Towards Low-carbon Energy Transitions with Diffusion of Multiple Low-carbon Innovations in Ontario

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
York University, Toronto, Ontario, Canada

July 30, 2020

Abstract

According to the Intergovernmental Panel on Climate Change (IPCC), maintaining average global temperature rise within 1.5°C by 2030 is a far safer limit than 2°C because going beyond 1.5°C would have catastrophic results.

The key to limiting the temperature increase to 1.5°C within such a short timeframe is to destabilize the fossil fuel regime and accelerate the low-carbon systemic transformation. Disruptive low-carbon innovations are innovations that can result in reduction of fossil fuel consumption and greenhouse gas (GHG) emissions, which can speed up large-scale systemic transformation. However, the majority of existing low-carbon innovations are incremental not disruptive and the percentage of innovations that can be diffused into the mass market is only one third of total. In addition, current literature focuses on the supply-side innovations. However, compared to energy supply-side innovations, efficient demand-side technology innovations have higher social returns on investments according to large-scale modeling studies and larger potential to contribute to GHG emission reductions.

This research, therefore has the purpose of identifying the factors that influence the disruptive potential of demand-side low-carbon innovations and exploring the diffusion of these disruptive innovations. Our research model is based on Clausen and Fichter's work. We use dissemination rate to measure the diffusion of innovations. We also introduced a new dependent variable: system innovations to investigate the disruptive potential of low-carbon innovations and their potential contribution to low-carbon systemic transitions.

We undertook desk research followed by two surveys and phone interviews to collect data for 132 demand-side low-carbon innovations. Our study is an important contribution to sustainability transitions research because it simultaneously analyzes multiple innovations across different sectors and policy domains.

The results of this research show that the average dissemination rate of demand-side low-carbon innovations is roughly 15%. 88% of these innovations have dissemination rate that are below 30%. Amongst all the demand-side low-carbon innovations, only 17% of them have disruptive potential to contribute to low-carbon energy transitions. The low dissemination rate and the low disruptive potential of demand-side low-carbon innovations are the results of lack of public assessable data, lack of attention and funding in the diffusion stage, insufficient support from policy instruments and neglect of democratization. Demand-side low-carbon innovations mostly focusing on energy efficiency also contribute to the low dissemination rate and low disruptive potential.

To expand the diffusion of innovations and increase the disruptive potential of low-carbon innovations, data transparency should be improved. Additionally, more efforts should be put in diffusion stage. Innovation-specific policy instruments should be deployed to support disruptive innovations in the diffusion stage. A consistent and aligned policy mix across policy domains should be implemented to facilitate the low-carbon energy transitions. On top of that, low-carbon innovations should not only focus on energy efficiency, but should also provide energy users with new attributes of convenience, comfort, autonomy and democratization.
Key Words: Low-carbon innovation; Demand-side; Diffusion; Low carbon-energy transition

Foreword

This section describes the nature and role of the research in fulfilling the requirements of the Master of Environmental Studies degree. My area of concentration focuses on learning about climate change mitigation and adaptation from the aspect of low-carbon energy transitions. My research topic is linked to this by exploring how to facilitate low-carbon energy transitions through the diffusion of low-carbon innovations.

My Major Paper allows me to incorporate my learning objectives, including energy system and low-carbon energy transition, energy-related climate change mitigation and adaptation and public engagement into a unique investigation of the diffusion of low-carbon innovations and how it can contribution to low-carbon energy transitions.

The first learning component, energy system and low-carbon energy transition, is satisfied by the major paper by its focus on facilitating low-carbon energy transitions and establishing a low-carbon energy system through diffusion of low-carbon innovations. This paper explores what are the factors that influence the low-carbon energy transitions and how to facilitate the low-carbon energy transitions through expanding the diffusion of demand-side low-carbon innovations and increasing the disruptive potential of these innovations.

The second learning component, energy-related climate change mitigation and adaptation, is satisfied by the potential approach discussed in this paper. Expanding the diffusion of disruptive demand-side low-carbon innovations plays a critical role in facilitating low-carbon energy transitions, which will also contribute to climate change mitigation and adaption by reducing carbon emissions. Much of the paper is spent detailing the factors that influence the the disruptive potential of demand-side low-carbon innovations to contribute to low-carbon energy transitions and the diffusion of these innovations. To gain a solid understanding of these demand-side low-carbon innovations, surveys, desk researches and phone interviews are conducted during the study.

The final learning component, public engagement, is satisfied by constructing and assessing the independent variable *democratization*. Democratization is defined as the transfer of ownership and control of energy resources from incumbents to communities and/or individuals. Being energy users is one of the most common but significant role that the public can play in the energy sector. Energy citizenship emphasizes the role of individuals as active participants, rather than passive stakeholders. Energy users can play multiple roles in different transition phases, including innovators, legitimators, intermediaries and consumers. All of these contribute to my understanding of public engagement.

Overall, this major research paper is the culmination of these learning components. Through this major paper, I expand my knowledge of the demand-side low-carbon innovations and their diffusion, low-carbon energy transitions and public engagement, which are all important components of climate change mitigation and adaptation pathways to limiting global warming by 1.5°C.

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1 Introduction

1.1 Overview

According to the Intergovernmental Panel on Climate Change (IPCC), maintaining average global temperature rise within 1.5°C by 2030 is a far safer limit than 2°C because going beyond 1.5°C would have catastrophic results (IPCC 2018). A temperature increase of 1.5°C compared to 2°C greatly limits the risk of extreme weather events, sea-level rise, coral reef loss, and loss of water availability and agricultural yields (Schleussner, et al., 2016). However, the challenge to limit global warming by 1.5°C is very ambitious because it implies that we have to achieve net zero CO_2 emissions globally by around 2050 (IPCC, 2018).

The key to limiting the temperature increase to 1.5°C within such a short timeframe is to destabilize the incumbent fossil fuel regime and accelerate the low-carbon energy transition (Schot, Kanger, & Verbong, 2016). The low-carbon energy transition refers to a wide-ranging and long-lasting shift from one socio-technical regime to another, resulting in the establishment of a low-carbon energy system (Schot, Kanger, & Verbong, 2016).

Disruptive low-carbon innovations are innovations that can result in reduction of fossil fuel consumption and greenhouse gas (GHG) emissions, which can contribute to large-scale systemic transformation (Johnstone et al., 2020). Therefore, disruptive low-carbon innovations should play a significant role in the formation of a low-carbon energy system. However, due to carbon lock-in effects, most innovations in the ETIS are more likely to be incremental or reinforcing (Geels et al., 2018). Incremental innovations can offer improved cost-benefits to consumers in the existing markets but can not provide novel attributes to the socio-technical system (Dixon et al., 2018).

Low-carbon innovations can be either supply-side or demand-side. Supply-side innovations are aimed at improving the process of extracting, processing, transporting and converting energy resources into a useful form to the energy users (Wilson et al., 2012). Demand-side innovations are aimed at achieving low-carbon energy transition through uptake of advanced technologies or changes in energy users' behavior and practices (Mundaca, Ürge-Vorsatz, & Wilson, 2019). Compared to supply-side innovations, efficient demand-side innovations have large potential of contributing to more GHG emission reductions and higher social returns on investments (Wilson et al., 2012). Therefore, more efforts should be put in developing the efficient demand-side low-carbon innovations and encouraging the diffusion of these innovations (Wilson et al., 2012).

The Energy Technology Innovation System (ETIS) is a systemic framework of low-carbon innovations, which can be used to better understand the role of a wide range of actors, institutions, and networks in supporting the research, development, demonstration, market formation and diffusion of the innovations (Gallagher et al., 2012; Jordaan et al., 2017). Innovations developed in the ETIS are aimed at encouraging sustainable development, reducing GHG emissions or improving energy efficiency. At the first three stages of the innovation system, both public sector and private sector play an important role in advancing innovations by providing funding (Jordaan et al., 2017). However, at the market formation stage and diffusion stage, the public sector and private sector usually take different strategies to increase the market demand. The public sector usually implements carbon regulations and standards or subsidize uptake of innovations, while the private sector focuses on providing knowledge, data and insights for the innovations (Jordaan et al., 2017).

The diffusion stage is a process that innovation is communicated through certain channels among members of a social system over time (Karakaya, Hidalgo, & Nuur, 2014). Therefore, the diffusion of innovations is an essential component of ETIS. However, current research is focused on the earlier stages of low-carbon innovations and overlooks diffusion stage (Jordaan et al., 2017). In addition, the percentage of low-carbon innovations that can be diffused into the mass market is only one third of the total due to the lack of attention and investment from both public and private sectors (Fichter and Clausen, 2016; Jordaan et al., 2017).

To fill in the research gaps mentioned above, this research intends to identify the factors that influence the disruptive potential of these demand-side low-carbon innovations and the diffusion of these innovations. The research questions are as follows:

- What are the factors that influence the disruptive potential of demand-side low-carbon innovations that can contribute to low-carbon energy transitions?
- What are the factors that influence the diffusion of these demand-side low-carbon innovations?

1.2 Structure of Paper

To answer these questions, the second section is a literature review regarding demand-side low-carbon innovations, challenges and opportunities of low-carbon energy transitions, the role of ETIS in contributing to low-carbon energy transitions, especially the diffusion of demand-side low-carbon innovations. Theories of multi-level perspective (MLP) are also included in the literature review for better understanding of how demand-side low-carbon innovations can contribute to sustainability transitions. The literature review also summarizes the role of policy in sociotechnical regime change.

The methodology is then discussed in the third section. The methodology for the whole project will be briefly introduced at first. Next, my contribution to this research project is discussed in details, including developing and distributing surveys, gathering and coding data, and running inter-rater reliability analysis.

The results are reported in the forth section and further discussed in the fifth section. The last section will be conclusions and potential implications.

2 Literature Review

2.1 Demand-side Low-carbon Innovations

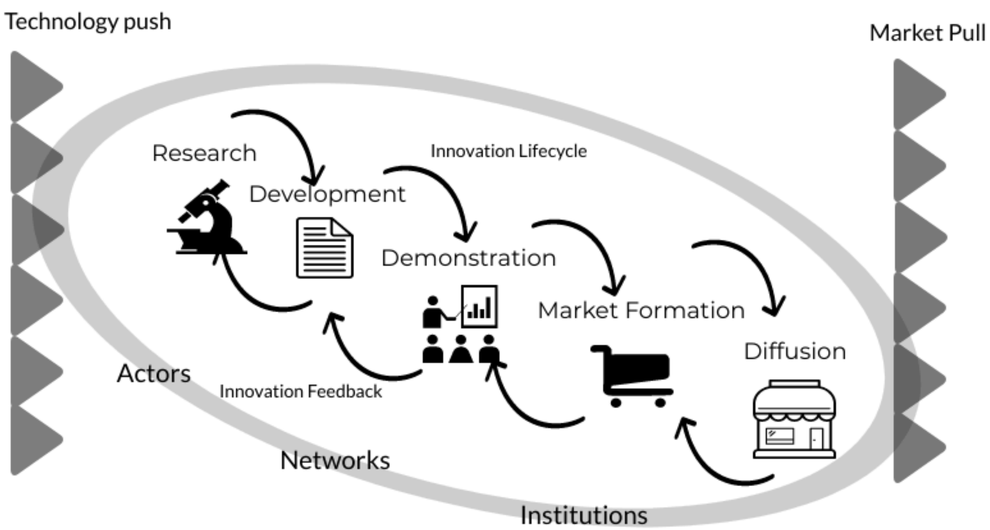
Demand-side low-carbon innovations refer to "new technologies, organizational arrangements and modes of behavior or social practices" that are targeted at improving energy efficiency and/or reducing energy demand through influencing technology choices, consumption, behavior and lifestyles, such as green financial products (Karakaya, Hidalgo & Nuur, 2014; Creutzig, et al., 2018; Geels, et al., 2018). Supply-side low-carbon innovations are aimed at improving the process of extracting, processing, transporting and converting energy resources into a useful form to the energy users (Wilson et al., 2012). Public institutions, financial resources and policies are more willing to support the development of energy-supply innovations in most cases (Wilson et al., 2012). The first reason for this support is that demand-side innovations are smaller-scale, more dispersed, and more diverse (Wilson et al., 2012). The second reason is that demand-side innovations cannot capture enough attention due to their small scale and low visibility (Wilson et al., 2012). The third reason is carbon lock-in, which is a typical case of path dependency. Path dependency is a significant problem that need to be solved by fostering transitions toward less-carbon-intensive emissions trajectories (Wilson et al., 2012; Seto et al., 2016). Fourthly, directed innovation efforts continue to reinforce the dominant influence of energy-supply industry (Wilson et al., 2012). Therefore, directed innovation efforts are misaligned with the need for emission reductions (Wilson et al., 2012).

However, compared to energy-supply innovations, efficient demand-side innovations have a wider range of benefits, including fewer environmental risks, larger potential of contributing to more GHG emission reductions and higher social returns on investments (Wilson et al., 2012; Creutzig et al., 2018). The reason why demand-side innovations have a wider range of benefits is that demand-side innovations are more closely associated with "synergistic co-benefits for health, pollution, security, equity, living standards, and system costs" (Mundaca, Ürge-Vorsatz & Wilson, 2019). Also, demand-side innovations encompass fewer risks than supply-side innovations because demand-side innovations can introduce "greater flexibility into the choice of energy-system transitions" (Mundaca, Ürge-Vorsatz & Wilson, 2019).

2.2 Energy Technology Innovation System

Shown in Figure 1, the Energy Technology Innovation System (ETIS) is a systemic framework of low-carbon innovations, which can be used to better understand the role of a wide range of actors, institutions, and networks in supporting the research, development, demonstration, market formation and diffusion of the innovations (Gallagher et al., 2012; Jordaan et al., 2017).

Figure 1: Energy technology innovation system



Note: this figure is adapted from figure 1 the evolution of thinking on innovation processes, from Gallagher et al., 2012

Technology, energy users, policy and institutions usually co-evolve in a low-carbon transition (Geels, et al. 2018). To accelerate the shift to a low-carbon energy system, transitions in all aspects of the ETIS are required, including the physical, technological, social, economic, political and institutional aspects. Three key drivers of energy technology innovations are knowledge and learning, economies of scale, and the roles of actors and institutions (Gallagher et al., 2012). The creation of new knowledge is an important driver of innovations, and the process of learning is an essential way to improve technology innovations (Gallagher et al., 2012; Jordaan et al., 2017). Therefore, funding from public and private sectors directed towards technology innovation usually functions as a technology push in the stages of research, development and demonstration. Public or private investments in the first three stages will support the supply of the innovations, such as reducing the cost of innovations or improve the relative advantage of innovations in the market (Wilson et al., 2012). Investments in the latter two stages, market formation and diffusion, usually function as market or demand pull, which means these investments can increase the demand for low-carbon innovations by creating a new market or encouraging the uptake of these innovations (Jordaan et al., 2017). When unit size or production increases, unit costs will decrease, which indicates that the scaling-up of low-carbon innovations will encourage the availability of these innovations (Gallagher et al., 2012).

Actors, networks and institutions strongly influence the ETIS, especially when the innovation system becomes more mature (Gallagher et al., 2012). Innovation intermediaries are those actors or institutions that can facilitate skill development and knowledge diffusion by connecting and mediating between stakeholders (Bush et al., 2017). Innovation intermediary usually plays a pro-active role in an ETIS. From the economic perspective, innovation intermediaries can activate network relationships, which can reduce investment and managing costs (Abbate & Coppolino, 2012; Bush et al., 2017). In the environmental dimension, these brokers can propose a sustainable plan for firms to face competitive challenges (Abbate & Coppolino, 2012). From a social point of view, innovation intermediaries can facilitate the knowledge diffusion in two ways: they can help firms get access to the innovative solutions and they can help sell the ideas (Abbate & Coppolino, 2012; Bush et al., 2017).

There are three major research gaps identified in ETIS studies: innovation diffusion, demand-side innovations, and actor-level assessment. Firstly, studies on ETIS often focus on the research and development stages of low-carbon innovations rather than innovation diffusion (Karakaya, Hidalgo, & Nuur, 2014; Jordaan et al., 2017). However, the major problem with the ETIS exists in the diffusion stage. Only one third of innovations is observed to be diffused into the mass market (Jordaan et al., 2017). Thus, more research is needed to examine the diffusion of demand-side low-carbon innovations, such as analyzing the relative importance of different factors that influence the diffusion of innovations (Karakaya, Hidalgo, & Nuur, 2014).

The second gap mentioned in Mundaca et al. (2019) is that most research on climate change mitigation have analyzed the supply-side solutions such as integrated Assessment Models, which emphasize supply-side technologies and carbon dioxide removal options. However, supply-side solutions may not always result in climate change mitigation without sufficient measures and research. Social and cultural norms can cause issues towards the implementation and adoption of renewable energy sources. Thus, it is suggested that more research can be conducted to assess the demand-side of ETIS in a broader analytical framework (Creutzig et al., 2016). For example, we can examine how is the diffusion of demand-side low-carbon innovations.

System-level studies attract more attention while actor-level research is ignored, which results in the third gap (Mignon & Bergek, 2016). More research should be conducted to analyze the role of actors in low-carbon energy transitions.

2.3 Diffusion of Low-carbon Innovations

Diffusion of low-carbon innovations refers to a process in which innovation is communicated through certain channels among members of a social system over time (Karakaya, Hidalgo, & Nuur, 2014). The diffusion of low-carbon innovations comprises four essential elements: innovation (an idea or practice), communication channel, time, and social system (Karakaya, Hidalgo, & Nuur, 2014).

The diffusion of disruptive innovations can result in significant improvements in environmental sustainability through stimulating the whole industries (Perez, 2010; Johnstone et al., 2020). In the past decades, many environmental products and energy services have been developed. However, only one third of them have a chance to be diffused into the mass market (Jordaan et al., 2017). The major problem existing in the ETIS, therefore, is not the research or development of environmental innovation, but the lack of diffusion (Clausen and Fichter, 2019).

The rationale behind the slow diffusion of innovations is that these innovations are usually not compatible with the existing "basic architecture of the socio-technical system". (Kemp et al., 1998; Geels, 2014) For example, it is highly possible that the adoption of these new innovations requires customers to change their behaviors.

Clausen and Fichter (2019) conducted a cross-sector analysis of the factors that influence the diffusion of low-carbon demand-side innovations in Germany. Their model is the first of its kind and is an important contribution to sustainability transitions research because it simultaneously analyzes multiple innovations across different sectors and policy domains. Their research was based on 130 case studies in Germany The cluster analysis model developed by Clausen and Fichter (2019) was applied to explore the diffusion processes of environmental product and service innovations. Five clusters are created: (1) product-related factors; (2) adopter-related factors; (3) supplier-related factors; (4) sector-related factors and (5) policy-related factors (Clausen & Fichter, 2019). Although Clausen and Fichter summarized 22 key factors that drive or hinder the diffusion of environmental product and service innovations, they failed to precisely describe the impacts of these innovations on low-carbon energy transitions. Our research is aimed at filling in this gap.

2.4 Sustainability Transition and Multi-Level Perspective

Sustainability transition refers to a wide-ranging and long-lasting shift from one socio-technical regime to another, resulting in the establishment of a low-carbon energy system (Schot, Kanger, & Verbong, 2016). Literature regarding sustainability transitions emphasizes the importance of multi-level perspective (MLP) in understanding how demand-side low-carbon innovations can contribute to sustainability transition (Loorbach et al., 2017). The MLP theory distinguishes three analytical levels. The first level is niche innovations, which refer to new technologies, new behavior practices or new business models that are vulnerable in the mainstream market (Geels et al., 2018). Niches usually function as incubation rooms to protect these low-carbon innovations, such as particular applications, geographical areas, markets or subsidized programs (Geels et al., 2018).

The second level is sociotechnical regime, which is “an interdependent mix of technologies, industries, supply chains, consumption patterns, policies, and infrastructure” (Geels et al., 2018). The fossil fuel regime remains locked-in due to the complex network of infrastructural, institutional, technological and behavioral systems that support the continued use of carbon-intensive innovations, which act as major barriers to the adoption and diffusion of alternative low-carbon innovations (Unruh, 2000; Seto et al., 2016). These interlocking systemic forces contribute to the generation of sociotechnical and policy inertia that support the incumbent regime and impede the development of alternative low-carbon innovations. In addition, the actors who benefit from existing sociotechnical regime will also advocate policies and regulations that support their interests and therefore reinforce the existing regime.

Due to carbon lock-in effects, most innovations in the ETIS are more likely to be incremental or reinforcing (Geels et al., 2018). Incremental innovations can offer improved cost-benefits to consumers in the existing markets but can not provide novel attributes to the socio-technical system (Dixon et al., 2018). Reinforcing innovations are typically path-dependent, aimed at stabilizing and strengthening the incumbent socio-technical system by perpetuating system-reinforcing characteristics, such as operating under existing regulations in the established regime or preserving behavior routines that support the incumbent regime (Geels et al., 2018).

The third level is sociotechnical landscape, which is “an exogenous environment beyond the direct influence of niche and regime actors” (Geels et al., 2018). The change of sociotechnical landscape is gradual and slow, which is often the result of changes in “cultural preference, demographics, and macro-political developments” (Geels et al., 2018).

Therefore, sustainability transitions literature highlights the importance of disruptive innovations, who have the ability to disrupt the established sociotechnical regime and create socio-technical landscape changes, including introducing new social norms and political beliefs, involving new actors in the ETIS and establishing new regulations (Johnstone et al., 2020). The “basic architecture of the sociotechnical system” is comprised of technology and innovations, ownership and actors, markets and business models, policy and regulations (Johnstone et al., 2020).

The degree of regime destruction is determined by whether there are more or less profound changes in the “basic architecture of the sociotechnical system”. (Geels, 2014) According to Wilson (2018), disruptive innovations have the potential to contribute to regime destructions because they can create a new market with a new set of demands and preferences, which can change the “basic architecture of the socio-technical system” and facilitate large-scale systemic transformations.

There are 13 important and contentious areas of research that are identified in transition research (Geels, et al., 2018). Five areas of research are identified in terms of the urgency of low carbon innovations: the relative role of outsiders and incumbents, the scalability of niche-innovations, place and geography, the economic and business dimensions of niche innovations and changing user practices (Geels, et al., 2018).

Three pressing areas of research regarding the diffusion of low carbon innovation are summarized in the following questions: “how does the multi-level perspective analysis relate to diffusion models? How does systemic innovation diffuse across space and over time? And how can diffusion be accelerated?” (Geels, et al., 2018).

Three further debates are proposed concerning the impact of low carbon innovations on energy demand. The first debate is about the rebound effect. Second, there is a critical debate on the construction of impact scenarios (Geels, et al., 2018). The last debate is about the use of quantitative modeling tools to predict the future impacts and feasibility of sociotechnical transitions (Geels, et al., 2018).

Two debates that cross all three themes of emergence, diffusion and impact are also identified. The first debate is on how impacts of low-carbon innovations are co-constructed in the early stage of innovation systems (Geels, et al., 2018). The second debate is about the influence of policy and governance on the emergence, diffusion and impacts of low-carbon innovations (Geels, et al., 2018). Some of the debates will be discussed in this study.

2.5 The Role of Policy in Sociotechnical Regime Change

There is a wide range of factors that can influence the sociotechnical regime change through the diffusion of disruptive demand-side low-carbon innovations. Policy is an important one among these factors. The transition management literature argues that policy instruments have significant impacts on the diffusion of disruptive innovations because policy instruments have the ability to embed new practices in the existing sociotechnical regime and also put pressure on the incumbent regime (van den Bergh et al., 2006; Kivimaa & Kern, 2016; Seto et al., 2016).

Policy instruments can be broadly divided into three major types: (1) economic, (2) regulatory, and (3) informational and educational (Weimer & Vining, 1992). Economic policies and regulatory policies are mostly control policies. These policies are intended to challenge the existing social practices (Seto et al., 2016). Control policies can contribute to both creating and developing niche innovations as well destabilizing the existing regime because control policies can help to create an "extended level playing field" for niche innovations and incumbent technologies to be competitive on fair market through internalizing the environmental costs of carbon emissions. (van den Bergh et al., 2006). Control policies include policies that using economic instruments to put pressure on the regimes, such as pollution taxes, carbon trading or road pricing. Control policies also include regulatory instruments, such as banning certain technologies or implementing import restrictions and regulations (Kivimaa & Kern, 2016). Regulatory policy instrument is important in sociotechnical regime change because the implementation of regulatory instruments can ensure the low-carbon innovations are disruptive in a way that reduce carbon emissions and increase social welfare (Wilson & Tyfield, 2018).

Besides control policies, informational and educational policies also play an important role in supporting the sociotechnical regime change. Informational and educational policies that targeted at facilitating knowledge creation and diffusion are those policy interventions that can contribute to embedding new practices in the incumbent sociotechnical regime (Seto et al., 2016).. Compared to control policies that aimed at challenging the existing social practice, informational and educational policy interventions are argued to be more effective because they are intended to embedding new practices in the incumbent sociotechnical regime (Seto et al., 2016).

Policy instruments can also be divided to general policy and innovation-specific policy (Bergek et al., 2014). Compared to general policy instruments that provide general support to the whole industry, innovation-specific instruments – both control policy and informational and educational policy – are necessary to support disruptive innovations, from their early research and development, via market formation, to the critical diffusion stages. Without such innovation-specific policies to support niche innovation, regime change is not likely to occur (Elzen, Geels, & Green, 2004). A detailed comparison table of different types of policy instruments can be found in Table A1 in Appendix.

3 Methods

The unit of analysis of this research is demand-side low-carbon innovations. The objective of this research is to investigate the factors that influence the disruptive potential of these innovations, the diffusion of low-carbon innvoations, and how they can contribute to low-carbon energy transitions. These innovations were identified through desk research, a survey of experts, who were identified through four policy domains, and a survey of the organizations that offer these innovations.

The methodology for the entire project will be briefly described in section 3.1. *Methods for the entire project*. Then, the specific methods relevant to my contribution to this project will be elaborated in section 3.2 *Data collection,* section 3.3. *Data coding and section* 3.4 *Application of the coding framework.* Prior to my arrival to this project in May 2019, 132 innovations were identified through desk research and the first survey. My work has been focused on developing, programming and distributing the second survey to organizations that offer innovations; developing the coding scale system based on the literature; coding half of the low-carbon demand-side innovations; running inter-rater reliability analysis and building analytical models in the Summer and Fall 2020.

3.1 Methods for the Entire Project

To better understand the demand-side low-carbon innovations, and the diffusion of these innovations in Ontario, Christina Hoicka, Runa Das, Jenny Lieu, Susan Morrissey Wyse, Maria-Louise McMaster and I have been working together to investigate this issue. This project was initially funded by SSHRC Insight Development Grant. The research was continued with internal funds from Faculty of Environment Studies, and the grant that Maria-Louise McMaster and I won from Smart Prosperity Institute (https://institute.smartprosperity.ca/). My major research paper is part of this big project.

3.1.1 Research Prior to My Arrival

To answer the research question, the first step was to identify what are the demand-side low-carbon innovations that are currently available in Ontario. Therefore, the first task of this research project is to conduct desk research across policy domains and identify low-carbon demand-side innovations that are currently available or under development in Ontario and have the ability to contribute to the low-carbon energy transition. Four policy domains were identified as relevant domains in this research, including (1) energy policy; (2) environment and climate change policy; (3) science, technology, and industrial innovation policy; and (4) social enterprise and innovation strategy. Policy documents within these policy domains were collected and reviewed for relevant policies, actions, experts, mechanisms and desired outcomes. During this process, 475 experts were identified across different policy domains and a list of individual contacts in organizations were developed.

A semi-structured survey was then sent to these experts between March and November 2017. The aim of this first survey was to identify the demand-side low-carbon innovations that have the potential to have a significant impact on the transition to low-carbon energy system in Ontario. The first survey received 136 responses, a 25% response rate. 90 low-carbon demand-side innovations were identified via the first survey. Meanwhile, 32 low-carbon demand-side innovations were identified via desk research.

3.1.2 Research I Conducted

A second survey was then circulated between June and October 2019 to gain a deeper understanding of these 90 low-carbon demand-side innovations identified in the first survey. Participants were also allowed to identify any new innovations. After gathering 68 responses from the second survey, we identified 10 new innovations. A total of 132 demand-side low-carbon innovations were identified through desk research and two surveys. However, uptake data of 54 services in our dataset of innovations were still lacking. Therefore, phone interviews and desk research were also conducted to collect the uptake data.

In the meantime, the coding scale system was created in order to explore what are the factors that influence the disruptive potential of demand-side low-carbon innovations.

3.1.3 Next Steps

After coding the sample of 132 low-carbon demand-side innovations for dissemination rate and system innovation, statistic models will be built to run the data analysis in the Summer and Fall 2020.

3.2 Data Collection

The dataset is existing when I came to this project, which includes 119 innovations identified by first survey and 50 innovations identified through desk research. Among these innovations identified through survey 1, a total of 90 innovations was identified as low-carbon demand-side innovations. Besides 7 innovations outside the research scope and 10 overlapped with innovations identified through survey 1, a total of 32 low-carbon demand-side innovation was identified through desk research. Detailed information can be found in Table 1.

Table 1 Status of innovations

Status	Survey 1	Desk Research
Active	69	15
Discontinued	21	18
Not yet an innovation	8	/
Insufficient information provided by respondents to identify the innovation	7	/
Outside the research scope	14	7
Overlap	10	
Total	119	50

However, the characteristics of these 90 demand-side low-carbon innovations identified through first survey were still lacking. A second survey was circulated between June and October 2019 to gain a deeper understanding of the characteristics of these 90 low-carbon demand-side innovations, such as the uptake data, the characteristics of end-users and the type of stakeholders involved.

My first task in this research project is to develop and distribute the second survey. The second survey was sent to 90 individuals and 4 networks identified in the previous survey. It was also distributed via social media networks, i.e. LinkedIn. Within the survey, participants were asked to provide details of a low-carbon demand-side innovation offered by their organization, such as the update data.

We got 68 responses in total in the second survey. After gathering all the data from survey 1 and survey 2, the uptake data of 54 services are still lacking. Therefore, phone interviews and desk research are also undertaken to gather more uptake data.

3.3 Data Coding

Developing the coding scale system for system innovation and coding the demand-side low-carbon innovations was one of the most challenging work in this project. In section 3.3.1 *Summary of the codebook*, the complete codebook of the system innovation will be briefly introduced. Then, my contribution to developing the codebook will be discussed in detail in section 3.3.2 *Establishment of coding framework*. Section 3.3.3 *Application of the coding scale system* is regarding the application of the coding scaling system into assessing the level of disruptive potential of low-carbon innovations. The final section 3.3.4 *Inter-rater reliability* is focused on how to ensure inter-rater reliability during the process of coding.

3.3.1 Summary of the Codebook

Four dependent variables, the "dissemination rate", "system innovations", "energy justice" and "pro-environmental behavior" of demand-side low-carbon innovations were measured in the research project in order to answer the research questions. Each dependent variable comprised multiple independent variables. This paper exclusively discussed the "dissemination rate" and "system innovations" as these were what my research focused on.

3.3.1.1 Dissemination Rate

Based on the literature review, especially the study conducted by Clausen and Fichter (2019), "dissemination rate" was chosen as the first dependent variable to measure the diffusion of a demand-side low-carbon innovation because it is the most straightforward way to show the state of market diffusion for each innovation. The formula to calculate the dissemination rate is:

$$Dissemination\ Rate = \frac{Uptake\ of\ the\ \ innovations}{Population\ size\ of the\ reference\ market}$$

To determine the dissemination rate, desk research, two surveys and phone interviews were undertaken to collect the necessary data on the number of users of each demand-side low-carbon innovation and data on the population size of the reference market which is needed to calculate the dissemination rate.

3.3.1.2 Level of System Innovation

Based on the theory of disruptive innovations and sustainability transitions, we also constructed a new dependent variable “system innovation”, to explore the potential of an innovation that can contribute to low-carbon energy transitions. We decided to construct this new dependent variable because these dependent variables constructed by Clausen and Fichter, found in the literature review, cannot precisely describe the impacts of these innovations on sustainability transitions. Dissemination rate can indicate the diffusion rate of innovations, while diffusion dynamics can measure the theoretical diffusion potential of innovations (Clausen & Fichter, 2019). However, the construction of “system innovation” allowed us to further explore the influence of these innovations on sustainability transitions. The detailed information of the coding scale system for the system innovation can be found in Table A2 in Appendix.

“System innovation” can be an indicator of the theoretical ability of an innovation that can contribute to the low-carbon energy transition. The “system innovation” variable is the sum of the values coded for eight independent variables for each demand-side low-carbon innovation. The eight independent variables for the “system innovation” were constructed based on the literature. The eight selected independent variables are (1) fossil fuel regime change; (2) decentralization; (3) democratization; (4) policy for scale-up through regulations;

(5) policy for scale-up through economic instruments; (6) policy for scale-up through informational and education instruments; (7) legitimacy through positive discourse framing; and (8) legitimacy through actors. The theoretical ability of an innovation to contribute to low-carbon energy transition was hypothesized to be higher if all independent variables have higher values.

Prior to developing the coding scale tables for each independent variable, we firstly created a scale table for the disruption or regime reinforcement. This coding table was created based on sustainability transitions literature.

Table 2 Scale of disruption or regime reinforcement

Scale	Definition	Literature
-2	The product/service *strongly* reinforces and strengthens the incumbent regime and sustains the existing carbon-intensive technological paradigms.	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	The product/service slightly reinforces the carbon-intensive incumbent regime and sustains the existing technological paradigms.	
0	No change/no effect/ unknown effect on the established regime.	
1	Incremental innovations offer improved cost-benefits to consumers for products/services in already established markets (Dixon et al., 2018). These innovations do not offer novel attributes to the socio-technical system.	
2	Disruptive innovations provide new features (attributes) to products/services that disrupt the existing technological paradigm (Dixon et al., 2018,; Wilson, 2018) and the "innovations stimulate whole industries" (Perez, 2010) and "strong interconnectedness and interdependence of the participating systems in their technologies and markets.	

The purpose of creating this table is to establish a standardized assessment of innovations' ability to contribute to low-carbon energy transition. When we create other coding scale tables, this one was used as an overarching criteria to ensure the reliability and consistency of the whole coding system. Therefore, the coding scale for eight independent variables are also 5-

point scales (-2 to +2). This coding scale system of "system innovations", which comprised of eight coding scale tables, can be utilized as a standardized method to assess the potential of each innovation that can contribute to low-carbon energy transitions.

My major contribution to the codebook development are focused on creating coding scale tables for independent variables: (1) fossil fuel regime change; (4) policy for scale-up through regulations; (5) policy for scale-up through economic instruments; and (6) policy for scale-up through informational and educational instruments. The following sections will present the coding scale tables for these four independent variables based on the theory of disruptive innovations and sustainability transition.

3.3.2 Establishment of Coding Scale System for System Innovation

3.3.2.1 Fossil Fuel Regime Change

Based on sustainability transitions literature, Table 3 was created as the coding scale table of fossil fuel regime change. Demand-side low-carbon innovations can either reinforce the incumbent fossil fuel regime and strengthen path-dependency or create the demand for a new regime, which can potentially lead to a system transformation and the destabilization of the existing fossil fuel regime (Seto et al., 2016; Unruh, 2000).

Table 3 Coding scale table for fossil fuel regime change

Scale	Definition	Examples
-2	Strongly reinforces the incumbent fossil fuel regime and strengthens path-dependencies: Creation of new demand for fossil fuels; Fuel switch from lower density to higher density carbon.	• Switch from electric heating to fossil fuel heating • Switch from gas to coal or oil • Investments in fossil fuel
-1	Slightly reinforces fossil fuel regime and path dependencies: Fuel switch from higher density to lower density carbon; Higher efficiency replacement of fossil fuel use.	• Replace coal with gas, oil with gas • More efficient furnace, car

0	No detectable change/ no effect/ unknown effect on the established fossil fuel regime.	Continued path dependency of carbon lock-in.
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.	• Removal of fossil fuel use • improvement of building envelope to reduce heat losses • Divestment from fossil fuels (with some or none investment in renewable energy) • Invest in renewable energy (without divestment)
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 *and* contributes to system building of renewable energy/no-carbon.	• Electric vehicle is a fuel switch away from fossil fuel, and has potential to support additional renewable energy • Fuel switch to hydrogen, electricity, conservation, renewables, ground source heat pump • Large divestment from fossil fuel and invest in renewable energy

3.3.2.2 Policy for Scale-up

Based on the literature review regarding sustainability transitions, policy was selected as one of the independent variables for system innovation because policy instruments have the ability to embed new practices in the existing sociotechnical regime and also put pressure on the incumbent regime (van den Bergh et al., 2006; Seto et al., 2016). Policy was originally constructed as a single independent variable under system innovation. However, this independent variable itself is complicated and vague. In order to figure out the impacts of different types of policy instruments on scaling up these demand-side low-carbon innovations, policy instruments are divided into three major types: (1) economic instruments, (2) regulations, and (3) informational and educational instruments.

3.3.2.3 Policy for Scale-up through Regulatory Instruments

Table 4 shows the coding scale for policy for scale-up: regulatory instruments. Regulatory instruments refer to regulations that deal with setting standards, prohibiting or granting permissions, and establishing regulations to enforce certain behaviors (Weimer & Vining, 1992)

Table 4 Coding scale table for policy for scale-up through regulatory instruments

Scale	**Code**	**Examples**
-2	Significantly weaken the low-carbon innovation: Removal of innovation-specific regulatory instruments that has impact on diffusion of innovations, (Bergek et al., 2014), or polices that strongly contradicts the promotion of innovations (Lieu et al., 2018).	• Lower the technology-specific standards and requirements • Create significant regulatory barriers to promote low carbon innovation such as too many restrictions on the innovations or high taxation excessive monitoring and control or taxation
-1	Slightly weaken the innovation: Removal of general regulatory policy instruments that have impacts on diffusion of innovations (Bergek et al., 2014 or polices that slightly contradicts the promotion of innovations (Lieu et al., 2018)).	• Abrupt removal or cancellation of a policy or eliminates support • Abrupt cancellation of feed-in tariff contracts • Planned removal of support--policy cap on programs, target. • Excessive monitoring obligation that create some hardship on innovating firms
0	No detectable change/no effect/ unknown effect on scale-up	no relevant or detectable policies
1	Promote innovation: Presence of general regulatory policy instruments have positive impact on innovations (Bergek et al., 2014).	• Policy instruments that provide general support, such as setting emissions target or cap on specific industry.
2	Strongly promotes innovations: Presence of technology specific regulatory instruments that has positive impact on innovations (Bergek et al., 2014).	• Setting higher standards and requirements for specific technology

3.3.2.4 Policy for Scale-up through Economic Instruments

Table 5 shows the coding scale table created for policy for scale-up through economic instruments. Some examples of economic instruments are economic incentives or cost internalization including charging users fees to internalize externalities and price goods and services appropriately (Weimer & Vining, 1992).

Table 5 Coding scale table for policy for scale-up through economic instruments

Scale	Definition	Examples
-2	Significantly weaken the low carbon innovations through removal of technology-specific economic instruments that has impacts on diffusion of innovations, (Bergek et al., 2014), or polices that strongly contradicts the promotion of innovations (Lieu et al., 2018).	• Cutting R&D funding for specific technology • Taxes placed on innovation technologies that increase its cost • Tax breaks for regime/fossil technologies
-1	Slightly weaken the low-carbon innovations through removal of general economic instruments that have impacts on diffusion of innovations (Bergek et al., 2014) or polices that slightly contradicts the promotion innovations (Lieu et al., 2018)).	• Abrupt removal or cancellation of a policy or eliminates support • Abrupt cancellation of feed-in tariffs contracts • Planned removal of support--policy cap on programs, target.
0	No detectable change/no effect/ unknown effect on scale-up	No relevant or detectable economic policies
1	Promote innovation through implementation of general economic instruments that have impact on diffusion of innovations (Bergek et al., 2014).	• Reducing tax on specific industry.
2	Promotes innovations through implementation of technology specific economic instruments that have impact on diffusion of innovations (Bergek et al., 2014).	• Providing R&D funding for specific technology, such as on solar panel

3.3.2.5 Policy for Scale-up through Knowledge Creation and Diffusion

Knowledge creation and diffusion are supported by informational or educational policies, such as information and education campaigns, media, and voluntary self-regulation (Weimer and Vining 1992). Table 6 shows the coding scale table for this type of policy instrument.

Table 6 Coding scale table for policy for scale-up through informational and educational instruments

Scale	Definition	Examples
-2	Strongly reinforcing regime: Removal of policies that strengthen the network that allow actors in the public and private sectors whose "activities and interactions initiate, import, modify and diffuse new knowledge" (Geels et al., 2018). Network weaknesses can hinder knowledge development because firms, institutions and networks will become 'locked in' to the 'old' technologies (Jacobsson & Bergek, 2011).	• Withdraw support for the establishment of supplier-user network and/or industry-academia network for low carbon innovations
-1	Slightly Reinforcing regime: Removal of policies that provide niche-level support for knowledge creation, such as R&D funding schemes(Kivimaa & Kern, 2016).	• Change R&D funding scheme that provide support for low carbon innovations
0	No impact on knowledge creation and diffusion	No relevant policies or no support for knowledge creation and diffusion
1	Incremental: Policy instruments provide niche-level support to complement or strengthen knowledge development (Jacobsson & Bergek, 2011) Presence of policies and activities that improve the knowledge creation and development	Government R&D funding allowing a broad search and knowledge development in the following areas: • Scientific • Technological • Production • Market • Logistics • Design (Kivimaa & Kern, 2016).
2	Disruptive: Policies aim to increase knowledge creation and diffusion through establishment of new networks (Kivimaa & Kern, 2016). With networks, different actors may interact effortlessly across large distances, exchange knowledge and thus increase	improving social, political and learning networks for knowledge diffusion • Create innovation platform to provide reference guidelines

	their contribution to upscaling (Meelen, Truffer, & Schwanen, 2019). Presence of policies and activities that support the establishment of new networks, which can contribute to the knowledge diffusion	for best available technology (Kivimaa & Kern, 2016). • Organizations emerged that aim at connecting local user initiatives (Feola & Butt, 2017)

3.3.3 Application of the Coding Scale System

A coding team was built to evaluate the eight independent variables for system innovation by assigning a value to each independent variables for each low-carbon demand-side innovation. The coding team comprised two researchers. These two researchers were responsible for coding 132 demand-side low-carbon innovations.

Before these two coders started to code independently, these two coders made an agreement on what source of information they would based on to make a decision. The innovation database was the major source of information. Other source of information included official websites of the innovations' providers, survey response, and other desk research. Information regarding the aim of innovation and innovation mechanisms was provided in the innovation database, which was used to determine the value of independent variables "fossil fuel regime change", "democratization" and "decentralization".

The innovation database also contained information about type of actors involved in developing, delivering, funding and using the innovations, which was useful for coding independent variables "legitimacy through positive discourse framing" and "legitimacy through actors". If these two coders need more detailed information to decide a value, they will retrieve the original survey response or search the official websites of the innovations' providers for more information.

All the implementation policies, mechanisms and activities that supported the innovation system for demand-side low-carbon innovations had been identified in a reference table and relevant documents had been stored for retrieval. This information was used as a reference when the two coders assigned a value to independent variables "policy for scale-up through economic instruments", "policy for scale-up through regulations" and "policy for scale-up through informational and educational instruments". Take CUTRIC Electric Buses for example. The aim of this CUTRIC Electric Buses project is to "design, develop, and integrate, battery-electric buses with charging systems that can operate interactively despite being made by different manufactures" (CUTRIC website). When assigning a value to independent variable "policy for scale-up through economic instruments" of innovation "CUTRIC Electric Buses", these two coders will go through the policies, mechanisms and activities outlined in the reference table to find whether there is a relevant economic instrument that is implemented to support the development and/or delivery of "CUTRIC Electric Buses". After identifying the presence of economic instruments that provided financial support targeted at low-carbon transportation, such as Electric Vehicle Charging Incentives, Electric Vehicle and Hybrid Vehicle Incentives and EV financing and rebate opportunities, the coder will retrieve the original documents for more detailed information about the economic instrument in order to make a final decision. In this case, the coder assigned value 1 to this independent variable "policy for scale-up through economic instruments". The value assigned was 1 instead of 2 was because these economic instruments were aimed at providing general economic support to the electric vehicle industry but not specifically for the development and/or diffusion of battery-electric buses with charging systems made by different manufactures. If there is any economic instrument that provides exclusive financial support to this specific type of innovation, then the value assigned to "policy for scale-up through economic instruments" will be 2.

Meetings were scheduled once a week for all six researchers to discuss the difficulties and derivations these two coders had in assigning a value to an independent variable. For example, when coding the "democratization" of education and capacity building program, one coder assigned the value 0 to the "democratization" because she cannot find the change in ownership or control that individuals and/or communities can gain through this program. Another coder assigned 1 to this independent variable because she believed that through this program, community and individuals can gain more control and/or gain more share in the ownership of energy projects. During the team meeting, six researchers discussed the question regarding whether this program offered the potential for increase in the control or ownership of energy projects. After the discussion, six researchers reached an agreement. All of them agreed that the education and capacity building program helped equip communities and individuals with knowledge and skills, which created more opportunities for the individuals and communities to participate in Ontario's energy sector, including participating in the generation and management of energy. Therefore, the final value assigned to the democratization of education and capacity building program was 1.

3.3.4 Inter-rater Reliability

In order to ensure that two coders assign the same value to the same innovation, we employed Cohen's Kappa statistic to ensure inter-rater reliability. Inter-rater reliability measures the extent to which members in the coding team assign the same value to the same variable (McHugh, 2012). In this study, two researchers are responsible for coding 132 demand-side low-carbon innovations. Therefore, ensuring inter-rater reliability is important because it is possible that two researchers may assign different values to the same variable. The Cohen's Kappa statistic is frequently used to indicate the inter-rater reliability (McHugh, 2012). The Cohen's Kappa statistic is hypothesized to be higher if two researchers had more agreement on the value assigned to the same variable. The Cohen's Kappa reference table can be found in Table 7, which demonstrates the six score range of Cohen's Kappa statistic and the degree to agree each of them represents.

Table 7 Cohen's Kappa reference table

Score Range	Degree to Agree
Less than or equal to 0	no agreement
0.01 – 0.20	none to slight
0.20 – 0.40	fair
0.41 – 0.60	moderate
0.61 – 0.80	substantial
0.81 – 1.00	almost perfect

This reference table was provided by Dr. Runa Das

To ensure the inter-rater reliability, a pre-test was conducted. During the pre-test, two researchers coded the same demand-side low-carbon innovations independently and then the Cohen's Kappa was calculated afterwards. The pre-test was undertaken three times. The rest of the team joined to discuss the derivations and strategies to improve the Kappa score after each round. The coding test continued to be conducted until the Kappa score for all the independent variables are close to or beyond 0.8, which indicates the inter-rater reliability is almost perfect. The results of Kappa score for each round can be found in Table 8.

Table 8 Results of Cohen's Kappa Calculation

Variable	1st round	2nd round	3rd round
Fossil Fuel regime change	0.467	0.528	0.818
Decentralization	0.368	0.455	1
Democratization	0.783	0.715	0.905
Policy for scale up through economic instruments	0.623	0.633	0.931
Policy for scale up through regulatory instruments	0.219	0.643	0.779
Policy for scale up through informational and educational instruments	0.405	0.706	0.891
Legitimacy through positive discourse framing	0.697	0.702	0.935
Legitimacy through actors	0.671	0.605	0.860

In the first round, two researchers coded the eight independent variables for 20 low-carbon demand-side innovations. The third researcher calculated the inter-rater reliability and the Kappa score for the first round was shown in Table 8. To improve the scores, we divided the independent variables into two types. For the Kappa score that is below 0.6 in the first round, two researchers read each other's journal of coding and recoded the 20 cases. For the score that was above 0.6, two researchers code 5 additional innovations. Then, the Kappa score was recalculated in the 2nd round.

In the second round, as the Kappa scores of variables "Fossil Fuel Regime Change" and "Decentralization" were still below 0.6: a meeting was scheduled to go through the logic for these variables carefully and in detail. The six researchers also discussed the specific innovations that two researchers had coded differently and went through these differences.

After the meeting, two researchers recoded these two independent variables for 20 innovations and also coded additional 5 innovations for these two independent variables. For independent variables whose score that are between 0.6-0.8, a comparison table was created to demonstrate all the specific innovations that were coded differently. Then, two researchers discussed the logic and information used for coding these innovations via email.

After the discussion between two researchers, they recoded the 25 innovations for independent variables: “Democratization”; “Policy for scale-up through economic instruments”; “Legitimacy through positive discourse framing”; “Legitimacy through actors” and recoded the 20 innovations for independent variables: “Policy for scale-up through regulatory instruments” and “Policy for scale-up through informational and educational instruments”. These two researchers also code additional 5 innovations for independent variables: “Policy for scale-up through regulatory instruments” and “Policy for scale-up through informational and educational instruments”. The Kappa score based on evaluating eight independent variables for 25 innovations were calculated for the third round. All the Kappa score for the eight variables close to or lie in the range 0.81-1.00, which indicates the inter-rater reliability is almost perfect. After these three rounds of coding tests, two researchers continued to code the rest of low-carbon demand-side innovations.

4 Results

4.1 Survey Response

Table 9 shows the breakdown of the type of stakeholders of the innovations that were coded. The average response rate of survey 1 is 20%, while the average response rate of survey 2 is 19%. The response rate of participants from nonprofit organizations (49%, 22%), universities (41%, 67%) and consultancy firms (35%, 50%) are higher than other types of stakeholders in both surveys.

Table 9 Survey response

	Survey 1			Survey 2		
Type of stakeholder	# of contacted individuals	# of individuals that completed the survey	Response Rate	# of contacted individuals	# of individuals that completed the survey	Response Rate
Incubator/ Accelerator	87	2	12%	3	3	100%
Government - First Nation	2	0	0	0	0	0
Government - Municipal	177	20	11%	9	1	11%
Government - Provincial	20	4	20%	13	1	8%
Government - Federal	11	2	18%	3	0	0
Nonprofit	65	32	49%	32	7	22%
University	22	9	41%	3	2	67%
Utility	90	7	8%	8	0	0
Consultancy	17	6	35%	4	2	50%
Conservation authority	3	1	33%	0	0	0
Think tank/ research institute	3	0	0	2	0	0
Regulator	9	0	0	0	0	0
Group/ Association/ Network	27	0	0	0	0	0
Private business	55	11	20%	13	1	8%
Total	475*	94	20%	90	17	19%

Note: * 475 is the exact number of individuals we contacted in the survey, but not the sum of contacted individuals of each type because the type of stakeholders is not exclusive to each other. Some individuals identified themselves as more than one type of stakeholders, which makes the sum of contacted individuals of each type larger than the exact number of individuals we contacted in the survey.

4.2 Innovation Dataset

The empirical data of this research includes 132 demand-side low-carbon innovations. 90 of them were identified through survey 1, 10 of them identified through survey 2, and 32 of them identified through desk research. Detailed information can be found in Table 10. Active innovations refer to innovations that are currently available in the market. Discontinued innovations refer to innovations that have been cancelled.

Table 10 Demand-side low-carbon innovations identified in desk research and surveys

Information Source	Number of innovations identified
Survey 1	69 active innovations
	21 discontinued innovations
Survey 2	9 active innovations
	1 discontinued innovations
Desk Research	14 active innovations
	18 discontinued innovations
Total	92 active innovations
	40 discontinued innovations

Table 11 shows the breakdowns of the aims of innovations that were coded. More than half (61%) of the innovations were aimed at improving energy efficiency. The next most common aim of innovation was retrofits/installations (31%). It is clear that demand-side low-carbon innovations with the aim of improving energy efficiency attract the most attention.

Table 11 Aim of innovation

Aim	Frequency	Percentage
Battery Storage	5	4%
Demand-side Management	29	22%
District Energy	2	2%
Electric Vehicles	9	7%
Electric Vehicle Charging Stations	5	4%
Energy Efficiency	80	61%
Local Energy Plans	7	5%

Micro-grid	2	2%
Natural gas infrastructure	1	1%
New construction	7	5%
Program design	1	1%
Public/ Shared/ Alternative transportation	7	5%
Renewable energy - location not specified	22	17%
Renewable energy - onsite	14	11%
Renewable energy - offsite	4	3%
Retrofits/ Installations	41	31%
Smart meters	6	5%
Submetering	1	1%
Total	132*	100%

Note: *132 is the exact number of innovations identified in desk research and surveys, but not the sum of innovations of each type of aim because the type of aim is not exclusive to each other. Some innovations have multiple aims, which makes the sum of innovations of each type of aim larger than the exact number of innovations identified in the desk research and surveys.

Table 12 shows the mechanisms deployed by each innovation. More than half (62%) of the innovations use information as their mechanisms. Material incentives (38%) are much more popular than non-material incentives (4%). Approximately 10% low-carbon innovations choose financing as their mechanisms.

Table 12 Mechanisms of low-carbon Innovations

Mechanisms		Frequency	Percentage
Incentives (Material)	Incentive - payment for electricity produced	8	6%
	Incentive - Grant	16	12%
	Incentive - pay per performance	1	1%
	Incentive - Rebate	19	14%
	Incentive - tax credit	4	3%
	Incentive - other/not specified	9	7%
	Incentive (ALL Material)	50	38%
Incentives (non-material)	Non-material	5	4%
Disincentive (material)	Disincentive - Price on carbon (cap and trade)	1	1%
Financing	Financing - bonds	4	3%
	Financing - Loans	4	3%
	Financing - Local Improvement Charges	4	3%
	Financing - on-bill	2	2%

	Financing - other/not specified	4	3%
	Financing (ALL)	13	10%
Information	Information - Audit	26	20%
	Information - Advancement of data	22	17%
	Information - Benchmarking	4	3%
	Information - Building a network	8	6%
	Information - Capacity-building, training, education	38	29%
	Information - Certification/Standard	7	5%
	Information - Lobbying	4	3%
	Information - Research	9	7%
	Information (ALL)	82	62%
Project	Demonstration project or Pilot Project	5	4%
Total		132*	100%

Note: * 132 is the exact number of innovations identified in desk research and surveys, but not the sum of innovations of each type of mechanism because the type of mechanism is not exclusive to each other. Some innovations have employed multiple mechanisms, which makes the sum of innovations of each type of mechanism larger than the exact number of innovations identified in the desk research and surveys.

Table 13 shows the frequency and percentage of different types of end-users of demand-side low-carbon innovations. Private business (48%) and households (42) are the most common end-users.

Table 13 Types of end-users of innovations

Type of end-users	Frequency	Percent
Building professionals	4	3%
Cooperatives	18	14%
Government - Federal	5	4%
Government - Municipal	27	20%
Government - Provincial	8	6%
Households (homeowners)	33	25%
Households - low income	10	8%
Households (tenant)	8	6%
Households (unspecified)	56	42%
Indigenous Communities	13	10%
Individuals	49	37%
Institutional	30	23%
MURBs	18	14%
Nonprofit	23	17%
Private businesses	64	48%
Utilities	7	5%
Industry	6	5%
Total	132*	100%

Note: * 132 is the exact number of innovations identified in desk research and surveys, but not the sum of innovations of each type of end-users because the type of end-users is not exclusive to each other. Some innovations are targeted at multiple end-users, which makes the sum of innovations of each type of end-users larger than the exact number of innovations identified in the desk research and surveys.

Table 14 shows the type of actors involved in developing, delivering and funding the demand-side low-carbon innovations. Provincial government (31%) and nonprofit organizations (29%) are the most active participants in the development of low-carbon innovations, followed by utilities (25%), private business (21%) and municipal government (20%). Roughly one fifth of the innovations is delivered by private business (22%) and/or nonprofit organizations (20%). Actors are not actively engaged in funding low-carbon innovations. Federal (12%), provincial (16%) and municipal governments (8%) are the major sources of funding flowing into the development and diffusion of these demand-side low-carbon innovations, which added up to 36% of the total funding.

Table 14 Types of actors involved in innovation creation and diffusion

Type of Actors	Developing		Delivering		Funding	
Cooperatives	8	6%	5	4%	0	0%
Government (federal)	20	15%	8	6%	16	12%
Government (municipal)	27	20%	11	8%	11	8%
Government (provincial)	41	31%	13	10%	21	16%
Households	6	5%	0	0%	0	0%
Indigenous communities	4	3%	0	0%	0	0%
Individuals	6	5%	0	0%	0	0%
Industry and industry associations	21	16%	4	3%	2	2%
Institutions (universities, colleges, and other academic institutions)	20	15%	5	4%	2	2%
Nonprofit organizations	38	29%	27	20%	8	6%
Private businesses	28	21%	29	22%	5	4%
Utilities	33	25%	20	15%	3	2%
Unknown	30	23%	10	8%	29	22%

4.3 Dissemination Rate

Table 15 is a summary table to show the dissemination rate of demand-side low-carbon innovations. The dissemination rate of 65 innovations were calculated. The dissemination rate of the rest 67 innovations can not be calculated due to the lack of data. The uptake data of 50 innovations and the population size of the reference market of 17 innovations were missing. The average dissemination rate of the demand-side low-carbon innovations is approximately 15%. The results show that the dissemination rate of the majority of innovations (88%) are below 30%. Only 9% of innovations have dissemination rate that is above 50%. Detailed information about the dissemination rate of the 65 innovations can be found in Table A3 *Dissemination rate of Demand-side low-carbon innovations* in Appendix A.

Table 15 Dissemination rate of demand-side low-carbon innovations

Dissemination rate range	Number of innovations	Percentage
Above 50%	6	9%
30%-50%	2	3%
Below 30%	57	88%
Total	65	100%

4.4 System Innovation

Table 16 shows the score for dependent variable "system innovation". The majority (80%) of the low-carbon innovations falls in the range [1,8], which indicates that the majority of the low-carbon innovations are incremental innovations, which have limited ability to contribute to system change. Only 17% of low-carbon innovations are disruptive. Table 16 provides the empirical evidence that the majority of demand-side low-carbon innovations in the market do not have the disruptive ability to contribute to low-carbon energy transitions.

Table 16 Score for system innovation

Type of Innovation	Range of score	Frequency	Percentage
Disruptive	[9,16]	23	17%
Incremental	[1,8]	105	80%
No impact	0	1	1%
Slightly reinforcing	[-8,-1]	3	2%
Strongly reinforcing	[-16,-9]	0	0%
Total	/	132	100%

Table 17 shows the total and average scores for eight independent variables of system innovation. Legitimacy through actors has the highest scores (total 203, average 1.54), followed by legitimacy through discourse framing (total 199, average 1.51). Independent variables policy for scale-up through informational and educational policy instruments (total 28, average 0.21), policy for scale-up through regulatory instruments (total 32, average 0.24) and democratization ((total 32, average 0.24) have the lowest scores.

Table 17 Score for independent variables of system innovation

Independent Variable	Total Score	Average Score
Fossil Fuel Regime Change	89	0.67
Decentralization	113	0.86
Democratization	32	0.24
Policy for scale-up through economic instruments	66	0.5
Policy for scale-up through regulatory instruments	32	0.24
Policy for scale-up through informational and educational policy instruments	28	0.21
Legitimacy through discourse framing	199	1.51
Legitimacy through actors	203	1.54

Table 18 indicates that more than half (52%) of the demand-side low-carbon innovations have incremental impacts on fossil fuel regime change but only 20% of these innovations have disruptive impact on the fossil fuel regime change.

Table 18 Coding results for fossil fuel regime change

Scale	Frequency	Percent
2:Disruptive	27	20%
1:Incremental	69	52%
0:No impact	3	2%
-1:Slightly reinforcing	32	24%
-2:Strongly reinforcing	1	1%
Total	132	100%

Table 19 through 21 shows the frequency and percentage that innovations are coded for policy for scale-up through regulations, economic instruments and informational and educational instruments. The following observations can be made. 76% of innovations are not supported by regulations and 77% of innovations are not supported by informational and educational policies. Although economic instruments are used the most frequently, only 49% innovations are supported by economic instruments.

Table 19 Coding results for policy for scale up through regulations

Scale	Frequency	Percent
2:Disruptive	8	6%
1:Incremental	21	16%
0:No impact	100	76%
-1:Slightly reinforcing	1	1%
-2:Strongly reinforcing	2	2%
Total	132	100%

Table 20 Coding results for policy for scale up through economic instruments

Scale	Frequency	Percent
2:Disruptive	16	12%
1:Incremental	49	37%
0:No impact	56	42%
-1:Slightly reinforcing	7	5%
-2:Strongly reinforcing	4	3%
Total	132	100%

Table 21 Coding results for policy for scale up through informational and educational instruments

Scale	Frequency	Percent
2:Disruptive	4	0
1:Incremental	23	2%
0:No impact	102	77%
-1:Slightly reinforcing	3	17%
-2:Strongly reinforcing	0	3%
Total	132	100%

Table 22 presents a comparison of the results coded for three types of policy instruments. Economic instruments are used the most frequently to support the development and diffusion of innovations, followed by regulations. Informational and educational policy instruments are implemented less frequently. Roughly 75% demand-side low-carbon innovations are not supported by any regulatory instruments or informational and educational instruments.

Table 22 Comparison of the frequency of three types of policies for scale up

Scale	Policy for scale up through regulations	Policy for scale up through economic instruments	Policy for scale up through informational and educational instruments
2:Disruptive	8	16	4
1:Incremental	21	49	23
0:No relevant policy	100	56	102
-1:Slightly reinforcing	1	7	3
-2:Strongly reinforcing	2	4	0

5 Discussion

5.1 Next Steps of Research

This paper discusses the results of desk research, survey responses and the coding stages of the project. The next step of this research is to build the statistical models. In the summer and fall of 2020, we will develop statistical models for analyzing the factors that influence the diffusion of low-carbon innovations to energy users in Ontario, and their disruptive potential to contribute to a low-carbon energy transition. The results of running statistic models will be reported in the working paper submitted for Smart Prosperity Clean Economy Working Paper Series.

5.2 Limitations in the Research Approach

The two objectives of this research are to investigate the factors that influence the disruptive potential of an innovation that can contribute to low-carbon energy transition and their diffusion to energy users. To do this, we have conducted interdisciplinary research by examining the “dissemination rate” and “system innovation” of demand-side low-carbon innovations in Ontario, using desk research, surveys and phone interviews.

Dissemination rate was chosen as the first dependent variable to show the diffusion status of an innovation. However, there are limitations to this analysis, such as the inability to access sufficient innovation uptake data , which is a key value in calculating the dissemination rate. Some of the uptake data were not publicly accessible through desk research, either because they are confidential or they were not collected by the innovations’ providers. For these reasons, the uptake data of 67 demand-side low-carbon innovations were not able to be calculated. Innovation providers and researchers of these low-carbon innovations have put extensive effort into the research, development and demonstration of the innovations, but have paid less attention to the market formation and diffusion of the innovations, which could explain the lack of uptake data.

The second limitation was the inability to identify the accurate population size of the reference market for certain diffusion cases. Take the Electricity Conservation and Automated Peak Saver innovation as an example. The target users of this innovation are households and small business. Although we were able to obtain the population data of households from the Ontario Energy Board, we could not find accurate information on the total number of small businesses in Ontario. We have to use the population size of commercial businesses instead. Due to the limitations of data access and availability, we were not able to calculate the dissemination rate for multiple innovations in the dataset. Nevertheless, we can still get a rough idea of the current status of low-carbon innovation diffusion in Ontario. This research is a starting point for future research on the diffusion of multiple demand-side low-carbon innovations. Future research should include more desk research, surveys and interviews to supplement the information we have gathered.

5.3 Research Findings

The objective of this study is to investigate the diffusion of demand-side low-carbon innovations and the factors that influence the disruptive potential of these demand-side low-carbon innovations to contribute to low-carbon energy transitions. Although there are some limitations of this research approach, the research questions can still be answered through this study.

Our findings demonstrate that the average dissemination rate of the demand-side low-carbon innovations is approximately 15%, which indicates that most of these innovations are not adopted by mainstream markets.

A wide range of factors can influence the disruptive potential of demand-side low-carbon innovations. The factors that influence the disruptive potential of low-carbon innovations have been summarized as eight independent variables in this study: "democratization"; "decentralization"; "policy for scale-up through regulations"; "policy for scale-up through economic instruments"; "policy for scale-up through informational and educational instruments", "legitimacy through positive discourse framing" and "legitimacy through actors".

According to the coding results shown in Table 17 in section 4.4 *System innovations*, “legitimacy through positive discourse framing” and “legitimacy through actors” contribute the most to facilitating system change, followed by “decentralization”. In contrast, “policy for scale-up through regulatory instruments”, “policy for scale-up through informational and educational instruments”, and “democratization” contribute the least to facilitating system change, which indicates that these factors should be improved. Key findings are elaborated in the following sections.

5.3.1 Low Dissemination Rate for Demand-Side Low-Carbon Innovations

Our findings demonstrate that the average dissemination rate of the demand-side low-carbon innovations is approximately 15%. Only 9% of these innovations have dissemination rate that is larger than 50%. The majority (88%) of the innovations have dissemination rates that are below 30%. Our findings provide the empirical evidence that demand-side innovations are marginalized and overlooked in the ETIS for climate protection (Wilson et al., 2012). There are four potential reasons behind the low rates of diffusion for demand-side low-carbon innovations, including lack of attention in the diffusion stage, lack of funding, lack of publicly available data, and energy efficiency dominated innovations.

One possible reason is that both public and private sector are focused on the research, development and demonstration stages of innovation, but do not pay enough attention to the market formation and diffusion of these low-carbon demand-side innovations. As Clausen and Fichter (2019) argued, the major problem with the ETIS is not the research or development of environmental innovation, but the low rates of diffusion.

The second reason is the lack of funding. The low rates of diffusion are usually caused by lack of investment in demand-side low-carbon innovations and in the diffusion stage. It was found by Jordaan et al. (2017) that investments are heavily weighted towards carbon-intensive technologies. In addition, both public sector and private sector prefer to support the early stages of ETIS, such as the implementation of carbon regulations, subsidizing research and development of innovations, and supporting laboratory research in universities (Jordaan et al., 2017). This causes a lack of funding focused on the market formation and diffusion stages of ETIS, which explains why the dissemination rate is low. On top of that, demand-side innovations are smaller in scale which make them less detectable and these innovations have more difficulty capturing the attention of investors (Wilson et al., 2012). Also, the demand-side low-carbon innovations are more dispersed and varied (Wilson et al., 2012). For example, energy efficiency can be traded-off against the style, comfortableness and convenience. This characteristic of demand-side low-carbon innovations will make the investors feel uncertain of choosing which innovation to invest.

The fourth possible reason for low rates of diffusion for demand-side low-carbon innovations is that the majority of the demand-side low-carbon innovations are targeted at improving energy efficiency. As presented in Table 11, 61% of the innovations are dedicated to improving energy efficiency. In most cases, however, energy efficiency is an invisible attribute of low-carbon innovations, which is less likely to incentivize energy users to purchase this innovation. Compared to energy efficiency, innovations with more visible attributes, such as convenience and comfort, are more welcomed by energy users because energy consumption is influenced by habitual behavior (Geels et al., 2014).

5.3.2 The Predominance of Incremental Innovations

The majority (80%) of the innovations falls within the range [1,8], which indicates that the majority of the demand-side low-carbon innovations are incremental. Only 17% of low-carbon innovations have the disruptive potential of contributing to a low-carbon energy transition. As discussed in section 2.4 *Sustainability transition and multi-level perspective*, incremental innovations have limited ability to change the "basic architecture of the sociotechnical regime", and therefore cannot make a significant contribution to energy systemic change (Johnstone et al., 2020). Theories of sustainability transitions emphasize the importance of disruptive innovations to facilitate large scale energy systemic transformations.

Eight independent variables were constructed in this study: "democratization"; "decentralization"; "policy for scale-up through regulations"; "policy for scale-up through economic instruments"; "policy for scale-up through informational and educational instruments", "legitimacy through positive discourse framing" and "legitimacy through actors". According to the coding results shown in Table 17 in section 4.4 *System innovations*, "legitimacy through positive discourse framing" and "legitimacy through actors" contribute the most to increase the ability of the low-carbon innovations to contribute to system change, followed by "decentralization". In contrast, "policy for scale-up through regulatory instruments", "policy for scale-up through informational and educational instruments", and "democratization" contribute the least to increase the ability of the low-carbon innovations to contribute to system change.

The legitimacy factor is highly important for the disruptive potential of demand-side low-carbon innovations. The degree of regime destruction is determined by whether there are profound changes in the "basic architecture of the sociotechnical system" (Geels, 2014). Among the factors that build the "basic architecture of the sociotechnical system", the legitimacy contributes the most to increase the ability of these low-carbon innovations to contribute to system transitions as presented in Table 17. Building the legitimacy of low-carbon innovations for system disruption requires positive discourse framing and visioning strategies by actors and institutions such as plans and reports (Duygan et al., 2019; Geels & Verhees, 2011; Ruef & Markard et al., 2010). It also requires the presence of actors with agency that facilitate the diffusion of low-carbon innovations across multiple scales (Schlaile et al., 2017; Duygan et al., 2019; Geels & Verhees, 2011). The high score of legitimacy's coding results shows that the presence of positive discourse framing and visioning strategies, and the presence of actors with agency have provided sufficient support for increasing the disruptive potential of these demand-side low-carbon innovations.

Decentralization ranks third highest out of eight independent variables of system innovation as shown in Table 17, which indicates that these low-carbon innovations have strong ability to contribute to the geographic decentralization from a currently centralized energy system. Energy generation tends to switch from centralization to distributed generation.

In this study, democratization is defined as the transfer of ownership and control of energy resources from incumbents to communities and/or individuals. When it ranked, the low score of democratization implies that energy resources are still firmly controlled by incumbents. Democratization is a key component of disruptive innovations because democratization can be "a political act of creating an opening that allows alternative forms of social relations to emerge and replace existing structures of domination with processes of self-determination" (Becker & Naumann, 2016). Energy citizenship is one way to democratize the energy systems as it emphasizes the role of individuals as active participants, rather than passive stakeholders (Devine-Wright, 2007). Thus, the disruptive potential of low-carbon innovations can be significantly increased by the transfer of ownership and control of energy resources from incumbent systems to communities and/or individuals.

Table 17 shows that policy instruments do not provide enough support for increasing the disruptive ability of demand-side low-carbon innovations, which will be discussed in a separate section 5.3.3.

Besides system innovation, another possible reason why the majority of innovations are considered incremental is because more than half (61%) of them are dedicated to improving energy efficiency. The literature states that low-carbon innovations designed for improving energy efficiency are predominately incremental innovations because they only improve the cost-benefits of the existing technologies instead of creating a new technology that creates a new market with a new set of demands and preference. Their sustainable transformative potential is therefore low. Improving the energy efficiency may even result in reinforcing the fossil fuel regime because the total energy consumption is not necessarily decreased. The energy users may use the product more frequently due to its energy efficiency, making the innovation counterproductive.

Overall, the data suggests that most demand-side low-carbon innovations are hardly considered disruptive innovations because they mostly focus on energy efficiency, they lack democratization, and there is a lack of support from policy for scale-up.

5.3.3 Comparison of Three Policy Instruments for Scale-up

As presented by Table 22 *Comparison of the frequency of three types of policies for scale up*, only half of the innovations are supported by economic instruments. This is a problem because economic policy instruments are one of the most effective way to make low-carbon innovations more competitive in the market as they can internalize environmental externalities (Weimer & Vining, 1992). Finding a market is the biggest challenge that most disruptive innovations encounter, more so than technological challenges. Implementing economic instruments therefore becomes extremely important since this type of policy can encourage market formation and innovation diffusion.

There is even less support for regulatory instruments. The majority of innovations (76%) are not supported by regulatory instruments. This is a problem because the sustainability transitions literature emphasizes the importance of control policies in putting pressure on the sociotechnical regime by challenging the incumbent social practice (van den Bergh et al., 2006). Also, regulatory policy instruments are important in ensuring that the low-carbon innovations are disruptive in a way that reduces carbon emissions and increases social welfare (Wilson & Tyfield, 2018).

Compared to control policies, there are fewer informational and educational policies that support the development and diffusion of low-carbon innovations according to Table 22. However, informational and educational policy interventions play a critical role in embedding new social practice in the existing regime, which is a more successful policy instrument in facilitating sociotechnical regime change as discussed in section 2.5 *The role of policy in sociotechnical regime change*.

In addition, as described in the section 2.2 *Energy technology innovation system*, the trajectories of low-carbon innovations are primarily determined by technology push approaches and market pull approaches, however market pull approaches have been under-used. Policy is one of the most common approaches used for both technology push and market pull. Science, technology, and industrial innovation policies, focusing primarily on providing research and development support for specific innovation, is always an important component of technology push approaches. However, less attention is paid to market pull approaches. Market pull approaches include energy policy, and social enterprise and innovation strategy. Energy policy that is being deployed as market pull approaches includes mainly regulation and standards. Social enterprise and innovation strategy have the ability to influence the basic architecture of the sociotechnical regime through promoting knowledge creation and diffusion and the establishment of innovation networks. Overall, more attention should be focused on market pull approaches.

Although there is a consensus that policy plays a significant role in the research, development, demonstration, market formation, and diffusion stages of demand-side low-carbon innovations, the challenge is that policy makers have strong incentives to maintain the incumbent sociotechnical regime. Policy makers are then less likely to provide sufficient support for these demand-side low-carbon innovations to facilitate sociotechnical regime change. Politicians and policy makers need to be representative of the public and maintain public support. If the public prefers the mainstream energy services instead of the demand-side low-carbon innovations, politicians and policy makers will be more interested in developing a range of policies that can sustain the status quo.

Furthermore, due to the characteristics of being small-scale and more dispersed, demand-side low-carbon innovations usually lack coherent influence in the political economy (Wilson et al., 2012). However, the fossil-fuel industry, especially the energy-supply companies who are the largest and most capitalized corporate interests in the world, can exert political and market pressure to the government in order to preserve the dominance of incumbent technologies (Wilson et al., 2012).

6 Conclusion

Developing and diffusing disruptive demand-side low-carbon innovations is increasingly recognized as an important pathway to reducing GHG emissions and contributing to low-carbon energy transitions. However, the majority of these low-carbon innovations are incremental. Only 17% of low-carbon innovations have the disruptive potential of contributing to a low-carbon energy transition. The average dissemination rate of demand-side low-carbon innovations is 15%, and 88% of these low-carbon innovations have dissemination rate that are below 30%, which is very low.

These unresolved issues about the lack of disruptive innovations and their diffusion demonstrate a clear need for attention to and actions toward increasing the disruptive ability of low-carbon innovations and diffusing these disruptive innovations on a larger scale.

6.1 Potential Policy Implications

6.1.1 Expand Diffusion of Low-carbon Innovations

In order to expand the diffusion of low-carbon innovations, data transparency must be improved. Although business and financial markets are primarily motivated by profits, they also pursue the stability that can increase their predictable capital returns on long-term investments. Data transparency is an effective way to reduce this uncertainty. With access to data and information, both private and public sector can coordinate their efforts in different innovation stages and make more strategic investments to support the diffusion of demand-side low-carbon innovations. Both public and private sectors should shift their investing focus from innovation research, development and demonstration to market formation and diffusion, to help expand the diffusion of efficient demand-side low-carbon innovations.

As discussed in section 2.5 *The role of policy in sociotechnical regime change*, informational and educational policies are more easily enforced because these types of policies seek to improve instead of eliminate existing social practices by changing energy users' behaviors and habits. Instead, they can embed new social practices in the current sociotechnical regime. For example, to reduce the GHG emissions from vehicle use, informational and educational instruments can help to embed new social practices by advocating the adoption of electric vehicles. During the process, informational and educational instruments will not change energy users' behaviors and habits by enforcing people to abandon the use of cars. Therefore, policy makers should realize the importance of the informational and educational policies in diffusion of low-carbon innovations.

The policy portfolio for the diffusion of low-carbon innovations should encompass policy instruments across the four different policy domains, including (1) energy policy; (2) environment and climate change policy; (3) science, technology, and industrial innovation policy; and (4) social enterprise and innovation strategy as identified in the methods. This policy mix can make policy implementation more flexible and successful.

Policy intervention is likely to be volatile. Abrupt cancelation of policy is damaging to both innovators and investors. Therefore, policy instruments should be flexible but also credible. It is critical that more consistent and aligned policy instruments are implemented to reduce uncertainty and stabilize the economic market.

6.1.2 Increase the Disruptive Ability of Low-carbon Innovations

Given the low percentage (17%) of disruptive demand-side low-carbon innovations in the existing ETIS found in our research, it is important to increase the disruptive potential of low-carbon innovations since theories of sustainability transitions emphasize the importance of disruptive innovations to facilitate large scale systemic energy transformations. Among the factors that influence the disruptive potential of low-carbon innovations, regulatory instruments, informational and educational policy instruments, and democratization are very important for system change, but our data suggests that they have been overlooked in demand-side low-carbon innovations. More attention must be given to these three factors to improve the disruptive ability and diffusion of demand-side low-carbon innovations.

Demand-side low-carbon innovations can become more disruptive if they are not only aimed at improving energy efficiency, but also at providing energy users with new attributes of autonomy and democratization. The low score of democratization implies that energy resources are still firmly controlled by incumbents. However, to increase democratization, energy users should be active participants in the control of energy resources instead of passive stakeholders. Thus, the disruptive ability of low-carbon innovations can be hugely increased from the transfer of ownership and control of energy resources from incumbents to communities and/or individuals.

Disruptive innovations are not compatible with the basic architecture of the sociotechnical system, which makes them vulnerable in the mainstream market. Policy instruments, especially innovation-specific policy instruments, should be enforced to support disruptive innovations, from their early research and development, via market formation, to the critical diffusion stages. Regulatory policy instruments are also important in sociotechnical regime change because the implementation of regulatory instruments can ensure the low-carbon innovations are disruptive in a way that reduces carbon emissions and increases social welfare. Regulatory policy instruments therefore merit further attention.

6.2 Implications of This Research

The coding scale system created for system innovation in this research can be utilized as a standardized assessment to analyze the disruptive ability of an innovation that can contribute to low-carbon energy transitions. This coding scale system can be applied on all low-carbon innovations in any other Canadian provinces or countries. One possible application is that based on the coding results of a low-carbon innovation, innovators can get a rough idea of how to increase the disruptive ability of the innovation that they are researching and developing.

Another potential application of our research is that both public and private sectors can utilize our scale system of system innovation to evaluate the disruptive ability of the low-carbon innovation in driving systemic energy change before making a decision on whether or not to invest in an innovation.

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Appendix A

Table A 1 Types of policy instruments

Types	Description	Specific examples	Literature
Economic instrument	Providing actors with incentives to adopt innovations	Economic incentives: • R&D funding, • deployment subsidies, low-interest loans, • venture capital, • tax exemptions, Market-based: • certificate trading, • feed-in tariffs, • public procurement, deployment subsidies, labeling).	Weimer & Vining, (1992); Jacobsson & Bergek, (2011); Bergek et al., (2014) ; Kivimaa & Kern, (2016); Lieu et al., (2018); Meelen, Truffer, & Schwanen, (2019);
Regulatory instrument	Direct regulation aim at controlling the actions of firms	Command and control: • Performance standards (an absolute upper emission level) • Design standards(a particular technology's usage)	
Informational and educational instrument	Policies in the educational and informational sphere as well as laws and rules that govern the operation of media and education systems	• Policy regarding information and education campaigns, media, and voluntary self-regulation	
Technology-specific instrument	Technology-specific instruments directly support or regulate specific technologies	• Setting technology-specific standards and requirements • Technology-specific economic instruments, such as R&D funding for specific technology	
General instrument	Policy instruments aim at increasing sustainability without pinpointing any particular technology	Taxes and cap-and-trade systems Carbon tax Setting emission standards for the industry	

Table A 2 Coding scale system for system innovation

Independent Variables	Scale
Fossil Fuel Regime Change	-2: Strongly reinforces FF regime
	-1: Slightly reinforces FF regime
	0: No change to FF regime
	1: Incremental innovation toward FF regime change
	2: Disruptive innovation toward FF regime change
Decentralization	-2: Strongly reinforces centralized grid
	-1: Slightly reinforces centralized grid
	0: No effect on grid
	1: Incremental innovation towards decentralization
	2: Disruptive innovation towards decentralization
Democratization	-2: Incumbent gains all or nearly all control and controlling share of ownership
	-1: Incumbent gains more control or gains share of ownership
	0: status quo/incumbent maintains control and ownership.
	1: Community or individuals gains more control or gains share in ownership.
	2: Community or individuals gains all or nearly all control and gains controlling share in ownership
Policy for scale-up through economic instruments	-2: Presence of economic policy instruments that significantly weaken innovation diffusion; Removal of technology-specific economic 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 provide general economic support for innovation diffusion
	2: Presence of economic policies that provide technology-specific economic support for innovation diffusion
Policy for scale-up through regulatory instruments	-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 provide general support for innovation diffusion
	2: Presence of regulatory policies that provide technology-specific support for innovation diffusion
Policy for scale-up through Informational	- 2: Presence of policy instruments for knowledge creation and diffusion that strongly reinforces incumbent regime.

and educational policies	-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.
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.
	2: Presence of plans/strategies spanning policy domains that significantly strengthen the legitimacy of niche innovation and support innovation diffusion.
Legitimacy through Actors	2: Strong network of regime actors operating across policy domains to constrain the delivery and diffusion of innovation.
	-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 across policy domains facilitating the diffusion of innovation.
	2: Innovation intermediary and regime-level actors interacting across policy domains facilitating the diffusion of innovation.

Table A 3 Dissemination rate of demand-side low-carbon innovations

Innovation	Type of user	Population of end-users	Uptake of innovations	Dissemination Rate
Electricity Conservation & DSM Coupons	Individuals	13,793,260	48,778,759	353.642%
NG DSM Residential Participants (Enbridge)	Homeowners - Natural Gas customers	3,636,582	3,335,694	91.726%
Indigenous Community Energy Plan program	Indigenous communities and organizations	141	99	70.213%
NG DSM Residential Participants (Union Gas)	Homeowners - Natural Gas customers	3,636,582	2,305,180	63.389%
NG DSM Commercial	Commercial businesses	1,063,756	633,140	59.519%
Culture of Conservation - Information on Conservation	Individuals who took the Power Pledge	133,000	70,000	52.632%
Electricity Conservation & DSM Automated Peak Saver/ Demand Response (Household and Small Commercial)	Households + small businesses	5,586,917	2,709,250	48.493%
Electricity Conservation & DSM Social Benchmarking	Private businesses	1,063,756	365,988	34.405%
Electricity Conservation & DSM Incentives for Retrofits (Business)	Private businesses	1,063,756	289,912	27.254%
Electricity Conservation & DSM Incentives for Retrofits (Residential)	Households (electricity)	5,164,196	1,139,133	22.058%
Electric Vehicle Charging Incentive program	Eligible participants: receieved an Ontario Electric Vehicle Incentive	15,000	3,000	20.000%
EcoENERGY Retrofit	Homeowner	3,582,238	640,000	17.866%
NG DSM Residential Showerhead Replacement	Homeowners - Natural Gas customers	3,636,582	625,801	17.208%

Electricity Conservation & DSM Appliances Removed	Households (electricity)	5,164,196	866,985	16.788%
Commercial Building Metering & Submetering	Commercial businesses	1,063,756	170,000	15.981%
Bike Share Toronto	Individuals living in the city of Toronto	2,930,000	400,000	13.652%
NG DSM Industrial	Industrial	36,355	3,716	10.221%
NG DSM Multi-Residential	MURB units	1,411,185	132,907	9.418%
Ontario Home Energy Savings Program - Audits	Households	5,169,175	428,000	8.280%
Electricity Conservation & DSM Household Manual Peak Saving	Households (electricity)	5,164,196	380,000	7.358%
Ontario Home Energy Savings Program - Retrofits	Households	5,169,175	380,000	7.351%
PeakSaver PLUS	Homeowners, Commercial	4,645,994	315,000	6.780%
FIT program - Registered Renewable Energy Co-operatives	Cooperatives	1,500	75	5.000%
Green Municipal Funds	Municipalities	444	21	4.730%
NG DSM Residential Low-Income Program	Households (low income)	896,405	20,567	2.294%
Municipal Energy Plan program	Government - municipality	444	8	1.802%
Electricity Conservation & DSM Tailored Information & Retrofit Support (Residential)	Households (electricity)	5,164,196	87,323	1.691%
NG DSM Residential Equipment Replacement	Homeowners - Natural Gas customers	3,636,582	44,917	1.235%
EnerGuide for Houses Audits	Households	5,169,175	60,424	1.169%
Green bank (Green Ontario Fund)	Homeowners	3,582,238	37,000	1.033%
Culture of Conservation Power Pledge	Individuals	13,793,260	133,000	0.964%

Conservation Awareness Campaign				
Toronto's High-Rise Retrofit Improvement	MURB units	1,411,185	11,861	0.840%
Green Ontario Fund (GreenON) - residential solar rebates	Households	5,169,175	33,000	0.638%
Referigerator Roundup	Individuals	13,793,260	47,500	0.344%
Electricity Conservation & DSM Tailored Information and Retrofit Support for Business	Private businesses	1,063,756	3,542	0.333%
Home Energy Coach	Households	5,169,175	15,000	0.290%
Community Bonds	Cooperatives, Nonprofit, Private businesses	1,124,861	3,000	0.267%
EnerGuide for Houses Retrofits	Households	5,169,175	11,343	0.219%
Culture of Conservation - Unplug Your Stuff Campaign	Youth ages 14 to 17 in Ontario in 2010	696,549	1,500	0.215%
Electricity Conservation & DSM Demand Response (Business)	Private businesses	1,063,756	2,117	0.199%
Electric Vehicle Discovery Centre	Individuals	13,793,260	20,000	0.145%
Clean Air Commute - Individuals	Individuals	13,793,260	16,000	0.116%
Electric and Hydrogen Vehicle Incentive program	Individuals	13,793,260	15,000	0.109%
FIT program - Members of energy co-operatives	Individuals	13,793,260	8,000	0.058%
Culture of Conservation Artwork Contest	Students enrolled in elementary and secondary schools in Ontario in 2010	2,051,865	900	0.044%
energy star program	Private businesses	1,063,756	350	0.033%
Electric Vehicle Chargers Ontario (EVCO) grant program	Private businesses	1,063,756	346	0.033%

Toronto Green Standard (TGS) - MURBs	MURB units	1,411,185	346	0.025%
Cap and Trade program	Private businesses, industry	1,100,111	269	0.024%
CarbonShift Tracker	Households	5,169,175	1,000	0.019%
SolarShare Community Solar Bonds	Individuals	13,793,260	1,600	0.012%
Clean Air Commute - Organizations	Private businesses, Nonprofit	1,123,361	114	0.010%
Ontario Sustainable Energy Association (OSEA): Information for members	Cooperatives, Municipal governments, Indigenous communities, Nonprofit, Commercial businesses	1,125,446	59	0.005%
Agents of Change: Climate change solutions	Private businesses	1,063,756	40	0.004%
Home Energy Loan Program (HELP)	Households	5,169,175	160	0.003%
Helping SME's Go Low Carbon initiative	Private businesses	1,063,756	30	0.003%
Green Button Program - Residential	Households	5,169,175	101	0.002%
NG DSM Residential Rebate for Appliances	Homeowners - Natural Gas customers	3,636,582	64	0.002%
Intermediation	Private business, Nonprofit	1,123,361	10	0.001%
MaRS Energy Hackathon	Individuals	13,793,260	115	0.001%
EV charging	Individuals, Households	18,962,435	150	0.001%
Climate Hack-to-Action	Individuals	13,793,260	80	0.001%
FIT Contract	Individuals	13,793,260	60	0.000%
Microgrid Distributed Energy Resource Automation System (MiDAS)	Private businesses	1,063,756	1	0.000%
Knowledge Hub	Individuals	13,793,260	5	0.000%