks there may be along the way. In that sense it outlines the *journey* required for a given class of technologies to evolve to full deployment, whether or not the journey contains various dead-ends, retracements of steps, or learning about better options along the way as a technology in practice iterates through phases of 'learning-by-searching' and 'learning-by-doing' (see eg. GHN (2014) Chapter 9, Box 9.1 'Iterating innovation'). We return to this point below.

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[11] Indeed Balconi et al (2010, p.11) note a danger of over-emphasizing the networked and interactive nature of technological change in policy advice, since "*it might become exceedingly difficult to design, implement and evaluate policies in a fully interconnected system. On some occasions, a simplified representation of the process of innovation which decomposes a complex system of interactions into (linearly) interconnected subsystems might not only be necessary but also desirable.*"

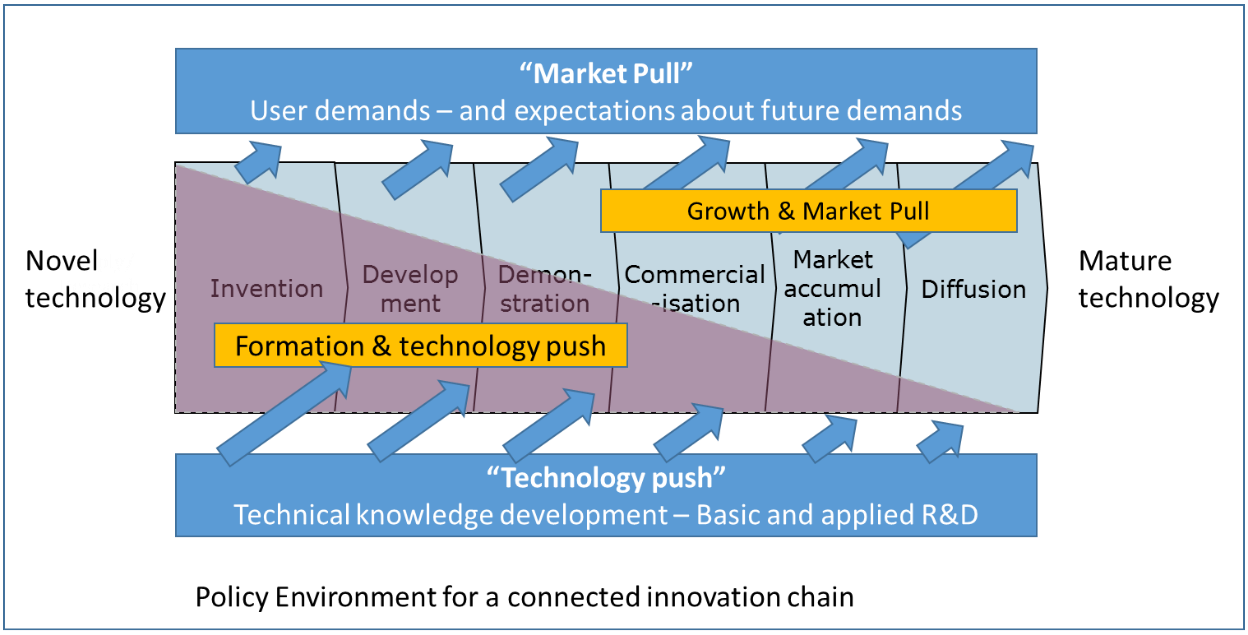
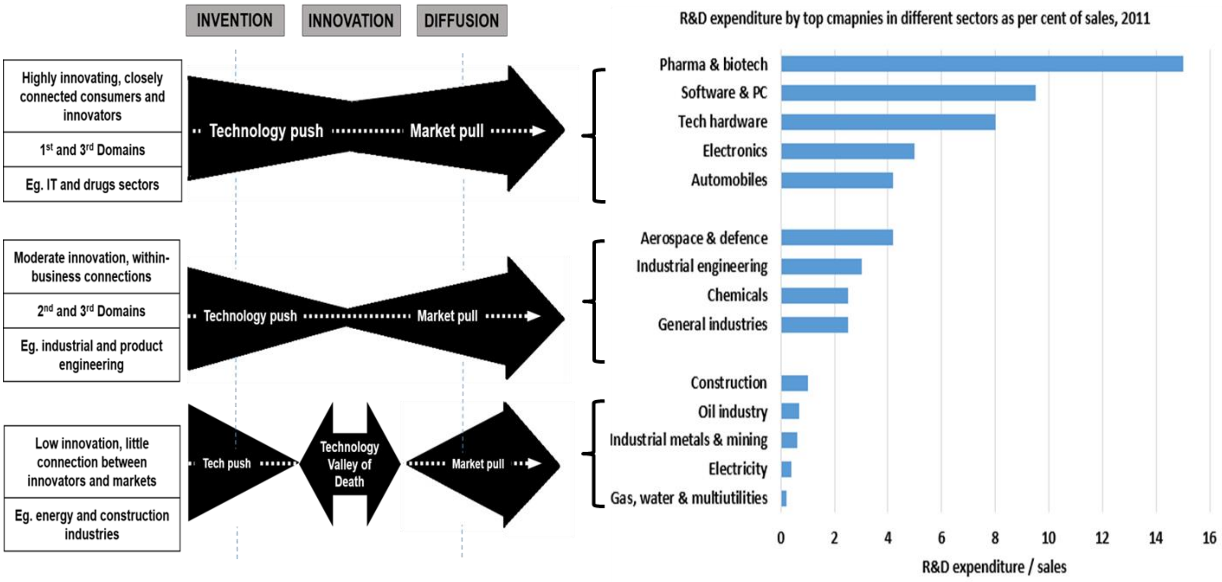


Figure 6: The Innovation chain

The exact structure of the innovation chain of course can be presented in varied ways, depending on the focus of interest; Figure 6 shows an innovation chain, drawn from experience with the UK Carbon Trust's commercialization programmes, which emphasises the central components involved in the process of moving from 'technology-push' to 'market pull' (the latter, in the context of the frontier diagram, being pressures from consumers 'pushing' up against the frontier).

The innovation chain is a useful structure for thinking about the policy mix across stages of maturity of a technology. Different sectors and technology fields face different challenges in enabling innovations to develop along this chain, and an understanding of differences in the innovation patterns within specific sectors or technology fields can inform how the chain can best be used to inform design of an appropriate policy mix.



Source: Grubb, Hourcade and Neuhoff (2014), Figure 9.7

Source: Grubb, Hourcade and Neuhoff (2014), Figure 9.3.
Data from EU – JRC R&D Scoreboard 2012, database of world's top 1500 companies

Figure 7: R&D intensities across different sectors and the relationship to the innovation chain

Figure 7 (right hand panel) shows the private R&D intensity (% of revenues spent on R&D) of major companies in different sectors, drawn from a database of the world's top 1500 companies. The striking feature is the scale of sectoral differences. Sectors that are generally considered to be highly innovative – like pharmaceuticals and biotechnology – spend in the region 10-15% of their turnover on R&D.

However, the energy utilities sectors – electricity, gas (along with water and multi-utilities) spend under 0.5% of their sales on R&D. The oil industry (even for this data, 2011, still in era of high oil prices driving new exploration and the emergence of the shale industry) was under 1%; the major energy-intensive sectors of metals, mining and construction were similar in aggregate. Of course the data is incomplete – energy innovation could occur at least in the middle level (eg. general & industrial engineering companies) or in smaller 'challenger' companies. But the scale of differences still demand explanation and, from a high-level policy perspective, suggests a challenge that decarbonisation requires radical innovation in what appear to be some of the least innovative sectors of the economy.

Why such large differences in R&D intensities of major companies between sectors? The innovation systems literature has recognised structural differences in the innovation performance of sectors and technology fields at least since Pavitt (1984) and Dosi (1982). Their work, and subsequent developments (Breschi et al. 2000; Malerba 2002) aimed to describe and explain heterogenous innovation patterns across sectors. This body of work emphasizes that sectors differ in their *conditions of appropriability* (the ease with which the value of R&D investments can be captured), the *nature of the knowledge base* (distinguishing, for example, the relative role of know-how and craft skills and codified scientific knowledge in sectors), alongside the relative technological opportunities across sectors.

More recently developed systemic perspectives on innovation have their roots in this tradition, but they have tended to focus attention on specific technological innovation systems, and as a result have at times overlooked these structural differences across sectors or technology fields. Instead, they have emphasized system functions within a given technological innovation system (following Hekkert et al. 2007, and Bergek et al. 2008b), or the broader concept of socio-technical systems that incorporate a wider set of concerns (Geels 2004). This backgrounding of structural differences between sectors is unfortunate: the conditions of appropriability and nature of the knowledge base remain helpful in understanding sectoral patterns of innovation, and corresponding policy interventions across phases of the innovation chain. Such a perspective is useful both across broad sectoral groupings (explaining differences between energy and pharmaceuticals, for example), but is also useful in comparing technology fields within the field of energy.

The recognition of differences in the innovation system characteristics among sectors and technology fields is useful, and it is made more so by combining it with the idea of an 'innovation chain', as suggested by the left hand illustration in Figure 7:

- In the highly innovative sectors, the development cycle is *relatively* quick and cheap, and product pull is strong: think of the profits potentially available to Apple from the *i*phone, or to a drugs company from a 20-year patent on cancer-inhibiting drug. In such sectors, the innovation chain functions effectively, linking technological opportunities with market opportunities and enabling new technologies to develop.
- In the electricity sector, in contrast, the product development cycle tends to be long, expensive, and risky: consider nuclear, or indeed, carbon capture and storage which has been pursued for 25 years now, and it is still only at the stage of demonstration plants. At the other end of the process, all innovations in power generation basically sell the same product – electrons. There is no 'premium' market for a radically new product, they compete largely on cost grounds with incumbent technologies that produce the same thing but have benefitted from a century of development. The conditions of appropriability – i.e. the degree to which investors can recoup the value of their innovation investments – are thus weak. Hence all the energy literature about the technology 'valley of death', reflecting the fact that these characteristics largely break the innovation chain, as graphically suggested in the bottom part of Figure 7 (a).

Of course this is a simplification. A significant part of energy-sector innovation has occurred in the industrial engineering companies, which are in the mid range of Figure 7(b), and which typically spend around 3% of their turnover on R&D. This is still considerably less than the highly innovating sectors, and moreover is directed mainly towards the interests of their major clients – the incumbent energy industries. From an evolutionary perspective, this implies that the energy sector will be less capable than many other sectors of generating the *variety* that is essential to enable radical evolutionary change. Hence the pattern reflected in Figures 4 & 5 for power generation – innovations in incremental improvements for established interests (coal and gas generation), but not radical change until governments intervened forcibly to support wholly new forms of power generation, with an important step being when wind energy markets had built up enough for some of these companies to enter the field, with all the expertise and resources they could bring to bear on scaling up the technology.

So the caveats on data and interpretation do not undermine some basic conclusions: the descriptive value of the innovation chain as a useful heuristic framework for structuring understanding about

stages of maturity of emerging energy technologies; the sector- or technology-field characteristics that enable a better-connected innovation chain; and the implication of the data that major energy transformation beyond established trajectories has to involve strong government action, to bridge the technology valley of death and to build markets in radically new ways of making (and using) energy.
Hence (and complementing the specific studies of wind energy cited in the previous section) the sometimes-derided innovation chain provides an obvious answer to 'the puzzle of fast innovation despite modest R&D increases' observed for renewable energy in the major study by Bettencourt, Trancik and Kaur (2013), whose empirically-based model 'reveals a regular relationship between patents, R&D funding, and growing markets across technologies.'

Combined with underpriced environmental concerns, this makes these sectors a *prima fascia* case for Mission-oriented innovation policies, with a strong dose of Pillar III policies on strategic investment.
For the pursuit of vertical (sector/technology-specific) innovation, the relationship between the innovation chain and the three policy pillars is in many respects straightforward. 'Technology push' is largely driven by strategic investments. These are usually led by public sector but not always: large companies in particular also make strategic investment decisions based on judgement about future trends, risks and positioning, rather than the more specific project cost-benefit appraisal based on current markets, or indeed other explicit cost-benefit evaluations. Individuals and occasionally philanthropic agents may also undertake strategic technology investments. Whatever the funding source, the *'technology push'* end of the innovation chain is basically a combination of technology-neutral processes arising from general R&D and technology spillover, with the way in which Pillar III policies contribute to reorienting the technology frontier of Figure 1.

Demand pull, however, is strongly influenced by the other two policy pillars: standards or consumer engagement (Pillar 1), or relative prices in competitive markets (Pillar II), driving demand for the product. Thus whilst the contribution of 'technology push' can be understood largely in terms of spillovers and strategic investments, the challenge of transformation necessarily involves inquiring into the demands for new products, arising from current markets (second Domain), as influenced also by behavioural and organizational factors (first Domain). Correspondingly, policy pillars I and II may help to accelerate innovation – but, in the absence of strategic investments or fortuitous spillovers (as with LEDs), this may predominantly be of an incremental kind, as illustrated with fossil fuel generating technologies.

For sectors like energy in which the 'technology valley of death' reflects in part a lack of consumer product differentiation, attempts to more radically change the technology landscape for public benefit are unlikely to succeed without *strategic demand-pull* – deliberate, usually subsidized, fostering of markets for the new products, usually at higher cost. This, as noted, has been amongst the most controversial aspect of innovation policy, for example in renewable energy, but the evidence of Figure 7 and the logic underpinning it – along with, but not confined to, inadequate carbon pricing - does offer clearer economic logic, which as noted is becoming more accepted in some of the economics literature (eg. Lehmann and Gawel 2013; Zachman et al 2014).

7. The Multiple Journeys

The rich characterisation provided by innovation systems theories—which see innovation as complex, multi-level and path-dependent processes—provides a clear justification for such strategic demand-pull policies in driving (or redirecting) a sectoral transformation. The systems literature already cited expands beyond 'technology push' and 'demand pull' forces, to also emphasise soft & systemic instruments, and notes the role of complementarity and consistency in policy mixes.

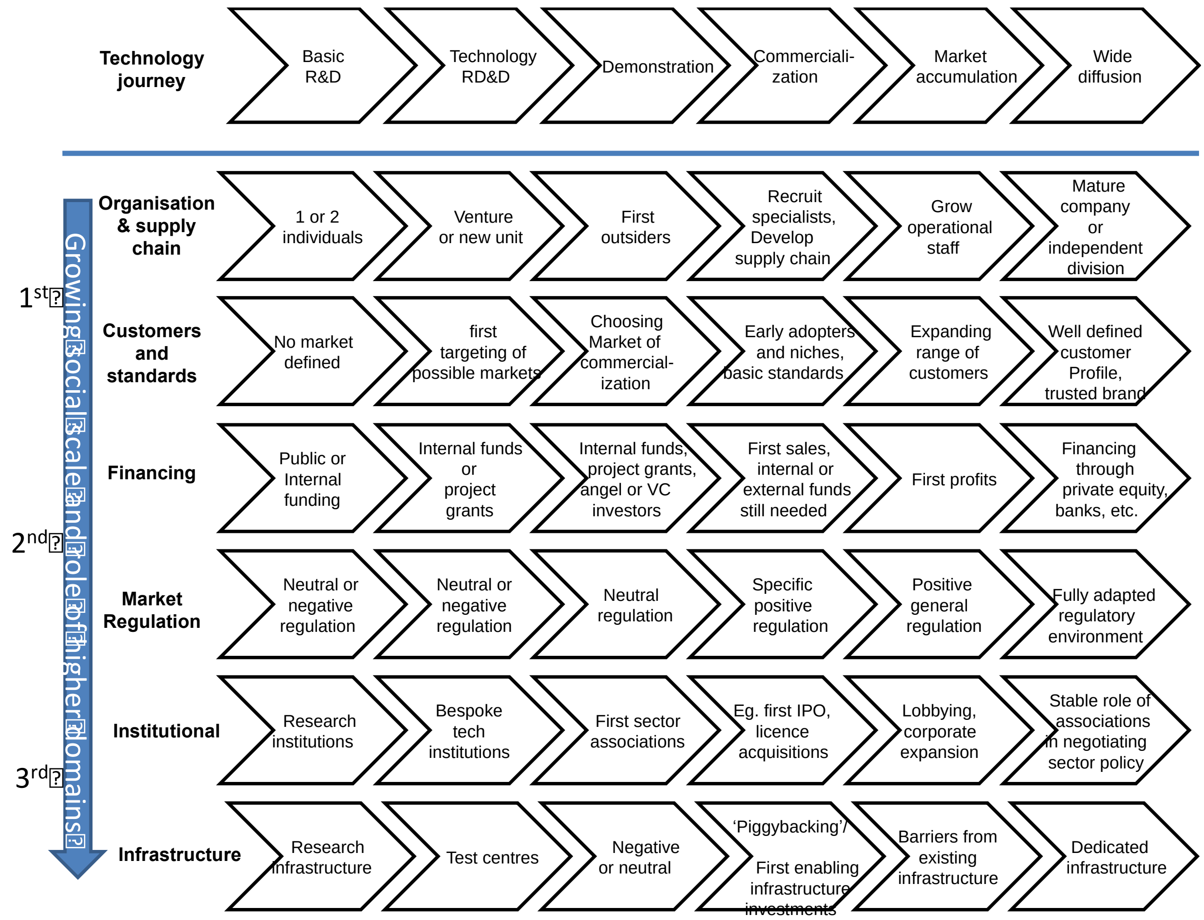
More broadly, existing conceptual frameworks in the innovation systems literature emphasise multiple co-evolving 'sub-systems' that accompany technological developments. The frameworks of Freeman and Louca (2011), Foxon (2011), or the elements of socio-technical systems articulated by Geels (2004) –deal with technological developments, institutions, user behaviour, business practices, supply chains, and so on. Bergek et al. (2008a,b) articulate several specific 'functions' of innovation systems which can be considered similarly as addressing the multiple processes involved in major transformations. The sheer complexity of full vertical innovation processes can thus be considered as arising from the need for innovations to go through multiple stages, which combine supply chain developments in the business relations along with the corresponding developments that are far outside the control of any company.[12]

These broader frameworks in the systems literature are often perceived as inimical to the simple 'innovation chain', and the very richness and complexity of such frameworks can sometimes hinder communication and the derivation of clear and specific policy recommendations. This complexity also makes it hard to establish a clear analytical relationship to or dialogue with the simpler (and quantitatively-oriented) perspectives of classical 'second Domain' economic approaches to innovation.

To draw us back to our starting point – the division between the economics and systems innovation / evolutionary communities – this paper concludes by suggesting one way to construct a bridge from the technology innovation chain to these wider considerations - a relatively simple way of relating them - is by considering the path from novel to mature technology as involving multiple journeys, as illustrated in Figure 8.

Figure 8: The Multiple Journeys

[12] See for example Special Issue on "Making, Buying and Collaborating for More Sustainable Production and Consumption" edited by the Journal of Cleaner Production in 2017 (vol. 155 part 2)



As with the chain itself, this can be done at various levels of granularity, and Figure 8 shows the basic technology journey from novelty to maturity accompanied by multiple other journeys. These reflect developments, across all three domains of socio-economic decision processes, that must accompany the evolution of many new technologies – particularly disruptive ones.[13]

- In their earliest phases of development, new inventions are often developed by individuals operating in a research-based organisation (or corporate R&D lab). As the technology moves into the innovation phase however, the scale grows and the emphasis shifts towards producing some kind of workable product that can be sold – hence, managerial skills, organisation and interface with the private sector becomes important, as the technology starts to become a product and a business – a classic point at which the transition falters and technologies languish for years or decades. If and as the technology navigates its way across this chasm, the organisational unit must transform with it and start to extend its links with others in the supply chain required. Williams (2000) noted that "Inasmuch as these two work in tandem, we need to find ways to treat technical and organisational innovation in a combined manner.."[14]

[13] This is an elaboration by the author from Carbon Trust (2008) Memorandum 64 presented to the UK House of Commons Select Committee Enquiry

[14] *Williamson, O.E. (2000)* The New Institutional Economics: Taking Stock, Looking Ahead, *Journal of Economic Literature*, vol 38, no 3: 595-613 (p.600)

- The journey for *customers and standards* may be a 'slow burn', but failure to identify and engage potential customers - markets for the products - in the early stages will cripple attempts to bring in private finance. Market development requires early adopters or niche markets, which may often involve both first (behavioural) and second (classical economic) drivers. Information campaigns – marketing for the private sector – may be important, but the technology, and its uptake and brand value may be influenced by the development of standards relating to performance, safety etc, and associated component standardisation which can help supply chain development. If the company is a new venture owning the IP, during the stage of commercialisation it may sell out to larger companies that have established customer bases, networks and brand value, along with the financial muscle to sustain and expand the journey - providing the new technology doesn't threaten to undermine the incumbent's core interests.
- The *finance* journey starts with public or (sometimes) internal corporate funding: there is no market, there is merely faith that the idea may prove to yield something of value. Hope and intellectual curiosity cannot sustain technology development: that requires money, which sooner or later will start to outstrip the capacity of public funding (and may test the patience of parent corporate funders). New entrants, not shielded by a parent organisation, may be particularly vulnerable as they seek to move beyond pure public grant finance to persuade a bewildering array of sceptical private sector 'angel' and 'venture' capital fund managers that their idea is worth backing. Indeed, Hall et al (2016) represent the finance sector itself as a complex system spanning all three of the domains – behavioural finance, the main 'market' characteristics of the established finance industries, and finance as an evolutionary system deeply intertwined with regulatory and institutional structures.
- Hence, often overlooked in economics of innovation studies, yet prominent in innovation systems research, is the importance of the *regulatory journey.* Regulation can initially be neutral, but is more likely has been designed around incumbent products which may be poorly suited for new technologies. As the technology moves towards market, many regulatory barriers may need to be overcome – and because of regulatory complexity and the powerful influence of incumbent interests this may be a slow process, as with reform of rules around network connection and charging and electricity market design in relation to distributed energy resources.
- Related to this, *Institutional structures* often need to evolve. A growing sector needs to develop its own associations that are eventually able to stand alongside incumbents in the struggles for influence over key regulatory, financing and governance decisions. The priorities and structures of government departments themselves may reflect the structures of technological systems, and the ability to drive change may owe much to the institutional robustness of decisionmaking institutions to make rules contrary to incumbent interests.
- Finally, as the scale grows, and disruptive technologies may often require new infrastructure to grow at scale. The alignment - or not – of a technology with established infrastructure may become more and more important.[15] Indeed, the evolutionary economics literature emphasises not only the role of niche markets, but the potential for 'piggybacking' on existing infrastructure until a sector has matured sufficiently to fund – or lobby effectively – for its own infrastructure, as with the evolution from modems to broadband.

[15] Thus the motor car only finally came to realise its potential as horse tracks gave way to tarmac roads. The most obvious modern energy analogy is the mismatch between power systems designed for one-way flows from huge centralised stations generating baseload power, compared to the characteristics of decentralised renewable energy sources and smart meters which may embed the generation and dynamic use of electricity throughout the system.

The schematic of 'multiple journeys' remains a simplification since it does not illustrate the feedbacks or (overtly) linkages, but it underlines the point that technology evolution involves multiple processes, alongside the evolution of the technology itself. We suggest that this 'journeys' schematic provides a clearer mapping of co-evolving sub-systems to the stages of maturity of the technology itself. This provides, in our view, a useful way of articulating the need for a policy mix that develops across the chain. For policymakers, it provides the outlines of a policy roadmap that goes well beyond the classic prescriptions from the economics of innovation (related to pricing and demand-pull), but also provides a clearer narrative about innovation support than existing guidance based on avoiding system failures (Klein Woolthuis et al. 2005) or supporting key functions (Hekkert et al. 2007).

Figure 8 orders the 'other journeys' going down roughly according to increasing scales, and hence, the relative influence of the different domains. The journeys of organisational structure and development of the initial customer base, brand and associated standards can be clearly identified with the first Domain. The next two – journeys of finance and regulatory structures (including market design and tax policies), that help to define the market, risk allocations and the prices faced, influence quite directly second Domain decision-making – classical economic – processes, as influenced by the structures of financial markets and product markets. The journeys of institutional structures and infrastructure correspond chiefly to third Domain processes, and their need to be adjusted to fit new technological system regimes. As noted, to an important degree this approach of articulating multiple 'journeys' has clear relations to existing strands of the innovation systems literature. The regulatory, institutional and infrastructural journeys can be related to the 'landscape' and 'regime' levels of the multi-level perspective (Geels 2002). Similarly, whilst we would not claim a simple 'one to one' relationship, most of the functional categories of Bergek *et al* (2008a) can similarly be mapped: their first three functions are largely identified with the technology, organisation and supply chain journeys; their functions 4 and 5 (market formation and resource mobilisation) correlate quite well with the market and finance journeys.[16]

On complementary perspectives and metrics

Emphasising the multiple journeys required for successful transformation helps to pinpoint two quite distinct components to the intellectual gulf (with which this paper opened) between economic-innovation and systems innovation / evolutionary perspectives, in terms of the typical metrics of quantification: prices, and patents.

Prices are generally assumed to reflect intrinsic technology costs. But they also have to encompass all the other costs and risks represented in Figure 8: the costs of establishing a business and its organizational development, the cost of finding and building new supply chains, the risk premia imposed by the financial community (particularly for innovations that do not generate a new consumer product, but depend on regulated markets contingent on governments and regulatory decisions); the institutional hurdles and costs facing a technology striving to displace current industry

[16] The first three functions articulated in Bergek et al (2008a) are knowledge development and diffusion; influence on direction of search; and entrepreneurial experimentations, which are followed in their ordering by (4) market formation and (5) resource mobilisation. Their final two functions (legitimisation and positive externalities) are harder to map – they note that 'positive externalities' are "not independent of the other functions but rather indicates the dynamics of the *system* on a functional level" - though of course the Third Domain processes involving the Third Domain 'journeys' in Figure 8 (regulatory structures, institutions and infrastructure) may be particularly important in this.

models. Thus, the economic interpretation tends to focus on price as indicating the intrinsic resource requirements of a *technology*, i.e. just the first of the journeys, but it may just as much indicate misfits with current systems and the obstacles that need to be overcome on all the other dimensions of the multiple journeys required. Of course these are also real costs – but essentially transitional ones, a measure of the effort required to overcome the barriers to a more 'level playing field' between new and incumbent technologies.

The other indicator concerns *patents*, the main workhorse of most economic studies of the innovation process, widely used as an index of the productivity of both R&D and market incentives to promote innovation. But patents only record one form of innovation – and one that is likely to predominate in the earlier stages of the innovation chain. The latter stages – the economic improvements from scale, experience, and better supply chains; the growing management expertise and value of more confident financiers; the gains from more appropriate regulation, institutions and infrastructure – none of these generate patents.

In short, the two main metrics used to inform the more quantified 'second domain' economic perspectives on innovation tend to focus attention and measurement on just the top-left hand area of Figure 8. Not surprisingly, therefore, the discourse defined in terms of 'correcting' for the 'market failures' of spillover, and inadequately priced externalities, lead to policy recommendations emphasizing R&D and carbon prices, and tend to decry the 'inefficiency' of the strategic demand-pull policies (as typified by renewable energy feed-in tariffs) (e.g. Boehringer and Rosendahl, 2011; Fischer et al. 2013). Some economists have started to challenge this on grounds of learning-by-doing, path dependency and potential co-benefits of renewable energy supports (eg. Lehmann and Gawal 2013) but this remains controversial within the discipline.

Yet effective mission-oriented innovation has to span the full scope of Figure 8. Not surprisingly therefore, systems innovation researchers – and the companies pursuing the new technologies - naturally place far more emphasis upon the necessity of support – or at least, consistency and coherence - across the multiple journeys associated with practical deployment.

A map for the evolution of policy packages

The frameworks presented in this paper can inform policy mixes at two distinct levels. The high-level implications are as illustrated in Box 1 (Figure 2): the value of policies across all three pillars, to influence decision-making in the corresponding domains. As discussed elsewhere (GHN 2014, concluding chapter) for energy transformation this can also provide a more compelling narrative around the prospects for keeping energy bills constant, as progress on energy efficiency and innovation offsets the price impact of internalising external costs.

Beyond this somewhat high-level categorisation, Figure 8 offers a tool for more specific diagnosis. Nothing in Figure 8 implies the need for *central* coordination, but it quite clearly implies potential need for multiple instruments in any transformative process. To use the typology developed in Rogge and Reinhardt (2016), it offers a map of potential *elements* to be considered. These are more likely to be *consistent* if different instruments support a technology's evolution across the different journeys. This requires a *policy strategy* (loosely – a high-level view of how a technology could evolve from left to right, ie. objective and principal plans), supported by *coherence of process* – most obviously, a perspective spanning from top to bottom of Figure 8 to ensure that the very different actors involved in the different journeys (Treasuries and sectoral departments, regulatory agencies etc) share in the same ultimate goal of mission-oriented innovation.

Innovation, like health, is complex: there is no universally right policy mix, any more than a doctor would prescribe treatment without examining the patient. Technologies like IT & pharmaceuticals may require little beyond the standard prescription of markets, industry standards and the protection of property rights. The data of Figure 7, however, indicate that energy sector innovation, left to itself, is in much poorer health.

The process of innovation on the technology journey cannot proceed too far (or efficiently) if there are major roadblocks on the other journeys. Policy packages need to be grounded not only in the general nature of the problem (an innovation chain broken by expensive technology push, network dependency, and lack of product differentiation, amongst other factors). They need to reflect the stage of evolution and where on the multiple journeys the critical obstacles lie. Thus for example, one can see that even with improved renewable technology and strong market supports from government, important roadblocks in the evolution of renewables have included unfamiliarity to the finance sector, a range of regulatory barriers (including planning consents, generator licencing and terms of grid connection), with multiple barriers in the regulatory, institutions and infrastructure journeys arising from the current organisation of most power systems around large, centralised generation.

To conclude: this should not be interpreted as simply a way of supporting the case for 'systems innovation' approaches in contrast to mainstream economic approaches. It is entirely possible that those pre-occupied with trying to help demonstrated technologies through the multiple journeys may overlook both the greater potential of even newer technologies (actual or prospective) that could emanate from R&D, and the strategic value of broad-based incentives like carbon pricing to change the positioning of major players essential to the transition. But it equally true that more traditional economic perspectives, focused on the familiar second Domain indices of prices, competition, and patents, are likely to overlook and undervalue the importance of addressing all the journeys, across all the domains, in ways that can only really be delivered by strategic deployment with clear public goals in mind.

The case is thus not that one of the London conferences mentioned in the opening was more useful than the other – but that to really help improve policy mixes for transformative changes, the two communities need to combine around a common and broader framework of understanding, big enough to recognize what each can bring to the table.

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