Understanding the formation and influence of complementary innovations in large energy technology systems: The case of urban energy storage in Ontario's electricity system

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Abstract

The question of how electricity systems are evolving or transitioning to new systems in response to resource and climate change pressures requires a systematic approach that is sensitive to political, social, technical and economic influences. The purpose of the research is to describe the effects of a complementary innovation on the endogenous dynamics of change in the Ontario electricity sector, using the specific case of large scale Li-ion battery energy storage. The purpose of this paper is to present a conceptual framework that is developed for future research that will empirically contribute to the growing theory on the formation and influence of complementary innovations in large energy technology systems. The Ontario electricity sector provides an appropriate context within which to apply this framework in exploring the endogenous elements of change in a sector, and the influence of complementary innovations. This is because the sector is: (1) in a process of transition in response to government pressure most notably through the Green Energy Act and FIT program; and (2) it has active actors, networks and institutions in the niche and complementary innovation fields. The case of Li-ion batteries has been chosen because of access to companies developing and marketing these in Ontario. Ryerson University (2010) and the University of Toronto (2011) are conducting research on the implementation of modular Li-ion storage units of 340kWh capacity and 250kWh capacity respectively to be scaled to MW capacity in partnership with companies in Ontario. Each of those projects is funded by various government and regime actors.

Introduction

Electricity systems are large technical systems that present the complex challenge of meeting societal demands while responding to pressures from resources and the progression of climate change (Sims et al., 2007). Carlsson and Stankiewicz (1991. p.111) describe technological systems as *"… network(s) of* *agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology. Technological systems are defined in terms of knowledge or competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks."* Understanding electricity systems, and energy systems in general, is difficult because they operate within a socio-technical realm that involves a large range of activities politically, socially, technically and economically (Hughes & Strachan, 2010; Kemp & Volpi, 2008; G. P. J. Verbong & Geels, 2010). The question of how these systems are evolving or transitioning to new systems in response to resource and climate change pressures thus requires a systematic approach that is sensitive to the influences of activities within each of these fields.

A common approach, both nationally and internationally, to developing policy and facilitating change for energy and climate change is scenario building. In a review of low carbon scenarios, Hughes and Strachan (2010) recognized persistent challenges with much of the scenario building exercises. One challenge was that the popular approach of 'backcasting' encourages a scenario building that is too deterministic, as if the end result is inevitable, which engenders a generous view of the contribution of activities. Another challenge is the tendency to describe scenarios as a somewhat linear domino effect; where endogenous events are spurred by exogenous events, as opposed to a co-evolution of events both endogenous and exogenous to the system. A third major criticism was that the scenarios weren't clear in describing which actors were playing what types of roles in bringing the change about. Each of these challenges, they report, stem from a theoretical focus in the literature on exogenous factors with less attention to endogenous factors.

Given these limitations to the current scenario building approaches, academics have been developing methods to provide a more thorough understanding of endogenous events within electricity systems and the roles of the related actors, networks and institutions (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; T. Foxon & Pearson, 2008; T. J. Foxon, Hammond, & Pearson, 2010; Jacobsson & Bergek, 2004; Konrad, Truffer, & Vofl, 2008; Markard & Truffer, 2008b)

Within this literature a proposed framework integrating two approaches to analyzing these systems has emerged (Markard & Truffer, 2008b). This framework anchors technology innovation systems (TIS) (Bergek et al., 2008; Carlsson & Stankiewicz, 1991; Malerba, 2005) at the niche level of the multi-level perspective (MLP) transition approach (Elzen, Geels, & Hofman, 2002; Geels, 2005; Kemp & Rotmans, 2005; Kemp & Volpi, 2008; Rip & Kemp, 1998; G. Verbong & Geels, 2007). Current research in the UK (T. Foxon & Pearson, 2008; T. J. Foxon et al., 2010) is attempting to implement this integrated framework by analyzing the current system and developing scenarios for the transition of the UK electricity system to a low carbon system. In the above referenced literature on developing and applying these frameworks, the need for more empirical research exploring the endogenous dynamics of such socio-technical systems as electricity sectors is stated in order to further develop the frameworks and refine the application of them.

Motivated by low carbon targets for electricity systems internationally and nationally, most electricity system transition research focuses on the development of radical niche-innovations (namely renewable energy technologies such as wind and solar) and their influence on the incumbent regimes (T. J. Foxon et al., 2010; Jacobsson & Bergek, 2004; G. P. J. Verbong & Geels, 2010). But not all innovations are considered radical or disruptive. Discussing the literature on niche development and the interaction between niches and regimes, Markard and Truffer (2008a) highlight that there seems to be a lack of specific attention to the effects of complementary innovations on regimes. Bergek et al. (2005) take complementary innovations into account from a functional perspective, in that they act as resources for, and positive externalities to, niche-innovations (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2005; Markard & Truffer, 2008b). However, the interaction of complementary innovations between existing regimes and niche innovations simultaneously is only theoretically considered as illustrated in the review of Markard and Truffer (2008a). Li-ion batteries in their more commonly intended purpose are radical innovations to vehicular transportation. Yet, they can be technologically complementary (Boyer, 2005) to both the niche innovations and existing regimes for electricity systems, and thus can provide a useful case for exploring the effects of complementary innovations.

The primary purpose of this paper is to present a framework that can help understand the effects of a complementary innovation on the endogenous dynamics of change in the Ontario electricity sector. Our framework of analysis will focus on the role of complementary technologies by analyzing cases of actor, network and institutional treatment of Li-ion batteries at the regime, niche and landscape level of the Ontario electricity sector.

Integrating the framework for TIS with the MLP as Markard and Truffer have done (2008a), this paper includes a functional analysis from the regime and niche level. It will adopt a functional approach to analyze complementary innovations and their interactions with niches and regimes amidst landscape changes as developed by researchers analyzing electricity systems in Germany, Sweden and the Netherlands (Bergek et al., 2005; Bergek et al., 2008; Jacobsson & Johnson, 2000). While Foxon, Hammond and Pearson (2010) are using the integrated TIS and MLP framework in a predictive way to explain current dynamics and develop scenarios for electricity in the UK, we intend to use it to explore the influence of complementary innovations which span the regime and niche levels.

Urban electricity storage technologies in particular are an interesting set of technologies to analyze because, as we will argue, they may be considered as complementary rather than as radical or disruptive innovations to electricity systems (Markard & Truffer, 2008b). The literature on the implications of the diffusion of complementary technologies posits that they can be treated differently than disruptive technologies (Boyer, 2005; Carlaw & Lipsey, 2002; Delgado, Porter, & Stern, 2010; Gatignon, Tushman, Smith, & Anderson, 2002; Hall & Martin, 2005; Kemp & Volpi, 2008; Walsh, 2009). Collectively these authors suggest that complementary innovations can be more attractive and adopted or integrated more readily into existing systems (Gans & Stern, 2003; Teece, 1986; Veugelers & Cassiman, 1999). If this is the case, then this could have significant implications on sectoral strategies and policy making. Considering the literature on industry and product lifecycles, complementary technologies have the potential to serve as bridging mechanisms from incremental to radical change in a regime (Eyer & Corey, 2010; Jacobsson & Bergek, 2004). However, as is stressed in the literature on sectoral transition and innovation systems, change or transition is a co-evolution of iterative dynamic events as opposed to a linear model (T. Foxon & Pearson, 2008; Geels, 2005; Jacobsson & Johnson, 2000). Therefore, certain innovations may not be recognized as complementary throughout the various stages of development.

Thus whether niche and regime actors treat Li-ion batteries as complementary can be investigated when applying the framework to case research as a means of exploring complementarity and checking research bias.

Within the proposed framework, complementary innovations are expected to contribute to the mobilization of resources, and the formation of positive externalities (Bergek et al., 2005). Foxon and Pearson (2008) treat positive externalities as virtuous cycles that support the transition of niche-innovations from a formative phase to a growth phase. Accordingly, we use indicators and diagnostic questions regarding the mobilization of resources and the development of positive externalities or virtuous cycles (Bergek et al., 2005).

Institutional Change

The process of change in a sector such as electricity has been differentiated from the study of change in other technology sectors by recognizing the implications of: the large physical infrastructure and sunk costs in technology; the competitive nature of the market given significant government policy intervention and; the dynamics of active resistance to change by what are usually a few very large incumbents (Geels, 2004; Jacobsson & Bergek, 2004; Kemp & Volpi, 2008). To capture the dynamics of change in these large technical systems within societies, (Geels, 2004) authors have drawn from the fields of sociology (the sociology of technology in particular) and institutional theory and incorporated analytical tools from evolutionary economics, and the study of innovation diffusion (Carlsson & Stankiewicz, 1991; Elzen et al., 2002; Geels, 2002; Kemp & Rotmans, 2005; Malerba, 2005; Markard & Truffer, 2008b; Rip & Kemp, 1998; Walsh, 2009). To specify a unit of analysis they have adopted actor-network theory, with the general consensus that these systems can be analyzed by their actor, network and institutional behaviours and perspectives at various system levels (Geels, 2002; Jacobsson & Bergek, 2004; Malerba, 2004).

There are two widely accepted approaches for analyzing change in these systems, and a third that attempts to bring them together. These are referred to as the (technology) innovation systems (TIS) approach (Bergek et al., 2008; Carlsson & Stankiewicz, 1991; Malerba, 2005), the multi-level perspective (MLP) transition approach (Geels, 2002; Kemp & Rotmans, 2005; Rip & Kemp, 1998; G. P. J. Verbong & Geels, 2010), and the integrated TIS and MLP approach (T. Foxon & Pearson, 2008; Markard & Truffer, 2008b). This third approach explicitly captures the influence of complementary innovations to the system. With the objective of studying the influence of Li-ion batteries on the endogenous Ontario electricity system dynamics, this third approach is the foundation of our framework. But the application of the framework will be drawn from the TIS approach that provides a more detailed and systematic analysis of the endogenous dynamics of the formation of change within the sector (Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Hekkert & Negro, 2009; Kemp & Volpi, 2008).

To support the applicability of our framework a literature review was undertaken to explore:

- institutional theory when combined with economic, technical and innovation theories;
- frameworks for analyzing change in large technical systems;

- the concept of complementarity in innovation diffusion and;
- case study methodology for exploring the functionality of an innovation system.

The first three literature reviews are presented here in this paper as they are relevant to the development of the framework.

Institutional theory with economic, technical and innovation theories

Institutional theory describes the social structures formed and reinforced by rules, norms, beliefs and routines within a population (Zucker, 1987). The social behaviour of individual and organizational actors and networks within the institution are influenced by these structures in a way that tends to encourage conformity and promote homogeneity. Although institutions tend toward stability, institutional theory can also be used as a basis to explain endogenous and exogenous dynamics of change (Geels, 2002; Oliver, 1990; Oliver, 1997).

In order to facilitate a more applied analysis of the dynamics of actual institutions, researchers have combined other theories with institutional theory. Relevant concepts from these theories are summarized in Table 1. In their seminal work with institutional theory, Baum and Oliver found that integrating other fields of study (such as the resource-based view and population ecology) provided a more detailed explanation of the aggregate behaviour of organizations within an institution, and the behavioural dynamics of managers within the organizations (Baum & Oliver, 1992; Baum & Oliver, 1996; Oliver, 1997). TIS and MLP approaches have arrived at a theoretical approach in a similar fashion, wherein the factors influencing behaviour at various levels of the system, and the system as a whole, can be explained in a co-evolutionary process of institutional change with economic and social factors (Bergek et al., 2008; Carlsson & Stankiewicz, 1991; Geels, 2002; Kemp, 1994; Kemp & Rotmans, 2005; Malerba, 2005; Rip & Kemp, 1998). Despite academic knowledge of change as an iterative co-evolution of factors, Foxon et al. (2010) note that the problem with current modelling approaches to policy making is that they assume a highly economically rational behaviour from the actors and networks. It is for this reason that researchers continue to focus on the endogenous dynamics of change in order to advance the theoretical understanding of these change processes, but also practically to better enable stakeholders within the system to make informed decisions (T. J. Foxon et al., 2010; Suurs, Hekkert, Kieboom, & Smits, 2010; G. P. J. Verbong & Geels, 2010).

The inclusion of economic theory employs the rational decision making elements such as those presented in the resource-based view (Barney, 2001; Oliver, 1997) as a sort of counterbalance to the social decision- making elements recognized in institutional theory. Economic theory also allows for the issues of price and market risk to be included within the analysis, both of which are two prominent issues in the discussion of new technologies or technology systems (Delucchi & Jacobson, 2010; EPRI, 2010; Eyer & Corey, 2010; Peterson, Whitacre, & Apt, 2010; Schoenung & Eyer, 2008). It also recognizes the influence of an organization’s competencies (Henderson, 2006; Prahalad & Hamel, 1990) and complementary assets (Gans & Stern, 2003; Teece, 1986; Walsh & Walters, 2009) in deciding on alternatives. Concepts within network externalities (Katz & Shapiro, 1986) such as lock-in and path dependence, often used to describe demand patterns, have also been used to describe the patterns and behaviours of firms within an industry (Baum & Oliver, 1991; Baum & Oliver, 1996).These economic factors are often part of the literature on technology development and adoption as well.

Table 1: Relevant concepts to institutional change processes in large technical systems.

	Relevant Concepts	Authors
Institutional Theory	Rules, norms, routines, beliefs Emergence, conformity, conflict, change Legitimacy Organizational embeddedness	(Zucker, 1987) (Oliver, 1990) (Baum & Oliver, 1992)
Economic Theory	Resource-based views Population ecology, population density (Core) Competence Complementary assets Price; cost/benefit Market risk Network externalities; lock-in, path dependence Clustering	(Barney, 1991; Barney, 2001; Oliver, 1997) (Baum & Oliver, 1996) (Prahalad & Hamel, 1990) (Teece, 1986) (Schoenung & Eyer, 2008) (Katz & Shapiro, 1986) (Delgado et al., 2010)
Technology Theory and Innovation Theory	Technology cycles; design competition, incremental change Dominant design Technological discontinuity Absorptive capacity Commercialization strategy Diffusion; technology push / pull strategy Business & Process innovation / Technology & Product innovation Disruptive innovation	(Anderson & Tushman, 1991) (Abernathy & Utterback, 1978) (Utterback, 1996) (Cohen & Levinthal, 1990) (Teece, 1986) (Gans & Stern, 2003; Roberts & Liu, 2001) (P. R. Walsh, 2009) (Rogers, 1995) (Markides, 2006) (Christensen, 2003; Christensen, 2006) (Edquist, 2005)
Actor-network Theory and Evolutionary Theory	Actors, networks Social order Sociology of Technology Co-evolution of technology and society Techno-economic networks Non-linearity	(Latour, 2000) (Callon, 1991) (Geels, 2004; Geels, 2005)

The inclusion of technology theories, and often in close relation innovation theories, brings in cyclical processes of learning (Cohen & Levinthal, 1990) and innovation (Anderson & Tushman, 1991) to the processes of institutional change. This allows researchers to consider the life cycles that industries and products go through in their search for a dominant design (Abernathy & Utterback, 1978) and the efficient exploitation of it through various commercialization and process strategies (Abernathy & Utterback, 1978; Gans & Stern, 2003; Roberts & Liu, 2001; Siegel, Hansen, & Pellas, 1995; Teece, 1986;

Utterback, 1996; Walsh, 2009; Zahra & Nielsen, 2002). Included as a "pull" force on the technology development and diffusion are phases of technology adoption from market demand (Rogers, 1995; Walsh, 2009). "Push" forces on technology development and diffusion tend to come from policy or research and development (R&D) strategy (Brown, Berry Rajeev, & Linda, 1991; Carayannis, Alexander, & Ioannidis, 2000; Carley, Lawrence, Brown, Nourafshan, & Benami, 2010; Kemp & Volpi, 2008; Markides, 2006).

Innovation theory has become a richly explored field often associated with technology (Carlsson & Stankiewicz, 1991; Christensen, 1997; T. Foxon & Pearson, 2008; Jacobsson & Johnson, 2000; Kemp & Volpi, 2008; Lundvall, 2010). But Christensen—one of the principal authors on the subject—has also explored innovation within public services such as education and health care (Christensen & Raynor, 2003; Christensen, Aaron, & Clark, 2003). In looking at public services, Christensen recognizes the difference in the barriers and incentives to change that exist within a heavily regulated public institution as compared to the free, competitive market context which much of the innovation diffusion theory adopts (Assink, 2006; Dodgson, Gann, & Salter, 2006; Hall & Martin, 2005; Henard & Szymanski, 2001; Rogers, 1995; Utterback, 1996). These considerations are taken into account in both the TIS and MLP transition approach. The concept of disruptive innovation is of particular interest to the innovation systems and transition approaches because it captures the general process of something new substituting something old through a means of better defining or reshaping demand (Bergek et al., 2008; Bower & Christensen, 1995; Carlsson & Stankiewicz, 1991; Christensen, 2006; Geels, 2004; Malerba, 2004).

Underlying the study of technology cycles, industry cycles and institutional change, is the inclusion of actor-network theory which brings together the social and technical parts of a heterogeneous network where each part is equally important to the social order (Callon, 1991; Latour, 2000). In this way Geels (2004) has described the transition approach as a socio-technical approach which recognizes the co-evolution of both technology and society. While actor-network theory originally analyzed the individual, these concepts have been extended to organizations through the recent literature on technology adoption models (Bagozzi, 2007) and innovation systems where change is brought about through an individual and collective act (Carlsson & Stankiewicz, 1991; Jacobsson & Bergek, 2004).

A functional framework of analysis

The concepts summarized in Table 1 are brought together in both the TIS and MLP transition approaches to analyzing sectoral change. The TIS and MLP approaches are described separately below, but as will become evident many concepts are shared between them and are applied to their respective frameworks in a similar fashion. Thus it is possible to integrate the two, as has been reviewed in the integrated TIS and MLP approach section.

Technology Innovation Systems Theory

Summarizing the work of Carlsson & Stenkiewicz (1991), Edquist (2005) and Malerba (2005), an innovation system is defined as "...composed of networks of actors and institutions that develop, diffuse and use innovations" (Markard & Truffer, 2008a, p.597). The innovation system approach recognizes change in a sector or system in its ability to function as an innovation system. Using a case study methodology the concepts in Table 1 are applied in a framework for structural and functional analysis. The structural components include actors, networks (formal and informal) and institutions (Bergek et al., 2008). A system function captures the contribution toward a system's performance by a component or set of components (Bergek et al., 2008; Hekkert & Negro, 2009). Performance is implicitly left to mean technology diffusion but as will be addressed in the section on integrating the TIS and MLP transition approaches this may not be the change pathway. The functional approach to studying innovation systems can be used to assess the innovation system and compare it to others (Bergek et al., 2008; Markard & Truffer, 2008b). Recent literature (Bergek et al., 2008; Hekkert et al., 2007; Hekkert & Negro, 2009) has synthesized the literature on innovation systems to produce seven functions for analysis. These functions interact with each other resulting in what Hekkert and Negro (2009) describe as virtuous or vicious cycles that transform a system. The interactions of these functions are noted below where the stronger links have been suggested by Hekkert and Negro (2009), but are not considered prescriptive or exhaustive in their application to each function. In a case study analysis Hekkert and Negro (2009) described the TIS functions more fully as described in Box 1 .

These functions assist in creating a detailed explanation of the endogenous dynamics of the system, but as acknowledged by Hekkert and Negro (2009) they offer limited observations on the interaction between events internal and external to the system. Consideration of relevant events external to the system within the analysis helps to present a fuller explanation of an innovation system. Thus, as proposed by Markard and Truffer (2008a) the transition approach adds value by delineating a multi-level perspective to frame the analysis.

Transition Approach and Multi-Level Perspective

The transition approach uses 3 general levels or perspectives within a system or sector to explain the endogenous and exogenous dynamics of transition: landscape, regime and niche (Geels, 2002). The landscape level describes the pressures on a sector such as legislation, public opinion, the price of inputs and so on. The regime level is the most tangible and identifiable level of the system, which includes the incumbent actors and networks, infrastructure and technology. The niche level includes radical or disruptive innovations pioneered by actors and networks often characterized as entrepreneurs and small business acting within protected spaces (often called niche markets). The mechanics of change on the regime are brought about by the combination of actions and pressures from the niche and landscape levels. These levels are described graphically in Figure 1. Using those perspectives to build a narrative, the observed transition pathways of large technical systems has been categorized into 4 types (G. P. J. Verbong & Geels, 2010). They are briefly summarized here in Box 2.

Box 1: The 7 functional assessments of an innovation system as described in (Hekkert & Negro, 2009)

<u>Function 1:</u> Entrepreneurial Activities. This is also titled **"Entrepreneurial Experimentation"** by Bergek et al. (2008). This function assesses the level and nature of activity by entrepreneurs attempting to take advantage of new knowledge (Function 2), efforts of networks or associations (Function 7) and new markets (Function 5) with concrete business attempts.

<u>Function 2:</u> Knowledge Development (learning) Hekkert and Negro (2009) describe this function as 'learning by searching' and 'learning by doing'. The function assesses the level of R&D and working knowledge regarding a technology or innovation being produced and built upon. This function is evidence on entrepreneurial activity (Function 1) in addition to formal R&D.

<u>Function 3:</u> Knowledge Diffusion through Networks. This function differs from the previous function in that it assesses the level and nature of knowledge exchange between actors and networks by assessing the level of integration of this knowledge into other system mechanics, such as policy making and program design (Function 4). Hekkert and Negro (2009) describe this as "a precondition to 'learning by interacting'. When user producer networks are concerned, it can also be regarded as 'learning by using'." (p.586)

<u>Function 4:</u> Guidance of the Search. This function assesses articulation of the demand for a technology or system capabilities in terms of visibility and clarity. The manifestation of this articulated demand is itself indicative of a degree of legitimacy (Function 7) to the development of the technologies and in turn stimulates the mobilisation of resources (Function 6) toward further knowledge development (Function 2) and often entrepreneurial experimentation (Function 1). The assessment of this function also includes less formal indicators such as expectations from various stakeholders.

<u>Function 5:</u> Market Formation. This function assesses the creation of protected spaces for new technologies. This can take into account demand stimulated by subsidies and other incentive programs, but also incentives set up by agents outside of government. It also assesses the maturity and capability of a market to absorb new technology. Increased functionality of market formation encourages entrepreneurial experimentation (Function 1) and in establishing the legitimacy of an alternative technology for the existing system (Function 7).

<u>Function 6:</u> Resource Mobilisation. This function assesses the availability of financial and human capital to support knowledge development (Function 2) and entrepreneurial activity (Function 1). This function also considers the accessibility of existing infrastructure and capabilities to the entrepreneurs or development of the new technologies in general.

<u>Function 7:</u> Creation of legitimacy/counteracting resistance to change. This function assesses the receptiveness of stakeholders (incumbents, government policy, the public etc.) to a particular technology or innovation. It also considers the actions of advocacy coalitions and supporters of the technology or innovation. The receptiveness has an influence on the resource availability (Function 6), market formation (Function 5) and the development of policies and programs to support the development and diffusion of a technology (Function 4).

For infrastructural regimes like the electricity sector, Verbong and Geels admit that the technological substitution pathway is less likely as a complete replacement of the electricity system is doubtful. The other pathways, then, can be used to identify patterns of change within sectors by identifying periods where the combination of events reflects them. Acknowledging these pathways, the previously defined TIS concept of "performance" can be called into question as the change pathway may not simply be a matter of technology diffusion. The MLP technology transition approach therefore adds a level of refinement to assessing the overall system change. On its own, however, it does not facilitate the detailed analysis of the endogenous dynamics between niche and regime the same way that the TIS framework does.

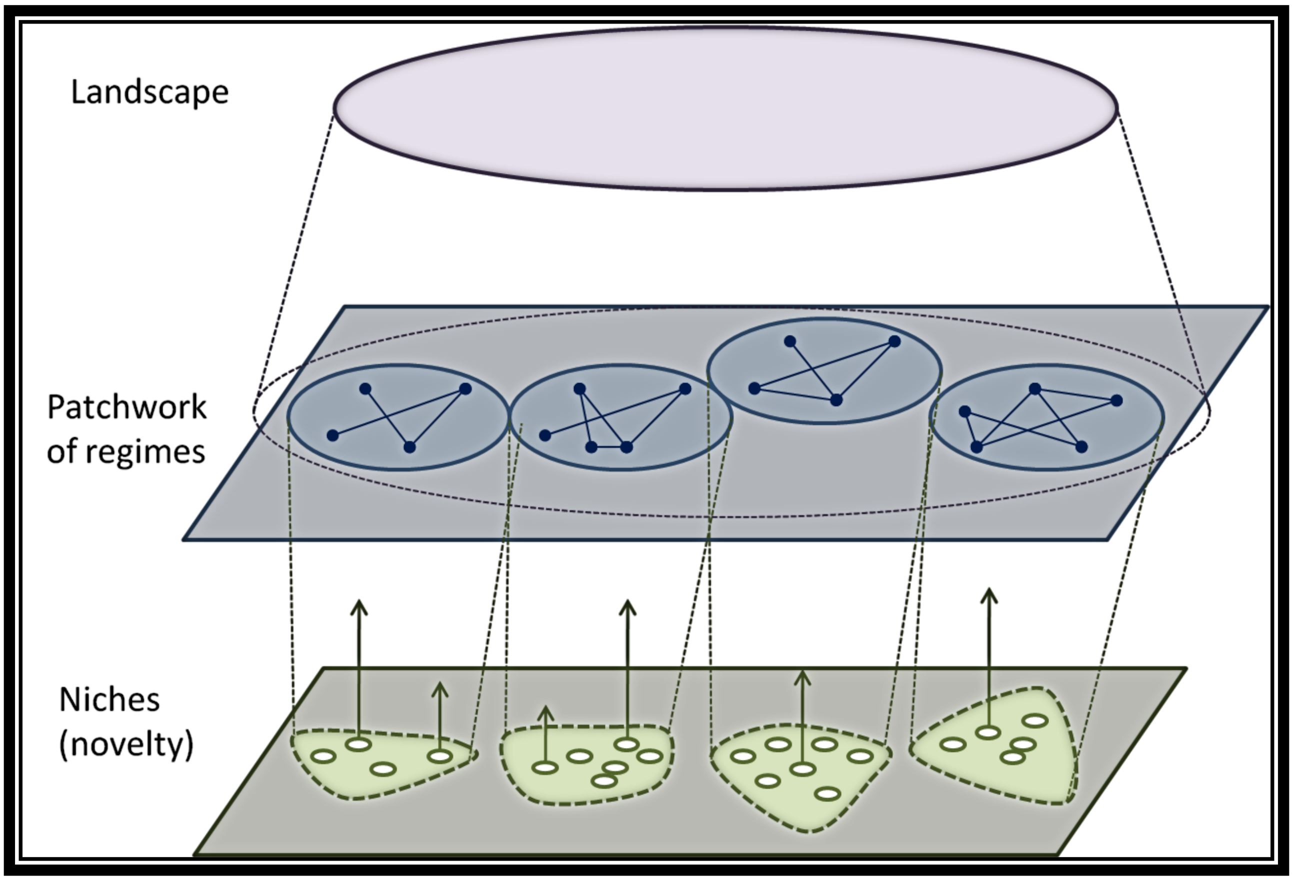

Figure 1: Multiple levels as a nested hierarchy from the multi-level perspective of sectoral transition (Geels, 2002; 2010)

Box 2: The 4 broad categories of transition in large technical systems (Verbong & Geels, 2010).

1. **Transformation:** external pressure from the landscape is exerted on the regime causing a search for alternatives, however niche innovations are not developed enough to move beyond formative stages of development. Thus the regime retains control but they change their trajectory. Radical innovations stay within niches.

2. **Reconfiguration:** niche-innovations are more developed, regimes struggle under external landscape pressures (perhaps input prices), and begin to adopt certain niche-innovations

3. **Technological substitution:** landscape pressures create windows of opportunity for niches. Their accumulation and clustering eventually take over and replace the existing regime.

4. **De-alignment and re-alignment:** landscape pressures create major problems for regimes that collapse and de-align. There's a period of searching for dominant design with multiple niche experiments but eventually the whole system is restructured.

The integrated TIS and MLP approach

Markard and Truffer (2008a) found that the large technical systems were similar to the innovation systems described by Bergek at al. (2008). They also found that integrating the TIS approach into the MLP transition approach could be done in a way that leveraged the strengths of both. In attempting to integrate the 2 approaches, they propose that the environment of the TIS would be "composed of regimes, competing and complementary technological innovation systems and landscape level influences." (Markard & Truffer, 2008a, p.613). The explicit inclusion of complementary technological innovation systems is of particular significance and will be explored more in the next section.

Referring back to Figure 1 there are a few nuances to point out in the MLP technology transition approach. One is that the dynamics are aligned with the hierarchical description of the system, such that influences are mainly considered up and down the system between landscapes, regimes and niches, but less so laterally across regimes or niches. Konrad, Truffer and Voß (2008) explored the influence of regimes on each other with the cases of German utility sectors and found that they are significant, particularly for a future oriented analysis where systems can start to become more integrated, as can be the case with transportation and electricity, electricity and heating, and electricity and telecommunications. A second and related characteristic from Figure 1 is that niches are presumed to influence a single regime when, under the multi-regime dynamics that Konrad et al. recognize, niche innovations could influence multiple regimes. Markard and Truffer (2008a) realized this in their conception of the interaction between the technology innovation system and existing regimes. In doing so, they further create a theoretical space to analyze complementary innovation systems within the MLP transition approach.

Visually the integration of the TIS and MLP approach could be indicated as in Figure 2 where in addition to placing the TIS approach, the overlap between regimes indicates a lateral influence across the regime networks and the multi-regime influence of niche innovations.

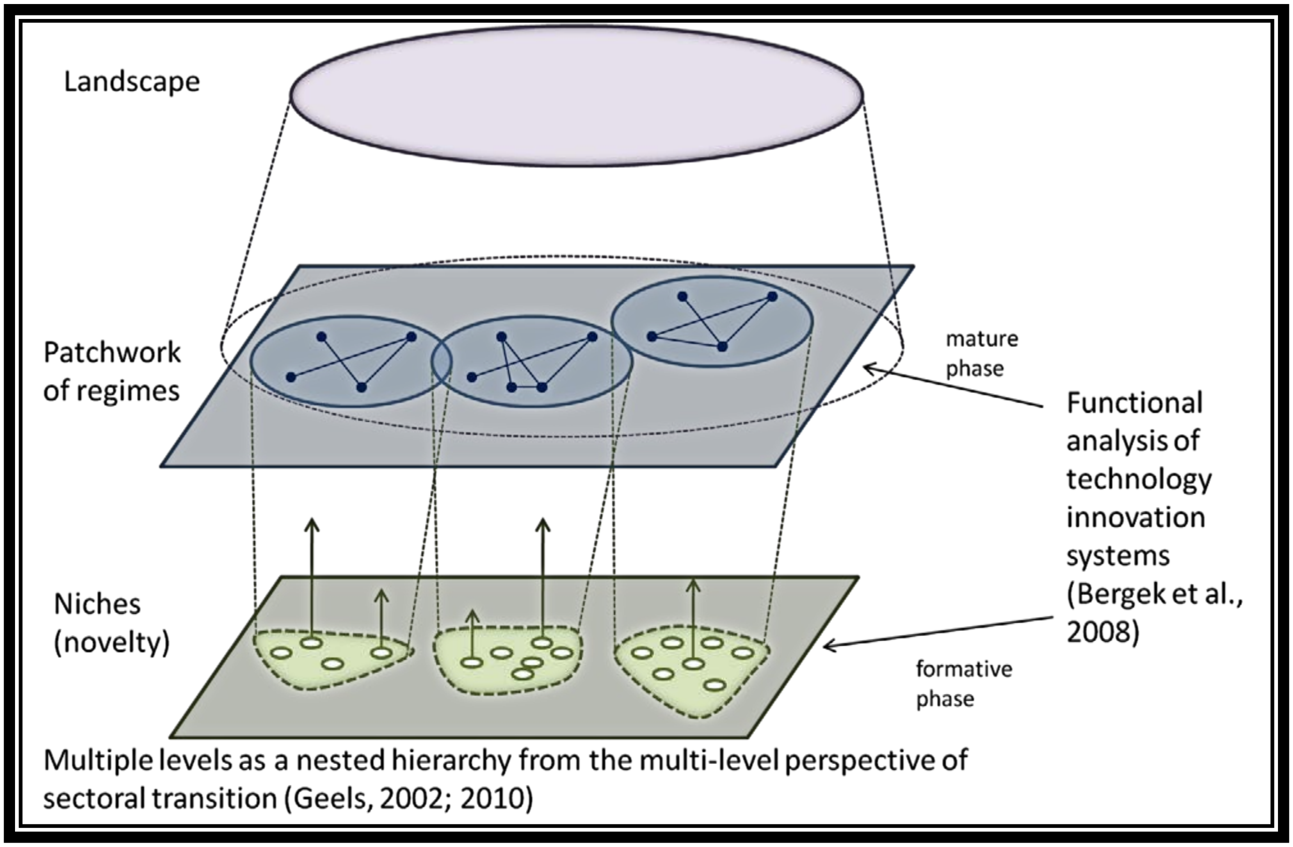

Figure 2: Integrating the technology innovation systems (TIS) approach within the multi-level perspective (MLP) technology transition approach as interpreted by Markard and Truffer (2008a).

Although Markard and Truffer created a different graphical depiction of their concept, we have chosen to build off of the Geels (2002) graphic because it indicates visually how the TIS and MLP approaches come together. What this graphic doesn't explicitly highlight is the presence of complementary technologies or innovations. In order to identify how these would relate to the existing regime and niche-innovations a review of the literature on complementary innovations is required.

Complementary Innovations

Complementarity has been discussed throughout the innovation diffusion literature. In many cases it is studied in terms of complementary assets that aid in the dissemination of innovation, which often means commercialization capabilities, product support (Cassiman & Veugelers, 2006; Delgado et al., 2010; Gans & Stern, 2003; Teece, 1986; Veugelers & Cassiman, 1999), or business clusters (Carlsson & Stankiewicz, 1991; Delgado et al., 2010; Markman, Siegel, & Wright, 2008). This type of complementarity is usually in the form of business or process innovation as opposed to technology or product innovation (Markides, 2006). Relating back to the integrated TIS and MLP approach, this could facilitate the development or adoption of niche-innovations by the incumbent regimes and facilitate the eventual transition of the whole system.

Another form of complementarity considered in the literature is complementary technologies, products or innovations. Complementary innovations differ from the radical or disruptive innovations in that they are value enhancing as opposed to value destroying for existing technologies or systems (Boyer, 2005; Carlaw & Lipsey, 2002; Charitou & Markides, 2002; Markides, 2006; Smith, 2004). In this way, complementarity is considered as an alternative to competition in much of the innovation diffusion literature. Boyer (2005) goes into more detail on the types of complementarity that can be seen empirically. He divides them into categories of natural complementarity, technical complementarity, complementarity by design, ex post discovered complementarity, and functional complementarity.

Table 2: Categories of complementarity in capitalist economies as delineated by Boyer (2005).

Natural complementarity	Value derived from the combination of naturally existing properties such as chemical properties.
Technical complementarity	Man-made properties that combine in a coherent way to add value, such as car production and oil consumption and production.
Complementarity by design	Man-made properties strategically chosen to enhance value, such as assembly lines and equipment design.
Ex-post discovered complementarity	An emerging co-evolution of technology and management models observed in retrospect as a system matures or goes into decline, such as ICT and profit optimization in the airline industry which took over a decade to realize the advantages or real-time price adjustments to online booking in order to manage demand and fill more seats.
Functional complementarity	The added value to systems due to the social roles that complement each other, such as supply and demand, or credit and debt repayment.

By these differentiations, the case of Li-ion batteries would be considered a technical complementarity because the ability to store electricity in a large variety of environments allows it to increase the value of the electricity service to the customer or generator. In the case of electricity generated by wind and solar technologies, the Li-ion batters would increase the quality of the power generated by regulating the voltage and the reliability of the power because it could be drawn from the battery regardless of the weather conditions. Thus the value of the electricity generated through niche technologies such as wind and solar could be enhanced. Considering electricity distribution and the progression toward a distributed energy "smart grid," Li-ion batteries would be an appropriate technology for managing demand so that peak demand during the day didn't require extra generation, but could rather draw from excess generation stored during the nights. Thus the value of the electricity service in the existing system could be enhanced.

It is this type of complementarity that can be explored through the integrated TIS and MLP approach, using the case of Li-ion batteries. Returning to the study of sectoral change, Kemp & Volpi (2008) conducted a review of the literature on the diffusion of clean technology innovations. They framed the dilemma that management faces around choosing between end-of-pipe or new solutions. The sunk costs and previously adapted technology, they argued, dictates a strong bias for one of those two options. The implications of that choice could be related back to the 4 types of transition that Verbong and Geels (2008) derived, presented in Box 2. End-of-pipe solutions would facilitate a transformation, and new solutions would facilitate either a reconfiguration or technological substitution. Using our framework we can explore the implications of a complementary technology on that choice.

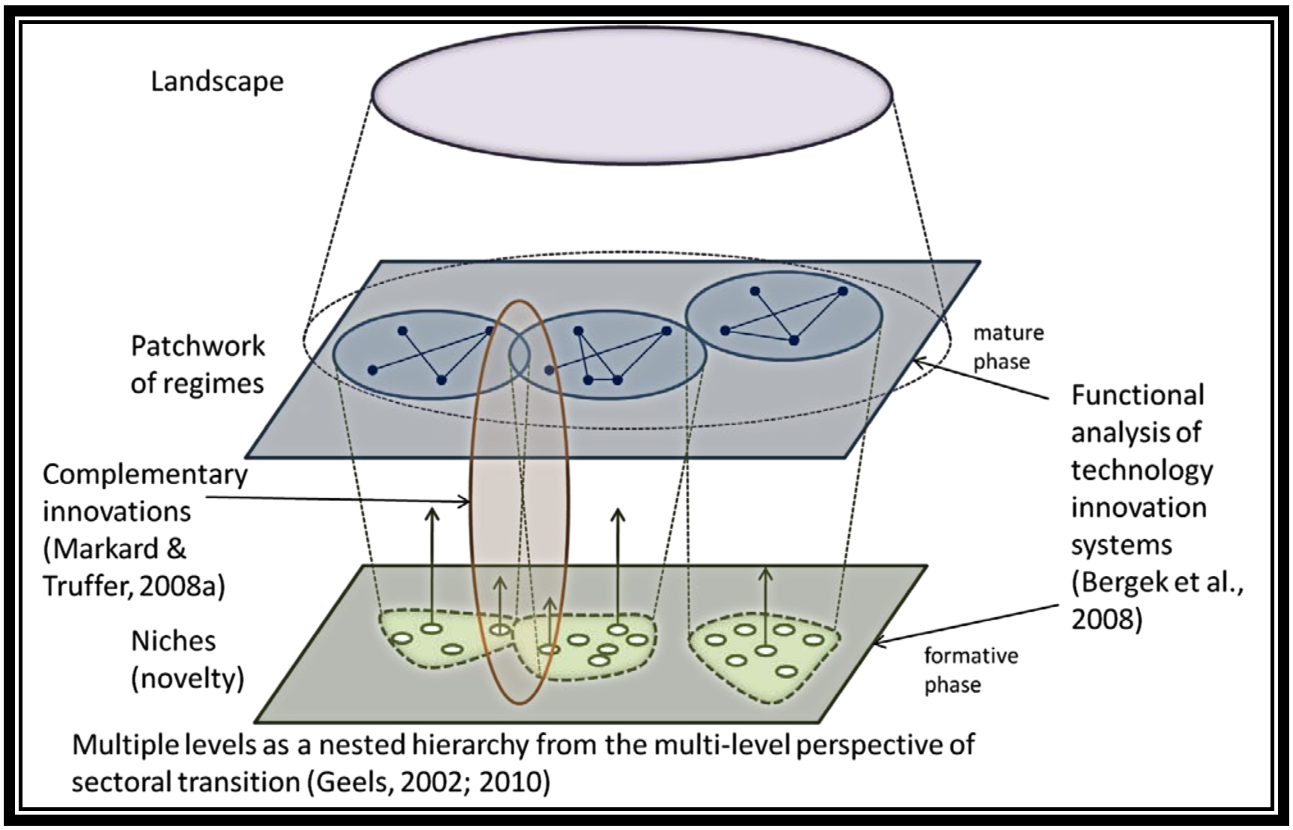

Figure 3: Complementarity in the multi-level perspective of sectoral change.

Concluding their review, Kemp & Volpi (2008) identified the need to incorporate complementary innovations into empirical studies of the diffusion of clean technologies as one of their 10 recommendations for future work. Markard and Truffer's (2008a) integrated framework indicates the presence of complementary innovation systems in their model, and leaves the empirical exploration of the implications of complementarity to future work. Their later work applies the framework in an actor-oriented analysis of stationary fuel cells (Markard & Truffer, 2008a). The technological interrelatedness of stationary fuel cells with electricity systems was acknowledged from the perspective that its diffusion is dependent on further infrastructure developments and coordinated efforts between supplier, manufacturers, utilities, installers and customers. In their study they classify fuel cells as radical innovations because their widespread adoption would facilitate a shift from a centralized power production, to a distributed power production electricity system. Their analysis then focused on the strategic intent by the actors developing fuel cells to address the barriers to the diffusion of a radical innovation. Fuel cells are generators of power and as such “radical” is an appropriate classification. Li-ion batteries could serve a similar role in facilitating the shift to a decentralized power system; however their influence may be more value enhancing for the regime and other niche innovations. In order to investigate this complementarity in the social and institutional dynamics of the Ontario electricity system we return to the integrated framework developed by Markard and Truffer (2008a) and graphically indicate the influence of complementary innovations in Figure 3. We can explore the effects of a complementary innovation by analyzing the strategic response by regime and niche actors who would benefit from the complementarity of them, and by analyzing government policy intent. This framework will be used to delineate the system around Li-ion batters in the way that Bergek et al. (2008) recommend, and guide the data collection and analysis of the system as it has for Hekkert and Negro (2009) and Markard and Truffer (2008b).

Urban Energy Storage in Ontario’s Electricity System

The Ontario electricity sector provides an appropriate context within which to explore the endogenous elements of change in a sector, and the influence of complementary innovations. This is because the sector is: (1) in a process of transition in response to government pressure most notably through the Green Energy Act and FIT program (Province of Ontario, 2009; OPA, 2010); and (2) it has active actors, networks and institutions in the niche and complementary innovation fields (O’Malley, 2010).

The landscape, regime and niche level actors, networks and institutions can be identified and included in the appropriate units of analysis:

- The landscape pressures of regulation and government incentives from the provincial and federal government, along with increasing public pressure can be analyzed in its role as influencing investment decisions within the sector.
- The regime actors and networks can be identified as the provincial government, utilities supplying most of the electricity generation in Ontario, the local distribution companies (LDCs), the not-for-profit players such as the Independent Electricity System Operator (IESO), and associations facilitating R&D on behalf of the actors such as the Centre for Energy Advancement through Technological Innovation (CEATI) and Canadian Electricity Association (CEA).
- The niche-innovation actors and networks can be identified as the developers, retailers and proponents of renewable electricity such as the Canadian Solar Industries Association (CanSIA), the Canadian Solar Manufacturer’s Association (CANSMA), the Canadian Wind Energy Association (CanWEA), and their member organizations. In addition, university and government research labs provide support to the development of these niche innovations. Finally, the niche market perspective can include potential investors and consumers of Li-ion batteries as electricity storage options.
- The complementary innovation actors and networks can be identified as developers, retailers and proponents of Li-ion electricity storage as one example. Here the actors and networks can be found in niche environments where battery storage technologies are being advanced and invested in from the private sector, universities and associations. They can also be found in

regimes as incumbents such as LDCs electricity generators invest in R&D toward incremental innovations upon their existing infrastructure. Conveniently, they are all outlined in the Energy Storage Working Group briefing paper for stakeholders (O'Malley, 2010).

The case of Li-ion batteries would be considered a case of technical complementarity for existing regimes and niche innovations because the ability to store electricity in a large variety of environments allows it to increase the value of the electricity service to the customer or generator. In the case of electricity generated by wind and solar technologies, the Li-ion batters would increase the quality of the power generated by regulating the voltage, and the reliability of the power because it could be drawn from the battery regardless of the weather conditions. The value of the electricity generated through niche technologies such as wind and solar could be enhanced. Considering electricity distribution and the progression toward a distributed energy "smart grid," Li-ion batteries would be an appropriate technology for managing demand so that peak demand during the day didn't require extra generation, but could rather draw from excess generation stored during the nights. Thus the value of the electricity service in the existing system could be enhanced. It is this type of complementarity that can be explored through the integrated TIS and the MLP of sectoral change approach, using the case of Li-ion batteries.

Ryerson University (2010) and the University of Toronto (2011) are conducting research on the implementation of modular Li-ion storage units of 340kWh capacity and 250kWh capacity respectively to be scaled to MWh capacity in partnership with companies in Ontario. Each of those projects are funded by various government and regime actors making the actors and networks easier to identify and more accessible to the researchers.

Conclusions

This conceptual framework (Figure 3) allows for the exploration of the effects of a complementary innovation, such as Li-ion energy storage systems, by analyzing the strategic response of regime and niche actors who would benefit from the complementarity of them, and by analyzing government policy intent. This framework will be used to delineate the system around Li-ion batteries in the way that Bergek et al. (2008) recommend, and guide the data collection and analysis of the system as it has for Hekkert and Negro (2009) and Markard and Truffer (2008). The theoretical contribution of this paper is the increased understanding of the dynamics of change surrounding complementary innovations within an existing energy system. The practical contribution is the creation of a framework that will help gain insight into the internal dynamics of change in Ontario's electricity sector as it begins to introduce urban energy storage into the markets. This insight enables the various actors to make more informed decisions about battery storage commercialization, investment, and policy support.

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