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Integrating structural tensions into technological innovation systems analysis: Application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada

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ABSTRACT

This paper augments the technological innovation systems (TIS) framework to provide policy guidance on how to manage interactions between a core technology and its larger sectoral context. A *TIS development cycle* is presented that combines the TIS framework's ability to clearly illuminate policy gaps with Erik Dahmén's idea that technological diffusion creates structural tensions that introduce transformation pressure. This pressure can result in stagnation and unrealized development potential or spur sectoral complementarities and the evolution of a TIS into a larger "development block" of interlinked technological systems. Integrating structural tensions into TIS analysis highlights how the evolution of a focal technology induces technological complementarities and creates a need to continuously re-design policies. This underscores the continued benefit of a technology system perspective, even as a technology matures.

The revised TIS framework is applied to a case study of the Canadian province of Nova Scotia that explores how variable renewable electricity diffusion introduces structural tensions with existing electricity grids, requiring the use of complementary technologies that add storage and flexibility. Nova Scotia aggressively developed wind energy and built a high-voltage direct-current transmission line to import hydroelectricity that could back-up variable renewable energy sources like wind.

1. Introduction

Scholars have made extensive use of the technological innovation system (TIS) framework (Bergek et al., 2008a) to study emerging or "niche" sustainable energy technologies (Jacobsson and Bergek, 2004; Kamp, 2008; Negro et al., 2007; Markard et al., 2009; Dewald and Truffer, 2011; Binz et al., 2014; Walrave and Raven, 2016; Markard et al., 2016). As these emerging technologies mature, a re-examination of the TIS framework is warranted. Technology diffusion will re-shape technological system barriers and opportunities, and create the need for sectoral adaptations that introduce new institutions, technologies and infrastructures.

Renewable energy technologies, such as wind and solar, are moving beyond their niche stages. The levelized costs of renewable technologies are competitive with fossil fuel resources in a number of jurisdictions (Lazard, 2016) and global renewable electricity diffusion rates are increasing (BNEF, 2016). Yet, these technologies face challenges integrating into existing electricity systems because they depend on solar and wind resource availability (i.e. their output is "variable" or "intermittent"). Energy transition momentum could be slowed unless the electricity sector makes technical as well as institutional changes to integrate large amounts of variable renewable energy technologies.

The integration of variable renewables into electricity grids presents an example of what the Swedish economist Erik Dahmén (1989) called "structural tensions". Dahmén's ideas influenced the development of the technological innovation systems (TIS) framework, yet this framework has neglected to consider how a TIS will increase interactions with its larger sectoral environment as it matures. The paper integrates the notion of structural tensions into the TIS framework by introducing a *technological innovation system development cycle*. This new framework is used to explore sustainability transitions in Nova Scotia, a Canadian province that aggressively developed wind energy and could further enable variable renewable deployment by building a high-voltage direct current (HVDC) transmission line to import hydroelectricity from a neighbouring jurisdiction.

The next section of this paper reviews the technological innovation system approach and presents a new analytical framework. The third section describes the methodological approach used to apply the new framework. The fourth section presents the Nova Scotia case study by analyzing the history of variable renewable development and

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Table 1
Technological Innovation System Functions.[1]
Adapted from Bergek et al. (2008a), Hekkert et al. (2007), Markard and Truffer (2008).

Innovation Function	Description
Entrepreneurial experimentation	New firms, incumbents, as well as public and social actors experiment to find new opportunities and increase the diversity of socio-technical options.
Knowledge development and diffusion	Research and development. Sharing knowledge through social networks and searching for existing knowledge.
Guidance of the search	Enticing new actors to enter the innovation system and increasing expectations by providing a clear development goal or mission.
Market formation	Creation of markets from small niches to large-scale diffusion.
Resource mobilization	Financial, human, and physical (e.g. infrastructure) resources that act as important inputs and enablers of production and learning.
Creation of political legitimacy	The presence of advocacy coalitions and public support helps counteract resistance to change.

renewable integration structural tensions, followed by a discussion of future development possibilities. The fifth section discusses lessons for technological system analysis, and the final section concludes by calling for TIS research to consider the implications of structural tensions.

2. Technological innovation systems and complementarities

Sustainability transitions scholars use the technological innovation systems approach to study the evolution of novel technologies. A technological system focuses on the “generation, diffusion, and utilization of technology” (Carlsson and Stankiewicz, 1991), in contrast to innovation systems with national (Nelson, 1993) or sectoral (Malerba, 2004) boundaries. The TIS framework was refined by Bergek et al. (2008a) and Hekkert et al. (2007) by introducing the concept of “functions”. Functions are key sub-processes or activities that serve the purpose (i.e. function) of developing, diffusing, and using new technologies. Six key functions are listed in Table 1. The functions present a practical check-list of the technological as well as social and institutional changes that policy actors can influence.

As these functions are strengthened they build up an innovation system’s structure, which is composed of actors, networks, institutions, and technologies (Jacobsson and Bergek, 2011). As the system structure builds, it can further reinforce the functions. For instance, entrepreneurial experimentation can increase the number of actors within the system, which would then improve the human resource mobilization function. Policymakers should aim to trigger these positive feedbacks, or processes of “cumulative causation” (Jacobsson and Bergek, 2004; Suurs and Hekkert, 2009), by analyzing strong or weak functions, as well as the structural characteristics that support or hinder the activation of these key innovation processes (Jacobsson and Bergek, 2011).

Sustainability transitions scholars use the framework to study specific, focal technologies (e.g. wind, solar, energy efficiency) with the promise of triggering societal transitions (Markard et al., 2012). This focus guides the development of “technology specific” policies (Jacobsson and Bergek, 2011; Sandén and Azar, 2005). However a technology focus comes at the expense of considering the wider contexts within which technological systems are embedded (Bergek et al., 2015). This includes understanding how focal technologies interact with other emerging technologies (Sandén and Hillman, 2011), infrastructure systems (Andersen, 2014), and sectoral environments (Markard and Truffer, 2008; Smith and Raven, 2012). Considering these wider contexts is increasingly important in sustainability transition studies, because as clean technologies diffuse their interactions with other technologies and sectoral socio-technical systems are likely to increase. The structural rigidities of a sectoral “regime” can hinder the development of new technologies (Geels, 2002). However, existing sectors might also enable sustainable innovations (Haley, 2015, 2014; Mäkitie et al., 2018), and foster complementary technology interactions (Markard and Hoffmann, 2016). Creating the right complementarities might be integral to the further development a TIS.

As sustainable energy technologies diffuse more widely, there is a need for a framework that combines the clear policy guidance that comes from TIS analysis with insights on the frictions and complementarities that can occur as new innovations evolve and interact with their larger environments. This paper presents such a framework by integrating TIS with the theories of Erik Dahmén (1989). As will be discussed, this is in many ways a theoretical re-integration because Dahmén’s ideas informed the TIS approach used in sustainability transitions.

2.1. Dahmén’s development blocks and structural tensions

Erik Dahmén was a Swedish economist who considered the role of social and technological complementarities in the evolution of an industry or group of industries. He understood industrial evolution as resulting from the “resolution of a series of structural tensions” (Carlsson, 1989, p. 7). A structural tension is a mismatch or imbalance between an innovation and its wider sectoral system.[2] These tensions can be alleviated by adapting connected technologies or by changing other elements such as organizations, laws, marketing strategies, or political structures to overcome the resistance of vested interests.

Structural tensions introduce both positive and negative transformation pressure. ‘Positive transformation pressure’ exists because innovations create new opportunities for increasing the performance of the entire sector by combining complementary technologies, institutions, and firms to create what Dahmén called a “development block”. To create positive pressure, other system elements must change to create a balanced or complementary situation. For instance, Dahmén (1989, pp. 115–116) discussed how the introduction of cement induced follow-on innovations in concrete product industries, and how improvements in electric machinery and equipment demonstrated their true potential after large investments were made in hydroelectricity and electrification.

Innovations can also introduce ‘negative transformation pressure’ because they can make the old ways of doing things obsolete or less effective. This is a process of ‘creative destruction’ that pushes some economic sectors or actors out of the economy. Dahmén discussed how failing to find the complementarities that would build a new development block led to the dominance of negative pressure. An inability to find complementarities might also result in unrealized development potential, which would indicate a failure to fully exploit structural tensions to create positive pressure.

There is a constant interplay between negative and positive transformation pressure. Structural tensions can create negative pressure, which is converted to positive pressure if the tensions are alleviated. The resolution of one structural tension can also create new imbalances and tensions (Carlsson et al., 2002, p. 235). For instance, Dahmén (1989, p. 120) explained how weaving innovations in 18th century

[1] Some lists include “creation of positive externalities” (Bergek et al., 2008b). This paper does not use this function because the interaction dynamics it describes are included within the analytical framework.

[2] Structural tensions are similar to what Hughes (1983) called “reverse salients”.