

**Modelling the diffusion of multiple demand-side low-carbon energy
innovations within a 1.5°C scenario**

by

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A Major Paper submitted to the Faculty of Environmental
Studies in partial fulfillment of the requirements for the
degree of Master in Environmental Studies.

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July 30, 2020

Abstract

Keywords: Low-carbon innovation; Energy transitions; Demand-side; Diffusion; Canada

Decarbonizing the energy sector is a critical component in meeting global climate change mitigation commitments in a 1.5°C scenario. In order to accelerate the transition to a low-carbon energy system, solutions will need to be deployed at all stages of the energy system, including the diffusion and adoption of innovations by energy users. If deployed at scale (achieving market shares above 15%), disruptive demand-side low-carbon innovations have the potential to accelerate a low-carbon energy transition through the destabilization of the established socio-technical regime. However, demand-side innovations tend to be overlooked in favor of supply-side energy solutions. Moreover, many of the innovations needed to achieve sizable emission reductions already exist, yet experience slow rates of diffusion. Diffusion of innovation studies that attempt to address these issues often assess a single technology or a small scope of factors in isolation, which limits the application of the research findings. This empirical study investigates the factors that influence the diffusion of 132 demand-side low-carbon energy innovations in the Canadian province of Ontario that have the potential to contribute to a low-carbon energy transition. A framework was developed for analyzing and evaluating low-carbon innovations based on their potential contribution to system change. Each innovation was coded in accordance with the model framework. This research found that there is currently limited potential for low-carbon demand-side energy innovations to create a system transformation through disruptive innovation in Ontario. This research also found that legitimacy is a necessary but not sufficient condition for influencing system disruption. More empirical studies that apply the model framework presented in this analysis are needed in order to effectively map the range and combination of factors that can facilitate a low-carbon energy transition in Canada through system disruption.

Forward

This major research paper was written in fulfillment of course ENVS 7899 and was developed from my Major Research Paper proposal submitted to OSAS in January of 2020. This research paper is to be received in partial fulfillment of the requirements for the degree of Master in Environmental Studies in the Faculty of Environmental Studies at York University. The subject matter and themes explored in this research paper cover the topic of Low-Carbon Energy Systems and satisfies elements of the learning components and objectives outlined in my Plan of Study. This research is informed by the following research fields: Sustainability transitions (ST); Innovation systems (IS); Energy technology innovation systems (ETIS); Diffusion of innovation theory (DOI); and disruptive low-carbon innovation literature. Through the exploration of these complex and interdisciplinary concepts and ideas, I have contributed to my understanding of the relationship between energy systems and the environment and the mechanisms through which sustainable energy transitions can be accelerated. Working on this research project has also given me the opportunity to improve my skills in large data management, processing, and statistical analysis using computational software.

Acknowledgements

I would like to acknowledge and sincerely thank Dr. Christina Hoicka for her incredible guidance and continued support, as a supervisor and as a mentor, throughout the development of this research paper and my MES degree. I would also like to thank the research team, including Dr. Christina Hoicka, Dr. Runa Das, Dr. Jenny Lieu, Susan Wyse, and Yuxu Zhao, without whom this research paper would not be possible. I would especially like to thank Yuxu for all her hard work and support as my research partner. Finally, thank you to the members of the Social Exergy and Energy Lab at York University, including Jessica Conroy, Katarina Savic, Susan Wyse, Yuxu Zhao, Natalia Bekirsky, and John Lau, for their adept advice and feedback on the many drafts of this research paper that they reviewed. I sincerely appreciate all of the advice and support that I have received.

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1. Introduction

The most recent and reliable scientific reports emphasize the urgency of greenhouse gas emission reductions for maintaining safe and sustainable average global temperatures below 2°C, and ideally below 1.5°C, in order to avoid severe impacts on human and natural systems (Intergovernmental Panel on Climate Change 2018). Meeting these benchmarks will necessarily require urgent and fundamental changes to the way in which our economies and natural systems interact (Intergovernmental Panel on Climate Change 2018). In order to achieve the level of systemic transformation required to stabilize global temperatures, we will need to accelerate and scale the deployment of disruptive mitigation strategies, particularly in the energy sector (Creutzig et al. 2016; Intergovernmental Panel on Climate Change 2018:315).

Transitioning to a low-carbon energy system is a critical component of climate change mitigation strategies within a 1.5°C scenario. The production and consumption of energy is responsible for 81% of Canada's total greenhouse emissions and 78% of emissions globally (Natural Resources Canada 2019:28). In 2017, fossil fuels (natural gas, crude oil and natural gas liquids, and coal) supplied 76% of Canadian primary energy use, while renewable energy (hydro, biofuels and waste, wind, solar, and geothermal) supplied only 17%* (Natural Resources Canada 2019:36). Fossil fuels as an energy source have negative environmental externalities in the form of carbon emissions released as a bi-product of combustion. As such, decarbonizing the Canadian energy system has been identified as a priority for meeting Canada's commitment to reduce greenhouse gas emissions 30% below 2005 levels by 2030 (Environment and Climate Change Canada 2016). Realizing emission reductions in the production and consumption of energy requires a reconfiguration of current technologies, institutions, and user practices; thereby creating opportunities to build new and sustainable socio-technical systems (Loorbach, Frantzeskaki, and Avelino 2017). This process of reconfiguration and transformation is referred to as a low-carbon energy transition.

Within a centralized energy system, energy is generated (electricity produced), transmitted (moved from the location of generation to the location of use), distributed

* The remaining primary energy use was supplied by nuclear. These statistics do not include electricity trade.

(circulated to the consumer), and finally, consumed by energy users (individuals, households, governments, organizations, etc.) (Hoicka and MacArthur 2019). Demand-side low-carbon innovations are products or services that reduce or remove carbon emissions at the end-use stage of the energy system, such as smart metering, demand-response, and distributed generation technologies. Demand-side low-carbon innovations are a critical component of a low-carbon energy transition, but they are given much less attention than supply-side innovations in both integrated assessment models and in popular media (Creutzig et al. 2016).

A low-carbon energy transition can be achieved through accelerating the development and diffusion of low-carbon energy innovation (OECD, 2018). Diffusion is the process through which an innovation gains increasing market share through the adoption and continued use of the product or service (Karakaya, Hidalgo, and Nuur 2014:393; Kowalska-Pyzalska 2018:3571; Mignon and Bergek 2016:106). Despite significant investments in the research and development stages of the innovation process, studies in this field suggest that low-carbon innovations experience difficulties during market formation, commercialization, and adoption, resulting in slow rates of diffusion (Clausen and Fichter 2019; Kowalska-Pyzalska 2018:3571; Organisation for Economic Co-operation and Development 2018). Many of the low-cost and commercially viable technologies required to meet global mitigation targets already exist, yet are unable to achieve successful market diffusion (Organisation for Economic Co-operation and Development 2018:5).

Diffusion of innovations literature also tends to focus on a single sector, or single technology case study, and on a small scope of factors that influence innovation diffusion (Clausen and Fichter 2019). Energy technologies are not often adopted and used in isolation (Grübler and Wilson 2014:5), so analyzing the characteristics of a single innovation independently limits the potential insights and the generalizability of the research findings (Clausen and Fichter 2019). Simultaneously analyzing the range and combination of factors that influence the diffusion of multiple low-carbon energy innovations can contribute immensely to identifying the barriers and predictors of their diffusion. In understanding these influencing factors, strategies toward accelerating a low-carbon energy transition can be informed.

1.1. Research question

This research paper presents a model for analyzing the diffusion of multiple demand-side low-carbon energy innovations in Ontario that have the potential to contribute to a low-carbon energy transition. This analysis is a contribution to a larger, ongoing research project affiliated with the Social Exergy and Energy Lab at York University. Research team members include Dr. Christina Hoicka, Dr. Runa Das, Dr. Jenny Lieu, Susan Wyse, Yuxu Zhao and myself. The research project was initially funded through an SSHRC Insight Development Grant. The research was continued through internal funding from the Faculty of Environmental Studies at York University, as well as a research grant awarded from the Smart Prosperities Institute (SPI) Economic & Environmental Policy Research Network (EEPRN). My involvement in this research project began in April, 2019, and focuses on the development of a model framework and coding the innovations for statistical analyses.

The purpose of the broader research project is (1) to investigate the factors that influence the diffusion of demand-side low-carbon energy innovations and the mechanisms through which their diffusion can be accelerated; and (2) to determine how– and to what extent– these innovations contribute to a low-carbon energy transition through influencing system innovation. Understanding these influencing factors is critical for identifying the barriers to– and opportunities for– accelerating the widespread commercialization and adoption of low-carbon energy innovation.

This research paper presents one application of the broader model framework developed by the research team. The purpose of this analysis is to present my contribution to the development of the model framework and innovation coding, in reference to the larger project, and to:

1. Measure the current potential for low-carbon demand-side energy innovations to contribute to a low-carbon energy transitions through system disruption; and
2. Analyse the role of system actors in creating legitimacy for innovations in order to facilitate their diffusion.

This investigation will contribute to our knowledge of the most efficient (in terms of resources and time) and effective (in terms of decarbonization) methods for achieving a low-carbon energy transition that aligns with the Canadian greenhouse gas abatement targets within a 1.5°C scenario. Through mapping the current landscape of low-carbon innovation being offered to energy users, this investigation can inform policy makers, industry experts and professionals on the key factors that influence the scaling and diffusion of existing low-carbon innovation.

1.2. Paper structure

The structure of this research paper is as follows. The *Literature Review* section provides background information on the state of knowledge in the following research fields: low-carbon energy transitions; the energy technology innovation systems; disruptive innovation; and the role of legitimacy in disruptive low-carbon innovation diffusion. The *Methods* section outlines the sampling frame and dataset development; how the research framework and model components were developed; the operationalization of the model variables; and the coding of the innovations. The *Results* section outlines the results from the coding and data analysis. The *Discussion* section presents the limitations of the research; analyzes the main findings; and outlines the next steps for the research. The *Conclusion* section summarizes the research findings; identifies potential applications; and suggests opportunities for future research.

2. Literature Review

2.1. Low-carbon energy transitions

Carbon intensive technologies remain locked-in through a complex network of technological, institutional, infrastructural and behavioral systems that support their continued use (Seto et al. 2016; Unruh 2000). These interlocking forces create inertia within a system that sustains the existing regime and prevents the emergence of alternative innovation (Unruh 2000:817). Resistance to the diffusion and adoption of new, innovative technologies is due in part to self-reinforcing incentives. These are path-dependent processes that reinforce positive feedback loops, creating further resistance to change among carbon intensive industries and institutions that perpetuate carbon lock-in (Seto et al. 2016). *Path-dependency* is the continued use of a technology due to favorable market conditions and first mover advantages, despite the existence and availability of more efficient technologies (Seto et al. 2016). *Carbon lock-in* refers to a combination of systemic forces working together to support the established carbon intensive socio-technical regime in the presence of viable low-carbon alternatives (Unruh 2000:817). Institutional lock-in reinforces technological lock-in, preventing new entrants from achieving market shares through the support and influence of powerful economic, social, and political institutions (Seto et al. 2016).

Reducing emissions in the energy sector necessitates a multi-scale, disruptive transition away from the established carbon intensive regime toward a low-carbon energy system. The field of *sustainability transitions* has recently emerged to address the need for this system-wide socio-technical regime change and provides approaches to accelerating transition pathways (Loorbach et al. 2017). A *socio-technical regime* is the stable environment of established technology, practices, regulations and networks that reinforce the existing technological system and influence the direction of innovation (Geels 2005:684; Kemp, Schot, and Hoogma 1998:181; Markard and Truffer 2008:603). The term *socio-technical* specifically refers to the relationship and interactions of society and technologies. A regime transition takes place as “a gradual process of societal change spanning the economy, technology, organizations, rules, systems, values and behaviors – essentially, a profound change in the way in which society operates” (Andrews-Speed 2016 as cited in Meadowcroft, J., 2009).

Sustainability transitions occur through the continued destabilization of the established socio-technical regime using disruptive niche innovations that co-evolve with changing landscapes (Araújo 2014:118). Weakening the established regime through the use of policies and regulations plays an important role in establishing windows of opportunity for disruptive innovations to scale-up and suffuse into mainstream markets (Kivimaa and Kern 2016:210). A sustainable transition will require a combination of established regime destruction and new regime creation, and disruptive innovation plays a critical role in facilitating both (Kivimaa and Kern 2016; Loorbach et al. 2017). Sustainability transitions theory and research approaches can be applied to the energy sector (Andrews-Speed 2016; Araújo 2014; Loorbach et al. 2017) and can help describe the processes and pathways to achieving a low-carbon energy transition through the diffusion of disruptive low-carbon innovations.

There are many diverse disciplinary perspectives and epistemological approaches to sustainability transitions research, and as a result, there are a wide range of theories and models that are applied in this field (Loorbach et al. 2017:609). Though technological change is critical for a low-carbon energy transition to take place, the literature surrounding sustainability transitions emphasizes the importance of institutional and societal transformations in achieving large-scale and system-level change (Loorbach et al. 2017:601). The *socio-technical approach* has gained increasing attention in sustainability transitions research, providing a foundational framework for understanding the interactions and relationships between technology, institutions, and user practices (Loorbach et al. 2017:609; Marques, Morgan, and Richardson 2018:506). This socio-technical approach has two main analytical lenses: multi-level perspective (MLP), which is described below, and the technological innovation system (TIS), which is described in section 2.2 (Loorbach et al. 2017:609).

The *multi-level perspective* (MLP) presents a model for understanding how a regime transition is achieved through innovation (Loorbach et al. 2017) and is illustrated in **Figure 1**. The MLP theorizes that there are three inter-connected layers that comprise a socio-technical system: the small and flexible *niche* where research and innovation occur; the dominant socio-technical *regime*, where established technologies and user practices are locked-in; and the stable social, economic, and environmental *landscape* that provides both the context for

regime stability as well as the necessary pressures forcing the existing regime to change (Fischer and Newig 2016; Gliedt, Hoicka, and Jackson 2018; Jørgensen 2012; Loorbach et al. 2017:606). The MLP model posits that a regime transition occurs through the use of disruptive niche technologies that co-evolve with changing landscapes to destabilize of the established socio-technical regime (Araújo 2014:118).

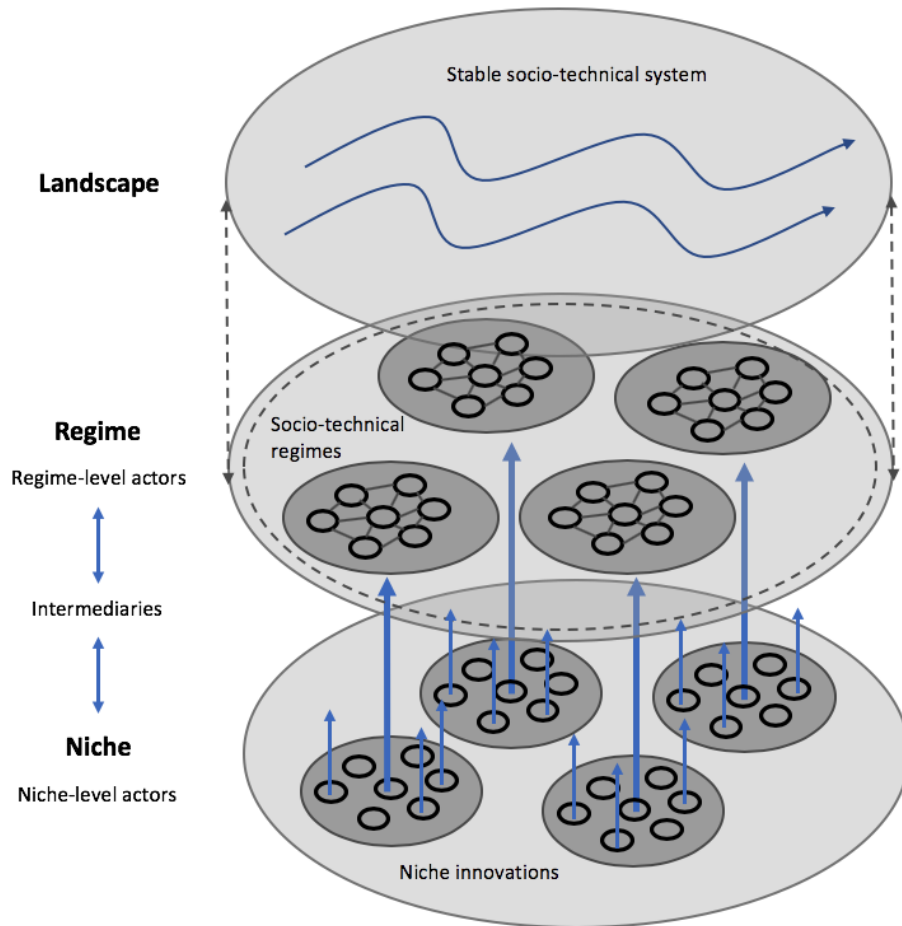


Figure 1 Multi-Level Perspective (adapted from Geels 2002; Loorbach 2016).

Actors play an important role in a low-carbon energy transition. *Actors* in sustainability transitions research are defined as "participants in purposive actions in an attempt to prevent or generate change" (Fischer and Newig 2016:3). *Niche-level actors* support the small-scale development, learning, and visioning of novel innovations (Loorbach et al. 2017) but can be

limited by unfavorable regulatory and policy environments that perpetuate socio-technical lock-in (Fischer and Newig 2016:6). In other words, niche-level actors can be constrained by regime conditions that support the continued use of mainstream technologies. *Regime-level actors* have more agency and support a transition through advocacy and building strong networks (Fischer and Newig 2016:13), interacting simultaneously with niche actors and other regime actors to support the scale-up of niche innovation (Gliedt et al. 2018). *Intermediaries*, which operate between the niche and regime levels, strengthen the innovation system by playing a 'bridging role' (van Lente et al. 2003) and "connect niche-level activities with regime-level institutions, and diffuse new technologies and practices through the regional level" (Fischer and Newig 2016:14). Transition focused *innovation intermediaries* play a critical role in both supporting the development of an innovation, and disrupting the dominant socio-technical regime at a system-level to create a climate for innovation diffusion (Kivimaa et al. 2019:1068). For the purposes of this analysis, the focus is on collective actors (actors as organizations or agencies), which have varying degrees of power, agency, and influence.

One of the major challenges for energy system transitions is the limited understanding of the role of the energy user in the innovation process (Creutzig et al. 2016; Mignon and Bergek 2016; Wilkinson et al. 2019). Traditional understanding of the energy user is as a consumer and passive recipient of technology (Ryghaug, Skjølvold, and Heidenreich 2018:286). But favorable societal views are essential for technological regime change, as both the technology and the user coevolve to form new socio-technical configurations (Kemp et al. 1998:183). Energy system transitions will create new innovations, new relationships, and new capacities for participation in energy systems (Ryghaug et al. 2018:289). *Energy citizenship* is a concept that has emerged recently in transitions literature and refers to users taking on diverse roles of engagement in the production and consumption of their energy (Ryghaug et al. 2018:288). However, energy technology innovation policies tend to focus on the characteristics of the technologies themselves and overlook the institutional and societal context, including technology adoption and use (Gallagher et al. 2012:151). In order to better understand the mechanisms that influence an energy transition, it is important to know the types of energy users and the system actors operating within an energy technology innovation system.

2.2. The energy technology innovation system

Innovation system theory studies how innovations are developed and embedded into a socio-technical regime. The innovation system framework incorporates a complex set of interconnected system components (or structural elements) that coevolve to facilitate innovation, including actors, networks, and institutions, in addition to the technologies themselves (Araújo 2014; Jacobsson and Bergek 2011:45). The *technological innovation system* (TIS) approach has been increasingly employed to describe the processes and pathways toward a low-carbon energy transition, and “considers the development, diffusion and use of a specific technology” within the socio-technical regime (Araújo 2014:118). The *energy technology innovation system* (ETIS) is the study of technological innovation processes as they pertain to the production and consumption of energy. The ETIS is a central framework in this research.

The ETIS is an approach to understanding the energy innovation system, incorporating a comprehensive perspective of the production, distribution, and consumption of energy through the lens of technology (Gallagher et al. 2012). The ETIS determines the availability, efficiency, and cost of energy supply and demand services, as well as the social and environmental outcomes (Gallagher et al. 2012:139). The four key dimensions of the ETIS process are (1) knowledge; (2) actors and institutions; (3) resources; and (4) adoption and use (Grübler and Wilson 2014:12). These dimensions comprise the framework with which energy technology innovations are examined as they move through the innovation system. The knowledge dimension involves both the generation of new knowledge, as well as the exchange of knowledge between actors and the learning process (Grübler and Wilson 2014:12). The resource dimension refers to the different forms of natural, financial, and human capital required to develop and scale an energy innovation for successful diffusion (Grübler and Wilson 2014:12). The ETIS generally occurs in five consecutive steps: research, development, demonstration, market formation, and diffusion (Gallagher et al. 2012; Jordaan et al. 2017; Söderholm et al. 2019). **Figure 2** illustrates the system innovation process as outlined by the ETIS, including actors, networks and institutions.

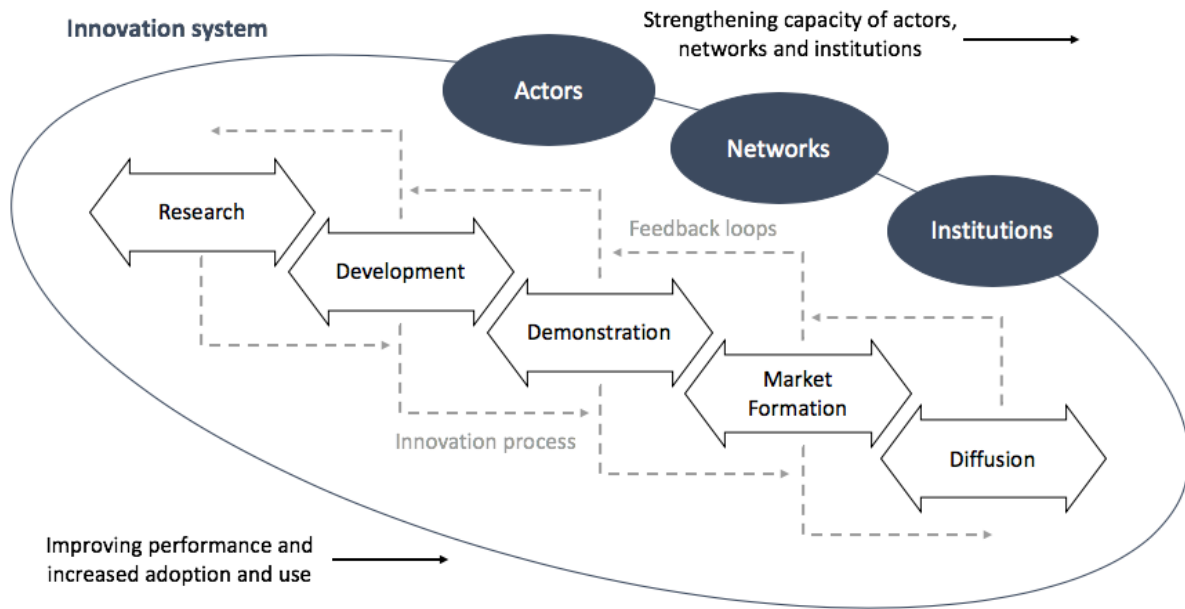


Figure 2: Innovation System Process (adapted from Jordaan et al. 2017; Grübler & Wilson 2014; Söderholm et al. 2019).

Innovation for a sustainable transition experiences significant challenges throughout all stages of the system, but particularly during the market formation and diffusion stages (OECD, 2018). Innovation system research tends to focus on the earlier stages of the innovation process, such as research and development of technologies, and fails to sufficiently address the subsequent diffusion stage (Kebede and Mitsufuji 2017:243; Mignon and Bergek 2016:105). *Diffusion* is defined as the process whereby a niche innovation captures increasing market shares, gradually leading to the widespread adoption and persistent use of the innovation throughout the system (Karakaya et al. 2014:393; Kowalska-Pyzalska 2018:3571; Mignon and Bergek 2016:106). The difference between the diffusion and adoption of an innovation is that adoption takes place at the individual level while diffusion takes place at the societal level (i.e. multiple cases of adoption) (Karakaya et al. 2014:395).

The dominant diffusion model within innovation systems literature is the *diffusion of innovation theory* (Wilson and Dowlatabadi 2007:177). The diffusion of innovation theory “focuses on the process and the conditions at which innovations and ideas become diffused and adopted by users/customers within wider social networks”. Successful diffusion tends to follow a five step process: knowledge acquisition, opinion formation, acceptance or rejection,

decision implementation, and decision confirmation (Kowalska-Pyzalska 2018:3571). Innovation adoption will only occur following the decision confirmation stage, provided that the adopter(s) continue to use the product or service (Kowalska-Pyzalska 2018:3571).

Diffusion is a necessary component of the innovation system, but research and empirical evidence suggest that there are slow rates of diffusion for innovations that contribute to a low-carbon energy transition (Kowalska-Pyzalska, 2018, p. 3571; OECD, 2018, p. 5). Furthermore, diffusion research tends to focus on a single sector or on single technology case studies and on a small scope of factors that influence diffusion, which limits the generalizability of research findings, potential insights, and research applications (Clausen and Fichter 2019:66).

Research in this field also tends to overlook the integration of low-carbon innovations, particularly in local contexts, and neglects the later stages of the transition process relating to the actual use of the technologies (Barnes 2019:769). There needs to be a better understanding of how innovations are adopted and subsequently integrated into socio-technical systems and then embedded into the local physical geography (Barnes 2019:779). This process is described in the literature as *local embedding*, the “process through which multiple system elements are increasingly aligned into place specific configurations that work ” (Barnes 2019:770). The local embedding of technologies brings attention to the importance of the deployment of existing low-carbon innovations, rather than continuing to focus efforts on upstream research and development of new technologies (Barnes 2019). Local embedding also gives attention to the local context, and how socio-technical configurations can be place-specific and require attention to local institutions and user practices (Barnes 2019).

2.3. Disruptive innovations

Low-carbon innovations are novel products or services that result in lower carbon emissions compared to established technologies (Wilson 2018). Eco-innovation, a term synonymous with low-carbon, green, sustainable, and environmental innovation, is defined as the “creation or implementation of new, or significantly improved, products, processes, marketing methods, organizational structures and institutional arrangements which lead to environmental improvements compared to relevant alternatives” (Karakaya et al., 2014, p. 394; OECD, 2009).

Karakaya et al. (2014:398) suggests that there is already a strong knowledge of the attributes and factors that affect the diffusion and adoption of eco-innovations. Only one third of eco-innovations are diffused into the broader consumer market, while two thirds remain in niche markets with average market shares below 15% (Clausen and Fichter 2019:64).

An important contributing factor to understanding this slow rate of environmental innovation diffusion is path-dependency and sustained carbon lock-in of the existing socio-technical regime (Clausen and Fichter 2019:68; Seto et al. 2016). Most technological innovations are never adopted by main stream markets due to dominant and rigid socio-technical regimes, particularly for innovations that require changes in consumer behaviors or are incompatible with existing technological and physical infrastructure (Kemp et al. 1998:182). Eco-innovations are forced to compete with conventional technologies that produce negative externalities, often without reprisal, which can make low-carbon alternatives less attractive to consumers and less competitive (Kanda et al. 2018:1014; Wilson 2018:217). In order to increase the rate of diffusion of social and technological innovations that can influence a low-carbon energy transition, we need to address the system level barriers that prevent actors and institutions from participating in their adoption.

Facilitating the diffusion of environmental innovations has the potential to accelerate energy system decarbonization and a sustainable energy transition (Clausen & Fichter, 2019; Karakaya et al., 2014; OECD, 2018). However, the diffusion of such innovations are not necessarily indicative of system-wide decarbonization. It is also important to consider how– and to what extent– these innovations contribute to energy system transformations. There has been increasing attention in transitions literature to the need for disruptive innovation to accelerate energy system transitions, rather than incremental innovation (Johnstone et al. 2020:2). An *incremental* innovation improves the efficiency or cost-benefit of the established process within a system, but does not change the system itself (Markard and Truffer 2008:599; Wilson 2018:217). A *disruptive* innovation has the potential to destabilize the established regime and contribute to system innovation (changing the system itself) (Johnstone et al. 2020:1). There is an important distinction between rapid innovation diffusion and energy system disruption, which refers to the potential for a range of technologies to lead to system-

level change (Johnstone et al. 2020:1). Therefore, it is critical to examine an innovation's potential for system disruption when considering diffusion as a metric for energy system decarbonization (Johnstone et al. 2020; Wilson 2018). This research field is of particular importance considering the urgent need to accelerate efforts to reduce emissions, as outlined by leading climate science experts (Intergovernmental Panel on Climate Change 2018).

2.4. The role of legitimacy in disruptive low-carbon innovation diffusion

There are a range and combination of factors that influence socio-technical system disruption for a low-carbon energy transition. Among these important factors is the concept of building legitimacy for niche innovations to support their scale-up. Institutional and organizational *legitimacy* is defined in the literature as “a generalized perception or assumption that the actions of an entity are desirable, proper or appropriate within some socially constructed system of norms, values, beliefs and definitions” (Suchman 1995:574). Legitimacy in the context of sustainability transitions assess the role of actors and institutions in supporting low-carbon innovation diffusion and incumbent regime disruption. “Conceptualizations based on institutional theory build upon the notion that the acceptance of any innovation, or any other form of change challenging an incumbent institution, depends, by and large, on its (regulative, normative and cultural-cognitive) legitimacy” (van Oorschot, Hofman, and Halman 2018:6).

Building legitimacy of niche innovations is fundamental for successful diffusion, and can be as important as the technological components of the innovation (Rosenbloom, Berton, and Meadowcroft 2016:1277). Legitimacy is created through a series of intentional actions and strategies deployed by system actors to “shape institutions in favour of a particular technology or management practice” (Duygan, Stauffacher, and Meylan 2019:15). Legitimacy is often required for niche scale-up to work, including resources to be mobilized, markets to form, and actors to acquire political strength (Kivimaa and Kern 2016). Building an innovation's legitimacy for socio-technical system disruption requires the presence of two factors: (1) positive discourse framing and visioning strategies by actors (Duygan et al. 2019; Geels and Verhees 2011; Ruef and Markard 2010); and (2) the presence of actors with legitimacy facilitating the diffusion of niche innovations across multiple scales (Duygan et al. 2019; Geels and Verhees

2011; Schlaile et al. 2017). In other words, legitimacy requires a strong network of system actors that actively support the innovation across scale (or policy domains).

The literature identifies the concept of 'discourses' as central to agency and policy evolution for a sustainable transition (Duygan et al. 2019:19 as cited in Hajer, 1995:56). *Discourse* is the creation of storylines through which "actors in a field construct meanings and frame how issues should be perceived and addressed" (Duygan et al. 2019:19 as cited in Smith and Kern 2009). Positive discourse, or narrative framing, are used to "link the content of innovations (e.g., performance and efficiency) with the context of innovations (e.g., broader developments in the regime or landscape) in order to build legitimacy" (Rosenbloom et al. 2016:1276 as cited in Smith et al. 2014). Positive discourse framing through articulating a favorable vision or expectation has a critical role in building the legitimacy of an innovation (Duygan et al. 2019:19 as cited in Konrad et al. 2012). The collective visioning and discourse framing by system-level actors influences the development and diffusion of niche technologies (Duygan et al. 2019:19). Policies, visioning strategies and public statements contribute significantly to the creation of legitimacy (Kivimaa and Kern 2016), and socio-technical regime disruption requires a combination of policies that both create legitimacy for niche-innovations, as well as policies that weaken (delegitimize) the established socio-technical regime (Rosenbloom et al. 2016). It is a combination of both niche legitimization and incumbent delegitimization policies that will ultimately lead to system disruption.

The mobilization of actors with agency across multiple scales is also necessary in forming legitimacy for niche innovation scale-up (Schlaile et al. 2017:8), producing the conditions for socio-technical system disruption. A system disruption requires the presence of institutions, agencies, and actors with agency (those that can influence or impact the energy system) facilitating the diffusion of niche innovations across scales (Duygan et al. 2019; Geels and Verhees 2011; Gliedt et al. 2018; Schlaile et al. 2017). The literature suggests that niche innovation scale-up occurs through the interaction of (1) innovation intermediaries interacting with niche and regime-level actors; and (2) regime-level actors operating across policy domains (Loorbach et al. 2017). Intermediaries interact with niche-level actors to assist in scaling-up experiments that support the low-carbon transition by encouraging technology diffusion and

market adoption (Gliedt et al. 2018:1256). Intermediaries also interact with regime actors to assist in the creation of political and institutional space for subsystem changes within the regime (Gliedt et al., 2018). Regime-level actors create the conditions for system change to take place and identify opportunities for institutional change (Gliedt et al. 2018:1255). This is the process through which disruptive niche innovations build legitimacy and achieve widespread diffusion through the support of actors operating at different levels of the system.

Building legitimacy is one factor that influences an innovation's potential for socio-technical system disruption leading to system innovation. This analysis will investigate an innovation's potential for system disruption across *all* factors that influence system innovation. This research will then specifically explore the role of system actors in creating legitimacy for niche innovations in order to support their diffusion. Finally, this analysis will compare the relationship between the presence of legitimacy and overall disruptive potential.

3. Methods

This research quantifies qualitative data on low-carbon innovations to develop a statistical model that can predict their diffusion and understand their impact on system innovation. *System innovation* is the process through which disruptive innovations destabilize the existing socio-technical regime, creating a system-level transition to new socio-technical configurations. In this case, we are specifically interested in the ability of an innovation to influence a low-carbon energy transition. The units of analysis in the model are demand-side low-carbon energy innovations offered to energy users in Ontario, as identified through desk research and by industry professionals and experts operating in Ontario. The statistical model contains both dependent and independent variables. The value of a *dependent variable* directly depends on the independent variables and is an output (result) of the model. The value of an *independent variable* does not depend on any other variable and is an input to the model (i.e. it is analyzed in combination with other variables to produce a dependent variable). Four dependent variables were selected to comprise the model framework: (1) *dissemination rate*; (2) *system innovation*; (3) *pro-environmental behavior*; and (4) *energy justice*. Each dependent variable is comprised of multiple independent variables. This research paper focuses exclusively on the *dissemination rate* and *system innovation* dependent variables, as these variables were the focus of my contribution to the broader research project. In order to calculate the *dissemination rate* dependent variable, information on the number of energy users that adopted the innovation was compared to reference population statistics to determine the degree of diffusion for each innovation. In order to calculate the *system innovation* dependent variable, a range of eight independent variables (influencing factors) were selected based on sustainability transitions literature and diffusion of innovation theory. A coding scale was then developed to evaluate how each independent variable influences system innovation.

3.1. Sampling frame and data collection

The units of analysis in this research are demand-side low-carbon energy innovations. These innovations include policies, programs, products, projects, and services offered to energy users that have the potential to contribute to a low-carbon energy transition in Ontario. Energy users

include individuals, households, governments, Indigenous communities, cooperatives, non-profits, private businesses, institutions, utilities, industry, MURBs (multi-unit residential buildings), industry, and building professionals.

The dataset of demand-side low-carbon energy innovations contributing to our model was mainly developed prior to my involvement in the research project. The data were collected through a combination of desk research and surveys, outlined in **Table 1**. A total of 132 demand-side low-carbon energy innovations (92 active; 40 discontinued) were coded for statistical analysis. An *active innovation* is an innovation that— at the point of data collection— was actively being offered to energy users in Ontario; a *discontinued innovation* is an innovation that is no longer being offered to energy users. 32 innovations were identified through desk research; 90 innovations were identified through Survey 1; and 10 additional innovations were identified through Survey 2. The method of data collection that contributed to the master combined dataset is briefly described below.

Table 1 Summary of Sampling Frame

Method	<i>n</i>	Status
Desk research	32	14 active innovations
		18 discontinued innovations
Survey 1	90	69 active innovations
		21 discontinued innovations
Survey 2	10	9 active innovations
		1 discontinued innovations
Total (combined)	132	92 active innovations
		40 discontinued innovations

3.1.1.1. Data collection*

Data collection began with desk research. Four relevant policy domains were identified in Ontario: (1) Energy Policy; (2) Environment and Climate Change Policy; (3) Science, Technology, and Industrial Innovation Policy; and (4) Social Enterprise and Innovation Strategy. A policy

* Elements of this section were co-authored by other researchers on the team.

domain is used to identify a regime boundary within which governments and institutions deploy policies (Matti, Consoli, and Uyarra 2017). Desk research found 51 innovations offered to energy users in Ontario that have the potential to influence a low-carbon energy transition (**Table 2**). 10 of these innovations overlapped with innovations that were identified through Survey 1 and were combined to avoid double counting; 7 innovations were found to be outside the scope of analysis and were removed; 2 innovations had insufficient information to accurately identify the innovation and were also removed from the analysis. 32 innovations (14 active; 18 discontinued) identified through desk research were considered relevant to the analysis and were coded.

Table 2 Innovations Identified through Desk Research

51 innovations identified	7 innovations not applicable (outside scope of analysis)
	10 innovations overlap with innovations identified through Survey 1 (combined with Survey 1 data)
	2 innovations had insufficient information
32 innovations identified that are relevant to the analysis	14 active innovations
	18 discontinued innovations

Through the desk research process, experts from a variety of organizations were also identified through publicly available sources, and from these experts, potential survey participants were determined. Based on these experts and organizations identified through desk research, 475 experts were contacted to participate in an online survey, titled *Survey of Professionals* (referred to as Survey 1). The purpose of Survey 1 was to identify innovations under development, currently available, or intended for energy users in Ontario that have a potential to make an important contribution to a low-carbon energy transition. Participants were asked to identify up to three innovations, the organization that offers the innovation, how the innovation can influence a low-carbon energy transition, and the energy users for whom the innovation is intended. The total number of completed surveys was 94 (**Table 3**). A total of 119 innovations were identified through Survey 1; 14 of these innovations were outside the scope of analysis; 8 were not yet marketed innovations (i.e. ideas for an innovation); and 7 had insufficient information provided by respondents to accurately identify the innovation.

Innovations that fell under these three categories were removed from the statistical analysis. 90 innovations (69 active; 21 discontinued) identified through Survey 1 were considered relevant to the analysis and were coded.

Table 3 *Innovations Identified through Survey 1*

475 surveys sent to individuals	435 individuals identified through desk research
	40 additional individuals identified through chain link sampling (53 total, 13 overlap)
135 survey responses	5 individuals responded but declined to participate
	130 participated in the survey
	36 agreed to participate but left the survey incomplete (did not provide any innovation data)
94 participants completed the survey	
119 innovations identified	14 not applicable (outside scope of analysis)
	8 not yet an innovation (idea for an innovation)
	7 had insufficient information provided by respondents to identify the innovation
90 innovations identified that are relevant to the analysis	69 active innovations
	21 discontinued innovations

A second survey was created following Survey 1, titled *Ontario's Low Carbon Transition: Learning about Services Available to Energy Users & communities* (referred to as Survey 2). The purpose of Survey 2 was to (1) gain a deeper understanding of the innovations by seeking the perspective of the service providers themselves; and (2) to identify additional innovations. Survey 2 participants were identified using a chain link sampling method employed in Survey 1 (i.e. they were identified as offering the innovation by Survey 1 participants). Participants of Survey 2 were also invited to participate in the survey through relevant networks in Ontario (networks and associations whose members include the providers of energy services and through social media networks). 90 individuals were contacted to participate in the electronic survey and 17 participants completed the survey (**Table 4**). 17 innovations were identified through Survey 2, however, 7 of these innovations described innovations that were already captured by Survey 1. These innovations were combined with Survey 1 data to avoid double

counting. As such, 10 new innovations (9 active; 1 discontinued) identified through Survey 2 were considered relevant to the analysis and were coded.

Table 4 *Innovations Identified through Survey 2*

90 individuals contacted to participate	
68 survey responses	1 individual responded but declined to participate
	67 participated in the survey
	50 agreed to participate but left the survey incomplete (did not provide any innovation data)
17 participants completed the survey	7 responses described innovations from Survey 1
	10 responses identified a new innovation
10 (new) innovations identified	9 active innovations
	1 discontinued innovation

A total of 132 innovations (92 active; 40 discontinued) were identified and coded for statistical analysis. Each innovation was indexed and categorized according to a template, using both information provided by survey respondents and desk research obtained using publicly available information. This information comprises the master combined dataset that was used to code the innovations. A research folder was also created for each innovation, referred to as the *energy innovation profiles*, which contain detailed background information on each innovation (such as websites, reports, marketing materials) that were collected through desk research but not captured by the template and not included in the master combined dataset.

3.2. Building the statistical model

This research investigates the factors that influence the diffusion of multiple demand-side low-carbon energy innovations that have the potential to make an important contribution to a low-carbon energy transition in Ontario. Our research is inspired by a statistical model developed by Clausen & Fichter (2019), which undertook a comprehensive and detailed cross-sector analysis of the factors (drivers and barriers) that influence the diffusion of environmental product and service innovations in Germany. Based on a prior systematic review of diffusion of innovation literature (Clausen, J., Fichter, K., & Winter, W. 2011), Clausen & Fichter (2019) identified 22

factors that have the potential to influence the diffusion of environmental innovations across six fields of influence: (1) product-related factors; (2) adopter-related factors; (3) supplier-related factors, (4) sector-related factors; (5) government-related factors; and (6) path-related factors (Clausen, J., Fichter, K., & Winter, W. 2011; 2016). These 22 factors and six fields of influence “provide a holistic and systematic set of variables and scales that can be used for empirical investigations” (Clausen and Fichter 2019:69). Clausen and Fichter (2019) developed a statistical model in which these 22 factors (*diffusion dynamics* independent variables) were coded for each environmental product/service innovation to determine the degree to which they facilitated or inhibited environmental innovation diffusion. Our research model applies elements of the Clausen and Fichter 2019 model, but differs significantly in three key respects:

1. This research model extends beyond the *diffusion dynamics* independent variables to account for the influence on pro-environmental behaviours, energy justice, and capacity to create system innovation;
2. This analysis looks specifically at demand-side low-carbon innovations available to energy users (specific to the energy sector); and
3. This analysis focuses specifically on the disruptive potential of the innovations on the established socio-technical system.

The statistical model developed by the research team contains four dependent variables:

1. Dissemination rate
2. System innovation
3. Pro-environmental behavior
4. Energy justice

As mentioned previously, this research paper is a contribution to a larger and ongoing research project and presents one application of the broader statistical model developed by the research team. My contribution to the model focused on the development of the *dissemination rate* and *system innovation* dependent variables, and as such, the analysis presented in this paper investigates these two dependent variables exclusively.

3.2.1. Dissemination rate dependent variable

The *dissemination rate* dependent variable was used to assess the state of market diffusion for each innovation (i.e. the degree to which an innovation has diffused into a certain population).

Table 5 presents the information and sources that were collected in order to measure the dissemination rate for each innovation.

Table 5 Data Collection for Dissemination Rate Dependent Variable

Information collected	Source of information
Number of users/projects/units purchased (<i>n</i>)	Survey 1; Survey 2; desk research (websites and publicly available documents)
Types of users	Survey 1; Survey 2; desk research
Size of the reference market (<i>N</i>)	Statistics Canada; OEB; IESO; Government of Ontario; First Nations Communities Ontario; Ontario Cooperatives Association; etc.
Year	Survey 1; desk research (above sources)
Dissemination rate (<i>n/N</i>)	Emergent

The innovation uptake data (number of service users or units purchased) is a critical integer in calculating the *dissemination rate* variable (equation numerator). Therefore, it was necessary to have sufficient information on innovation uptake prior to running descriptive statistics and data analytics*. Uptake data were missing for approximately 65 innovations in the master dataset. A combination of desk research and phone surveys were issued to obtain the missing uptake information for these innovations. Uptake data for 4 innovations were obtained through phone surveys (Survey 2); 1 was obtained through re-sending the survey link; and approximately 10

* Survey 2 was initially circulated in July of 2019 and reminders were sent to prospective participants throughout August and September of 2019, which resulted in 17 participants completing Survey 2. In order to improve Survey 2 response rates, an amendment was made to the survey ethics that would allow the researchers to contact prospective survey participants (who had been identified through the approved chain link sampling method) to administer Survey 2 over the phone. The purpose of the amendment was twofold: (1) to conduct Survey 2 over the phone to individuals who were identified in Survey 1 but had not responded to the online survey requests for Survey 2; and (2) to contact Survey 2 respondents who had provided their contact information and had not fully completed the survey (i.e. to fill in missing or incomplete information). The ethics amendment was approved by York University's Ethics Review Board and the Human Participants Review Sub-Committee, and individuals were contacted at the beginning of April, 2020, to set up phone interviews.

were obtained through additional desk research. The total number of innovations with available uptake information was 82 (out of 132 innovations).

To calculate dissemination rate, innovation uptake needed to be compared to a reference population (i.e. how many users (n) within a given population (N) have adopted the innovation?). The appropriate reference population for each innovation was determined by evaluating the types of users and assigning each innovation a corresponding population. Population statistics were collected through desk research and are presented in **Table 6**. Population fields with an ‘unknown’ population signify cases where population statistics were not found or not available through desk research.

Table 6 Population Statistics (Ontario)

Types of users	Entire population	Electricity customers	Natural Gas customers
Individuals	13,793,260 ^a	n/a	n/a
Households	5,169,175 ^a	5,164,196 ^b	3,636,582 ^b
Households (homeowners)	3,582,238 ^a	unknown	unknown
Households (tenants)	1,559,720 ^c	unknown	unknown
Households (low income)	896,405 ^a	unknown	unknown
Nonprofit organizations	59,605 ^d	n/a	n/a
Cooperatives	1,500 ^e	n/a	n/a
Private businesses	1,063,756 ^f	unknown	unknown
Building professionals	unknown	n/a	n/a
MURBs	unknown	n/a	n/a
MURB units	1,411,185 ^g	unknown	unknown
Utilities	77	72 ^h	5 ⁱ
Indigenous communities	141 ^{j,k}	n/a	n/a
Municipal governments	444 ^l	n/a	n/a
Provincial government	1	n/a	n/a
Federal government	1	n/a	n/a
Institutions	unknown	unknown	unknown
Industrial	36,355 ^m	unknown	unknown

(a) Statistics Canada. 2017. *2016 Census of Population* ([Statistics Canada Catalogue no. 98-316-X2016001](#)); (b) Ontario Energy Board (OEB). 2018. [2017-2018 Annual Report](#); (c) Statistics Canada. 2017. *Census Profile, 2016 Census* ([Statistics Canada Catalogue no. 98-316-X2016001](#)) (d) Canadian Charity Law. 2014. [List of Ontario Non-profit Corporations](#); (e) Ontario Co-operatives Association. 2020. [Ontario Cooperatives](#); (f) Statistics Canada. 2017. *Canadian Business Counts, without employees, December 2017* ([Table: 33-10-0038-01](#)); (g) Statistics Canada. 2017. [Census in Brief: Dwellings in Canada](#); (h) IESO. 2020. [Find your local distribution company](#); (i) Ontario Energy Board (OEB). 2020. [Rules for natural gas](#); (j) K Net. 2020. [First Nations Communities Ontario](#); (k) Metis Nations. 2020. [Historic Métis Communities](#); (l) Government of Ontario. 2019. [List of Ontario municipalities](#). (m) Statistics Canada. 2019. [Businesses – Canadian Industry Statistics](#).

Dissemination rate was calculated using the following equation (developed by Clausen & Fichter (2019)):

$$\frac{n}{N} = \frac{\text{number of innovations currently in use}}{\text{reference population}}$$

Dissemination rates could only be calculated for innovations that had both population and uptake data. 82 innovations had the necessary uptake data, however, population statistics were not found or unavailable for 18 of these innovations. A total of 64 innovations had both population and uptake data. Therefore dissemination rates were calculated for 64 innovations and are presented in the results section 4.1, **Table 15**.

3.2.2. System innovation dependent variable

The *system innovation* dependent variable measures the potential for an innovation to contribute to socio-technical regime change through system disruption. Prior to developing the independent variables that influence *system innovation*, a template scale was created to evaluate an innovation’s level of regime disruption or reinforcement potential (outlined in **Table 7**). The purpose of this scale was to create a standardized assessment of each innovation that could be applied consistently to all independent variables. This scale established the criteria for analyzing the relationship between the type of innovation and how the different elements of the system are influenced. Each innovation in the dataset was evaluated based on this overarching criteria, assessing the innovation’s potential to create system disruption or reinforce the incumbent regime. The reason for this step was to ensure that all the model variables were reliable and consistent and supported by the literature.

Table 7 Regime Disruption and Reinforcement Scale

Scale	Literature
2: Disruptive leading to transformation	Dixon, T., Lannon, S., & Eames, M. (2018); Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020); Wilson, C. (2018); Wilson, C., & Tyfield, D. (2018); Geels, F. W. (2018); Geels, F. W. (2014); Johnstone, P., & Kivimaa, P. (2018); Rosenbloom, D., Berton, H., & Meadowcroft, J. (2016)
1: Incremental	
0: No change to the regime	
-1: Slightly reinforcing the regime	
-2: Strongly reinforcing the regime	

Innovations with the potential to destabilize the established socio-technical regime are disruptive and were coded as (2). Innovations that offer low-carbon improvement to established production and consumption practices are incremental innovations and were coded as (1). Innovations coded as (0) had either no effect or an unknown effect on the socio-technical regime. Innovations that slightly reinforce the incumbent socio-technical regime and sustain the existing technological paradigms were coded as (-1). Innovations that strongly reinforce and strengthen the incumbent socio-technical regime through regime stabilization and the perpetuation of path-dependencies were coded as (-2).

Following the development of the template scale, a range of eight independent variables (factors) that influence *system innovation* were selected based on the relevant literature. These variables were selected over the course of several weeks and were the product of weekly and bi-weekly collaborative research team meetings and an extensive literature review of the relevant research fields (sustainability transitions; innovation systems; ETIS; diffusion of innovations; disruptive innovations). The selected independent variables include: (1) *fossil fuel regime change*; (2) *decentralization regime change*; (3) *democratization*; (4) *policy for scale-up: economic instruments*; (5) *policy for scale-up: regulations*; (6) *policy for scale-up: knowledge creation and diffusion*; (7) *legitimacy through positive discourse framing*; and (8) *legitimacy through actors*. It was determined that, based on an extensive assessment of the relevant literature, these eight factors capture a comprehensive set of variables that act as drivers of- or barriers to- creating transformational change within a system.

Once the *system innovation* independent variables were selected, each variable was assigned attributes (values) using a scaling system. The scaling systems for the independent variables evaluates an innovation's degree of potential influence on the different aspects of the system that contribute to system innovation. Each innovation in the dataset was assigned a code between (-2) and (2) for all eight independent variables, depending on the innovation's characteristics and disruptive potential. This is the process through which our analysis transformed qualitative information about the innovations into quantitative values.

This research paper focuses exclusively on the (1) *fossil fuel regime change*, (7) *legitimacy through positive discourse framing*, and (8) *legitimacy through actors* independent variables (detailed in **Table 8**), as these are the variables I worked on and are my contribution to the development of the *system innovation* dependent variable.

Table 8 System Innovation Independent Variables

Independent variable	Scale	Literature
1. Fossil fuel regime change	2: Disruptive innovation toward fossil fuel regime change.	K.C. Seto, S.J. Davis, R.B. Mitchell, E.C. Stokes, G. Unruh, D. Ürge-Vorsatz (2016); G. Unruh (2000; 2002).
	1: Incremental innovation toward fossil fuel regime change.	
	0: No change to fossil fuel regime.	
	-1: Slightly reinforces fossil fuel regime.	
	-2: Strongly reinforces fossil fuel regime.	
7. Legitimacy through positive discourse framing	2: Presence of plans/strategies spanning policy domains that significantly strengthen the legitimacy of niche innovation and support innovation diffusion.	Duygan, M., Stauffacher, M., & Meylan, G. (2019); Geels, F. W., & Verhees, B. (2011); Kivimaa, P., & Kern, F. (2016); Mignon, I., & Bergek, A. (2016); van Oorschot, J. A. W. H., Hofman, E., & Halman, J. I. M. (2018); Ruef, A., & Markard, J. (2010); Rosenbloom, D., Berton, H., & Meadowcroft, J. (2016); Schlaile, M., Urmetzer, S., Blok, V., Andersen, A., Timmermans, J., Mueller, M., Fagerberg, J., & Pyka, A. (2017); Schot, J., & Geels, F. W. (2008); Suchman, M. C. (1995).
	1: Presence of plans/strategies within a single policy domain that slightly strengthen the legitimacy of niche innovation and support innovation diffusion.	
	0: No impact or unknown impact on legitimacy.	
	-1: Presence of plans/strategies within a single policy domain that slightly weaken the legitimacy of the niche innovation.	
	-2: Presence of plans/strategies spanning policy domains that significantly weaken the legitimacy of niche innovations; Removal of plans/strategies that support innovation diffusion.	
8. Legitimacy through actors	2: Innovation intermediaries and regime-level actors interacting within and across policy domains facilitating the diffusion of niche innovation.	Gliedt, T., Hoicka, C. E., & Jackson, N. (2018); Kanda, W., Hjelm, O., Clausen, J., & Bienkowska, D. (2018); Kivimaa, P., Boon, W., Hyysalo, S., & Klerkx, L. (2019); Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017); Matschoss, K., & Heiskanen, E. (2018); Mignon, I., & Kanda, W. (2018); Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016).
	1: Innovation intermediaries and niche-level actors interacting within multiple policy domains facilitating the diffusion of niche innovation.	
	0 : Silo of niche actors operating within a single policy domain facilitating the diffusion of the niche innovation (impact negligible).	
	-1: Regime actors operating within a policy domain to constrain the delivery and diffusion of niche innovation.	
	- 2: Strong network of regime actors operating across policy domains to constrain the delivery and diffusion of niche innovation.	

3.3. Operationalizing the system innovation independent variables

The following sections detail the coding scale development for the (1) *fossil fuel regime change*, (7) *legitimacy through positive discourse framing*, and (8) *legitimacy through actors* independent variables.*

3.3.1. Independent variable (1): Fossil fuel regime change

System innovation is influenced through the destabilization of the established fossil fuel regime. The fossil fuel regime is the incumbent carbon intensive socio-technical system that is currently locked-in through the interaction of path-dependent institutions, infrastructure, technologies, and behaviors (Seto et al. 2016). Destabilizing the fossil fuel regime with disruptive low-carbon innovation creates opportunities for system change. Fossil fuel regime change requires disruptive innovation to overcome the rigid and path-dependent innovation processes that currently exist in our energy systems. This scale was developed to measure the degree to which an innovation removes carbon from the energy system (and supports the adoption of renewable/no carbon technologies) as an indicator of the innovation's potential to disrupt the fossil fuel regime. This coding scale was developed in collaboration with other researchers on the project.

Innovations that remove or switch away from fossil fuel use and contribute to system building of renewable energy (or no carbon energy) are considered disruptive and have the potential to destabilize the fossil fuel regime. The innovations in the dataset that meet these criteria were coded as (2). Innovations that decrease the use of fossil fuels and create energy efficiency improvements relevant to both fossil fuels and renewables are considered incremental innovations that create a demand for a new regime, but are not themselves disruptive. These innovations were coded as (1). Innovations coded as (0) had either no effect or an unknown effect on the regime, and therefore contribute to continued fossil fuel path-dependency and carbon lock-in. Innovations that lead to a fuel switch from higher to lower

* The coding scale development for these three variables are presented in detail in this paper because these were the variables that I was responsible for developing. However, the innovations contained within the master combined dataset were coded for all eight *system innovation* independent variables (as outlined in section 3.4).

intensity carbon, or an efficiency improvement relevant to only fossil fuels, slightly reinforce the fossil fuel regime and work to strengthen path-dependencies. These innovations were coded as (-1). Innovations that create new demand for fossil fuels, or create a fuel switch from lower to higher intensity carbon, strongly reinforce the incumbent fossil fuel regime and significantly strengthen path-dependencies. These innovations were coded as (-2). For a detailed breakdown and examples of the scaling system for the *fossil fuel regime change* variable, see **Table 9**.

Table 9 Independent Variable (1): Fossil Fuel Regime Change

Scale	Definition	Examples
2	Disruptive innovation potentially leading to a system transformation and the destabilization of the existing fossil fuel regime; Fuel switch away from- or removal of- fossil fuels <i>and</i> contributes to system building of renewable/no carbon energy.	<ul style="list-style-type: none"> • Electric vehicle as a fuel switch away from fossil fuels, and has potential to support additional renewable energy. • Fuel switch to hydrogen, electricity, conservation, renewables, ground source heat pump, etc. • Large divestment from fossil fuels and investment in renewable energy.
1	Incremental innovation creating the demand for a new regime; Decrease in fossil fuel use; Improvement that is relevant to both fossil fuels and renewable energy.	<ul style="list-style-type: none"> • Removal of fossil fuel use. • Improvement of building envelope to reduce heat loss. • Divestment from fossil fuels (with some or no investment in renewable energy) • Investment in renewable energy (without divestment in fossil fuels). • Improvement in energy efficiency relevant to both fossil fuels and renewables.
0	No detectable change/no effect/ unknown effect on the established fossil fuel regime.	Continued path dependency and carbon lock-in.
-1	Slightly reinforces fossil fuel regime and path dependencies; Fuel switch from higher intensity to lower intensity carbon; Higher efficiency replacement of fossil fuel use.	<ul style="list-style-type: none"> • Replacement of coal or oil with natural gas. • Installing a more efficient gas furnace. • Purchasing a fuel efficient vehicle with an internal combustion engine.
-2	Strongly reinforces the incumbent fossil fuel regime and strengthens path-dependencies: Creation of new demand for fossil fuels; Fuel switch from lower intensity to higher intensity carbon.	<ul style="list-style-type: none"> • Switching from electric heating to fossil fuel heating. • Switching from natural gas to coal or oil. • New investment in fossil fuels.

3.3.2. Independent variable (7): Legitimacy through positive discourse framing

Building the legitimacy of niche innovations supports their scale-up and facilitates their potential for creating system innovation. One of the key components for building legitimacy of niche innovations is through positive discourse framing and visioning strategies carried out by system actors (Duygan et al. 2019; Geels and Verhees 2011; Ruef and Markard 2010).

Developing a positive discourse surrounding a niche innovation helps to connect the innovation to the broader context (Rosenbloom et al. 2016), which, in this case, is the need to transition to a low-carbon energy system. Positive discourse framing can take place within a single policy domain or span multiple policy domains creating impact at the system level. This scale was developed in order to measure the degree of positive discourse framing surrounding an innovation as an indicator of the innovation's legitimacy, which in turn influences diffusion.

The presence of plans and strategies that positively frame a niche innovation across policy domains signals legitimacy, and therefore, these innovations have a higher potential to contribute to system disruption. These innovations are considered disruptive and were coded as (2). Innovations that have supportive plans and strategies within a single policy domain are less likely to have the same degree of legitimacy and have less potential for system disruption. These innovations are considered incremental and were coded as (1). Conversely, weakening supportive plans and strategies that positively frame a niche innovation, or the presence of strategies that positively frame the incumbent regime within a single policy domain, can *slightly* weaken legitimacy. These innovations were coded as (-1). The removal of plans and strategies that positively frame a niche innovation or the presence of plans and strategies that positively frame the incumbent regime across policy domains can *significantly* weaken legitimacy. Accordingly, these innovations were coded as (-2). For a detailed breakdown and examples of the scaling system for the *legitimacy through positive discourse framing* variable, see **Table 10**.

Table 10 Independent Variable (7): Legitimacy through Positive Discourse Framing

Scale	Definition	Examples
2	<i>Significantly strengthen</i> the legitimacy of niche innovations in support of diffusion and scale-up through the presence of plans/strategies that create positive discourse framing <i>across policy domains</i> .	<ul style="list-style-type: none"> Action plans, annual reports, policy documents and strategies, etc., that positively frame discourse surrounding a niche innovation across policy domains being pushed forward by a strong network of system actors (government agents, industry associations, actor networks).
1	<i>Slightly strengthen</i> the legitimacy of niche innovations in support of diffusion and scale-up through the presence of plans/strategies that create positive discourse framing within a <i>single policy domain</i> .	<ul style="list-style-type: none"> Action plans, annual reports, policy documents and strategies, etc., that positively frame discourse surrounding the niche innovation within a single policy domain being pushed forward by system actors.
0	No/unknown impact on legitimacy.	No relevant or detectable strategies.
-1	<i>Slightly weaken</i> the legitimacy of niche innovations constraining diffusion and scale-up through the weakening of supportive plans/strategies delivered by system actors; Presence of plans/strategies limited to a <i>single policy domain</i> that strengthen the incumbent socio-technical regime.	<ul style="list-style-type: none"> Presence of government policy documents, strategies, plans or reports that positively frame competing fossil fuel intensive technologies within a single policy field (e.g. energy policy).
-2	<i>Significantly weaken</i> the legitimacy of niche innovations constraining diffusion and scale-up through the removal of supportive plans/strategies delivered by system actors; Presence of plans/strategies spanning <i>across policy domains</i> that strengthen the incumbent socio-technical regime.	<ul style="list-style-type: none"> Losing credibility when government cancels or removes strategies, leading to the phase out of specific innovations. Presence of action plans, annual reports, and/or policy documents that actively support and positively frame the incumbent socio-technical regime that span policy domains (e.g. energy policy <i>and</i> environment and climate change policy).

3.3.3. Independent variable (8): Legitimacy through actors

As mentioned in the previous section, niche innovations require legitimacy to disrupt a system. The second key component for building legitimacy of niche innovations is through the presence of actors with agency supporting the diffusion of niche innovation across multiple scales (Duygan et al. 2019; Geels and Verhees 2011; Schlaile et al. 2017). As outlined in the literature, a strong network of actors (including individuals, organizations, and institutions) with agency

working to support the innovations *within* and *across* scales is a strong indicator of legitimacy. This requires a combination of interaction between niche-level, intermediary, and regime-level actors supporting and advocating for niche scale-up *within* a policy domain; and the presence of regime-level actors supporting niche innovation *across* policy domains. The presence of both these factors create the necessary conditions for system disruption through legitimation. This independent variable codes for the *types* of actors with agency supporting the scale-up of the innovations within and across policy domains as a strong indicator of legitimacy.

The presence of innovation intermediaries and regime-level actors operating within and across policy domains facilitating the diffusion of niche innovations signals legitimacy. Innovations supported by these types of actors were coded as (2) for their disruptive potential. The presence of innovation intermediaries without the presence of regime-level actors operating across policy domains reduces an innovation's disruptive potential. These innovations are incremental and were coded as (1) . A silo of niche-level actors operating within a single policy domain, in the absence of intermediaries and regime-level actors, have negligible impact on creating system change and were therefore coded as (0). The presence of incumbent regime actors operating within a single policy domain to constrain the delivery and diffusion of niche innovations weakens legitimacy. These innovations were coded as (-1). A strong network of incumbent regime actors operating across policy domains to constrain niche innovation diffusion erodes legitimacy and acts as a barrier to system disruption. These innovations were coded as (-2). For a detailed breakdown and examples of the scaling system for the *legitimacy through actors* variable, see **Table 11**.

Table 11 Independent Variable (8): Legitimacy through Actors

Scale	Definition	Examples
2	Strong network of regime-level actors and intermediaries operating <i>across</i> policy domains facilitating the diffusion of the niche innovation.	<ul style="list-style-type: none"> • Support from government actors across policy domains (e.g. energy and environment policy) • Different types and/or multiple organizations, institutions, and networks actively supporting the innovation. • Presence of actors operating <i>within</i> and <i>across</i> all levels: niche, intermediary, regime.
1	Presence of innovation intermediary actors without presence of regime-level actors operating <i>across</i> policy domains facilitating the diffusion of the niche innovation. This includes regime-level actors within a single policy domain or niche-level actors operating across policy domains.	<ul style="list-style-type: none"> • Support from government actors within a single policy domain. • Support for the innovation from incubators, accelerators, intermediaries that span policy domains in the absence of regime-level actors.
0	Silo of niche-level <i>actors</i> operating within a <i>single</i> policy domain facilitating the diffusion of the innovation. Impact negligible to low-carbon innovation.	<ul style="list-style-type: none"> • Support for the innovation from individual firms or small networks within a single policy field, sector, industry. • Absence of government-level support.
-1	Presence of incumbent regime actors operating within a <i>single</i> policy domain to constrain the delivery and diffusion of the niche innovation and preserve incumbent regime.	<ul style="list-style-type: none"> • Government actors and/or incumbent utilities opposing the innovation within a single policy field, sector, industry. • Actor support for innovations that have a competitive advantage or act as barriers to market entry.
-2	<i>Strong network</i> of incumbent regime actors operating <i>across</i> policy domains to constrain the delivery and diffusion of the niche innovation and preserve incumbent regime.	<ul style="list-style-type: none"> • Governments actors (municipal, provincial and/or federal) and incumbent utilities actively opposing the innovation across policy fields, sectors, industries. • Presence of fossil fuel advocacy groups. • Industry actors and industry associations that actively work to preserve the incumbent fossil fuel regime

3.4. Coding the innovations for system innovation variables

Coding the innovations for the *system innovation* independent variables was undertaken by two researchers (myself and Yuxu Zhao). 132 innovations were coded in total (92 active; 40 discontinued), using a combination of information collected in Survey 1 and 2, desk research,

and the *energy innovation profiles*. Each innovation was evaluated based on all eight independent variables and was coded according to the corresponding scales. Innovation codes were recorded in two separate coding logs (one for each researcher). The purpose of the coding logs was to ensure that the researchers were not influenced by the codes of their counterpart, and to ensure every code was supported by relevant data. The codes were also recorded in separate Excel codebooks. A system innovation coding guide was developed at the outset of the coding process for convenience as well as to ensure the researchers were consistently evaluating the innovations based on the model framework. The coding guide contained the same information presented in **Table 8**, but for all eight variables (this table can be found in Appendix B, **Table 19**). The following section briefly details the coding process, which was done one innovation at a time in sequence for every innovation in the dataset that met the criteria for analysis (criteria outlined in section 3.1.1).

3.4.1. Coding

The first step in the coding process was to record information about the innovations that was contained in the master combined dataset. The following information was recorded in the researchers' coding logs: Who provided the innovation (organization name and type); How the innovation was provided to energy users (e.g. material incentives, informational mechanisms); The aim of the innovation (e.g. energy efficiency, demand-side management); The part of the energy system the innovation addresses (e.g. electricity, natural gas); If the innovation contributes to renewable energy clusters (e.g. flexibility, complementarity); Who uses the innovation (e.g. individuals, households, private businesses); How the innovation influences user behavior (e.g. antecedent interventions, consequence interventions); Who was involved in the development, delivery, and funding of the innovation (e.g. governments, non-profits, institutions). Next, additional qualitative information was recorded from the *energy innovation profiles* (compiled through desk research), which contained website pages, reports, and relevant documents pertaining to the innovation and which informed the coding.

In order to collect the necessary policy, program, and network information to inform the coding of the policy for scale-up and legitimacy variables (variables 4 to 8), two additional tables were used: (1) *Outline Ontario Innovation System for Energy Demand-Side Innovation*; and (2) *Outcomes of Ontario Innovation System for Energy Demand-Side Innovations* (Appendix C, **Table 20** and **Table 21**). These tables were created by Dr. Christina Hoicka during the desk research stage of data collection and were used with permission from the author. The tables were broken down by policy domain and provided detailed information on the policies and programs, actors and networks, mechanisms and activities, as well as the corresponding intentions and policy outcomes. These tables informed how the policy and legitimacy variables were coded.

In certain cases, more information was needed than was available in the master combined dataset, innovation profiles, and **Tables 20** and **21**. In such cases, the researchers conducted additional desk research as needed, which included internet searches and the review of policy and regulatory documents not captured in the above mentioned coding resources.

Once the necessary information about an innovation was compiled in the coding log, the researchers went through the innovation system coding guide and systematically coded each innovation for all eight independent variables in accordance with the *system innovation* coding framework (presented in section 3.2.2 and 3.3). Codes were initially recorded in the coding logs and then transferred to the Excel codebooks. The first 25 active innovations were coded by both researchers and were evaluated for interrater reliability (detailed in section 3.4.2). Once interrater reliability was established, the remaining innovations (both active and discontinued) were divided equally between the two researchers and coded independently.

3.4.2. Interrater reliability analysis

Cohen's Kappa coefficient was calculated to ensure interrater reliability. Cohen's Kappa is a statistic that measures the level of agreement between two researchers in their evaluation of a sample. If the Cohen's Kappa coefficient is closer to zero, there is less agreement between researchers; if the coefficient is closer to one, there is a higher level of agreement between

researchers (see **Table 12**). The aim was to ensure that there was, at minimum, substantial agreement between the researchers coding the innovations.

Table 12 Cohen's Kappa Levels of Agreement

Cohen's Kappa coefficient	Level of agreement
≤ 0	No agreement
0.01 – 0.20	None to slight agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 1.00	Almost perfect agreement

(Adapted from information provided by Dr. Runa Das).

Interrater reliability was assessed in three rounds (see **Table 13**). In the first round, the same 20 innovations were coded by both researchers. Cohen's Kappa produced a score that signified a low level of agreement between the researchers for most variables. The results in the second round of running Cohen's Kappa revealed that there were still inconsistencies in the way the researchers were coding the (1) *fossil fuel regime change* and (2) *decentralization regime change* variables. In order to improve the level of agreement between researchers for these variables, a meeting was set to review the variables in detail and to reconcile differences in the coding approach. The third and final round of Cohen's Kappa scores revealed substantial agreement for one variable ((5) *Policy for scale-up: regulation*) and almost perfect agreement for the remaining seven variables for a total of 25 innovations. It was assumed that this level of agreement between researchers was appropriate for the purposes of this analysis, and interrater reliability was confirmed. The researchers were then responsible for independently coding the remaining 107 innovations, which were split evenly between the two researchers.

Table 13 Interrater Reliability Analysis

Variable	Round 1	Round 2	Round 3
(1) Fossil fuel regime change	0.467	0.528	0.818
(2) Decentralization regime change	0.368	0.455	1
(3) Democratization	0.783	0.715	0.905
(4) Policy for scale-up: economic instruments	0.623	0.633	0.931
(5) Policy for scale-up: regulation	0.219	0.643	0.779
(6) Policy for scale-up: knowledge creation and diffusion	0.405	0.706	0.891
(7) Legitimacy through positive discourse framing	0.697	0.702	0.935
(8) Legitimacy through actors	0.671	0.605	0.860

3.4.3. Method for coding analysis

3.4.3.1. System Innovation Scores

Once coding was complete, the *system innovation scores* were calculated. The *system innovation scores* reflect an innovation's overall potential for system disruption and transformation and are calculated as the sum of the eight independent variable codes. For example, if an innovation was coded as (2) for all eight independent variables, its overall *system innovation score* would be 16; if an innovation was coded as (1) for four variables and a (-1) for four variables, its overall *system innovation score* would be zero. The possible range for *system innovation scores* is (-16) to 16. The scores are reported in section 0 of the results. In accordance with the coding scale framework and innovation typology detailed in section 3.2.2, innovations that received an overall score between 9 and 16 are considered disruptive and have the potential to influence system innovation. Innovations with an overall score between 0 and 8 are considered incremental, and therefore, have a lower potential for system innovation. Innovations that received negative scores, between (-1) and (-16), are considered system reinforcing and have a negative impact on system innovation.

3.4.3.2. Crosstabulations

Crosstabulations were used to determine the presence of a bivariate relationship between select *system innovation* variables and the *system innovation scores*. Descriptive statistics were run using SPSS statistical software. The first crosstabulation (Crosstabulation 1) examined the relationship between *legitimacy through positive discourse framing* and *legitimacy through actors* (reported in section 4.3, **Figure 6**). The purpose of this crosstabulation was to determine whether or not there is a relationship between networks of actors supporting innovation diffusion and positive discourse framing. Analyzing this relationship offers insights into the frequency of innovations that have the appropriate conditions for legitimacy: positive discourse framing by actors with agency operating across multiple scales supporting the diffusion of niche innovations.

The second crosstabulation (Crosstabulation 2) examined the relationship between *legitimacy through positive discourse framing* and the *system innovation scores* (reported in section 4.3, **Figure 9**). The purpose of this crosstabulation was to determine whether or not there is a relationship between positive discourse framing and overall disruptive potential. Analyzing this relationship offers insights into the correlation between positive discourse framing surrounding niche innovations and their potential for socio-technical regime disruption.

The third crosstabulation (Crosstabulation 3) examined the relationship between *legitimacy through actors* and the *system innovation scores* (reported in section 4.3, **Figure 12**). The purpose of this crosstabulation was to determine whether or not there is a relationship between networks of actors supporting innovation diffusion and overall disruptive potential. Analyzing this relationship offers insights into the correlation between actors with agency operating across multiple scales and the potential for socio-technical regime disruption.

The chi-square test of independence was used in order to test the significance of the relationships observed in the crosstabulations. The null hypothesis assumes that there is no significant relationship between the variables and that the observed values will match the expected values. The alternative hypothesis assumes that there is a statistically significant relationship between the variables and that the observed values will differ from the expected values. The level of significance chosen for the chi-square tests was 0.05, meaning that if p-

value is smaller than 0.05, the relationship between the two variables is statistically significant. Cramer's V test was then used to measure the magnitude of the relationship between the two variables. A Cramer's V result of 0.1 signifies a weak relationship between the variables; a result of 0.3 signifies a moderate relationship; and a result of 0.5 signifies a strong relationship .

4. Results

Table 14 presents the breakdown of the innovation aims. An innovation’s aim refers to the overall purpose of the innovation as it pertains to energy users. The results in **Table 14** exceed the total number of innovations that were coded (132) because most innovations have more than one aim. For example, an innovation that offers homeowners low-interest loans for home energy improvement retrofits would have the dual aim of energy efficiency and retrofits/installations. Approximately 54% of the innovations were aimed at energy efficiency, although it is likely that many of these innovations also had other aims. Around 27% were aimed at retrofits/installations and 21% were aimed at demand-side management. Other frequent innovation aims were renewable energy (altogether accounting for 27%), electric vehicles, local energy plans, new construction, and public/shared/alternative transportation.

Table 14 Breakdown of Aims of Innovation

Aim of the innovation	n	Examples
Battery storage	6	Community energy storage
Demand-side management	28	Residential showerhead replacement
District energy	2	Combined Heat and Power (CHP) incentives
Electric vehicles	9	Electric vehicle suitability assessments
Electric vehicle charging stations	5	Electric vehicle chargers grant programs
Energy efficiency	71	Financing through local improvement charges
Local energy plans	7	Capacity-building for smart energy communities
Microgrids	2	Micro-grid demonstration project
Natural gas infrastructure	1	Natural gas grant program
New construction	7	Energy efficiency incentives for new construction
Program design	1	Energy efficiency consultancy
Public/shared/alternative transportation	7	Community bike sharing services
Renewable energy (location not specified)	20	Energy efficiency retrofits for rooftop (PV) solar
Renewable energy (onsite)	12	Institutional research laboratories
Renewable energy (offsite)	4	Green electricity retailer
Retrofits/installations	35	Deep energy retrofit program
Smart meters	6	Residential energy data and analytics
Submetering	1	Commercial building metering and submetering.

4.1. Dissemination rate results

Dissemination rates were calculated for 64 of the 132 innovations.* These results are summarized in **Table 15** (see Appendix A, **Table 18** for the full list of dissemination rate results). The majority of the innovations analyzed received low to very low dissemination rates (below 15% market diffusion). 50 out of 64 innovations (78%) had a dissemination rate below 15%. 14 out of the 64 innovations achieved a dissemination rate above 15%, and of these 14 innovations, only 3 received a *system innovation score* above eight (i.e. only 3 of the innovations with higher rates of diffusion had disruptive potential). 24% of the innovations analyzed had dissemination rates of less than 1%. Only one innovation had a dissemination rate above 75%.

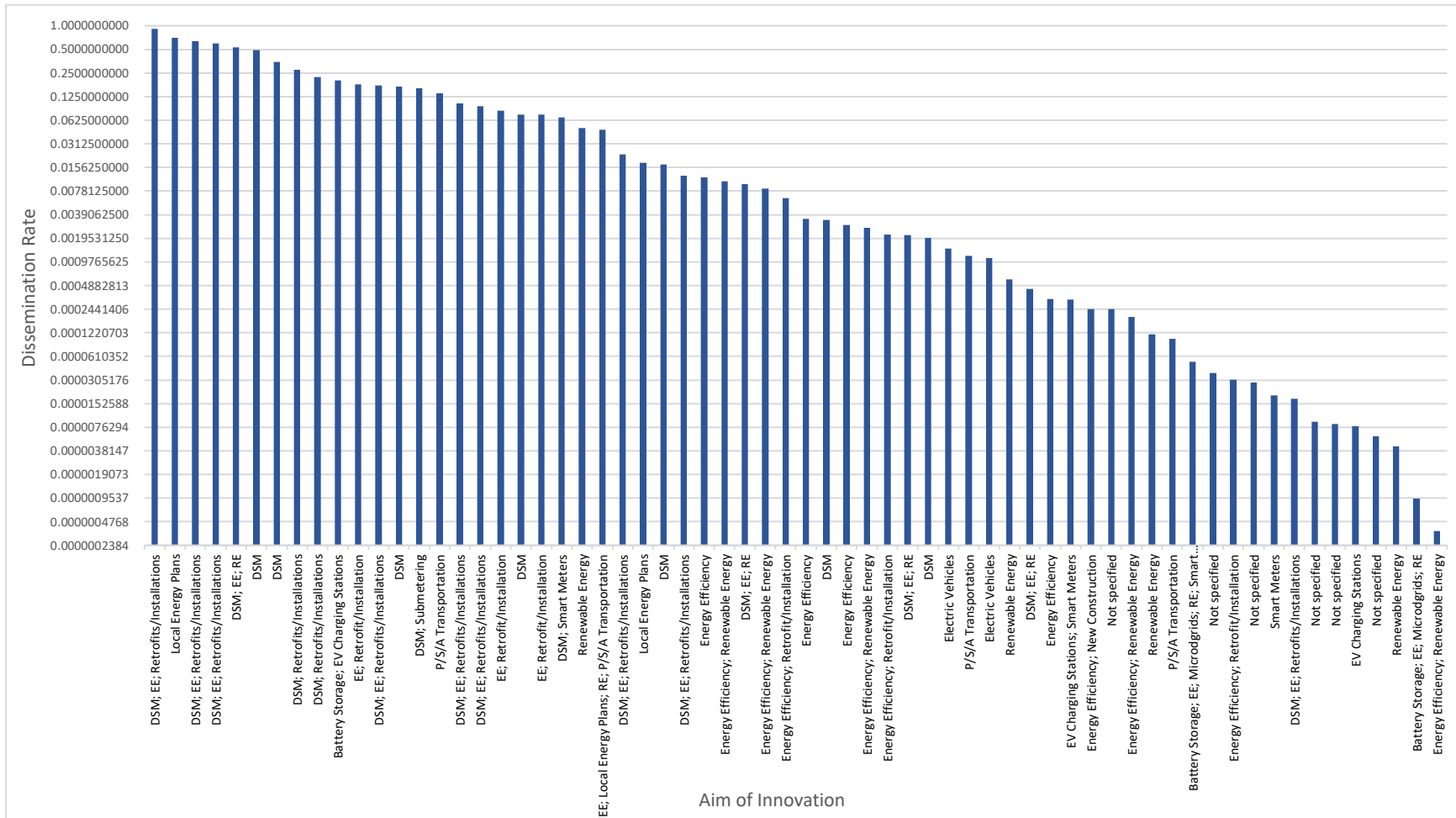
Table 15 Dissemination Rate Results

n	Dissemination Rate
32	Less than 1%
50	Below 15%
57	Below 30%
60	Below 60%
63	Below 75%
1	Above 75%

Figure 4 and **Figure 5** present a breakdown of the innovation dissemination rates in descending order by the aim and type of energy users for each innovation. The innovation that received the highest dissemination rate (92%) was a natural gas demand-side management incentive program offered to Ontario residents. All of the innovations that received a dissemination rate above 50% were natural gas demand-side management incentive programs, with the exception of one innovation aimed at local energy plans in Indigenous communities.

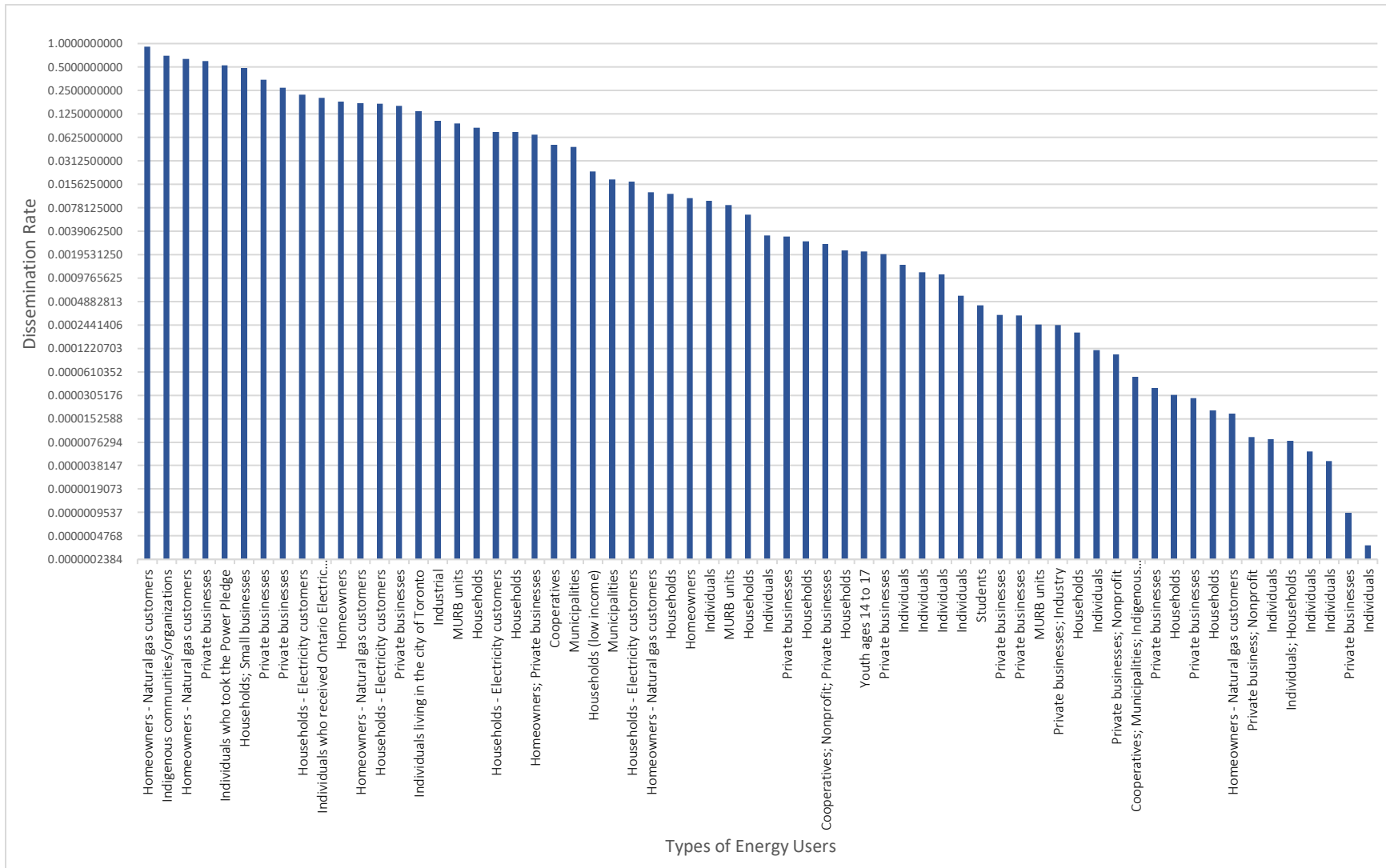
* Dissemination rates could only be calculated for innovations with available population and uptake data. For more information on the dissemination rate method, see section 3.2.1.

Figure 3 Dissemination Rate by Aim of Service



DSM = Demand-Side Management; EE = Energy Efficiency; RE = Renewable Energy; EV = Electric Vehicle; P/S/A = Public/Shared/Alternative

Figure 4 Dissemination Rates by Energy User Types



4.2. System innovation coding results

The tables presented in this section detail the results from coding the innovations. The method of data collection for the innovations that were coded is outlined in section 3.1. The innovations were coded according to the model framework and scaling system outlined in section 3.3. The results from coding the innovations for all eight *system innovation* independent variables is outlined in **Table 16**.

Table 16 Coding Results for System Innovation Variables

Independent variable	-2	-1	0	1	2
(1) Fossil fuel regime change	1	32	3	69	27
(2) Decentralization regime change	1	9	6	108	8
(3) Democratization	0	2	99	28	3
(4) Policy for scale-up: economic instruments	4	7	56	49	16
(5) Policy for scale-up: regulation	2	1	100	21	8
(6) Policy for scale-up: knowledge creation and diffusion	0	3	102	23	4
(7) Legitimacy through positive discourse framing	1	0	13	35	83
(8) Legitimacy through actors	0	1	18	22	91

Table 17 presents the results of the *system innovation scores*. The scores reflect an innovation's overall potential for system disruption and are calculated as the sum of the eight independent variables codes (method outlined in section 3.4.1). The results show that 4 innovations had an overall score equal to or below zero; 80% of the innovations (105) had an overall score between 1 and 8 and are considered incremental; and 17% of the innovations (23) had an overall score between 9 and 16 and are considered disruptive. No innovations had a score below (-4) and no innovation had a score above 12. The median score was 6 and the average score was 5.8.

Table 17 System Innovation Coding Scores

<i>n</i>	Score	Type of Innovation
23	9 – 16	Disruptive
105	1 – 8	Incremental
1	0	No impact
3	(-8) – (-1)	System reinforcing
0	(-16) – (-9)	System reinforcing

4.3. Results from the crosstabulations

The figures presented in this section detail the results from the crosstabulations and were exported from SPSS. The ‘count’ rows present the observed frequency from this analysis. The ‘expected’ rows present the expected frequency if there was no relationship between the two variables. The ‘%’ rows present the column percentages. * **Figure 6** presents the results from Crosstabulation 1, which examines the relationship between *legitimacy through positive discourse framing* and *legitimacy through actors*. The purpose of this crosstabulation is to determine whether or not there is a meaningful relationship between positive discourse framing and actor networks supporting the diffusion of the innovation. The results show that 60% of the innovations were coded as having both significant positive discourse framing across policy domains (2) and strong actor networks supporting the diffusion of the innovation across policy domains (2). Of the innovations that were coded as a (2) for positive discourse framing, 87% had strong networks of actors supporting the diffusion of the innovation across policy domains (2). The second highest frequency (11%) were innovations that were coded as having both slight positive discourse framing within a single policy domain (1) and the presence of actors with legitimacy operating across policy domains in the absence of regime-level actors (1).

* For example, if the row variable code is (1) for *Legitimacy through positive discourse framing* and the column variable code is a (1) for *Legitimacy through actors*, the column percentage row will report the percentage of innovations coded as a (1) for actor support of the innovations coded as a (1) for positive discourse framing.

Figure 5 Crosstabulation 1: Legitimacy through positive discourse framing * Legitimacy through actors

		Legitimacy through actors					Total	
		-2	-1	0	1	2		
Legitimacy through positive discourse framing	-2	Count	0	1	0	0	0	1
		Expected Count	.0	.0	.1	.2	.7	1.0
		% with Legitimacy through Actors	0.0%	100.0%	0%	0%	0%	0%
	-1	Count	0	0	0	0	0	0
		Expected Count	.0	.0	.0	.0	.0	.0
		% with Legitimacy through Actors	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	0	Count	0	0	7	3	3	13
		Expected Count	.0	.1	1.8	2.2	9.0	13.0
		% with Legitimacy through Actors	0.0%	0.0%	38.9%	13.6%	3.3%	9.8%
	1	Count	0	0	11	15	9	35
		Expected Count	.0	0.3	4.8	5.8	24.1	35.0
		% with Legitimacy through Actors	0.0%	0.0%	61.1%	68.2%	9.9%	26.5%
	2	Count	0	0	0	4	79	83
		Expected Count	.0	0.6	11.3	13.8	57.2	83.0
		% with Legitimacy through Actors	0.0%	0.0%	0.0%	18.2%	86.8%	62.9%
Total	Count	0	1	18	22	91	132	
	Expected Count	.0	1.0	18.0	22.0	91.0	132.0	
	% with Legitimacy through Actors	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	

Figure 7 presents the chi-square test for independence results for Crosstabulation 1. The results show that there is sufficient evidence to support the claim that variables from Crosstabulation 1 are dependent (Das 2020). The p-value reports an asymptotic significance of 0.000, meaning that there is a less than 0.01% chance that the observations could have occurred through random error. We can conclude with confidence that there is likely a relationship between these two variables. **Figure 8** presents the Cramer’s V test for significance results for Crosstabulation 1. Cramer’s V is reported as 0.729, meaning that there is a very strong relationship between the two variables (Das 2020).

Figure 6 Crosstabulation 1: Chi-square Tests

	Value	df	Asymptotic Significance (2- sided)
Pearson Chi-Square	210.307 ^a	9	.000
Likelihood Ratio	94.368	9	.000
Linear-by-Linear Association	69.187	1	.000
N of Valid Cases	132		

a. 10 cells (62.5%) have expected count less than 5. The minimum expected count is .01.

Figure 7 Crosstabulation 1: Significance Tests

	Value	Approximate Significance
Nominal by Nominal	Phi	1.262
	Cramer's V	.729
N of Valid Cases	132	

Figure 9 presents the results from Crosstabulation 2, which examines the relationship between *legitimacy through positive discourse framing* and *system innovation*. The purpose of this crosstabulation is to determine whether or not there is a meaningful relationship between positive discourse framing and the potential for system disruption. The results show that 96% of the innovations that have significant positive discourse framing of the innovation across policy domains (2) also received a *system innovation score* of (2). 57% of the innovations that have significant positive discourse framing of the innovation across policy domains (2) also received a *system innovation score* of (1). Of the innovations that received a *system innovation score* of (1), 30% had slight positive discourse framing within a single policy domain and 12% had no relevant plans or strategies that positively frame the innovation. Only one innovation that received a *system innovation score* between zero and (-2) had significant positive discourse framing of the innovation across policy domains.

Figure 8 Crosstabulation 2: Legitimacy through positive discourse framing * System innovation score

		Legitimacy through positive discourse framing					Total	
		-2	-1	0	1	2		
System innovation score	-2	Count	0	0	0	0	0	0
		Expected Count	.0	.0	.0	.0	.0	.0
		% with Legitimacy through positive discourse framing	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	-1	Count	1	0	0	1	1	3
		Expected Count	.0	.0	.3	.8	1.9	3.0
		% with Legitimacy through positive discourse framing	100.0%	0.0%	0.0%	2.9%	1.2%	2.3%
	0	Count	0	0	0	1	0	1
		Expected Count	.0	.0	0.1	0.3	0.6	1.0
		% with Legitimacy through positive discourse framing	0.0%	0.0%	0.0%	2.9%	0.0%	0.8%
	1	Count	0	0	13	32	60	105
		Expected Count	.8	.0	10.3	27.8	66.0	105.0
		% with Legitimacy through positive discourse framing	0.0%	100.0%	0.0%	91.4%	72.3%	79.5%
	2	Count	0	0	0	1	22	23
		Expected Count	.2	.0	2.3	6.1	15.5	23.0
		% with Legitimacy through positive discourse framing	0.0%	0.0%	0.0%	2.9%	26.5%	17.4%
	Total	Count	1	0	13	35	83	132
		Expected Count	1.0	.0	13.0	35.0	83.0	132.0
		% with Legitimacy through positive discourse framing	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Figure 10 presents the chi-square test for independence results for Crosstabulation 2. The results show that there is sufficient evidence to support the claim that the presence of positive discourse framing and disruptive potential are dependent (Das 2020). The p-value reports an asymptotic significance of 0.000, meaning that there is less than 0.01% chance that the observations could have occurred through random error. We can conclude that there is likely a relationship between these two variables. **Figure 11** presents the Cramer’s V test for

significance results for Crosstabulation 2. Cramer’s V is reported as 0.385, meaning that there is a strong relationship between the variable (7) and the *system innovation* scores.

Figure 9 Crosstabulation 2: Chi-square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	58.839 ^a	9	.000
Likelihood Ratio	27.636	9	.001
Linear-by-Linear Association	17.317	1	.000
N of Valid Cases	132		

a. 11 cells (68.8%) have expected count less than 5. The minimum expected count is .01.

Figure 10 Crosstabulation 2: Significance Tests

	Value	Approximate Significance
Nominal by Nominal	Phi	.668
	Cramer's V	.385
N of Valid Cases	132	

Figure 12 presents the results from Crosstabulation 3, which examines the relationship between *legitimacy through actors* and *system innovation*. The purpose of this crosstabulation is to determine whether or not there is a meaningful relationship between actor networks supporting the diffusion of the innovation and the potential for system disruption. The results show that 100% of the innovations that have strong actor networks supporting the diffusion of the innovation across policy domains (2) also received a *system innovation score* of (2). 65% of the innovations that have strong actor networks supporting the diffusion of the innovation across policy domains (2) also received a *system innovation score* of (1). Of the innovations that received a *system innovation score* of (1), just under 20% had the absence of regime level actors and 16% had silos of actors operating within a single policy domain. None of the innovations that received a *system innovation score* between zero and (-2) had strong actor networks supporting the diffusion of the innovation across policy domains.

Figure 11 Crosstabulation 3: Legitimacy through actors * System innovation score

		Legitimacy through actors					Total	
		-2	-1	0	1	2		
System innovation score	-2	Count	0	0	0	0	0	0
		Expected Count	.0	.0	.0	.0	.0	.0
		% with Legitimacy through Actors	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	-1	Count	0	1	1	1	0	3
		Expected Count	.0	.0	.4	.5	2.1	3.0
		% with Legitimacy through Actors	0.0%	100.0%	5.6%	4.5%	0.0%	2.3%
	0	Count	0	0	0	1	0	1
		Expected Count	.0	.0	.1	.2	.7	1.0
		% with Legitimacy through Actors	0.0%	0.0%	0.0%	4.5%	0.0%	0.8%
	1	Count	0	0	17	20	68	105
		Expected Count	.0	.8	14.3	17.5	72.4	105.0
		% with Legitimacy through Actors	0.0%	0.0%	94.4%	90.9%	74.7%	79.5%
	2	Count	0	0	0	0	23	23
		Expected Count	.0	.2	3.1	3.8	15.9	23.0
		% with Legitimacy through Actors	0.0%	0.0%	0.0%	0.0%	25.3%	17.4%
Total	Count	0	1	18	22	91	132	
	Expected Count	.0	1.0	18.0	22.0	91.0	132.0	
	% with Legitimacy through Actors	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	

Figure 13 presents the chi-square test for independence results for Crosstabulation 3. The results show that there is sufficient evidence to support the claim that strong actor networks supporting the diffusion of the innovation and disruptive potential are dependent (Das 2020). The p-value reports an asymptotic significance of 0.000, meaning that there is less than a 0.01% chance that the observations could have occurred through random error. We can concluded that there is likely a relationship between these two variables. **Figure 14** presents the Cramer's V test for significance results for Crosstabulation 3. Cramer's V is reported as 0.398, meaning that there is a strong relationship between variable (8) and the *system innovation scores*.

Figure 12 Crosstabulation 3: Chi-square Tests

	Value	df	Asymptotic Significance (2- sided)
Pearson Chi-Square	62.728 ^a	9	.000
Likelihood Ratio	34.112	9	.000
Linear-by-Linear Association	21.382	1	.000
N of Valid Cases	132		

a. 12 cells (75.0%) have expected count less than 5. The minimum expected count is .01.

Figure 13 Crosstabulation 3: Significance Tests

		Value	Approximate Significance
Nominal by Nominal	Phi	.689	.000
	Cramer's V	.398	.000
N of Valid Cases		132	

5. Discussion

The methods employed in this paper were appropriate for answering the research questions. This research used a combination of quantitative and qualitative data (mixed methods), as well as a combination of primary data from surveys and secondary data from desk research. Combining research approaches was critical for this project due to the complexity of the research objective. Qualitative data was useful for categorizing and indexing the innovations, while quantitative data was useful for coding the innovations and running statistical analyses. Through the use of mixed methods, this research was able to gain a rich understanding of the *breadth* and *depth* of the factors that influence the diffusion of low-carbon innovations. Additionally, the desk research and the chain-link sampling method employed in the surveys were effective in identifying demand-side low-carbon energy innovations in Ontario. This claim can be supported by the degree of data saturation in Survey 2, where 41% of the completed responses were innovations that had previously been collected in Survey 1. The research method was also successful in collecting the necessary information to code each innovation according to the model framework.

The major limitation of this research was access to sufficient innovation uptake and population data. 82 of the 132 innovations (62%) had available information on user uptake, while the remaining 50 innovations had unavailable or unknown uptake statistics. One possible reasons for unavailable uptake data is that the organization provisioning the innovation does not publicly report or publish uptake statistics. Another possible reason is that the organization simply does not collect this type of information about the adoption of their innovation. There were also missing population data for 33 innovations (the majority of which require information on the number of institutions operating in Ontario). Dissemination rates could not be calculated for innovations with missing uptake and population data, which limited the ability of the researchers to conduct statistical analyses and produced limited research findings for the *dissemination rate* dependent variable. The research team is in the process of acquiring this missing information. If this data cannot be found through additional desk research, new methods will need to be employed to ascertain missing population and uptake data.

The geographic specificity of this dataset is not a limitation but rather a strength. Regional energy systems, particularly at the provincial level, are distinctly heterogeneous in their governing policies, regulations, energy mix, ownership structures, etc. Technological, infrastructural, institutional, and behavioral landscapes influence how energy is used (Seto et al. 2016). In the context of Canada, energy systems are controlled and under the authority of provincial governments, and as such, the factors that facilitate the diffusion of low-carbon innovation in the Province of Ontario may differ from those of other Canadian provinces. Moreover, the factors that influence system innovation may also differ depending on market structures, available resources, provincial politics, etc. There is a benefit to conducting this type of analysis at the regional and local level in order to gain context specific insights into how a low-carbon energy transition can be accelerated. This remains true when comparing energy systems across countries and continents. As suggested by Barnes (2019), there needs to be a better understanding of how innovations are adopted and integrated into local socio-technical systems and geographies, a term that they refer to as *local embedding*, which takes into account local institutions and user practices.

5.1. Main findings

The purpose of this analysis was to present my contribution to the development of the model framework and innovation coding, in reference to the larger project, and to answer the following research questions:

1. What is the current potential for low-carbon demand-side energy innovations to contribute to a low-carbon energy transition in Ontario through system disruption?
2. What is the role of system actors in creating legitimacy for niche innovations in order to facilitate their diffusion?

As it stands, there is limited potential for low-carbon demand-side energy innovations to contribute to a low-carbon energy transition in Ontario through system innovation. Recall, system innovation is the process through which disruptive innovations destabilize the existing socio-technical regime, creating system-level transitions that lead to new socio-technical configurations. The mechanisms through which this system transformation occurs requires

disruptive rather than incremental innovation. As outlined in section 3.4.3, innovations with an overall *system innovation score* above eight are characterized as having the potential for disruption leading to system transformation; innovations with an overall *system innovation score* between zero and eight are characterized as incremental innovations, which do not themselves lead to regime destabilization. Only 17% of the innovations analyzed in this investigation had disruptive potential, while 80% of the innovations were found to be incremental (**Table 17**). Moreover, only 3 innovations with disruptive potential reported dissemination rates above 15% market share*. These findings suggest that there is limited capacity for the current landscape of demand-side low-carbon energy innovations to accelerate a low-carbon energy transition in Ontario.

Based on previous studies in this field, the literature suggests that low-carbon innovations experience slow rates of diffusion (Clausen and Fichter 2019; Kowalska-Pyzalska 2018:3571; Organisation for Economic Co-operation and Development 2018). Clausen and Fichter (2019:64) state that only one third of eco-innovations are diffused into the broader consumer market, while two thirds remain in niche markets with average market shares below 15%. The results presented in this paper found that *less* than one third of the low-carbon innovations for energy users in Ontario are diffused into the broader consumer market. In fact, this research found that less than *one fourth* (22%) of the low-carbon innovations achieved a diffusion rate above 15%, while the remaining (78%) were unable to sufficiently diffuse out of niche markets and into the broader consumer market. The results from this analysis confirm and elaborate on the existing research studying the diffusion of low-carbon innovation.

This research also contributes to our understanding of the important role of system actors in creating legitimacy for the scale-up of niche innovation. Sustainability transitions literature suggests that building legitimacy for system disruption requires positive discourse framing and visioning strategies by actors with agency supporting the diffusion of niche innovations across multiple scales (Duygan et al. 2019; Geels and Verhees 2011; Ruef and Markard 2010; Schlaile et al. 2017). The results from this analysis found a statistically significant

* Note that these results include innovations with available population and uptake data.

relationship between the presence of actors with agency and positive discourse framing supporting the diffusion of an innovation through legitimation. A possible interpretation of this finding is that these two variables are mutually inclusive. It is likely that the presence of strong actors with agency supporting an innovation will influence positive discourse framing, which will in turn draw more actor and network support. This pattern creates a positive feedback loop as the innovation gains increasing attention and increasing network support. This finding supports what is being articulated in sustainability transitions literature on the role of actors in building legitimacy for niche innovation.

One of the main objectives of this research paper was to better understand the role of system actors in creating legitimacy for innovations in order to facilitate their diffusion as a mechanism for accelerating a socio-technical regime transition. Based on the relevant literature and research findings, it is possible to infer that legitimacy is a necessary but not sufficient condition for system disruption. Over 60% of the innovations had both strong networks of actors and positive discourse framing supporting the diffusion of the innovation. As outlined in the literature, innovations that have both of these variables have the necessary conditions for achieving legitimacy. As such, it is possible to infer that 60% of the innovations in this analysis had the necessary conditions for achieving legitimacy. However, less than 20% of the innovations have disruptive potential leading to system innovation. Of these disruptive innovations, 100% have strong actor networks and 96% have positive discourse framing. These findings suggest that despite having the necessary conditions for achieving legitimacy, at least 40% of the innovations were missing other critical factors that contribute to system disruption, and were therefore not classified as having disruptive potential. These findings demonstrate that the presence of legitimacy is not sufficient for creating system disruption.

5.2. Next steps

This research paper is one application of the model framework and is a contribution to the larger, ongoing research project. The next steps in the broader research project are to ascertain the missing innovation population and uptake data with a goal of calculating the dissemination rates for 100% of the innovations. The research team will then run statistical analyses through regression modelling in order to identify the key factors that are significant across diffusion cases. Additionally, multiple research papers are being prepared for publication, including the model framework development and methodology; gaps and implementation of the *system innovation* dependent variable; gaps and implementation of the *pro-environmental behavior* dependent variable; and presentations of the regression analyses.

6. Conclusion

Accelerating the transition to a low-carbon energy system requires the swift diffusion and adoption of disruptive low-carbon innovation. Many of the technologies required to meet global climate change mitigation commitments within a 1.5°C scenario already exist but are not able to successfully diffuse into mainstream markets. Focus needs to shift from the research and development of novel low-carbon innovation toward the market formation, commercialization, and diffusion of *existing* low-carbon innovation. However, it is not enough for these innovations to simply be diffused. In order for these innovations to transform the incumbent energy system, they need to be disruptive. Incremental innovations do not have the capacity to overcome carbon lock-in and systemic path-dependencies. Disruptive innovations are needed to fundamentally alter the way in which energy users interact with energy technologies, creating system innovation toward a new low-carbon energy system. In the case of Ontario, less than one fifth of the demand-side low-carbon innovations studied in this analysis have disruptive potential. This suggests a need to better understand the specific factors that can be manipulated by system actors (policy makers, industry professionals, networks, etc.) across diffusion cases to improve the disruptive potential of existing low-carbon innovation and to accelerate their diffusion.

The model framework presented in this paper is a useful tool for assessing an innovation's potential for accelerating a low-carbon energy transition through system innovation. This framework can be used to inform policy makers on the factors that influence socio-technical regime disruption and the mechanisms through which a regional and local energy system transition can be facilitated. This model framework can be replicated and applied to regional and local empirical studies in order to quantify current disruptive potential, as well as to inform policy on the range and combination of factors that drive or act as a barrier to system disruption. Industry experts and professionals can use this type research to map the current landscape of low-carbon innovations being offered to energy users.

This research paper focused specifically on the role of system actors in building legitimacy for niche innovation in order to facilitate their diffusion. In the case of Ontario, demand-side low-carbon energy innovations that have strong networks of actors supporting

their diffusion tend to also have the presence of plans and strategies that positively frame discourse surrounding the innovation. It was also found that legitimacy was present in nearly all of the innovations that had disruptive potential, yet not all of the innovations that had legitimacy were disruptive. This suggests that legitimacy is a necessary but not sufficient condition for system disruption.

No single system factor can independently predict diffusion. In order to answer the research questions, it was of critical importance to analyze the full range and combination of factors that can facilitate innovation diffusion through system disruption. Approaching this type of research from a complex systems perspective and studying the relationships between the different system components can lead to a more comprehensive understanding of how diffusion cases can be influenced. This also ties into the importance of analyzing innovation diffusion from a regional and/or local perspective, as successfully influencing diffusion will necessarily require a good understanding of the economic, social, political, and environmental contexts within which energy systems operate. As Barnes (2019) suggests with their work on local embedding, it is important to understand the context and conditions within which innovation is being diffused in order to successfully accelerate the deployment of existing low-carbon innovation.

It should be acknowledged that this analysis does not address whether or not the transition to a low-carbon energy system will result in increased energy justice. It is possible that the reconfiguration of socio-technical systems will lead to increasingly unjust distribution of resources, energy poverty, and energy insecurity for individuals and/or communities. Energy justice is an emerging field of literature that applies justice principles in order to assess the distribution of benefits and risks within all aspects of the energy system (Jenkins et al. 2016). Though the concept of energy justice is not explored in this analysis, the research model accounts for this system factor through the *energy justice* dependent variable, and will be explored in future analyses.

There are many opportunities for future research through the application of the model framework to other regional and local empirical studies so that more data can be gathered. There is also a great deal of room for innovation within the model framework itself. For

example, a consideration that has not yet been addressed is the weighting of the *system innovation* independent variables. The statistical model currently assumes that all eight independent variables have the same potential to influence system innovation. For example, the model currently assumes that (1) *Fossil fuel regime change* and (2) *Decentralization regime change* variables have identical influence on system innovation. Though this may be the case, it cannot be confirmed as variable weightings have not yet been integrated into the model. Another opportunity for innovation within the model framework is in the development of additional variables. A model can only be made stronger through accounting for a more comprehensive set of system variables.

Tackling climate issues in the energy sector is not a simple task. Contemporary energy systems require expensive and long-term capital investments in infrastructure and technology. These path-dependent processes lock-in carbon intensive technologies, making energy systems rigid and resistant to change. Historically, energy transitions have been a gradual process that take place over the span of many decades (Smil 2017). It took 100 years for oil to outpace coal as the most important source of energy globally from the time the first successful oil well was drilled (Victor 2008). Leading climate scientists and experts report that we now have one– maybe two– decades to make a massive transition off fossil fuels toward low or (ideally) no carbon energy. There will need to be a swift and fundamental change to the way in which we generate, distribute, and consume energy, and existing demand-side low-carbon innovations for energy users can play a critical role in this transition if successfully deployed at scale.

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Appendix A

Table 18 Dissemination Rate Full Results

Service #	Types of Users	Population (N)	Uptake (n)	Dissemination Rate	DR Percent (%)
203g	Homeowners - Natural gas customers	3,636,582	3,335,694	0.917260768	91.73%
210b	Indigenous communities/organizations	141	99	0.702127660	70.21%
203h	Homeowners - Natural gas customers	3,636,582	2,305,180	0.633886435	63.39%
203j	Private businesses	1,063,756	633,140	0.595192883	59.52%
2b	Individuals who took the Power Pledge	133,000	70,000	0.526315789	52.63%
206d	Households; Small businesses	5,586,917	2,709,250	0.484927555	48.49%
206g	Private businesses	1,063,756	365,988	0.344052583	34.41%
206i	Private businesses	1,063,756	289,912	0.272536183	27.25%
206e	Households - Electricity customers	5,164,196	1,139,133	0.220582836	22.06%
18b	Individuals who received Ontario Electric Vehicle Incentive	15,000	3,000	0.200000000	20.00%
106	Homeowners	3,582,238	640,000	0.178659263	17.87%
203a	Homeowners - Natural gas customers	3,636,582	625,801	0.172084941	17.21%
206b	Households - Electricity customers	5,164,196	866,985	0.167883829	16.79%
77	Private businesses	1,063,756	170,000	0.159811084	15.98%
132	Individuals living in the city of Toronto	2,930,000	400,000	0.136518771	13.65%
203k	Industrial	36,355	3,716	0.102214276	10.22%
203f	MURB units	1,411,185	132,907	0.094181131	9.42%
127,129a	Households	5,169,175	428,000	0.082798512	8.28%
206c	Households - Electricity customers	5,164,196	380,000	0.073583574	7.36%
127,129b	Households	5,169,175	380,000	0.073512698	7.35%
80	Homeowners; Private businesses	4,645,994	315,000	0.067800346	6.78%
220b	Cooperatives	1,500	75	0.050000000	5.00%
9	Municipalities	444	21	0.047297297	4.73%
203d	Households (low income)	896,405	20,567	0.022943870	2.29%
210a	Municipalities	444	8	0.018018018	1.80%
206f	Households - Electricity customers	5,164,196	87,323	0.016909312	1.69%
203b	Homeowners - Natural gas customers	3,636,582	44,917	0.012351433	1.24%
211a	Households	5,169,175	60,424	0.011689293	1.17%
57	Homeowners	3,582,238	37,000	0.010328739	1.03%
2a	Individuals	13,793,260	133,000	0.009642391	0.964%
209b	MURB units	1,411,185	11,861	0.008404993	0.840%
214b	Households	5,169,175	33,000	0.006383997	0.638%
84	Individuals	13,793,260	47,500	0.003443711	0.344%
206j	Private businesses	1,063,756	3,542	0.003329711	0.333%
117	Households	5,169,175	15,000	0.002901817	0.290%

4	Cooperatives; Nonprofit; Private businesses	1,124,861	3,000	0.002666996	0.267%
211b	Households	5,169,175	11,343	0.002194354	0.219%
2c	Youth ages 14 to 17	696,549	1,500	0.002153474	0.215%
206h	Private businesses	1,063,756	2,117	0.001990118	0.199%
24	Individuals	13,793,260	20,000	0.001449984	0.145%
68a	Individuals	13,793,260	16,000	0.001159987	0.116%
18a	Individuals	13,793,260	15,000	0.001087488	0.109%
220a	Individuals	13,793,260	8,000	0.000579993	0.058%
2d	Students	2,051,865	900	0.000438625	0.044%
309	Private businesses	1,063,756	350	0.000329023	0.033%
7	Private businesses	1,063,756	346	0.000325263	0.033%
100a	MURB units	1,411,185	346	0.000245184	0.025%
43	Private businesses; Industry	1,100,111	269	0.000244521	0.024%
13	Households	5,169,175	1,000	0.000193454	0.019%
95, 118	Individuals	13,793,260	1,600	0.000115999	0.012%
68b	Private businesses; Nonprofit	1,123,361	114	0.000101481	0.010%
61	Cooperatives; Municipalities; Indigenous communities; Nonprofit; Private businesses	1,125,446	59	0.000052424	0.0052%
218	Private businesses	1,063,756	40	0.000037603	0.0038%
32	Households	5,169,175	160	0.000030953	0.0031%
219	Private businesses	1,063,756	30	0.000028202	0.0028%
34a	Households	5,169,175	101	0.000019539	0.0020%
203c	Homeowners - Natural gas customers	3,636,582	64	0.000017599	0.0018%
40	Private business; Nonprofit	1,123,361	10	0.000008902	0.00089%
216	Individuals	13,793,260	115	0.000008337	0.00083%
305	Individuals; Households	18,962,435	150	0.000007910	0.00079%
217	Individuals	13,793,260	80	0.000005800	0.00058%
26	Individuals	13,793,260	60	0.000004350	0.00044%
94, 125	Private businesses	1,063,756	1	0.000000940	0.000094%
114	Individuals	13,793,260	5	0.000000362	0.000036%

Appendix B

Table 19 System Innovation Independent Variables

Independent variable	Scale	Literature
1. Fossil fuel regime change	-2: Strongly reinforces fossil fuel regime.	K.C. Seto, S.J. Davis, R.B. Mitchell, E.C. Stokes, G. Unruh, D. Ürge-Vorsatz (2016); G. Unruh (2000; 2002).
	-1: Slightly reinforces fossil fuel regime.	
	0: No change to fossil fuel regime.	
	1: Incremental innovation toward fossil fuel regime change.	
	2: Disruptive innovation toward fossil fuel regime change.	
2. Decentralization regime change	-2: Strongly reinforces centralized grid.	J. Lowitzsch, C.E. Hoicka, F. van Tulder (2020); E. Judson, O. Fitch-Roy, T. Pownall, R. Bray, H. Poulter, I. Soutar, R. Lowes, P. Connor, J. Britton, B. Woodman, C. Mitchell (2020); L.F.M. van Summeren, A.J. Wiczorek, G.J.T. Bombaerts, G.P.J. Verbong (2020).
	-1: Slightly reinforces centralized grid.	
	0: No effect on grid.	
	1: Incremental innovation towards decentralization.	
	2: Disruptive innovation towards decentralization.	
3. Democratization	-2: Incumbent gains all or nearly all control and controlling share of ownership.	Becker, S. and Naumann, M. (2016); Berka, A. L., & Creamer, E. (2017); Brisbois, M. C.

Independent variable	Scale	Literature
	-1: Incumbent gains more control <u>or</u> gains share of ownership. 0: status quo/incumbent maintains control and ownership. 1: Community or individuals gains more control <u>or</u> gains share in ownership. 2: Community or individuals gains all or nearly all control <u>and</u> gains controlling share in ownership.	(2018); Burke, M. J. and Stephens, J. C. (2018); Campney, A. (2019); Devine-Wright, P (2014); Fraune, C. (2015); Gross, J. (2007); Jenkins, K., Mccauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016); Hoicka, C.E., & MacArthur, J.L. (2018); Sovacool, B. K. and Dworkin, M. (2015); Szulecki, K. (2018); van Veelan, B., and van der Horst, D. (2018).
4. Policy for scale-up: economic instruments	-2: Presence of economic policy instruments that significantly weaken innovation diffusion; Removal of technology-specific economic policy instruments that impact innovation diffusion. -1: Presence of economic policy instruments that slightly weaken innovation diffusion; Removal of general economic policy instruments that impact innovation diffusion. 0: No detectable change, no effect, or unknown effect on scale-up. 1: Presence of economic policies that promote incremental innovation diffusion. 2: Presence of economic policies that promote disruptive innovation diffusion.	Bergek, A., Berggren, C., & KITE Research Group. (2014); Dixon, T., Lannon, S., & Eames, M. (2018); Elzen, B., Geels, F. W., & Green, K. (Eds.). (2004); Feola, G., & Butt, A. (2017); Geels, F. W. (2018); Geels, F. W., & Johnson, V. (2018); Geels, F. W., Schwanen, T., Sorrell, S., Jenkins, K., & Sovacool, B. K. (2018); Jacobsson, S., Bergek, A., (2011); Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020); Meelen, T., Truffer, B., & Schwanen, T. (2019); Kivimaa, P., & Kern, F. (2016); van den Bergh, J., Faber, A., Idenburg, A., Oosterhuis, F., (2006); Weimer & Vining (1992).
5. Policy for scale-up: regulations	-2: Presence of regulatory policy instruments that significantly weaken innovation diffusion; Removal of technology-specific regulatory policy instruments that impact innovation diffusion. -1: Presence of regulatory policy instruments that slightly weaken innovation diffusion; Removal of general regulatory policy instruments that impact innovation diffusion. 0: No detectable change, no effect, or unknown effect on scale-up. 1: Presence of regulatory policies that promote incremental innovation diffusion. 2: Presence of regulatory policies that promote disruptive innovation diffusion.	Bergek, A., Berggren, C., & KITE Research Group. (2014); Dixon, T., Lannon, S., & Eames, M. (2018); Elzen, B., Geels, F. W., & Green, K. (Eds.). (2004); Feola, G., & Butt, A. (2017); Geels, F. W. (2018); Geels, F. W., & Johnson, V. (2018); Geels, F. W., Schwanen, T., Sorrell, S., Jenkins, K., & Sovacool, B. K. (2018); Jacobsson, S., Bergek, A., (2011); Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020); Meelen, T., Truffer, B., & Schwanen, T. (2019); Kivimaa, P., & Kern, F. (2016); van den Bergh, J., Faber, A., Idenburg, A., Oosterhuis, F., (2006); Weimer & Vining (1992).
6. Policy for scale-up: knowledge creation and diffusion	- 2: Presence of policy instruments for knowledge creation and diffusion that strongly reinforces incumbent regime. -1: Presence of policy instruments for knowledge creation and diffusion that slightly reinforces incumbent regime. 0: No detectable change, no effect, or unknown effect on scale-up. 1: Policy instruments for knowledge creation and diffusion provide niche-level support to complement or strengthen innovation. 2: Presence of policies that aim to increase knowledge creation and diffusion through the establishment of new networks.	Bergek, A., Berggren, C., & KITE Research Group. (2014); Dixon, T., Lannon, S., & Eames, M. (2018); Elzen, B., Geels, F. W., & Green, K. (Eds.). (2004); Feola, G., & Butt, A. (2017); Geels, F. W. (2018); Geels, F. W., & Johnson, V. (2018); Geels, F. W., Schwanen, T., Sorrell, S., Jenkins, K., & Sovacool, B. K. (2018); Jacobsson, S., Bergek, A., (2011); Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020); Meelen, T., Truffer, B., & Schwanen, T. (2019); Kivimaa, P., & Kern, F. (2016); van den Bergh, J., Faber, A., Idenburg, A., Oosterhuis, F., (2006); Weimer & Vining (1992).
7. Legitimacy through discourse framing	-2: Presence of plans/strategies spanning policy domains that significantly weaken the legitimacy of niche innovation; Removal of plans/strategies that support innovation diffusion. -1: Presence of plans/strategies within a single policy domain that slightly weaken the legitimacy of the niche innovation. 0: No impact or unknown impact on legitimacy. 1: Presence of plans/strategies within a single policy domain that slightly strengthen the legitimacy of niche innovation and support innovation diffusion.	Duygan, M., Stauffacher, M., & Meylan, G. (2019); Geels, F. W., & Verhees, B. (2011); Kern, F., & Smith, A. (2008); Kivimaa, P., & Kern, F. (2016); Mignon, I., & Bergek, A. (2016); van Oorschot, J. A. W. H., Hofman, E., & Halman, J. I. M. (2018); Russell, C., & Meehan, J. (2014); Ruef, A., & Markard, J. (2010); Rosenbloom, D., Berton, H., & Meadowcroft, J. (2016); Schlaile,

Independent variable	Scale	Literature
	2: Presence of plans/strategies spanning policy domains that significantly strengthen the legitimacy of niche innovation and support innovation diffusion.	M., Urmetzer, S., Blok, V., Andersen, A., Timmermans, J., Mueller, M., Fagerberg, J., & Pyka, A. (2017); Schot, J., & Geels, F. W. (2008); Suchman, M. C. (1995).
8. Legitimacy through actors	- 2: Strong network of regime actors operating across policy domains to constrain the delivery and diffusion of innovation.	Gliedt, T., Hoicka, C. E., & Jackson, N. (2018); Kanda, W., Hjelm, O., Clausen, J., & Bienkowska, D. (2018); Kivimaa, P., Boon, W., Hyysalo, S., & Klerkx, L. (2019); Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017); Matschoss, K., & Heiskanen, E. (2018); Mignon, I., & Kanda, W. (2018); Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016).
	-1: Regime actors operating within a policy domain to constrain the delivery and diffusion of innovation.	
	0: Silo of niche actors operating within a single policy domain facilitating the diffusion of the niche innovation (impact negligible).	
	1: Innovation intermediary and niche level actors interacting within multiple policy domains facilitating the diffusion of innovation.	
	2: Innovation intermediary and regime-level actors interacting across policy domains facilitating the diffusion of innovation.	

Appendix C

Table 20 Outline of Ontario Innovation System for Energy Demand-Side Innovation

Policy Domain	Implementation Policies	Organizations	Mechanisms / Activities	Intended Demand-side innovations for energy Users
Energy Policy	<ul style="list-style-type: none"> - Ontario Energy Board Act (1998b) - Electricity Act (1998a) - Electricity Restructuring Act (2004) - Green Energy and Green Economy Act (2009) - Ontario Long Term Energy Plan (2010, 2013, 2017) - Municipal ownership of local distribution companies (early 1900s-) - Local Improvement Charges, Municipal Act 2001 (2012) 	<ul style="list-style-type: none"> - Natural Resources Canada - Ontario Energy Board (1998-) - Ontario Ministry of Energy - Independent Electricity System Operator (IESO) (1998-) - Quality Urban Energy Systems of Tomorrow (QUEST) (2007-) municipal network - Local electricity distribution companies - Natural gas utilities - Electricity retailers (2002-) - Natural gas retailers - Service providers 	<ul style="list-style-type: none"> - Retailer participation in wholesale markets (1998) - Smart meters (2004-2010) - Time of use prices (2006-) - Electricity and natural gas demand management activities (1995-) - Local Improvement Charges can be applied to energy projects (2012-) - Municipal Energy Plan program (2013-) - Indigenous Community Energy Plan program (2013-) - Local energy plans (2013-) - GHG reporting for municipalities (2009-) - Electric Vehicle Discovery Centre (2017-) 	<ul style="list-style-type: none"> - Purchase electricity and gas from a service provider - Real-time electricity information - Demand response - Audits for building retrofits - Rebates, coupons - Demand response - Equipment removal - Demonstration projects (e.g., micro-grid and renewable energy) - Consultations for local energy plans - Grants for local energy plans - District energy - Energy demand management - Loans for building energy retrofits

Policy Domain	Implementation Policies	Organizations	Mechanisms / Activities	Intended Demand-side innovations for energy Users
Environmental and Climate Change Policy	<ul style="list-style-type: none"> - Government of Canada Action Plan on Climate Change (2000, 2009, 2014) - Pan-Canadian Framework on Clean Growth and Climate Change (2016) - EnerGuide Climate Change Program (1998-2006) - ecoEnergy Climate Change Program (2007-2012) - Go Green: Ontario's Action Plan on Climate Change (2007) - Climate Change Mitigation and Low-carbon Economy Act (2016a) - Ontario's Five Year Climate Change Action Plan 2016-2020 (2016b) - Municipal Partners for Climate Protection program 	<ul style="list-style-type: none"> - Environment Canada - Sustainable Development Technology Canada (SDTC) (2001-) (38) - Ministry of the Environment and Climate Change - Ontario Green Bank (aspirational) - Green Ontario (2017-2018) - Federation of Canadian Municipalities (1901-) - ICLEI Canada (1994-), (31) - Toronto Atmospheric Fund 	<ul style="list-style-type: none"> - Innovation funds- Sustainable Development Technology Canada (SDTC) - Funds targeted at clean technology development - Funds targeted at renewable energy in remote and Indigenous communities - Funds targeted at low-carbon transportation - Recycled revenue from cap and trade program to Green Ontario (2017-2018) - Partners for Climate Protection program (1994-) - Create conditions for Ontarian's to choose low-carbon options 	<ul style="list-style-type: none"> - Ontario Green Bank provides loans and information for energy retrofits - Tools, information for behaviour change - Building Retrofits - Renewable energy generation by homes and businesses - Electric Vehicles - Active Transportation - Public transit - solar photovoltaic and energy storage systems, modern wood heating pilots, air source heat pumps, ground source heat pumps, insulation, windows, smart thermostats, and social housing retrofits - Consultations and training for local energy plans - Grants for local energy plans
Science, Technology, and Industrial Innovation Strategy	<ul style="list-style-type: none"> - Ontario's innovation agenda (2008) 	<ul style="list-style-type: none"> - Ontario Network of Entrepreneurs (ONE) - Provincial Innovation Centres (PICs) (MaRS and the Ontario Centres of Excellence) - Regional Innovation Centres - University Innovation Hubs/Centres (e.g., Waterloo Institute for Sustainable Energy, Ryerson Centre for Urban Energy) 	<ul style="list-style-type: none"> - Incubation and acceleration services - Intermediation - Energy Transformation Network of Ontario/Ontario Smart Grid Forum (2008-) - Open innovation and crowd-sourced competitions - Advanced Energy Centre at MaRS (2014-) 	<ul style="list-style-type: none"> - Renewable energy - smart end-use devices/appliances - advanced metering connected to utility communications; - control interface - distributed generation and storage - real-time price and demand information, automated home controls for demand response - fuel switching and energy storage - electric vehicles - micro-grids to share power and isolate district heat - Micro-grid development - Meter Data Access Project (MDAP) - Green Button Program (standardized information for service providers to bring to customers) (2017-) - Green Button Pilot Program (2012) - Education around electricity consumption and energy savings - Enable standardized electricity consumption data - Cross-industry collaboration - Promotion of the Green Button standard
Social Enterprise and Innovation Strategy	<ul style="list-style-type: none"> - Ontario's innovation agenda (2008) 	<ul style="list-style-type: none"> - Ontario Network of Entrepreneurs (ONE) - Provincial Innovation Centres (PICs) (MaRS and the Ontario Centres of Excellence) - Regional/Sectoral Innovation Centres 	<ul style="list-style-type: none"> - Competitions for incubation and acceleration of innovative solutions - Incubation and acceleration of social enterprise 	<ul style="list-style-type: none"> - Investments in commercial scale solar energy projects through solar bonds; - Capacity-building support for co-ops who are developing renewable energy projects and social enterprises - Clarify details about investment in renewable energy (check, for e.g. FCPC and solar share)

Policy Domain	Implementation Policies	Organizations	Mechanisms / Activities	Intended Demand-side innovations for energy Users
		<ul style="list-style-type: none"> - University Innovation Hubs/Centres - Social Enterprise Partnership - Municipalities - Public and Private Foundations - Government Program Funds - Federation of Community Power Cooperatives (FCPC) - Ontario Co-Operatives Association - The Centre for Social Innovation - MIT Climate CoLab - Nonprofits 	<ul style="list-style-type: none"> - Incubation and acceleration of energy cooperatives - Agents of Change Accelerator (2016-) - MIT Climate Co-lab (2018) 	<ul style="list-style-type: none"> - Small and medium enterprise climate change mitigation and adaption - Climate change mitigation, adaption and geoengineering for SMEs

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Table 21 Outcomes of Ontario Innovation System for Energy Demand-Side Innovations

Policy Domain	Policies and Programs	Time-frame	Actors/ Networks	Outcome: uptake of demand-side innovations for energy user engagement	
Energy Policy	District Energy	1880- ^v	Municipalities District Energy companies	44	District energy systems ^k
	Local electricity distribution company ownership by municipalities	1900	Local electricity distribution companies Electricity Distributors Association Municipalities Ontario Energy Board (regulator)	76	LDCs ^l (Source above)
				69	LDCs currently operating in Ontario ^w
	Natural gas demand side management (DSM) programs (reporting 2007-)	1995-	Ontario Ministry of Energy Natural gas utilities Ontario Energy Board (regulator) Environmental Commissioner of Ontario	625,801	Residential Showerhead Replacement ^h
				44,917	Residential Equipment Replacement ^h
				64	Residential Rebate for Appliances ^h
				20,567	Residential Low-Income Program ^h
				10,767	Audits and Retrofit Program ^h
				122,971	Multi-Residential ^h
				2,256,596	Residential Participants (Union Gas) ^h
				41,650	Labeling programs (#Realtors enrolled) ^h
	603,266	Commercial ^h			
	3,212	Industrial ^h			
	Natural gas retailers	1997-	35 Gas marketers in 2017 ^c (45)	*1,133,479	Customers ^{b,c} (36% in 2006)
				*380,472	Customers ^{b,c} (11% in 2013)
	Electricity retailers	2002-	56 electricity retailers in 2017 ^a Ontario Energy Board (regulator)	732,032	Customers ^{b,c} (16% in 2006)
				299,290	Customers ^{b,c} (6.3% in 2013)
Electricity conservation and demand management programs	2007-	Ontario Ministry of Energy Ontario Power Authority (OPA)/ Independent Electricity System Operator (IESO) Local electricity distribution companies Retail stores Service providers Industry associations Ontario Energy Board (regulator)	39,744,958	Coupons ^d	
			866,985	Appliances Removed ^d	
			380,000	Household Manual Peak Saving ^d	
			2,147,507	Automated Peak Saver/ Demand Response (Household and Small Commercial) ^d	
			1,094,151	Incentives for Retrofits (Residential) ^d	
			83,634	Tailored Information & Retrofit Support (Residential) ^d	
			199,383	Social Benchmarking ^d	
2,117	Demand Response (Business) ^d				

				274,443	Incentives for Retrofits (Business) ^d	
				3,206	Tailored Information and Retrofit Support for Business ^d	
	Microfit Program (10kW or less)	2009-2017	Ontario Ministry of Energy Ontario Power Authority (OPA) / Independent Electricity System Operator (IESO) Local electricity distribution companies Retail stores Service Providers	26,000	Microfit contracts ^{e, f} 50MW procurement target ^g	
	Local Improvement Charge	2012-	Municipalities Banks Service providers Local electricity distribution company (Toronto Hydro) Natural gas utility (Enbridge) Toronto Atmospheric Fund Independent Electricity System Operator (IESO) Natural Resources Canada	160	Homes retrofitted (2014-2016) Toronto's Home Energy Loan Program (HELP) ⁱ	
				11 (1,1861)	Properties (individual units) retrofitted (2014-2017) Toronto's High-Rise Retrofit Improvement Support Program (Hi-RIS) ⁱ	
	Local Energy Plans	2013-	Ministry of Energy Municipalities Indigenous communities Ministry of Aboriginal Affairs Independent Electricity System Operator (IESO)	7	Municipalities developed Municipal Energy Plans ^m (MEP)	
				2	Municipalities updated/enhanced existing MEP ^m	
				49	Communities developed an Indigenous Community Energy Plan ^p	
	Environment and Climate Change Policy	EnerGuide for Houses	1998-2006	Natural Resources Canada Natural gas utilities Service companies Green Communities Canada and community based organizations Certified Energy Advisors Municipalities	60,424	Participants Received Information Audits ^q
					11,343	Participants Received Grants for Retrofits ^q
ecoEnergy Retrofit-Homes / Ontario Home Energy Savings Program		2007-2012/ 2007-2011	Natural Resources Canada Natural gas utilities Service companies Green Communities Canada and community based organizations (16) Certified Energy Advisors Municipalities Ontario Ministry of Energy	640,000	Participants received retrofits <i>across Canada</i> ^r	
				428,000	Ontario homeowners completed home energy audits ^s	
				380,000	Ontario homeowners completed home energy retrofits ^s	
Electric Vehicles		2011-2018	Plug N' Drive (non-profit) Ministry of Transportation Electrical Safety Authority Electric Vehicle Discovery Centre (2017-)	26,143	Electric vehicle ownership ^t	
				15,000	Received Electric and Hydrogen Vehicle Incentive ^j	
				3,000	Received Electric vehicle charging incentive ^j	
Cap and Trade Program and Revenue Recycling		2017-2018	Ministry of the Environment and Climate Change Western Climate Initiative Green Ontario (2017-2018)	269	Registered participants ⁿ	
				33,000	Installations completed and rebates received for solar photovoltaic and energy storage systems, modern wood heating pilots, air source heat pumps, ground source heat pumps, insulation, windows, smart thermostats, and social housing retrofits ^w	
	140,000			Program target ^w		
Science, Technology and Industrial Innovation Strategy	Green Button Program	2012-	Local electricity distribution companies Service providers MaRS Provincial Innovation Centre	132	Accounts ^u	
				101	Residential Accounts ^u	
				31	Commercial/Institutional ^u	
				10	Applications ^u	
				60%	Ontarian households and small businesses have access to their data in the Green Button format ^l	

			Local electricity distribution companies and natural gas utilities Independent Electricity System Operator (IESO) Ontario Energy Board (regulator) Ontario Ministry of Energy		
	MaRS Energy Hackathon	2013	MaRS Provincial Innovation Centre Ontario Ministry of Energy Information and Privacy Commissioner of Ontario	11 115	Solutions/ strategies ^o Participants (developers coders, designers, energy experts, utility representatives, behavioural economists, volunteers) ^o
	Climate Hack-to-Action	2016	Incubators/accelerators at Ryerson University: Brookfield Institute for Innovation, Social Ventures Zone Ministry of Environment and Climate Change TD Bank City of Toronto and TransformTO Non-profit/associations: CivicAction, carbon neutral Service provider ecobee, Think Fresh Group, the Goods, Solo	80	Participants in ^x
Social Enterprise and Innovation Strategy	Agents of Change: Climate change solutions	2016-	The Centre for Social Innovation (incubator/accelerator) Government of Ontario	40	Enterprises supported ^y
	Helping SME's Go Low Carbon initiative	2018	The Centre for Social Innovation (incubator/accelerator) MIT Climate CoLab Ontario Government	30	Proposals A
	Feed-in-tariff program	2009-2016	Federation of community power co-operatives co-operatives ^z Ontario Co-operatives Association	8000 75	Members of energy co-operatives ^z Registered Renewable Energy Co-operatives ^f

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