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On order and complexity in innovations systems: Conceptual frameworks for policy mixes in sustainability transitions

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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 successively larger scales of time and social structures. We note the high-level implications for policy mixes 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. Policy instruments 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

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renewable energy targets, and German PV supports in particular, commonly arguing for policy beyond R & D to be 'technology neutral' (e.g. a single emissions target, not multiple targets, and main emphasis on carbon pricing).[1] 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 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 policy instrument 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 mixes, 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,[2] 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 et al. (). 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 policy instruments, 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.

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 [3,4] of one instrument for each goal, with Lindblom's [5] critique); the gulf has merely taken on somewhat different forms in the context of modern economic treatments of endogenous technical change (e.g. The extensive modeling studies in the Innovation Modelling Comparison Project [6], 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 (e.g. [7]), justified with specific reference to identifying where the market barriers may lie (e.g. [8]), and with patents as the main index of innovation (e.g. [9]). 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 (e.g. [10]; Geels and Schot, 2007). 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 [11]), to be combined into a policy instrument mix to achieve (single or multiple) policy objectives. For example, from the economics perspective, Jaffe et al. [8] conclude that the interaction of market failures associated with environmental pollution and with innovation and diffusion of new technologies provide a

[1] 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 [69] – 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. [67,70]).

[2] 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.