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Low-carbon innovation from a hydroelectric base: The case of electric vehicles in Québec

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ABSTRACT

This article explores the transformative potential of hydroelectricity by examining interactions with electric vehicle (EV) technologies in Québec, Canada. It finds that structural features of Québec's hydroelectric regime enabled Québec's EV technological innovation system. Organizational and institutional characteristics of the socio-technical environment shaped by Québec's history of hydroelectric development played a particularly important role in promoting political legitimacy and early-stage EV innovation processes, such as knowledge development and exchange. While the technical complements between hydro and EV could lead to significant GHG reductions, technical overlaps between the two technologies were less responsible for initiating the momentum needed to build an EV innovation system. Québec's social history of hydroelectricity development provides actors with important resources for the development of EV technologies.

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Abbreviations: EV, electric vehicles; MLP, multi-level perspective; TIS, technological innovation system; GW, gigawatt; HQ, Hydro-Québec; IREQ, Hydro-Québec Research Institute; GWh, gigawatt hour; SAAQ, The Québec Automobile Insurance Corporation; MDEIE, Ministry of Economic Development, Innovation, and Exportation; CNRS, French National Centre for Scientific Research; AC, alternating current; DC, direct current; USABC, United States Advanced Battery Consortium; CEVEQ, Québec Electric Vehicle Experimentation Centre; NEV, neighbourhood electric vehicle; CEO, Chief Executive Officer; R&D, Research and Development; ITAQ, Québec Advanced Transportation Institute; GHG, greenhouse gas; FTQ, Québec Federation of Labour.

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1. Introduction

Québec is a Canadian province with an abundance of hydroelectric resources. Recently, provincial leaders have outlined the ambition of becoming a "North American leader in the field of sustainable mobility through the use of hydroelectricity" (Government of Québec, 2011). This corresponds with the province's traditional goal of using hydroelectricity as a catalyst for developing other industries such as aluminium, pulp and paper, and consulting engineering (Dales, 1957; Carpentier, 2006; Niosi and Faucher, 1987).

The goal of maximizing industrial linkages from natural resources, such as waterpower, is a recurrent issue in Canadian economic policy (Watkins, 1963, 2007). In the sustainability transition context, hydroelectricity could underpin new low-carbon technologies, such as electric vehicles (EV), and aid Canada's escape from carbon lock-in (Haley, 2011). Nevertheless, previous experience with hydroelectric based industrial policies highlights that potentially advantageous sectoral or technological complements might fail to be realized. Historically, Canadian provinces developed hydroelectricity with the expectation that secondary manufacturing and other spin-offs would naturally evolve, however, these expectations were not fulfilled (Froschauer, 1999). To avoid repeating historic shortcomings, present-day policy agendas should consider exactly how and why EV might develop from a hydroelectric base.

This paper draws on socio-technical perspectives to investigate the performance of the emerging EV technological innovation system (TIS) in a structural environment strongly influenced by a hydroelectric "regime". It seeks to determine how the hydroelectric regime enables, or possibly blocks, EV development by exploring the structural characteristics that influence certain innovation activities or processes, the extent to which the hydro regime versus other structural factors influence TIS development, and if there are gaps or weaknesses that policymakers should consider.

The paper is organized into the following sections: theoretical approach; research approach and methods; Québec hydroelectric and transport systems; case study of Québec EV innovations; survey of innovation processes complemented by hydroelectric structures; discussion of the findings; and conclusion.

2. Theoretical approach

Early systems of innovation approaches focused on strengths and weaknesses of structural components such as infrastructure, actors, networks, and institutions (Nelson, 1993; Lundvall, 1992). In response to drawbacks identified in this approach, researchers began to study "innovation functions" (Bergek et al., 2008; Hekkert et al., 2007). Rather than mapping the end result of innovation through technology diffusion curves or structural analyses, the functions approach permits a tracing of the activities or processes that lead to innovation. This approach provides clearer guidance to policy makers aiming to promote the evolution of new innovations. Alkemade et al. (2007) highlight that functional analyses are especially relevant to studying the performance of "technological innovation systems" (TIS), which are smaller-scale and less complex than national or regional systems.

More recently Jacobsson and Bergek (2011) identified studying the interaction of technology specific systems with higher system levels as a fruitful research avenue. They identified a need to consider not only the internal dynamics of a TIS, but also to consider how a TIS is formed by accessing "resources from their contexts", which could be provided by related industries or the structures of national, regional, or sectoral innovation systems. Likewise, Coenen et al. (2012) highlight the importance of regional context in understanding why a TIS might successfully develop in certain places over others.

Considering higher system levels re-introduces greater complexity and makes drawing system boundaries difficult (Carlsson et al., 2002). We must ask what aspects of the structural context to consider. One option is to explore how the diffusion of a particular technology (e.g. hydroelectricity) influences structure and thus influences the selection environment encountered by other technologies (see Sandén, 2004). Sandén and Hillman (2011) created a framework for studying technological interactions by examining "structural overlaps" between two systems. These overlaps can occur across a value chain because of shared production processes or input–output relations, but they can also exist across socio-technical dimensions. For example, shared knowledge, actor coalitions, organizational

structures, or cognitive understandings. The interactions across each dimension can be competitive or complementary. The diffusion of one technology will define the structural context encountered by a second technology if the two structures overlap. These overlaps influence the system functions, and thus the performance of the second technology.

The diffusion of one technology can have pervasive effects on future innovation trajectories if it dominates a sector or forms a wider technological system. The "regime" concept encapsulates this idea. Rip and Kemp (1998) defined the regime as a:

> "grammar or rule set comprised in the complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the *totality of technology*." (emphasis added)

Markard and Truffer (2008) note that regimes are defined from different perspectives, dependent on the research question. The concept is useful because it helps outline the structural environment, it encompasses different material as well as social dimensions of technology, and it explains the direction of future innovation trajectories. The regime is a prominent component of the multi-level perspective (MLP) (Geels, 2002), which describes how transitions occur via the interaction between the regime level and technologies and practices found within a niche level, which is protected from the selection pressure of the regime; as well as a landscape level that refers to macro phenomena. The MLP explores transition processes that occur when landscape pressures on the regime create windows of opportunity for the adoption of niche-level innovations seeking to provide the same service or function as the regime, such as electricity or transport, in a new way.

The MLP emphasizes competition between the regime and the niche, and the TIS framework has largely been internally focused without consideration of larger structural contexts (Markard and Truffer, 2008). These frameworks have not emphasized the role of *wider* structures *complementing* the development of new technologies. Yet, earlier innovation system scholars discussed the importance of complementarities between old technologies and new ones (Rosenberg, 1982), "technological convergence" (Rosenberg, 1963), and innovation linkages from related industries (Porter, 1990). Nelson and Winter (1982, 258–259) discussed "technological regimes" to outline how innovation trajectories were based on ideas of "what is feasible or at least worth attempting". Rip and Kemp (1998, 338) noted that "regimes are outcomes of earlier changes and they structure subsequent change". While the MLP seldom discusses a regime as an enabler of sustainable technologies, these definitions do not preclude that potential, especially if regime actors view the sustainable technology as feasible and capable of promoting expansion. From this perspective, the regime describes a highly stable and inter-related economic structure, centred on a particular technology, which can provide certain resources in a specific sectoral and regional context. Regime characteristics can help explain the performance of a TIS in certain places over others. Regime-TIS interactions can relate to complementarity or competitive relationships along production chains or socio-technical overlaps and could involve seemingly unrelated technologies. This is in contrast to regime-niche interactions, which refer to technologies that provide the same societal function or compete within the same sector.

Raven and Verbong (2009) highlight the potential for an innovation to cross regime boundaries, and trigger interactions between regimes. They list multi-regime interaction modes of competition, symbiosis, integration, or spill-over. An illustration of multi-regime competition is a situation where one regime enables a TIS, while another regime blocks the TIS because it creates a competitive niche.

Fig. 1 sketches a framework that encompasses the system dynamics explored in this paper. It includes the interplay between structure and function found within the TIS framework, as well as TIS structural overlaps with different regimes. The development of the TIS also creates different types of interactions between the regimes that overlap with it. Landscape factors can influence all systems.

The nature of the structural overlaps between the regime and the TIS can influence whether innovation performance is strong or weak. To date no Canadian-based study has analyzed this issue using the analytical tools provided by socio-technical frameworks. Functional analysis of an innovation system could provide earlier and more dynamic indicators of innovation strengths and weaknesses than alternative indicators such as input–output tables or diffusion rates. In addition, the regime concept helps describe the "totality of technology", which encompasses material as well as social-institutional characteristics that could overlap with other technologies.

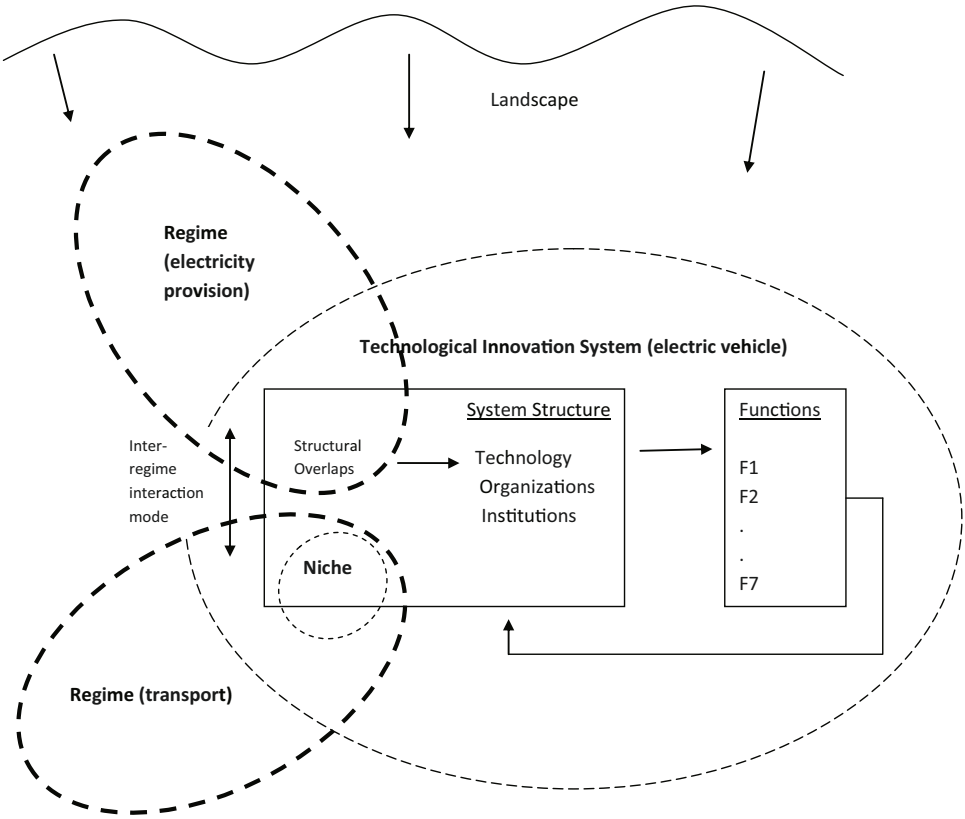

Fig. 1. Theoretical framework.

3. Research approach and methods

Assessing the strengths and weaknesses of TIS functions provides an indicator of EV innovation performance in different areas. The list of functions in Table 1 is relevant to the case, and previous studies demonstrate their general applicability (Hekkert and Negro, 2009). This paper will take the additional step of examining TIS interaction with an aspect of its wider environment by outlining the characteristics of the hydroelectric regime. In order to consider social as well as technical factors, structural characteristics will be divided into technical, organizational, and institutional dimensions. The technical dimension relates to characteristics of the core technologies of the regime, plus associated infrastructures and production chain technologies. The organizational dimension includes actors and networks. The knowledge possessed by actors is placed within this dimension. Hence, organizational characteristics might differ by configuration (e.g. level of centralization and connectivity) or knowledge stocks. The institutional dimension relates to formal laws as well as cultural and political values and conceptual understandings, often referred to as "rules" (North, 1990). A description of the transportation regime that encompasses the EV niche is also required to understand the role of multi-regime interactions.

The innovation processes and structures of interest are analytical constructs, which help trace processes of change that occur within particular contexts. Case study methodology offers a complete description of phenomena within a particular context (Yin, 2009). The context specific information provides useful examples and helps us judge which actions and interventions are desirable (Flyvbjerg, 2001). This paper explores the regional context in the province of Québec. Québec is Canada's second most populous province, and the only province with a francophone majority. It operates its own

Table 1
Technological innovation system functions.

Function		Description	Performance indicators
F1	Entrepreneurial experimentation	Entrepreneurs (new firms or incumbent companies) undertake risky experiments and upscale technologies to find business opportunities resulting from the potential found in new knowledge, networks, and markets	-New entrants -Diversification of incumbent actors -Experiments with new technology
F2	Knowledge development	Research and Development (R&D) and knowledge development. Learning by searching and doing.	-R&D projects and investments -Publications -Patents
F3	Knowledge exchange	Knowledge is exchanged between actors through networks. Learning by interacting and learning by using	-Workshops and conferences -Co-publications and projects -Network size and intensity
F4	Guidance of the search	A clear development goal based on technological expectations, user demands, and societal discourse used to guide the distribution of resources	-Government and industry targets -Expectations expressed in media
F5	Market formation	Creation of markets from small niches towards enabling large-scale diffusion	-Niche markets and lead users -Incentives for new technologies -Policies, codes and standards -Customer groups
F6	Resource mobilization	Financial, human, and physical resources act as important inputs	-R&D funding -Qualified personnel -Physical infrastructure programs -Actor perceptions on sufficiency of resources
F7	Creation of legitimacy	Presence of advocacy coalitions and societal understandings to counteract resistance to change	-Presence of interest groups -Visions -Depiction in media

Adapted from Hekkert et al. (2007); Bergek et al. (2008); Markard and Truffer (2008).

electricity system, since Canada does not have a comprehensive national grid. Case study information was collected from secondary literature, annual reports, technical documents, presentations, news articles, and interviews with nine electric vehicle experts.

Sections 4 and 5 will present the structural features of the hydroelectric and transportation regimes, and the EV niche within the transport regime, in order to reveal the structural resources available to the EV TIS in Québec. Historic factors that led to these particular structural characteristics will be highlighted, where appropriate. Next, a historic narrative of electric vehicle development will trace key events to evaluate which functions are strong and weak, following the approach suggested by Hekkert et al. (2007). The history will be divided into periods with unique socio-technical patterns, noting functional strengths, relevant landscape events and interactions between the transport and hydroelectric regimes, using Raven and Verbong's (2009) typology, and adding the potential for *disconnection* of the regimes. Section 7 will explore the connection between the structural characteristics outlined and the TIS functional performance observed in the case. It will discuss how different functions were enabled by particular hydroelectric structural characteristics. It is also of interest to consider *how much* hydroelectric structural overlaps influenced TIS functions compared to other structural overlaps or dynamics internal to the TIS. This question will be illuminated by referring to regime influence on functional performance indicators (see Table 1), such as the number of entrepreneurial entrants, publications, and relationships within social networks.

4. Québec's hydroelectric regime

4.1. Technology

With 35 GW of installed capacity, hydro supplies 98% of Québec's electricity (Hydro-Québec, 2012b). Québec has an extensive high-voltage transmission system, required to transport electricity

over long distances from mostly northern hydro dams towards southern demand centres. Due to the availability of inexpensive electricity and electric promotion activities 76% of households in Québec use an electric heating system (Natural Resources Canada, 2010a,b). This requires robust distribution grids capable of responding to high instantaneous demands.

4.2. Organizations

Hydro-Québec (HQ) is the provincially owned utility that operates the generation, transmission, and distribution of electricity throughout the province. It employs over 22,000 people and holds nearly $70 billion in assets (Hydro-Québec, 2012c). The Québec government can exercise control over electricity policy through legislative means and its influence as the sole shareholder of Hydro-Québec. Throughout its history the government has used the utility as a source of revenue, as well as an instrument for economic development and technology policy (Parenteau, 1986). For instance, electric-intensive industries, such as aluminium, were attracted with preferential electric rates.

The utility gained province-wide scope after the nationalization of private electric utilities in 1963. The centralization of activities enabled a massive building period in the 1960s and 1970s of large-scale dams and transmission networks. Centralized organization is a characteristic that flows from centralized generation and transmission technologies. HQ largely maintained this structure during the period of deregulation in the 1990s. Hydro technologies could not be easily divided up to foster competition. To help secure access to US export markets, HQ unbundled its production, distribution, and transmission units, while maintaining central corporate direction (see Doern and Gattinger, 2003; Nelles, 2003; Netherton, 2008). Hydro-Québec relies on outside suppliers for consulting engineering services and electric equipment (e.g. capacitors). Hydro-Québec also operates a research institute, named IREQ, which employs 500 and invests about $100 million a year in R&D. IREQ was created after the nationalization with the primary objective of optimizing and managing the high-voltage transmission grid, but its founders also wished to develop Québec's general expertise in electric technologies and undertake "long-term" research (Masson, 1995). IREQ can be understood as an actor somewhat separate from HQ because it has some autonomy and separate interest (Bataïni and Trépanier, 1999) and its employees can promote different technological trajectories.

4.3. Institutions

The nationalization of Hydro-Québec was not only linked to organizational changes, but cultural ones as well. The company became a symbol of the province's "Quiet Revolution", a new ideal of a "technological society led by French Canadians" (McRoberts and Posgate, 1980) focused on building a modern economy and society. The nationalization welcomed a francophone professional class to what was a sector dominated by English speakers. The application of francophone technological capabilities to hydro projects inspired the goal of making Québec renowned in electric technology. This history links hydroelectricity with ideals of technological modernity, independence, and emancipation (Savard, 2010).

The idea of a "social pact" to secure the benefits of hydro nationalization is prominent. The pact consists of (a) regionally uniform rates, (b) rate stability, (c) low rates, particularly for the residential sector and (d) public ownership (Hydro-Québec, 1999). During North America's move towards deregulation, Québec maintained this social pact through the "heritage contract", which commits the generation division of HQ to sell a block of electricity to the distributor at a set price (initially 2.79 cents/kwh). Faced with climate change and sustainable development, Québec quickly touted hydroelectricity as an asset. The solidification of Québec's identity as a clean energy jurisdiction was exemplified in the public rejection of a natural gas plant in 2004 (Boutin, 2004).

5. Transportation regime and EV Niche

The boundaries of the transportation system are difficult to draw, since we can divide it into subsystems based on public and private transportation. This paper's principle interest relates to fuel type

– electric vs. fossil. Thus, system boundaries will include public transport where electrification might have greater market shares as well as private transportation where electric drive exists within a niche.

5.1. Technology

Québec has extensive road, bicycle, and public transit systems. In Québec's largest city (Montreal), 22% of the population uses public transit to get to work, while 70% travel by car, truck or van (Statistics Canada, 2011). About 50% of public transit trips use electricity (367 GWh) in Québec (Hydro-Québec, 2012a). Public transit use is less frequent in smaller cities, rural, and remote communities. In 2011 about 0.2% of the vehicle fleet was electric (920 vehicles) (SAAQ, 2012). While a niche, in 2012 more than half of Canadian electric car sales took place in Québec (Klippenstein, 2013).

5.2. Organizations

While Canada is a major oil producer, Québec receives 90% of its oil from outside Canada (Statistics Canada, 2012). The petroleum sector is not a powerful regional actor, aside from refining operations and exploratory activity.[1] Québec's last auto assembly plant closed in 2002 (Boyer, 2006). The ground transportation sector contains 985 firms: 48% involved in specialized vehicles; 17% rail; 13% light vehicles; 11% recreational; and 10% public transport (MDEIE, 2010). Major companies include Bombardier (rail and recreational), Paccar (trucks), and Nova Bus. Fig. 2 provides a list of firms involved in electric transportation, grouped by number of firm employees. This distribution demonstrates the presence of firms across the value chain; a diversity of vehicle specializations outside of the private car; and the presence of large companies and start-ups.

5.3. Institutions

The socio-cultural and political forces that maintain the dominance of the car are relatively consistent throughout the industrialized world (see Paterson, 2007). Compared to the rest of Canada, Québec consumers have a stronger preference for smaller cars (Deveau, 2012). Civil society actors have linked transport electrification with the cultural understandings stemming from Québec's Quiet Revolution, calling for the province's *independence* and *liberation* from oil importation (Breton, 2009; Duchaine and Séguin, 2009).

6. Historic evolution of EV technologies in Québec

This section outlines the historic development of the EV technological field in Québec from the 1970s to 2013. A historic narrative will be divided into five periods. At the end of each section, a sub-section will describe the socio-technical pattern by referencing landscape factors, inter-regime interactions, and prominent TIS functions. This information is summarized in Table 2, with darker squares depicting stronger system functions.

6.1. 1970–1985: IREQ pioneer period and oil crisis

After the 1970 inauguration of IREQ, the research institute considered "long-term" projects outside of high-voltage transmission. Following the 1973 oil price shock, IREQ created a working group on electric vehicles, which concluded that transport electrification depended on the development of high-energy batteries over the next ten years. Throughout the 1970s, IREQ monitored electric vehicle related developments and directly supported battery research. Batteries could help smooth electric load curves and IREQ wished to maintain expertise in a technological field in which "the future of the

[1] However, there are prospects for oil exploration in the future (Van Praet, 2013). Hydro-Québec was closely implicated in the Québec government's intervention into oil and gas. HQ created an oil and gas division in 2002, later to be abandoned in 2006.

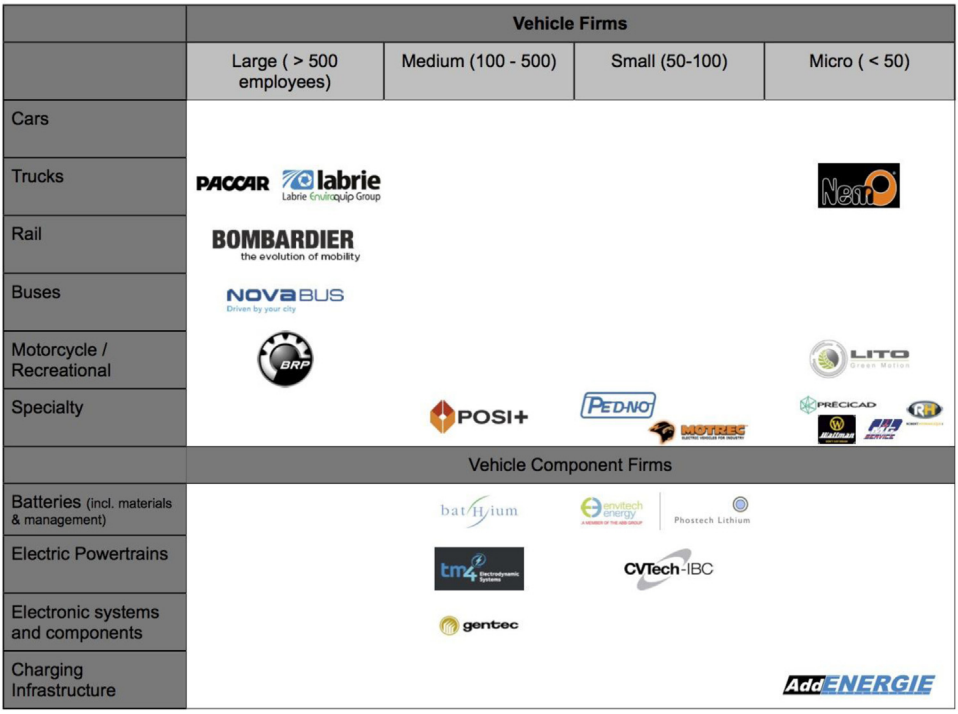

Fig. 2. Québec electric vehicle companies. (Information from Couillard and Desaulniers (2012), database "Répertoire d'entreprises du Québec", and Network of Centres of Excellence of Canada.)

electric vehicle depends" (IREQ, 1975). In 1979, IREQ entered a co-operation agreement with the oil company Elf Aquitaine and The French National Centre for Scientific Research (CNRS) to develop a lithium–polymer battery. This would link CNRS researcher Michel Armand's (1979) all-solid battery using polymer electrolytes concept with IREQ's expertise in lithium and molten salts, associated with researcher Michel Gauthier. An all-solid battery promised to enhance safety and durability. It could also be mass-produced via thin-film techniques used to make paper, aluminium foils, and electric capacitors.

A 3-person research group, quietly supported by an administrator (Masson, 1998), initiated another EV related project in 1982. Led by Pierre Couture, the project sought to develop a "motor wheel", placing a motor, AC–DC converter, and controller within each wheel. It switched the typical motor configuration to allow a permanent magnet rotor to spin around an immobile stator. Placing the equipment inside the wheel could reduce transmission losses and recoup power through regenerative breaking, while the inverted rotor configuration provides better torque and power density. To model this system, the team noted the benefit of its expertise in calculating magnetic configurations developed during thermo-fusion research at IREQ (Langlois, 2008, 66–72).

6.1.1. Socio-technical pattern

The oil crisis was the major landscape event during this period. The creation of IREQ and the expectation that it would play a large role in new research areas was also an important organizational evolution within the hydro regime. The interaction between the hydro and transport regimes is best characterized as spill-over, as expertise in battery and motor electro-technologies was directed towards EV applications. The strongest TIS functions were knowledge development and exchange. The entry of Elf Aquitaine demonstrates some entrepreneurial experimentation. The functions of political legitimacy, guidance of the search, and resource mobilization were supported by IREQ, which was

Table 2
Evolution of Quebec EV socio-technical patterns.

Period		1970-1985	1985-1990	1990-1997	1995-2007	2008-2013
Landscape Factors		Oil Crisis	End of Oil Crisis	California Standards	Electricity Deregulation	Lithium-ion; oil price spike; Tesla; Obama; Electric Surplus
Hydroelectric-Transport System interaction type		Spill-over/ Symbiosis	Disconnection	Symbiosis	Disconnection / Competition	Symbiosis towards integration?
EV TIS Functions						
F1	Experimentation by Entrepreneurs					
F2	Knowledge Development					
F3	Knowledge Exchange					
F4	Guidance of Search					
F5	Market Formation					
F6	Resource Mobilization					
F7	Creation of Legitimacy					

Legend
Absent/v. Weak Weak Moderate Strong

This table provides a synopsis of the socio-technical patterns outlined in Section 6, after each of the five time periods.

furnished with societal support for long-term research and sufficient autonomy to establish research direction and partnerships.

6.2. 1985–1990: deflated global interest

As the energy crisis waned so did interest in electric vehicles. In the mid 1980s, Elf Aquitaine dropped out of the battery project. Hydro-Québec expressed an interest in continuing, but recognized the need to find partners outside of the electric vehicle domain (IREQ, 1987). In 1990, HQ signed an agreement with the Japanese company YUASA to manufacture its battery for the telecommunications sector, with an intention to build a Québec-based plant by 1995 for EV (IREQ, 1990).

6.2.1. Socio-technical pattern

The end of the energy crisis shifted the landscape, creating a period of disconnection between transport and electric regimes. However, knowledge production activities continued within IREQ (supported by some knowledge exchange opportunities and financial resources), in partnership with telecommunications actors. Hydro regime actors guided the search towards a new regime coupling (electric-telecommunications), with plans to use the telecommunications partnership to eventually promote EV activities in Québec.

6.3. 1990–1997: California standards, new networks, and rising expectations

In 1990, The California Air Resources Board adopted zero-emission vehicle regulations. In 1991, IREQ accelerated the motor-wheel project. In 1993, *The United States Advanced Battery Consortium* (USABC) awarded Hydro-Québec a $100 million contract to assess and improve its battery, in collaboration with The 3M Corporation and Argonne National Laboratory in Chicago. The US government and three major automakers initiated USABC in response to the California regulations. In 1994, Hydro-Québec constructed a battery manufacturing pilot plant,[2] and in 1995 Armand established a lab at the University of Montreal.

In 1994, the motor-wheel technology was unveiled to the Québec public (Francoeur, 1994). That same year, in the midst of an election campaign, the Premier promised to invest in building an electric vehicle entirely designed and manufactured in Québec (Cauchon, 1994), but was subsequently defeated.

In 1996, The *Québec Electric Vehicle Experimentation Centre* (CEVEQ) was created with the financial aid of the Québec government and the Laurentides municipal region. This initiative was born out of Québec cluster development strategies and a partnership between the Laurentides and *La Rochelle*, a pilot city for electric vehicles in France. The existence of a test track and transport regime actors such as Paccar, Nova Bus, and a General Motors plant,[3] led the Laurentides to select advanced transport as a regional specialization.

In 1996, the recreational division of Bombardier introduced a *neighbourhood electric vehicle* (NEV), marketed to gated and planned communities and resorts in Arizona, California, and Florida. These jurisdictions permitted low-speed vehicles on roads. Bombardier envisioned a market since people were using golf carts for general transportation (Motor Trend, 1997).

6.3.1. Socio-technical pattern

The California standards brought the transport and electric regimes towards symbiosis, as major auto firms became interested in HQ's battery technology. This introduced new financial resources and access to international networks, which spurred intensive knowledge development and exchange activities along with entrepreneurial experimentation through the first battery pilot plant. Entrepreneurial experiments such as Bombardier's NEV were also launched. The motor-wheel technology demonstration raised the legitimacy of EV within Québec. Government cluster policies helped guide the search towards regional specializations in EV.

6.4. 1995–2007: diffusion stifled; hydro regime controversies; niche formation

The high expectations in the early 1990s were reduced as attempts to find markets for Québec's EV related technologies were frustrated alongside declining global interest, whilst internal conflicts within the hydroelectric regime erupted.

In 1995, Hydro-Québec's Board of Directors decided to manage the motor-wheel project by focusing efforts on the wheel itself, rather than its associated power train system. The reduced scope led to the resignation of lead researcher, Pierre Couture, which triggered prominent media coverage. An article in *Québec Science* (Rodrigue, 1995) explored remaining technological difficulties and reduced expectations, while an episode of the documentary television show *Decouverte* (Gélinas et al., 1996) presented

[2] Named Argo-Tech after the researchers Armand and Gauthier.
[3] As stated above, this plant closed in 2002.

the motor-wheel decision as a lost opportunity. This attention triggered a parliamentary committee where Couture claimed the project had been sabotaged and politicians urged Hydro-Québec to not give up on its vehicle electrification efforts. Despite the controversy, the motor-wheel was road tested in 1997 and Hydro-Québec created a subsidiary named TM4 to market the technology in 1998.

During this period the electricity regime experienced new pressures. The landscape trend towards electricity deregulation introduced the prospect of more competition, and the CEO of HQ perceived the need to focus on the "core" activities of electricity production, transmission, and distribution. Hydro-Québec's (1999) strategic plan suggested that R&D had "veered off course" and emphasized reaping commercialization benefits from R&D already undertaken. Hydro-Québec sought to accelerate commercialization of its battery technology in the telecommunications sector (Tison, 1999). In another move that garnered media headlines, Michel Gauthier resigned from Hydro-Québec, warning alongside Armand, that commercializing without further R&D could discredit the technology (Asselin, 1999; Francoeur, 1999). Armand and Gauthier went to the University of Montreal and made use of HQ patents[4] to develop a research interest in phosphate as an alternative cathode material, which led to the creation of Phostech Lithium in 2001.

By 2000, Bombardier cancelled production of its Neighbourhood Electric Vehicle, stating that their product was "a little in advance of our times" (Tison, 2000). The two Hydro-Québec subsidiaries (TM4 and Avestor) had difficulty finding markets for their products. TM4 searched for financing while they waited for the transport industry to take the electric turn (Jolicoeur, 2000). It developed a more conventional system with the motor housed within the body of the car instead of the wheel. Internationally based pilot projects, unconnected to major automakers, provided niche markets. This included the Cleanova I and II developed by the *Société de Véhicules Électriques* in France and the use of the wheel-motor in the Peugeot Quarks All Terrain Vehicle and Citroën C-Métisse.

Avestor demonstrated its battery in the Ford Th!nk City car, but later lost a contract to supply batteries for the Cleanova I. Stating that EV progress did not meet expectations, it cut staff (Turcotte, 2004). The company had some success marketing to telecommunications providers (e.g. AT&T). But, a battery system caught fire in California, and in 2006 the company declared bankruptcy. In 2007, France's Bolloré Group purchased Avestor, re-opened the Québec plant, and renamed it Bathium Canada. Bolloré was using its expertise in capacitor manufacturing to develop a lithium–metal–polymer battery[5], but lacked production-scale manufacturing facilities and knowledge of some of the Avestor techniques (Monfort, 2013). Bolloré re-oriented the battery technology towards EV, finding a niche market in the Paris car-sharing program (AutoLib'), using the *BlueCar* designed for urban environments.

Meanwhile the Laurentides cluster initiative commenced niche experimentation and network-building efforts. Between 2001 and 2008, CEVEQ organized annual conferences, alternating between Québec and France. Between 2000 and 2004, it launched pilot projects to integrate electric cars into commercial and institutional fleets and to explore security and traffic flow concerns with low-speed vehicles. CEVEQ was instrumental in the creation of a Canadian electric mobility association in 2005. In 2002, Laurentides cluster initiatives created *The Québec Advanced Transportation Institute (ITAQ)* to provide testing and development services to small businesses. It helped launch start-ups such as the low-speed, zero-emission, no-noise (ZENN) car and LITO Green Motion's electric motorcycle.

6.4.1. Socio-technical pattern

The gradual weakening of the California standards reduced landscape pressure on the transport regime and introduced another period of regime disconnection. Furthermore, resource competition between EV and the core activities of the hydro regime was introduced by deregulation landscape pressure and internal HQ actor strategies. Hydro-Québec's turn towards the telecommunications sector, principally to recoup prior investments, ultimately failed. The changes in both regimes significantly weakened the guidance of the search function.

[4] The patents involved had multiple owners other than HQ, including the University of Texas at Austin, CNRS, and the University of Montreal. See Fletcher (2011) for an interesting history.

[5] This expertise was especially useful in refining an extrusion process for cathodes. Extrusion is a material shaping process where a material is moved through the machine via screws and pushed through a dye.

However, transport niche actors (CEVEQ; ITAQ) continued to support system functions such as entrepreneurial experimentation. Some political legitimacy was maintained since actors still expected HQ to play a role in EV technological innovation, as demonstrated by public comments supporting the motor-wheel technology. The companies that branched from the hydro regime (TM4, Avestor/Bathium) faced market formation difficulties, but discovered international niche markets, which maintained entrepreneurial experimentation and knowledge exchange functions in Québec.

6.5. 2008–2013: the return of electric vehicles

Improvements in lithium-ion batteries, a new oil price spike, the unveiling of the Tesla Roadster electric car in 2006, and the election of Barak Obama in the US were all landscape factors that once again raised expectations.

In the fall of 2008, HQ created a working group to coordinate and lead its activities in transportation electrification. In its 2009–2013 Strategic Plan Hydro-Québec (2009) unveiled an electric ground transportation action plan, touting its reserves of hydropower, its low electric prices, and its robust distribution system able to integrate about 20% of Québec's vehicle fleet to electricity without significant grid upgrades (Desgagné, 2012). The HQ action plan contained four elements: (1) financial assistance for public transit electrification infrastructure; (2) development and marketing of battery and motor system technologies[6]; (3) the coordination of some of the largest vehicle trials in Canada to understand charging habits and vehicle performance in winter conditions. Since many models were not yet on the market, HQ negotiated partnerships with car companies to test their models in Québec before their release (Lampron, 2012); (4) the creation of Canada's first public charging network (the "circuit électrique"). In 2012, IREQ launched a vehicle-to-grid research project to understand how it might change power system operation.

In July 2008, the Québec government changed regulations to allow low-speed electric vehicles on some roads. A new research centre with a mandate to develop environmental recreational vehicles was created at Sherbrooke University in partnership with Bombardier Recreational Products. This led to the development of hybrid engine technology for a 3-wheel motorcycle. In 2009, Bombardier Transportation launched a wireless charging system for electric rail, buses, and road vehicles. In 2014, it will be tested in Germany and Montreal, in partnership with Hydro-Québec.

In 2011, the Québec government released an Electric Vehicle Action Plan. The plan noted the importance of transport electrification in achieving the province's target to reduce GHG emissions 20% below 1990 by 2020. It includes targets for the sale of light passenger vehicles (5% of fleet by 2020, 18% by 2030) and public transportation (95% of trips by 2020), and incentives for the purchase of electric vehicles by public transit authorities, taxi companies, car shares, and individuals. The plan also promotes industrial development initiatives through support for research, cluster development, and the design and construction of a Québec electric bus, involving actors such as Nova Bus, Bathium Canada (batteries), TM4 (power train), and the Aluminum Association of Canada.

During this period, the recession and the advent of "shale gas" also diminished HQ's export revenues. Québec projects a surplus supply of electricity until 2027. In 2013, the newly elected government, supported by environmental and renewable energy organizations, expressed its intention to use the surplus to expand the electrification of transport.

6.5.1. Socio-technical pattern

Another window of opportunity was opened due to a variety of technical, economic, and political landscape factors, bringing the two regimes into symbiosis. Projects based on configurations such as vehicle-to-grid also suggest the potential for regime integration, and EV induced changes to the electric regime. Concern for GHG reductions, and an electric surplus, enhanced the political legitimacy of EV

[6] HQ's strategy is to license battery-related intellectual property, rather than following an earlier practice of using its intellectual property to encourage local production. We can interpret this shift as prioritizing knowledge production and exchange activities. It de-emphasizes the attraction of domestic entrepreneurial experimentation within the battery field, or enhancing political legitimacy if we assume local economic activity also introduces new political actors. This policy change has led to objections and controversies (Francoeur, 2011).

and led the government and Hydro-Québec to strongly guide the search, not only towards promotion of battery and motor components, but the larger technological field. This period activated all functions.

7. Hydro-EV overlaps and inducement of functions

The case recounts a volatile history for EV in Québec. However, it also demonstrates the resilience of the EV TIS during periods when the transportation regime was less accommodating and when some hydro regime actors wished to disassociate themselves from EV activities. To more fully understand the dynamics that maintained and strengthened Québec's EV TIS, we can identify the particular system functions that were activated, and the structural overlaps that helped promote them. Emphasis will be placed on structural characteristics of the hydroelectric regime, as outlined in Section 4. This section will not only identify the linkages between functions and structure, but also discuss how much the linkages mattered by using additional case-study information and quantitative indicators. The following section discusses each function, and makes reference to the influence of hydro structural overlaps compared to other structural influences. Fig. 3 draws the structure–function linkages, across different dimensions.

7.1. Entrepreneurial experimentation

Hydro-Québec is an organizational actor that helped induce entrepreneurial experimentation. Firms linked to HQ's commercialization efforts include TM4, Phostech, and Bathium. HQ also contributed to this function through test drive projects, which encouraged car manufacturers to provide EV models to a variety of different user groups. However the influence of hydro should not be overstated. The majority of firms active in the EV TIS do not have histories associated with the hydroelectric regime (see Fig. 2). They are either incumbent players of the transport regime (e.g. Bombardier) or start-ups encouraged by initiatives, such as regional cluster development efforts.

7.2. Knowledge development

IREQ contributed to knowledge development by focusing its efforts on batteries and motors, and has more recently studied the impacts of EVs on the grid. The institute's initial mission was to optimize long-distance transmission systems, but it ventured into wider technological areas because of its independence and connection with the societal understandings linked to the Quiet Revolution. Fig. 4 counts publications and conference presentations by Québec research organizations in the area of batteries, where Hydro-Québec/IREQ is the most important knowledge producer. Fig. 5 counts research contributions within an "electric vehicles" keyword search. The lower number of publications reflects the more recent interest in the technological field. Here, the university sector plays a significant role, with HQ/IREQ remaining an important actor.

7.3. Knowledge exchange

Knowledge diffusion results from organizational overlaps, with both IREQ and HQ playing a role. IREQ principally shares scientific knowledge, while HQ is active in supplier, consumer, and policy networks. The case revealed the role of knowledge sharing between sectors encapsulated within the hydro regime, but less closely connected to hydro technologies in particular. The technical knowledge overlaps linked to the motor-wheel were related to thermo-fusion activities at IREQ. Knowledge about thin-film production from capacitor and aluminium sectors aided the lithium–polymer battery. IREQ created an organizational structure within which these knowledge linkages could occur. In addition, the research institute gained access to international knowledge networks, for example partnerships with CNRS and USABC. Hydro-Québec also partnered with auto manufacturers to test vehicle performance in winter climates and the impacts on the grid, which facilitates learning by using.

In order to consider the relative importance of hydro regime actors in knowledge sharing activities, Fig. 6 presents a social network diagram based on co-publications and conference presentations

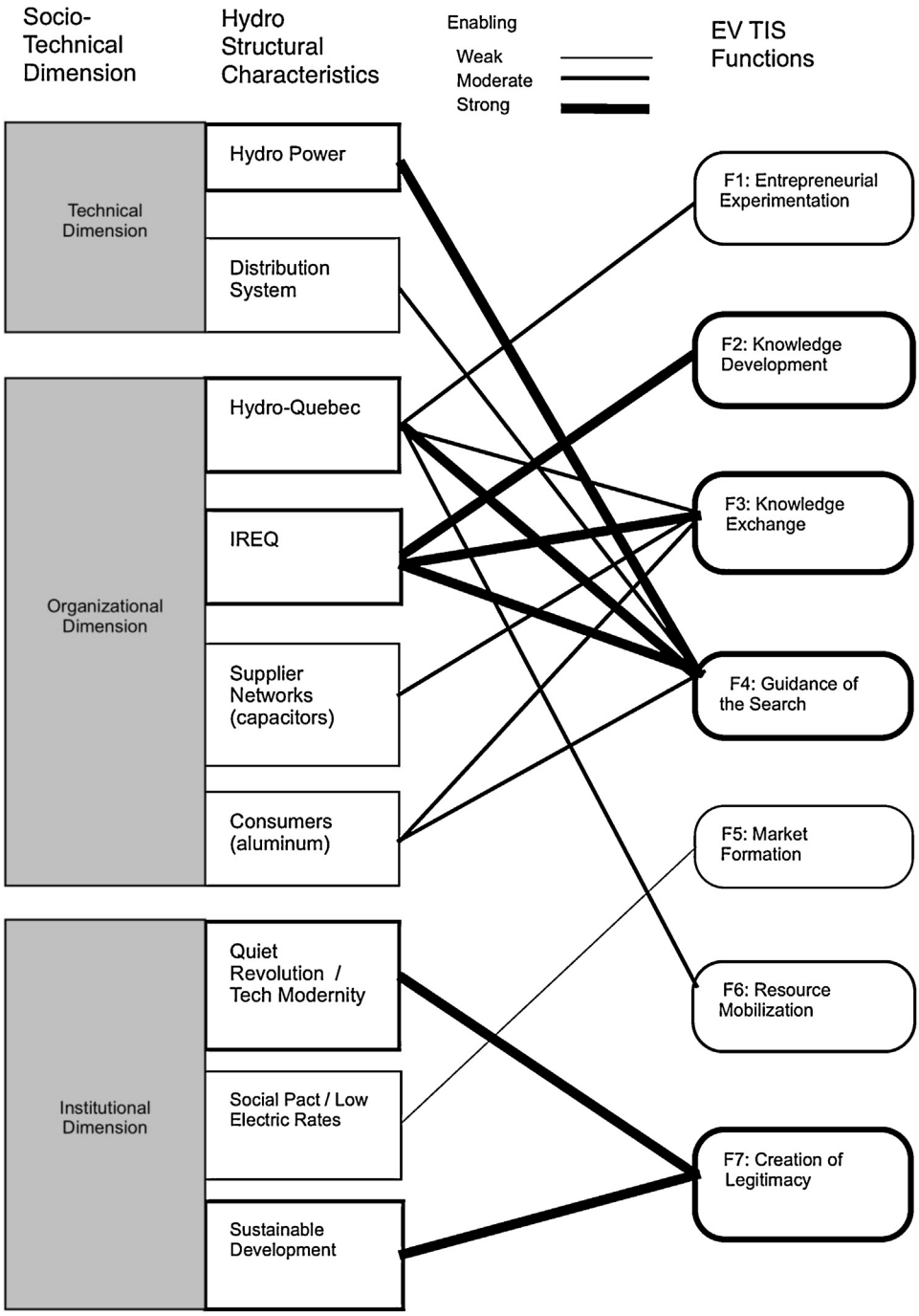

Fig. 3. Hydro structural elements inducement of functions.

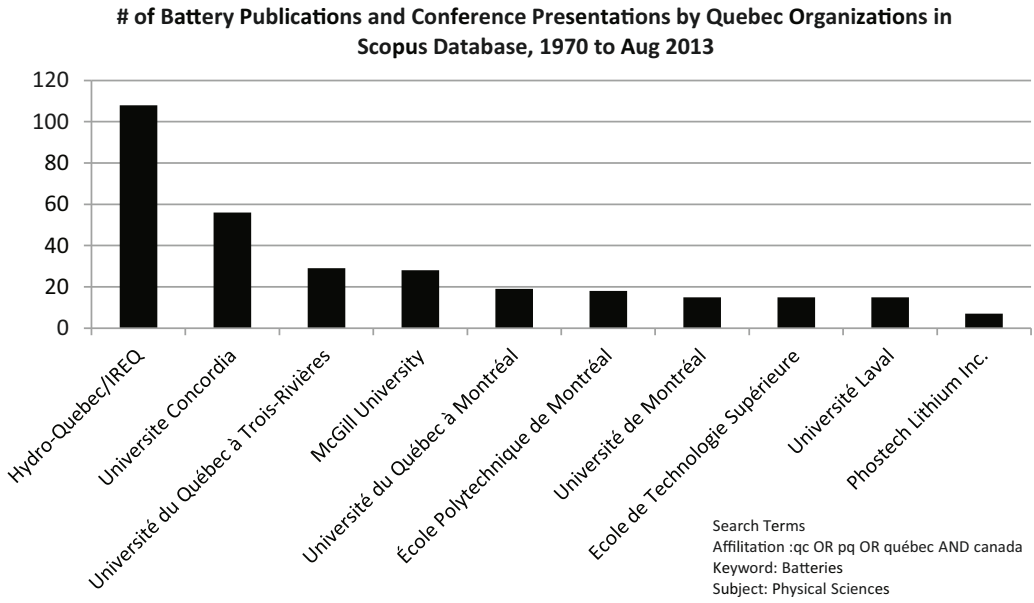

Fig. 4. # of battery publications and conference presentations by Quebec Organizations in Scopus Database, 1970 to August 2013.

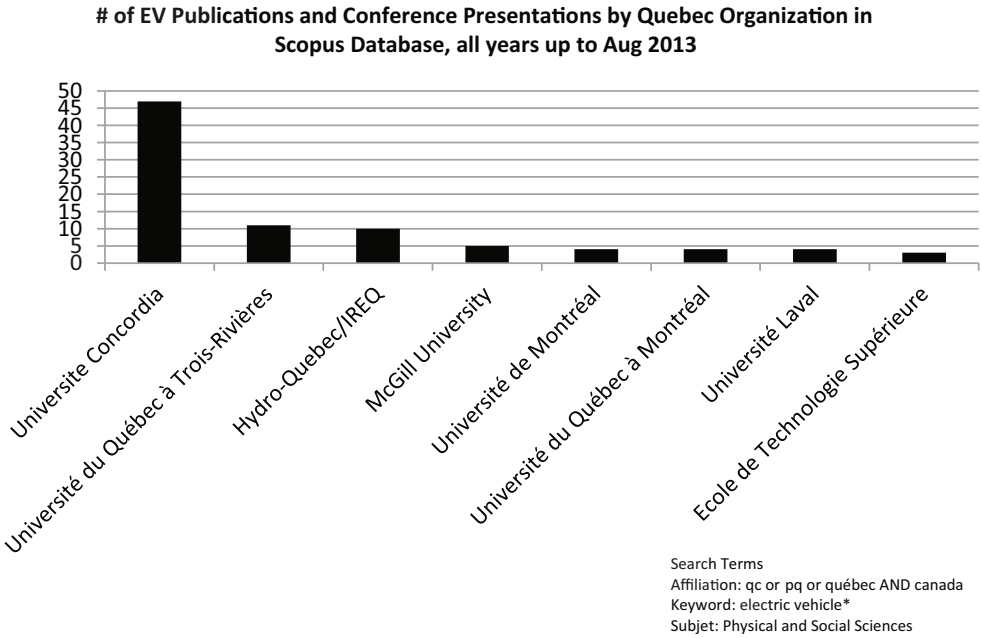

Fig. 5. # of EV publications and conference Presentations by Quebec Organization in Scopus Database, all years up to August 2013.

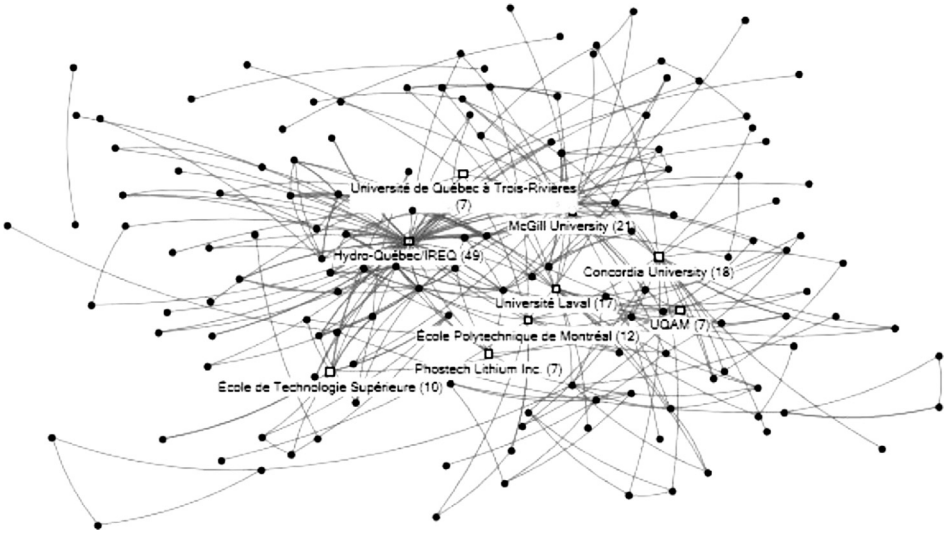

Fig. 6. Battery co-publications and conferences by Quebec organizations. (Scopus database, keyword "batteries" in physical sciences. Based on organizational affiliations, with the aid of BibExcel and NodeXL.)

involving Québec-based organizations within the field of batteries. Hydro-Québec/IREQ has the greatest number of direct ties to other organizations, indicating that hydro regime organizations play an important role in diffusing knowledge in this field. These linkages are both global and Québec-based.

7.4. Guidance of the search

Clearly, the presence of hydro helps guide the search towards EV, since policymakers link its low-carbon attributes to policy objectives related to climate change and energy independence. Plus, Québec's distribution infrastructure, built to manage the large electric heating loads that were encouraged by low electric prices and policy initiatives, gives Québec actors confidence in their ability to integrate EV. The existence of the aluminium sector, attracted by low electric prices, also helps guide the search towards EV, since actors have access to both lightweight materials and expertise.

In the early periods, IREQ helped direct efforts towards EV technologies, aided by a degree of legitimacy and organizational autonomy which gave researchers power to propose novel research areas. This base of expertise contributed to high expectations and guidance by Hydro-Québec and government during periods of symbiosis between electricity and transport regimes. Yet, guidance waned when the hydroelectric regime faced pressures during the electricity deregulation trend. This period demonstrated tensions between the ambition to maintain EV activity by IREQ personnel, the media, and some government representatives versus HQ's strategy of re-focusing resources on core regime activities.

Throughout the case history IREQ mostly directed technological trajectories towards hard science initiatives (batteries and motors), with less emphasis on exploring social factors such as government regulations and user interactions. EV TIS actors such as ITAQ and CEVEQ, and government directed effort towards these activities. However, more recently, Hydro-Québec has begun to explore consumer behaviours to understand how EV will change electricity system operations.

7.5. Market formation

Market formation is the function least supported by hydroelectric structures. Low electric prices and government incentives provide some support for consumers, but have not resulted in a take off of EV purchases. The case demonstrated the challenge HQ spin-off firms faced finding markets and

partners within the transport sector, and eventual success in markets outside of Québec. The lack of domestic market formation could have weakened other functions such as knowledge exchange through networks and the political legitimacy that comes from domestic user groups and firms.

7.6. Resource mobilization

This function refers to financial, human, and physical resources. With respect to financial resources, Hydro-Québec's electric rate and export earnings principally support the electric system's core activities, while also delivering revenue to government. However, Hydro-Québec contributes to the province's clean technology venture capital fund (cycle capital management), but it has yet to direct funds to EV. The case demonstrated that IREQ attracted financial partners. In addition, provincial and federal government, and social investment initiatives supported HQ spin-off firms.[7]

Concerning human resources, as part of its "social role", Hydro-Québec directs 1% of its net revenue to donations and scholarships. This includes engineering scholarships and university research chairs. Thus far no research chair is focused on EV. Actors note the need for more training in battery technologies (Laperrière and Gaba, 2012). Also, skills overlaps between HQ and EV firms might not always be prominent. For instance, TM4 has found more human resource overlaps with the aerospace sector (Cloutier, 2012).

The provision of physical resources or infrastructure is the primordial contribution of the hydro regime to this function. Hydro-Québec identifies public transit electrification infrastructure needs through feasibility studies. It coordinates a vehicle charging station network, which involves negotiating a standard agreement between purchasers and equipment manufacturers, and providing quality assurance and communications services. EV actors note the ease with which Hydro-Québec, as a province-wide utility, can coordinate these activities in contrast to more decentralized electricity systems with many distribution companies (Lampron, 2012; Hill, 2012), demonstrating a benefit of the hydro regime's organizational structure.

7.7. Legitimacy creation

The association of hydroelectricity with sustainable development and low GHG emissions supports the political legitimacy of EV in Québec. Cultural understandings associated with Hydro-Québec's position in the Quiet Revolution are prominent. Savard (2010) has traced how social and political actors have reinterpreted the meaning of Hydro-Québec to grapple with new challenges. Throughout this case, the utility's promotion of transport electrification has been linked to its historic role in facilitating independence, emancipation, and technological sophistication. Political legitimacy is also shaped by transport regime characteristics. Consider the absence of significant oil and auto sectors; the extent of oil importation; and the strength of the rail and public transit sectors, where electricity is more widely diffused.

8. Discussion of the findings

This paper considered how hydroelectricity could complement EV development. It examined this question by tracing linkages between EV functions and hydroelectric regime structural elements. This approach moves beyond technology-specific analysis, towards considering how EV development was influenced by its larger sectoral and regional context. The regime concept helped describe this larger context. While the multi-level perspective often describes a regime constraining a competitive niche, this paper considered how a regime could enable a technological innovation system. Since greater EV diffusion would expand the use of electricity, one would expect hydro to enable EV. The case confirmed this expectation, but also demonstrated the need to consider context-specific details that

[7] For instance, organizations providing financing for TM4 and Phostech include Canada's Industrial Research Assistance Program, Sustainable Development Technology Canada, Investissement Québec, Société générale de financement, Caisse de dépôt et placement du Québec (public pension plans), Fonds de solidarité FTQ (labour-sponsored fund).

explain how exactly hydro facilitates EV development, and if hydro provides sufficient resources for EV TIS performance, or if certain structural assets are overemphasized or neglected.

Even though EV would expand hydroelectric markets, the function of market formation was the most difficult process for the hydroelectric regime to complement. This can partly be explained by the lack of relevant resources that the hydroelectric regime was able to contribute, such as automotive marketing expertise. The case also demonstrated that the technical elements of hydroelectricity, while important, did not activate key functions related to EV performance. The technical overlaps found relate to GHG emission reduction and energy independence benefits from replacing fossil fuels with hydroelectricity and the presence of an accommodating distribution infrastructure for new electric loads. When we link these characteristics with functions, their principal role is to guide the search towards diffusion so Québec may take full advantage of these assets in the future. Yet, such a rate of diffusion is not anticipated until well after 2020 (see Villeneuve, 2012). While guidance of the search is critically important, the other system functions must be activated to actually reach the diffusion stage.

The Québec case showed that the important early stage functions of knowledge development and exchange were enabled by organizational elements of the regime. The creation of IREQ bestowed a structure that activated these processes to support battery and motor technologies. While batteries and motors were linked to general electro-technology competencies, the knowledge overlaps had little direct correspondence with hydroelectric production. In addition, the function of political legitimacy was strongly enabled by institutional elements of the regime. There were ambitious scientific goals associated with the Quiet Revolution and a connection with sustainable development objectives, which proved important for maintaining EV developmental momentum. These structural characteristics do not naturally flow from waterpower, but evolved from Québec's historic experience with hydroelectricity.

The unique linkages between Québec's hydro regime structural elements and EV functions warn against technological or resource determinism. Such beliefs might expect electric vehicles to naturally develop within a region due to the mere presence of hydroelectricity. While the case demonstrated that hydro enabled EV performance, this largely occurred because of organizational and institutional assets that could be quite unique to Québec. These insights should not discourage the potential for EV development elsewhere. It simply highlights that policymakers and researchers should identify the context-specific resources available to them to activate multiple system functions.

This study accomplished the analytical task of drawing linkages between structural context and technology-specific innovation performance by using and extending socio-technical theoretical approaches. As in other TIS studies, the case showed that tracing functions revealed innovation dynamics important for the early development of technologies and continued innovation system momentum. Furthermore, linking these functions with hydroelectric structural overlaps offered insights into the importance of institutional and organizational context. Within the socio-technical theoretic toolbox, the regime concept captured the extensive influence of hydroelectricity on Québec's economic and social structure, and insights from the multi-level perspective considered multi-regime dynamics with the transportation sector and the influence of landscape events. These concepts helped simultaneously consider the enabling potential of regime-TIS interactions, while recognizing regime-niche interactions between EV and the transportation sector. In this case, the hydro regime helped EV technologies take advantage of windows of opportunity when the transportation regime became more welcoming to its EV niche. Hydro-Québec and IREQ's ability to forge network relations with automotive companies and research institutes (e.g. USABC) were particularly important when windows of opportunity opened. When windows of opportunity closed the hydro regime was able to provide protection and help maintain EV TIS momentum, but the hydro regime's level of support was also prone to falter as a result of landscape changes (resource pressures from the electricity deregulation trend). These multiple contingencies and dynamics reinforce that hydro-EV complementarity is not predestined.

9. Conclusion

The paper studied the potential for hydroelectricity to complement the development of electric vehicles. It presents one case of a larger policy question related to how electricity systems can

maximize the low-carbon potential of hydroelectric resources. This question was explored by making use of the technological innovation system approaches' use of functions to evaluate EV performance, and supplemented it with analysis of linkages with the wider structural environment. This required a consideration of a "regime" as an enabler of a related TIS, instead of a blocker of competing niche technologies, as often discussed in MLP studies. The case demonstrated the benefits of coupling evaluation of system functions with identification of structural elements that enable those functions. This gives some clues to why an EV TIS was able to develop in the sectoral context of a hydroelectric system and the regional context of Québec. The case demonstrated the important role organizational and institutional elements of the hydroelectric regime played in enabling system functions. These elements are particularly prominent in the history of hydroelectric development in Québec, and point to the benefit of considering the totality of a technology's influence on its wider social as well as material environment.

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