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Method Article

Methodology to identify demand-side low-carbon innovations and their potential impact on socio-technical energy systems

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ABSTRACT

The rapid diffusion of demand-side low-carbon innovations has been identified as a key strategy for maintaining average global temperature rise at or below 1.5 °C. Diffusion research tends to focus on a single sector, or single technology case study, and on a small scope of factors that influence innovation diffusion. This paper describes a novel methodology for identifying multiple demand-side innovations within a specific energy system context and for characterizing their impact on socio-technical energy systems. This research employs several theoretical frameworks that include the Energy Technology Innovation System (ETIS) framework to develop a sample of innovations; the Sustainability Transitions framework to code innovations for their potential to impact the socio-technical system; the energy justice framework to identify the potential of innovations to address aspects of justice; and how characteristics of innovations are relevant to Innovation Adoption. This coding and conceptualization creates the foundation for the future development of quantitative models to empirically assess and quantify the rate of low-carbon innovation diffusion as well as understanding the broader relationship between the diffusion of innovations and socio-technical system change. The three stages of research are:

- Contextualization: surveys and desk research to identify low-carbon innovations across the ETIS;
- Decontextualization: the development of a codebook of variables
- Recontextualization: coding the innovations and analysis.

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A R T I C L E I N F O
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Subject Area	Energy
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Method name	Methodology to identify demand-side low-carbon innovations and their potential impact on socio-technical energy systems
Name and reference of original method	*Not applicable*
Resource availability	*Not applicable*

Method details

Introduction

Low-carbon innovations are novel products or services that result in lower carbon emissions compared to established technologies [112]. Eco-innovation, a term synonymous with low-carbon, green, sustainable, and environmental innovation, is defined as the "creation or implementation of new, or significantly improved, products, processes, marketing methods, organizational structures and institutional arrangements which lead to environmental improvements compared to relevant alternatives" (OECD 2009 cited in [53], p. 394;). The rapid diffusion of demand-side low-carbon innovations has been identified as a key strategy for maintaining average global temperature rise at or below 1.5 °C [16,40,73,82]. There are many research gaps in understanding how quickly multiple low-carbon innovations can be diffused to the demand-side in an urgent and accelerated timeframe. This paper describes a novel methodology for identifying multiple demand-side innovations within a specific energy system context and for characterizing their impact on socio-technical energy systems.

Diffusion research tends to focus on a single sector, or single technology case study, and on a small scope of factors that influence innovation diffusion [13]. Our methodology directly addresses this research gap by identifying multiple innovations and a range and combination of factors that influence diffusion, as well as how disruptive these innovations are to socio-technical systems. This research attempts to conceptualize and code the innovations according to possible factors that drive or inhibit innovation diffusion. Coding and conceptualization create the foundation for the future development of quantitative models for empirically assessing and measuring the rate of low-carbon innovation diffusion, as well as understanding the broader relationship between the diffusion of innovations and socio-technical system change.

Of interest is research by Clausen and Fichter ([13]) and [23] Fichter and Clausen 2016 who undertook a comprehensive and detailed cross-sector analysis of factors (i.e., drivers and barriers) that influence the diffusion of environmental product and service innovations in Germany. Based on a prior systematic review of the diffusion of innovation literature [12], Clausen and Fichter ([13]) identified 22 factors that have the potential to influence the diffusion of environmental innovations across six fields of influence: (1) product-related factors; (2) adopter-related factors; (3) supplier-related factors; (4) sector-related factors; (5) government-related factors; and (6) path-related factors [12,23]. These 22 factors and six fields of influence "provide a holistic and systematic set of variables and scales that can be used for empirical investigations" ([13], p. 69). In their statistical model, 130 environmental product/service innovations were coded according to these 22 factors (variables related to diffusion) in order to determine the degree to which the factors facilitated or inhibited environmental innovation diffusion. Their research is the first of its kind and is an important contribution to sustainability transitions research because it simultaneously analyses multiple innovations across different sectors and policy fields. While Fichter and Clausen [23] describe their research in detail, the dependant variables they constructed cannot precisely describe the impacts of the innovations they examined on sustainability transitions because they do not account for system innovation potential through disruption.

The Sustainability Transitions Research Network (STRN) recently assessed the sustainability transitions field of research and argued that a new research agenda includes "Ethical aspects of transitions: distribution, justice, poverty". They argue that "transitions have the potential to create or reinforce injustices", but that attention to aspects of justice and democracy with sustainability transitions have been limited ([59], p. 2). A focus on distributive and participatory struggles within sustainability transitions is required [59]. Our research applies elements of Clausen and Fichter's ([13]) research, but differs in three key respects:

1. This research extends beyond examining diffusion dynamics to account for innovation characteristics related to capacity for system disruption, energy justice, and innovation adoption behaviour;
2. This research looks specifically at demand-side low-carbon innovations available to energy users; and
3. This research focuses specifically on the disruptive potential of the innovations on the established socio-technical system.

The conceptualization and development of four variables are presented:

1. Dissemination rate
2. System innovation
3. Innovation adoption
4. Energy justice

Rather than strictly coding the demand-side innovations for the dissemination rate and diffusion dynamics (as was done in Clausen and Fichter's [13] research), we have developed indicators and scales for a range of concepts that influence not only innovation diffusion, but also the innovation's contribution to system change, the potential of innovations to address energy justice, and innovation characteristics relevant to innovation adoption behaviors. The demand-side innovations, coded for the aforementioned concepts, can be examined through a variety of multivariate analyses. Through quantitative analysis, we can further explore the innovations on the factors which lend to their characterization in order to improve understanding of the potential impact an innovation can have on socio-technical system change.

This research project is critical for building a comprehensive understanding of low-carbon innovation diffusion, and will contribute to increasing insights and research applications in this field. Energy Technology Innovation Systems, made up of actors, networks and institutions, and socio-technical systems, such as energy systems and the places where they are embedded, are different depending on the context. While this research focuses on the context of Ontario, the methodology and lessons learned can be applied to other contexts and energy systems, as the questions of impact and diffusion of innovations is a universal problem. Accordingly, this methodology will be of interest to researchers in the field of sustainability transitions and carbon lock-in, and to policy makers and practitioners focused on problems at the intersection of energy users, energy systems, and climate disruption.

Contextualization

The unit of analysis in this research is the demand-side low-carbon energy innovation. Further, this research focuses on innovations available to energy users, such as individuals, households, organizations, and businesses, that could contribute to a low-carbon energy transition. While Clausen and Fichter's [13] research focused on multiple sectors, our research focuses solely on the energy system. Similar to Clausen and Fichter [13], the current research focused on one jurisdiction, the Province of Ontario, due to proximity as well as knowledge of and access to climate change and demand-side energy policy. Further, Canada is a federalist system and energy and natural resources are the jurisdiction of the province; hence another reason for selecting the Province of Ontario rather than, for instance, Canada or a region within Ontario. In Ontario the energy system spans

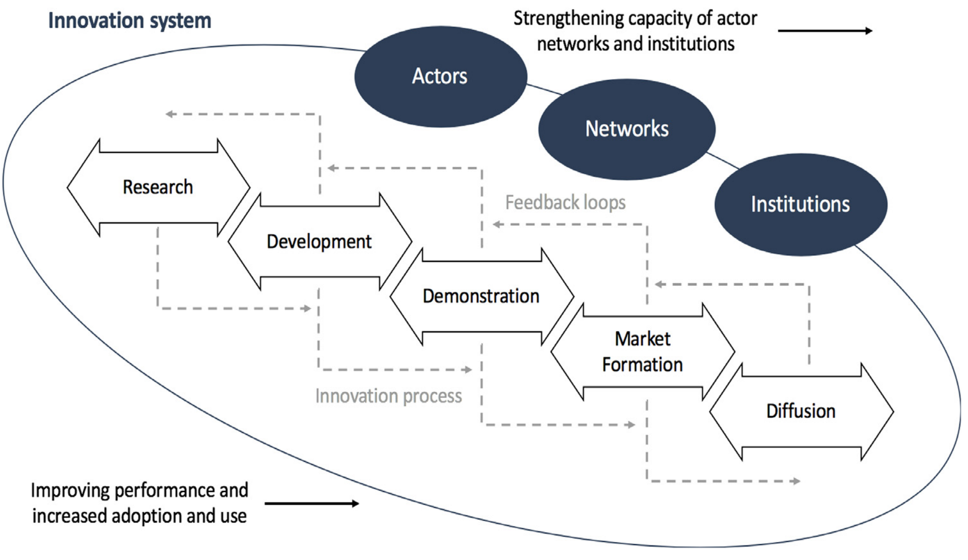

Fig. 1. Innovation system process (adapted from [39,49,91]).

most of the province (remote regions in the North have independent systems) and is comprised of two (formerly three) natural gas distribution companies providing most of the province's natural gas demand, one province-wide transmission system company, and the province-wide Electricity System Operator (IESO) that manages the electricity market. In other contexts, one energy system could envelop multiple jurisdictions, or there could be multiple energy systems within a jurisdiction. Our research methodology could also be applied to these contexts.

In order to identify the innovations, we employed the Energy Technology Innovation System (ETIS), a framework that is defined in Sims Gallagher et al. [90] and Grubler et al. [38]. It has already been applied to identify support for low-carbon innovations in the Canadian context by Jordaan et al. [49]. The ETIS approach focuses on how actors, networks, and institutions influence the emergence of novel innovations [5] from research, development, and demonstration stages to the diffusion stage [49], providing the knowledge and supports for socio-technical energy innovation. [49,90]. The ETIS has different structures in different contexts, and innovations in a particular context are determined by the ETIS. Therefore, we used the ETIS as a framework to identify low-carbon innovations.

Within the ETIS, a policy domain can be used to identify a regime boundary within which governments and institutions deploy policies [68]. To encourage innovation, governments and institutions deploy policy mixes (i.e., the mixture of policy instruments within or across policy domains [41] across multiple policy domains [25]. Energy innovation studies investigate outcomes across multiple policy domains and regime levels over time [68]. The policy domains that are typically investigated by ETIS studies include energy, environmental, science, technology and innovation, and industrial policy, but they vary by ETIS and are context dependant, defined by the institutions in a particular context (Fig. 1).

The sampling strategy that was used to identify low-carbon innovations for energy users in Ontario is described in Fig. 2. Over 15 years, between 2003 and 2018, the Province of Ontario pursued numerous decarbonization strategies that included various visions to provide energy users with demand-side innovations to engage in a low-carbon energy transition. The innovations offered over this timeframe comprise the scope of this research. In June 2018, there was an election of a Conservative provincial government and the ETIS changed dramatically, no longer supporting climate action; innovations post-election are therefore not considered. Prior to this timeframe, the ETIS policy domains specific to the context of Ontario that influence the diffusion of low-carbon innovations for

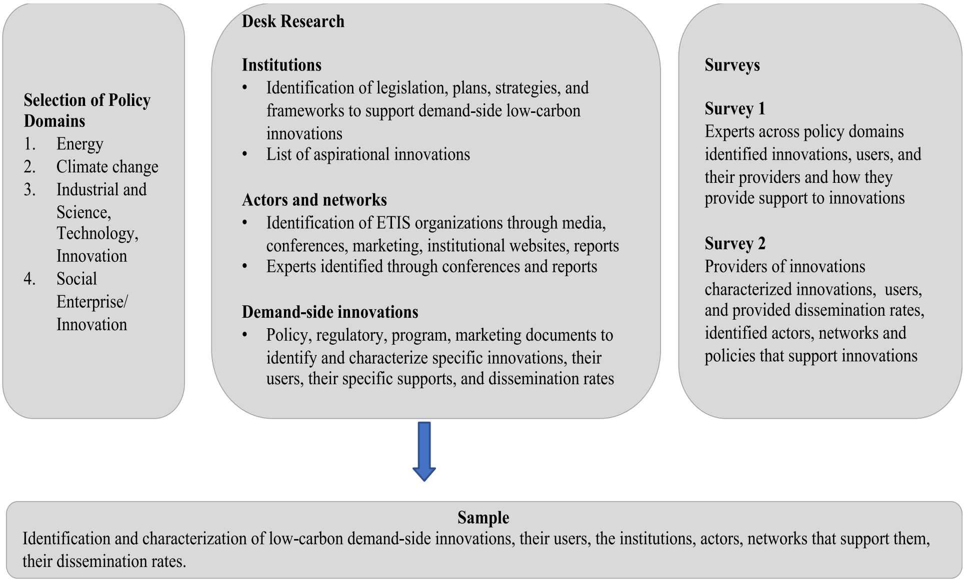

Fig. 2. Sampling the energy technology innovation system in Ontario.

the demand side were: climate change; energy; industrial and science, technology, innovation; and social enterprise and social innovation.

Desk research

In the first stage of the research, desk research was conducted to identify institutions and their associated legislations, plans, strategies, and policy frameworks; actors and networks; and the aspirational demand-side innovations identified in all of these documents. Policy documents falling under the selected policy domains were collected and reviewed for relevant policies, actions, experts, mechanisms and desired outcomes. The details of these are provided in Table 1.

Desk research across the four policy domains resulted in the identification of 32 innovations (14 active; 18 discontinued) offered to energy users in Ontario that have the potential to influence a low-carbon energy transition (Table 2).

Survey of experts in the energy technology innovation system

During the desk research process, through the examination of conference events and reports, 435 experts were identified across the different policy domains. A list of contacts of individuals belonging to the organizations in the ETIS was developed to determine potential survey participants. Based on these experts and organizations identified through desk research, these experts were contacted to participate in an online survey titled, *Survey of Professionals* (referred to as Survey 1). 40 additional individuals were identified through chain link sampling. The number of individuals contacted and the response rate are shown in Tables 3 and 4.

Survey 1 was semi-structured survey (i.e., Survey 1). It was sent to potential participants between March and November 2017. The purpose of Survey 1 was to identify innovations under development, currently available, or intended for energy users in Ontario that have a potential to make an important contribution to a low-carbon energy transition. The survey received 94 responses, a 19.8% response rate. Participants were asked to identify up to three innovations, the organization that offers the

Table 1
Desk research of the ontario energy technology innovation system.

Policy Domain	Key Policies and Strategies	Actors and Networks	Mechanisms / Activities	Aspirational Low-Carbon Innovations for the Demand-Side
Energy Policy	Ontario Energy Board Act (1998b) Electricity Act (1998a) Electricity Restructuring Act (2004) Green Energy and Green Economy Act (2009) Ontario Long Term Energy Plan (2017) (2010, 2013, 2017) Municipal ownership of local distribution companies (early 1900s-) Local Improvement Charges, Municipal Act 2001 (2012) Local energy plans (2013-)	Natural Resources Canada Ontario Energy Board (1998-) Ontario Ministry of Energy Electricity System Operator (IESO) (1998-) Quality Urban Energy Systems of Tomorrow (QUEST) (2007-) municipal network Local electricity distribution companies Natural gas utilities Electricity retailers (2002-) Natural gas retailers Service providers	Retailer participation in wholesale markets (1998 -) Smart meters (2004–2010) Time of use prices (2006-) Electricity and natural gas demand management activities (1995-) Local Improvement Charges can be applied to energy projects (2012-) Municipal Energy Plan program (2013-) Indigenous Community Energy Plan program (2013-) GHG reporting for municipalities (2009-) Electric Vehicle Discovery Centre (2017-)	Purchase electricity and gas from a service provider Real-time electricity information Demand response Audits for building retrofits Rebates, coupons Demand response Equipment removal Demonstration projects (e.g., micro-grid and renewable energy) Consultations for local energy plans Grants for local energy plans District energy Energy demand management Loans for building energy retrofits
Environmental and Climate Change Policy	Government of Canada Action Plan on Climate Change (2000; 2009; 2014) Pan-Canadian Framework on Clean Growth and Climate Change (2016) EnerGuide Climate Change Program (1998–2006) ecoEnergy Climate Change Program (2007–2012) Go Green: Ontario's Action Plan on Climate Change (2007) Climate Change Mitigation and Low-carbon Economy Act (2016a) Ontario's Five Year Climate Change Action Plan 2016–2020 (2016b) Municipal Partners for Climate Protection program	Environment Canada Sustainable Development Technology Canada (SDTC) (2001-) (38) Ministry of the Environment and Climate Change Ontario Green Bank (aspirational) Green Ontario (2017–2018) Federation of Canadian Municipalities (1901-) ICLEI Canada (1994-), (31) Toronto Atmospheric Fund	Innovation funds-Sustainable Development Technology Canada (SDTC) Funds targeted at clean technology development Funds targeted at renewable energy in remote and Indigenous communities Funds targeted at low-carbon transportation Recycled revenue from cap and trade program to Green Ontario (2017–2018) Partners for Climate Protection program (1994-) Create conditions for Ontarian's to choose low-carbon options	Ontario Green Bank provides loans and information for energy retrofits Tools, information for behaviour change Building Retrofits Renewable energy generation by homes and businesses Electric Vehicles Active Transportation Public transit solar photovoltaic and energy storage systems, modern wood heating pilots, air source heat pumps, ground source heat pumps, insulation, windows, smart thermostats, and social housing retrofits Consultations and training for local energy plans Grants for local energy plans
Science, Technology, and Industrial Innovation Strategy	Ontario's innovation agenda (2008)	Ontario Network of Entrepreneurs (ONE) Provincial Innovation Centres (PICs) (MaRS and the Ontario Centres of Excellence)	Incubation and acceleration services Intermediation Energy Transformation Network of Ontario/Ontario Smart Grid Forum (2008-)	Renewable energy Smart end-use devices/appliances Advanced metering connected to utility communications; Control interface

(*continued on next page*)

Table 1 (*continued*)

Policy Domain	Key Policies and Strategies	Actors and Networks	Mechanisms / Activities	Aspirational Low-Carbon Innovations for the Demand-Side
		Regional Innovation Centres University Innovation Hubs/Centres (e.g., Waterloo Institute for Sustainable Energy, Ryerson Centre for Urban Energy)	Open innovation and crowd-sourced competitions Advanced Energy Centre at MaRS (2014-)	Distributed generation and storage Real-time price and demand information, automated home controls for demand response Fuel switching and energy storage Electric vehicles Micro-grids to share power and isolate District heat Micro-grid development metre Data Access Project (MDAP) Green Button Program (standardized information for service providers to bring to customers) (2017-) Green Button Pilot Program (2012) Education around electricity consumption and energy savings Enable standardized electricity consumption data Cross-industry collaboration Promotion of the Green Button standard
Social Enterprise and Innovation Strategy	Ontario's innovation agenda (2008)	Ontario Network of Entrepreneurs (ONE) Provincial Innovation Centres (PICs) (MaRS and the Ontario Centres of Excellence) Regional/Sectoral Innovation Centres University Innovation Hubs/Centres Social Enterprise Partnership Municipalities Public and Private Foundations Government Program Funds Federation of Community Power Cooperatives (FCPC) Ontario Co-Operatives Association The Centre for Social Innovation, MIT Climate CoLab, Nonprofits	Competitions for incubation and acceleration of innovative solutions Incubation and acceleration of social enterprise Incubation and acceleration of energy cooperatives Agents of Change Accelerator (2016-) MIT Climate Co-lab (2018)	Investments in commercial scale solar energy projects through solar bonds; Capacity-building support for co-ops who are developing renewable energy projects and social enterprises Clarify details about investment in renewable energy (check, for e.g. FCPC and solar share) Small and medium enterprise climate change mitigation and adaption Climate change mitigation, adaption and geoengineering for SMEs

Table 2
Innovations identified through desk research.

Desk Research	
44 innovations identified	10 innovations overlap with innovations identified through Survey 1 (combined with Survey 1 data) 2 innovations had insufficient information
32 innovations identified that are relevant to the analysis	14 active innovations 18 discontinued innovations

Table 3
Survey 1 response rates across selected policy domains.

Policy domain	Number of individuals contacted	Number of individuals that completed surveys
Energy policy	152	15
Environmental and climate change policy	47	6
Science, technology and industrial innovation strategy	121	20
Social enterprise and innovation strategy	148	23
Unknown	0	30
Other	7	0
Total	475	94

Table 4
Response rates across type of innovation providers.

Type of innovation provider	Number of individuals contacted	Number of individuals that completed the survey	Percentage of individuals that completed the survey (%)
Incubator/accelerator	87	2	2
Government – indigenous	2	0	0
Government – municipal	177	20	11
Government – provincial	20	4	20
Government – federal	11	2	18
Nonprofit	65	32	49
University	22	9	41
Utility	90	7	8
Consultancy	17	6	35
Conservation authority	3	1	33
Think tank/research institute	3	0	0
Other_regulator	9	0	0
Other_group/association/Network	27	0	0
Other_private business	55	11	20
Total	588	94	16

innovation, how the innovation can influence a low-carbon energy transition, and the energy users for whom the innovation is intended. A total of 119 innovations were identified; 15 of these innovations were outside the scope of analysis; 8 were not yet marketed innovations (i.e. ideas for an innovation); and 7 were lacking in sufficient information provided by the respondents to accurately identify the innovation (Table 5). Innovations that fell under these three categories were removed from the data set. Survey 1 revealed 89 innovations (68 active; 21 discontinued) considered relevant to the analysis and were coded.

Survey of innovation providers

A second survey (i.e. Survey 2) was circulated between June and October 2019. This survey was titled *Ontario's Low Carbon Transition: Learning about Services Available to Energy Users & Communities* (referred to hereon as Survey 2). The purpose of Survey 2 was to (1) gain deeper understanding of

Table 5
Response to survey of experts across ETIS selected policy domains (survey 1).

475 surveys sent to individuals	435 individuals identified through desk research 40 additional individuals identified through chain link sampling (53 total, 13 overlap)
135 survey responses	5 individuals declined to participate 130 participated in the survey 36 agreed to participate but left the survey incomplete (did not provide any innovation data)
94 completed surveys	
119 innovations identified	15 not applicable (outside scope of analysis) 8 not yet an innovation (idea for an innovation) 7 insufficient information provided by respondents to identify the innovation
89 innovations identified that are relevant to the analysis	68 active innovations 21 discontinued innovations

Table 6
Survey 2 response rates across type of actors, networks and institutions.

Type of actor, network or institution	Number of individuals contacted	Number of individuals that completed the survey	Percentage of individuals that completed the survey(%)
Incubator/accelerator	3	3	100
Government–indigenous	0	0	0
Government–municipal	9	1	11
Government–provincial	13	1	8
Government–federal	3	0	0
Nonprofit	32	7	22
University	3	2	67
Utility	8	0	0
Consultancy	4	2	50
Conservation authority	0	0	0
Think tank/research institute	2	0	0
Other_regulator	0	0	0
Other_group/association/network	0	0	0
Other_private business	13	1	8
Total	90	17	19

the innovations by seeking the perspective of the service providers themselves; and (2) to identify additional innovations.

Survey 2 participants were identified using the chain link sampling method employed in Survey 1 (i.e. they were identified by Survey 1 participants). Participants of Survey 2 were also invited to participate in the survey through relevant networks in Ontario (networks and associations whose members include the providers of energy services) and through relevant social media networks. It was difficult to find networks that served Indigenous communities specifically, so these communities may have been overlooked. 90 individuals were contacted to participate in the electronic survey and 17 participants completed the survey (Table 7). The types of survey participants that responded are identified in Table 6. 17 innovations were identified through Survey 2. 7 of these were already captured through Survey 1. These innovations were combined with Survey 1 data to avoid double counting. As such, 10 new innovations (9 active; 1 discontinued) identified through Survey 2 were considered relevant and were coded.

Master dataset

Overall, a total of 131 innovations (91 active; 40 discontinued) were identified through the desk research and surveys (Table 8). The aim of the innovations were characterized and examples of the identified demand-side low-carbon innovations are provided in Table 9. Each innovation was indexed and categorized according to a template, using both the information provided by survey respondents

Table 7
Response to survey of service providers (Survey 2.

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

Table 8
Final sample.

Method for identifying	N	Status	
		Active	Discontinued
Desk research across ETIS and 4 Policy Domains	32	14	18
Survey 1: actors, networks, institutions across ETIS + 4 policy domains, chain link	89	68	21
Survey 2: innovation providers, chain link and networks	10	9	1
Total number of innovations	131	91	40

Table 9
Description of innovations in the sample.

Aim of the innovations	N	Example innovation
Battery storage	6	Community energy storage
Demand-side management	27	Residential showerhead replacement
District energy	2	Combined heat and power (CHP) incentives
Electric vehicles	9	Electric vehicle suitability assessments
Electric vehicle charging stations	5	Electric vehicle chargers grant programs
Energy efficiency	71	Financing through local improvement charges
Local energy plans	7	Capacity-building for smart energy communities
Microgrids	2	Micro-grid demonstration project
Natural gas infrastructure	1	Natural gas grant program
New construction	7	Energy efficiency incentives for new construction
Program design	1	Energy efficiency consultancy
Public/shared/alternative transportation	7	Community bike sharing services
Renewable energy (location not specified)	20	Energy efficiency retrofits for rooftop (PV) solar
Renewable energy (onsite)	12	Institutional research laboratories
Renewable energy (offsite)	4	Green electricity retailer
Retrofits/installations	34	Deep energy retrofit program
Smart meters	6	Residential energy data and analytics
Submetering	1	Commercial building metering and submetering.

as well as desk research on publicly available information. A research folder was created for each innovation, referred to as the innovation profiles, containing detailed background information on each innovation (such as websites, reports, marketing materials) that were collected through desk research but not captured by the template and not included in the master combined dataset.

De-contextualization

At this stage, each innovation was coded for a range of characteristics and factors that influence its diffusion as well as how disruptive these innovations are to socio-technical systems. This research project is critical for building a comprehensive understanding of low-carbon innovation diffusion, and will increase the replicability of the research methodology and broaden potential insights and research applications in this field. In the following sections we describe our conceptualization of and subsequent coding methods for four main variables: dissemination rate, system innovation, energy

Table 10
Reference market population statistics (Ontario).

Types of service users	Entire population	Electricity customers	Natural gas customers
Individuals	11,240,520[a]	n/a	n/a
Households	5169,175[a]	5164,196[b]	3636,582[b]
Households (homeowners)	3582,238[a]	Unknown	Unknown
Households (tenants/renter)	1559,720[a]	Unknown	Unknown
Households (low income)	896,405[a]	Unknown	Unknown
Nonprofit organizations	59,605[c]	n/a	n/a
Cooperatives	1,785[d]	n/a	n/a
Commercial businesses	1616,212[e,f]	Unknown	Unknown
Small businesses	417,742 g	Unknown	Unknown
Building professionals	542,800[h]	n/a	n/a
MURBs	19,415[i]	Unknown	Unknown
MURB units	1411,185[i,j]	n/a	n/a
Low-rise residential buildings	511,800[i]	Unknown	Unknown
Utilities	61	59[k]	2[k]
Indigenous communities	141[l,m]	n/a	n/a
Municipal government	444[n]	n/a	n/a
Provincial government	1	n/a	n/a
Federal government	1	n/a	n/a
Institutions	968[o,p,q,r]	n/a	n/a
Industrial	36,355[s]	Unknown	Unknown
Social housing providers	1500[t]	n/a	n/a
Licensed drivers in Ontario	10,539,055[u]	n/a	n/a
Individuals living in the Waterloo region	617,870[v]	n/a	n/a
Businesses in the Waterloo region (includes non-profits)	17,429[w]	n/a	n/a
Individuals living in the City of Toronto	2956,024[x]	n/a	n/a
Youth ages 14 to 17 in Ontario in 2010	696,549[y]	n/a	n/a
Students enroled in elementary and secondary schools in Ontario in 2010	2051,865[z]	n/a	n/a

(a) [95]; (b) [74]; (c) [9]; (d) [36]; (e) [100]; (f) [101] (g) [97]; (h) [98]; (i) [95]; (j) [7]; (k) [75]. (l) [51]. (m) [71]; (n) [34]; (o) [35].; (p) [102].; (q) [77]; (r) [10] (s) [96]; (t) [78]; (u) [84]; (v) [83] (w) [99]; (x) [11]; (y) [94].; (z) [76].

justice, and innovation adoption. These constructed codes can be applied to demand-side innovations in any context.

Dissemination rates

Based on the literature review, especially the study conducted by Clausen and Fichter [13], “dissemination rate” was used 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:

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

Uptake data was identified through desk research and responses from Survey 2. Following the completion of Survey 2, uptake data were still missing for approximately 64 innovations. A combination of desk research and phone surveys were employed to obtain missing information for these innovations. Subsequently, uptake data for 4 innovations were obtained through phone surveys (Survey 2); 1 was obtained through re-sending the survey link and approximately 10 were obtained through additional desk research. The total number of innovations with available uptake information was 81 (out of the total 131 innovations).

The population size of the reference market was determined through desk research. The appropriate reference population for each innovation was determined by evaluating the types of users and assigning each innovation a corresponding population. Population statistics were collected through desk research and are presented in Table 10. Population fields with an ‘unknown’ population signify cases where population statistics were not found or not available through desk research.

Dissemination rates were calculated for innovations that had both population and uptake data. Overall, uptake data was found for 81 of 131 innovations; population data was available for all 131 innovations. Therefore, dissemination rate was calculated for 81 innovations.

Variable 1: system innovation

In sustainability transitions theory, “disruptive” or “radical” innovations emerge in the context of socio-technical regimes—the institutional structuring of existing systems that favour path dependence and incremental change [59]. These disruptive or radical innovations (products or services) generally incorporate *new* features (attributes), which disrupt the existing technological paradigm and lead to broader socio-technical system change [19,112], including the emergence of new actors in low-carbon energy production and supply as well as regulatory interventions. New features and attributes emerge, in large part, from the innovation system [49,112]. Disruptive innovations can lead to major societal change, including the introduction of new social values and political beliefs [19,27,48,112].

Incremental innovations refer to improvements to products and/or services within or outside an existing technological paradigm [19,112]. Incremental innovations offer improved cost-benefits to consumers for products/services in already established markets [19]. These innovations do not offer novel attributes to disrupt the socio-technical system.

In large contrast to both disruptive and incremental innovations, regime reinforcing innovations are typically path-dependant and work to stabilize the incumbent socio-technical system. This occurs by perpetuating system-reinforcing characteristics, such as operating under favourable regulations within the established regime, contributing to large sunk costs in industry investments, benefiting from established economies of scale, and preserving entrenched social norms and behavioural routines that support the incumbent regime [30]. These types of innovations perpetuate carbon lock-in—the path dependency of complex systems of existing technologies, institutions, and behavioural norms that act in combination to constrain the rate and magnitude of carbon emissions reductions [89].

In order to explore the factors that influence the disruptive potential of demand-side low-carbon innovations, a coding system was used based on concepts of disruptive, incremental or regime reinforcing innovations that were defined in Dixon et al. [19], Geels [29], Geels [32], Johnstone et al. [48], Johnstone & Kivimaa [47], Rosenbloom et al. [85], Wilson [112], and Wilson & Tyfield [114]. The system innovation variable was comprised of eight variables. For each of the eight variables contributing to system innovation, a coding scale was developed, based on the relevant literature. The eight variables were:

1. Decarbonization
2. Decentralization
3. Democratization
4. Policy for scale up: economic instruments
5. Policy for scale up: regulations
6. Policy for scale up: knowledge creation and diffusion
7. Legitimacy through discourse framing
8. Legitimacy through actors and networks

Characteristics of disruption

The first three variables are characteristics or outcomes of disruption: decarbonization, decentralization and democratization of the energy and socio-technical system.

Decarbonization. The fossil fuel regime remains locked-in through the complex network of technological, institutional, infrastructural and behavioural systems that support the continued use of carbon intensive technologies and act as major barriers to the adoption and diffusion of alternative low-carbon innovations [89,107]. Carbon lock-in refers to a combination of systemic forces working together to support the dominant fossil fuel regime and constrain socio-technical system change toward low-carbon innovations, in the presence of viable low-carbon alternatives [107]. These interconnected networks perpetuate path-dependency and carbon lock-in of socio-technical systems. Path dependency here is the continued use of a technology due to favourable market conditions

Table 11
Decarbonization Scale.

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 intensity to higher intensity carbon.	Switching from electric heating to fossil fuel heating. Switching from natural gas to coal or oil. New investment in fossil fuels.
−1	Slightly reinforces fossil fuel regime and path dependencies; Fuel switch from higher intensity to lower intensity carbon; Higher efficiency replacement of fossil fuel use.	Replacement of coal or oil with natural gas. Installing a more efficient gas furnace. Purchasing a fuel-efficient vehicle with an internal combustion engine.
0	No detectable change/no effect/unknown effect on the established fossil fuel regime.	Continued path dependency and 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 loss. Divestment from fossil fuels (with some or no investment in renewable energy) Investment in renewable energy (without divestment in fossil fuels). Improvement in energy efficiency relevant to both fossil fuels and renewables.
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/no carbon energy.	Electric vehicle as a fuel switch away from fossil fuels and has potential to support additional renewable energy. Fuel switch to hydrogen, electricity, conservation, renewables, ground source heat pump, etc. Large divestment from fossil fuels and investment in renewable energy.

and first mover advantages, despite the existence and availability of more efficient, alternative technologies [89]. Hence, destabilizing the fossil fuel regime with disruptive low-carbon innovations creates critical opportunities for system change. This scale was developed to measure the degree to which an innovation removes carbon from the energy system (and supports the adoption of renewable/no carbon technologies) as an indicator of the innovation's potential to disrupt the fossil fuel regime. For a detailed breakdown and examples of the scaling system for the decarbonization variable, see Table 11.

Decentralization. The focus of this variable is on geographic or system decentralization from current centralised energy regimes, not on political decentralization. This coding is based on Lowitzsch et al.'s, [64] conceptualization of renewable energy clusters. Renewable energy clusters are a concept based in current engineering literature and refers to designing optimal localized energy systems that may have multiple energy carriers and end-uses [66]. Renewable energy clusters consist of 1) interconnectivity amongst a range of actors; 2) bi-directionality of energy flows that allows for prosumership, energy storage, energy sharing and peer-to-peer trading; 3) multiple renewable energy sources that can enhance complementarity; and 4) flexibility made up of energy efficiency, demand response, conservation, storage, aggregators, etc. [64]. In combination, these features challenge the architecture and logic of centralized grids, and greatly enhance the ability to shift to variable renewable energy sources.

Innovations that have multiple cluster features are more disruptive and are coded as +2 on the decentralization scale. Innovations that switch away from the centralized grid but that do not have multiple features of renewable energy clusters are coded as +1 on the decentralization scale. For a detailed breakdown and examples of the scaling system for the decentralization variable, see Table 12.

Democratization. The scale for energy democratization is based on whether the incumbent gains control/market share, or whether citizens or communities gain control. Incumbent energy producers have dominated energy ownership over the past decades, and mainly involve producers whose

Table 12
Decentralization scale.

Scale	Definition	Examples
−2	Strongly reinforces centralized grid	Long-term service demand shifting from peak to off peak to flatten curve to support centralized generation Build new connections for energy users to the centralized grid
−1	Slightly reinforces centralized grid	Demand shifting from peak to off peak to flatten curve to support centralized generation Switch particular use to more centralized option
0	No effect on grid	Stays on grid, fuel switch from one centralized grid to another (e.g., gas to electricity)
1	Incremental innovation towards decentralization (switch particular use to off-grid or to single actor grid)	Switch from centralization to distributed generation (any fuel) Adopt an EV Adopt storage Invest in RE (e.g., Bullfrog Power, shares in a cooperative)
2	Disruptive innovation towards decentralization (switch particular use to off main grid to multi-actor grid)	Switch use/join an interconnected grid (2 points or more, such as micro-grid or virtual power plant) with at least one of bi-directionality, complementarity, flexibility [64,73] DG with bi-directionality (prosumership)

interests are enmeshed with state interests [8]. Incumbents are defined as "those actors who wield disproportionate influence within a field and whose interests and views tend to be heavily reflected in the dominant organization of the strategic action field" ([26], p. 12). Democratization has been interpreted as "the 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" ([3], p. 4). Thus, democratization is a socially, politically and economically disruptive change in the energy system. Important in democratization are energy democracy and energy citizenship frameworks which emphasize process, the empowerment of citizens, and energy users as active participants, for example as single actor ownership and prosumership or community-based ownership [18,110]; the energy democracy and citizenship frameworks informed the definition of democratization for this research.

Both communities and individuals are central to the democratization scale. Energy citizenship emphasizes the role of individual citizens as active participants, rather than passive stakeholders [18], while energy democracy focuses primarily on the collective participation of communities in energy resources [110]. Here, types of communities include both communities of place and of interest, and may include cooperatives, Indigenous communities, community investment funds, non-profit organizations, municipalities, universities, schools and hospitals [43], and individuals, which may include individual people, homeowners and renters.

Control and ownership are also critical elements within the democratization scale. This follows from energy democracy scholarship, which emphasizes distributed ownership and enhanced community control as essential for building energy democracy [106,110]. Furthermore, it should be noted that community ownership is associated with beneficial local impacts [6] and is seen as a particularly meaningful form of participation [65]. Within our definition, the transfer of control refers to control over decision-making power concerning energy resources. A controlling share of ownership is defined here as greater than 50% of ownership. Specific community ownership types may include: full ownership, where a community holds 100% ownership; partnerships, which can vary considerably with a community holding any percentage of ownership [42]; membership in cooperatives where each member has only one vote regardless of number of owned shares, therefore distinguishing it from members from shareholders in firms [58]; community benefit agreements, which are contracts outlining community benefits regarding a development project and result from substantial community involvement [37]; and community trusts, which are bodies where revenue, dividends and royalties are stored but ownership structure can vary [42].

Lastly, two further considerations factored into our research. The first concerns incumbent-owned energy resources on individual or community-owned land (e.g. renting out rooftop to incumbent who is producing solar power). Here the literature is focused on ownership of energy resources and not on ownership of the land. As such, such examples were not coded as contributing to democratization.

Table 13
Democratization scale.

Scale	Definition	Example
−2	Incumbent gains all or nearly all control and a controlling share of ownership	Examples of near monopolies and oligopolies for incumbents, as seen in multinationals
−1	Incumbent gains more control or gains an increased share of ownership incumbent producers.	Consolidation of mid-sized incumbents into larger companies connected the central grid Renting out rooftop to incumbent who is producing solar power (gaining market share) Renting solar power from incumbent (gaining market share)
0	status quo: There is no change in ownership or control between incumbent producers and communities or individuals.	Energy efficiency services when operating in the domain of incumbents
1	Individuals and/or communities/community gains more control or gains an increased share of ownership	Municipal Energy Plan program (community provides input)
2	Individuals and/or communities/community gains all or nearly all control and a controlling share of ownership	Cooperative ownership of RE Full community or individual ownership, holding 100% ownership Energy efficiency services when operating in the domain of community-scale initiatives

The second concerns the role of energy efficiency services. Martinez [67] warns of the co-optation of energy efficiency services “for the benefit of maintaining the present corporate energy structure”(p. 32). When these services remain in the domain of incumbents, this maintains current structures and was coded as a 0, i.e., the status quo. Services provided through community-scale initiatives that employ local democratic governance structures, however, challenge the current system and contribute to energy democracy [67]. As such, energy efficiency services were only coded as contributing to democratization if they were provided by community-scale initiatives. This scale is presented in Table 13.

Policy for scale up

Interlocking systemic forces create socio-technical and policy inertia that sustain the existing regime and prevent the emergence of low-carbon innovations [107]. Institutional lock-in reinforces technological lock-in (preventing new entrants from achieving market shares) through the powerful support and influence of economic, social, and political institutions and actors [89]. The resistance to adopt new, innovative technologies is due in part to self-reinforcing incentives: path-dependant processes that reinforce positive feedback loops, creating further resistance to regime change amongst carbon intensive industries and institutions [89]. Incumbent actors that benefit from the existing institutional and infrastructural configurations advocate for policies and regulations that support their interests and reinforce their industry dominance [89].

Policies that support niche innovation scale-up play an important role in influencing socio-technical regime change through the diffusion of disruptive demand-side low-carbon innovations. Transition management literature argues that policy instruments have significant impacts on the diffusion of disruptive innovations because they have the ability to embed new practices into the existing socio-technical regime and put pressure on the incumbent regime [56,89,108].

Policy instruments can be broadly divided into three main types: (1) economic, (2) regulatory, and (3) knowledge creation and diffusion, such as information and education campaigns [111]. Economic policies and regulatory policies are primarily control policies, and are intended to challenge existing social practices [89]. Control policies can contribute to both creating and developing niche innovations, as well as destabilizing the existing regime, because control policies can help to create an extended level playing field for niche innovations through internalizing the environmental and social costs of carbon emissions, so that they can compete with incumbent innovations in the market [108]. Control policies include policies that use economic instruments to put pressure on the regime incumbents, such as pollution taxes, carbon trading, or road pricing. Control policies also include regulations, such as banning certain technologies or implementing import restrictions and regulations [56].

Policy instruments can be further divided into general policy instruments and technology-specific policy instruments [4]. General policy instruments are policy instruments that aim at providing general support or regulations to an entire industry without pinpointing any particular technology, such as carbon tax and cap-and-trade [4]. Technology-specific instruments support specific innovations [4]. Regime change is unlikely to occur without such innovation-specific policies to support niche innovation [21].

The scales for economic and regulatory policy instruments are presented in Tables 14 and 15.

Policy for scale-up: economic instruments

Table 14
Policy for scale-up: economic instruments scale.

Scale	Definition	Examples
−2	Strongly weaken the support for scale-up of the low carbon innovation through removal of technology-specific economic instruments that have impacts on diffusion of the innovation [4], or presence of policies that strongly contradict the scale-up of the innovation [62].	Abrupt removal or cancellation of a policy or eliminates support for specific technology Abrupt cancellation of deployment subsidies Abrupt cancellation of low-interest loans Abrupt cancellation of venture capital
−1	Slightly weaken the support for scale-up of the low-carbon innovation through removal of general economic instruments that have impacts on diffusion of the innovation [4], or presence of policies that slightly contradict the scale-up of the innovation [62].	Abrupt removal or cancellation of a policy or eliminates support for specific industry Abrupt cancellation of feed-in tariffs contracts Planned removal of support–policy cap on programs, target. Abrupt cancellation of tax exemptions
0	No detectable change/no effect/unknown effect on scale-up of the low-carbon innovation	No relevant or detectable economic policies
1	Support scale-up of the low-carbon innovation through implementation of general economic instruments that have impact on diffusion of the innovation [4]	Presence of economic policies that provide economic support for specific industry, such as tax exemptions, cap and trade and feed-in tariffs
2	Strongly support scale-up of the low-carbon innovation through implementation of technology specific economic instruments that have impact on diffusion of the innovation [4].	Presence of economic policies that provide economic support for specific technology, such as deployment subsidies and low-interest loans

Policy for scale-up: regulations

Policy for scale-up: knowledge creation and diffusion. Informational and educational policies also play an important role in supporting the socio-technical regime change. Compared to control policies aimed at challenging existing social practices, informational and educational policy interventions that facilitate knowledge creation and diffusion are argued to be more effective because they contribute to embedding new practices into the incumbent socio-technical regime [89].

Informational and educational policies can influence knowledge creation, development and diffusion, market formation, resource mobilization, and direction of research [56]. Knowledge creation and diffusion is an important support for niche-level low-carbon innovations attempting to scale-up and diffuse into mainstream markets. The creation and diffusion of knowledge can be influenced by a range of policies, including educational policies, training schemes, labour-market policies, and secondment of expertise [56,70].

The diffusion of knowledge refers to the process of “disembedding, travelling and re-embedding” of knowledge ([31], p. 29). A common upscaling pattern of knowledge described in sustainability transitions literature is comprised of the “development of aggregated form of knowledge that are then circulated and recontextualized to fit different circumstance” ([70], p. 98).

The scales for policy for scale-up: knowledge creation and diffusion are presented in Table 16.

Building legitimacy

Building legitimacy for niche innovations to support their scale-up is a key factor that influences socio-technical system disruption. Institutional and organizational legitimacy is defined as “a

Table 15
Policy for scale-up: regulations scale.

Scale	Definition	Examples
−2	Strongly weaken support for scale-up of the low-carbon innovation: removal of technology-specific regulations that have impacts on diffusion of the innovation [4], or policies that strongly contradict the scale-up of the innovation [62] weaken the low-carbon innovation: Removal of te-specific regulations that ha impact on diffusion of innovations, or polices that strongly contradicts the promotion of innovations	Lower the technology-specific design standards and requirements Create significant regulatory barriers to promote low carbon innovation such as too many restrictions on the innovations
−1	Slightly weaken support for scale-up of the low-carbon innovation: removal of general regulatory policy instruments that have impacts on diffusion of the innovation [4], or policies that slightly contradict the scale-up of the innovation [62].	Abrupt removal or cancellation of performance standards (an absolute upper emission level) Excessive monitoring obligation that create some hardship on innovating firms
0	No detectable change/no effect/unknown effect on scale-up**of the low-carbon innovation**	No relevant or detectable policies
1	Support scale-up of the low-carbon innovation: presence of general regulatory policy instruments that have positive impact on scale-up of the innovation [4].	Presence of regulations that provide general support for specific industry. Broad target or commitment for particular sector mentioned in long-term energy plan or climate change plan Setting performance standards (an absolute upper emission level)
2	Strongly support scale-up of the low-carbon innovation: Presence of technology specific regulations that have positive impact on scale-up of the innovation [4].	Setting higher design standards (a particular technology's usage) and mandatory requirements for specific technology

generalized perception or assumption that the actions of an entity are desirable, proper or appropriate within some socially constructed system of norms, values, beliefs and definitions" ([105], p. 574). Legitimacy, in the context of sustainability transitions, assesses the role of actors and institutions in supporting low-carbon innovation diffusion and incumbent regime disruption. Institutional theory suggests that building acceptance for a novel innovation and challenging the incumbent institution depends heavily on the creation of legitimacy [109].

Building legitimacy of niche innovations can be as important as the technological components of the innovation [85]. Legitimacy is created through a series of intentional actions and strategies deployed by system actors to build and favourably shape support for a specific technology or practice [20]. Legitimacy is often required for niche innovation scale-up to work, including resources to be mobilized, markets to form, and actors to acquire political strength [56]. Building an innovation's legitimacy for socio-technical system disruption requires the presence of two factors: (1) positive discourse framing and visioning strategies by actors [20,28,87]; and (2) the presence of actors with agency facilitating the diffusion of niche innovations across multiple scales [20,28,88]. In other words, legitimacy requires a strong network of system actors that actively support the innovation across scales (or policy domains).

The literature identifies the concept of 'discourses' as central to agency and policy evolution for a sustainable transition ([20], p. 19). Discourse is the creation of storylines through which system actors can "construct meanings and frame how issues should be perceived and addressed" ([20], p. 19). Positive discourse framing, or narrative framing, is the articulation of a favourable vision or expectation through connecting it to the broader regime or landscape environment, whereby building legitimacy for certain innovations [20,85]. The collective visioning and discourse framing by system-level actors influences the development and diffusion of niche technologies [20]. Policies, visioning strategies and public statements contribute significantly to the creation of legitimacy [56] and socio-technical regime disruption requires a combination of policies that both create legitimacy for niche-

Table 16
Policy for scale-up: knowledge creation and diffusion scale.

Scale	Definition	Examples
−2	Strongly weaken support for scale-up of the low-carbon innovation: 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” ([31], p. 25). Network weaknesses can hinder knowledge development because firms, institutions and networks will become locked in to the old technologies [45].	Removal of policies that support for the establishment of supplier-user network and/or industry-academia network for low carbon innovations
−1	Slightly weaken support for scale-up of the low-carbon innovation: removal of policies that provide niche-level support for knowledge creation and diffusion [45].	Removal of educational policies, training schemes, labour-market policies; Cancellation of educational campaigns, secondment of expertise and workshops
0	No impact on scale-up of the low-carbon innovation	No relevant or detectable policies for knowledge creation and diffusion
1	Support scale-up of the low-carbon innovation: presence of policies and activities that provide niche-level support to complement or strengthen knowledge creation and diffusion [45].	Presence of regulations that provide general support for specific industry. Implementation of policies, such as educational policies, educational campaigns, training schemes, labour-market policies, secondment of expertise and workshops that provide niche-level support to knowledge diffusion
2	Strongly support scale-up of the low-carbon innovation: presence of policies and activities that support the establishment of new networks, which can contribute to the knowledge diffusion. With networks, different actors may interact effortlessly across large distances, exchange knowledge and thus increase their contribution to upscaling [70].	Policies that improve supplier-user networks and/or industry-academia networks for knowledge diffusion Create innovation platform to provide reference guidelines for best available technology [56] . Support organizations that aim at connecting local user initiatives [22].

innovations, as well as policies that weaken (delegitimize) the established socio-technical regime [85]. It is a combination of both niche legitimization and incumbent delegitimization policies that will ultimately lead to system disruption.

The mobilization of actors with agency across multiple scales is also necessary in forming legitimacy for niche innovation scale-up [88], producing the conditions for socio-technical system disruption. A system disruption requires the presence of institutions, agencies, and actors with agency (those that can influence or impact the energy system) facilitating the diffusion of niche innovations across scales [20,28,33,88]. The literature suggests that niche innovation scale-up occurs through the interaction of (1) innovation intermediaries interacting with niche and regime-level actors; and (2) regime-level actors operating across policy domains [63]. Innovation intermediaries interact with niche-level actors to assist in scaling-up experiments that support the low-carbon transition by encouraging technology diffusion and market adoption [33]. Innovation intermediaries also interact with regime actors to assist in the creation of political and institutional space for subsystem changes within the regime [33]. Regime-level actors create the conditions for system change to take place and identify opportunities for institutional change [33]. This is the process through which disruptive niche innovations build legitimacy and achieve widespread diffusion through the support of actors operating at different levels of the system.

Legitimacy through discourse framing. Building the legitimacy of niche innovations supports their scale-up and facilitates their potential for to create system disruption. As mentioned above, one of the key components for building legitimacy of niche innovations is through positive discourse framing and visioning strategies carried out by system actors [20,28,87]. Developing a positive discourse surrounding a niche innovation helps to connect the innovation to the broader context [85], which, in this case, is the need to transition to a low-carbon energy system. Positive discourse framing can take place within a single policy domain or span multiple policy domains creating impact at the

Table 17
Legitimacy through discourse framing scale.

Scale	Definition	Examples
−2	Strongly weaken the legitimacy of the low-carbon innovation: constraining scale-up through the removal of supportive plans/strategies delivered by system actors; Presence of plans/strategies spanning *across policy domains* that strengthen the incumbent socio-technical regime.	Losing credibility when government cancels or removes strategies, leading to the phase out of specific innovations. Presence of action plans, annual reports, and/or policy documents that actively support and positively frame the incumbent socio-technical regime that span policy domains (e.g. energy policy *and* environment and climate change policy).
−1	Slightly weaken the legitimacy of the low-carbon innovation: constraining scale-up through the weakening of supportive plans/strategies delivered by system actors; Presence of plans/strategies limited to a *single policy domain* that strengthen the incumbent socio-technical regime.	Presence of government policy documents, strategies, plans or reports that positively frame competing fossil fuel intensive technologies within a single policy field (e.g. energy policy).
0	No/unknown impact on the legitimacy of the low-carbon innovation.	No relevant or detectable strategies.
1	Slightly strengthen the legitimacy of the low-carbon innovation: supporting scale-up through the presence of plans/strategies that create positive discourse framing within a single policy domain.	Action plans, annual reports, policy documents and strategies, etc., that positively frame discourse surrounding the niche innovation within a single policy domain being pushed forward by system actors.
2	Strengthen the legitimacy of the low-carbon innovation: supporting scale-up through the presence of plans/strategies that create positive discourse framing across policy domains.	Action plans, annual reports, policy documents and strategies, etc., that positively frame discourse surrounding a niche innovation across policy domains being pushed forward by a strong network of system actors (government agents, industry associations, actor networks).

system level. This scale was developed in order to measure the degree of positive discourse framing surrounding an innovation as an indicator of the innovation's legitimacy, which in turn influences diffusion.

For a detailed breakdown and examples of the scaling system for the legitimacy through positive discourse framing variable, see Table 17.

Legitimacy through actors and networks. The second key component for building legitimacy of niche innovations is through the presence of actors with agency supporting the diffusion of niche innovation across multiple scales [20,28,88]. As outlined in the literature, a strong network of actors (including individuals, organizations, and institutions) with agency working to support the innovations within and across scales is a strong indicator of legitimacy. This requires a combination of interaction between niche-level, intermediary, and regime-level actors supporting and advocating for niche scale-up within a policy domain as well as the presence of regime-level actors supporting niche innovation across policy domains. The presence of both these factors create the necessary conditions for system disruption through legitimation. This variable is coded for the types of actors with agency supporting the scale-up of the innovations within and across policy domains as a strong indicator of legitimacy.

For a detailed breakdown and examples of the scaling system for the legitimacy through actors variable, see Table 18.

Variable 2: energy justice

Another important factor in characterizing the potential for socio-technical system change through disruptive innovation is the concept of energy justice. Energy justice is defined through its concern with who is involved, who gains and/or benefits, and who is marginalized, or more specifically, the distribution of costs, benefits, and procedures [46,92,93]. It has emerged as a useful analytical tool for considering the framing of energy problems [92]. Our framework for assessing energy justice

Table 18
Legitimacy through actors and networks Scale.

Scale	Definition	Examples
−2	Strong network of incumbent regime actors operating *across* policy domains to constrain the scale-up of the low-carbon innovation and preserve the incumbent regime.	Governments actors (municipal, provincial and/or federal) and incumbent utilities actively opposing the innovation across policy fields, sectors, industries. Presence of fossil fuel advocacy groups. Industry actors and industry associations that actively work to preserve the incumbent fossil fuel regime
−1	Presence of incumbent regime actors operating within a *single* policy domain to constrain tscale-up of the low-carbon innovation and preserve the incumbent regime.	Government actors and/or incumbent utilities opposing the innovation within a single policy field, sector, industry. Actor support for innovations that have a competitive advantage or act as barriers to market entry.
0	Silo of niche-level *actors* operating within a *single* policy domain facilitating the scale-up of the low-carbon innovation. Impact negligible to low-carbon innovation.	Support for the innovation from individual firms or small networks within a single policy field, sector, industry. Absence of government-level support.
1	Presence of innovation intermediary actors without presence of regime-level actors operating *across* policy domains facilitating scale-up of the low-carbon innovation. This includes regime-level actors within a single policy domain or niche-level actors operating across policy domains.	Support from government actors within a single policy domain. Support for the innovation from incubators, accelerators, intermediaries that span policy domains in the absence of regime-level actors.
2	Strong network of regime-level actors and intermediaries operating *across* policy domains facilitating the scale-up of the low-carbon innovation.	Support from government actors across policy domains (e.g. energy and environment policy) Different types and/or multiple organizations, institutions, and networks actively supporting the innovation. Presence of actors operating within and across all levels: niche, intermediary, regime.

draws from Sovacool and coauthors [59,92,93]. Four indicators were developed in relation to four corresponding energy justice principles (availability, affordability, good governance and due process (see Table 19). These principles were selected due to the possibility of examination within the scope of the available data. The indicators were considered for 12 types of energy users, which emerged from desk research of policy documents related to the innovations and from the surveys. The energy users included governments (including federal, provincial and municipal), households (where homeowners, low income households and tenants are coded individually), Indigenous communities, individuals, the institutional sector, non-profit organizations, the private sector (including industry and other private businesses) and utilities. Based on these theoretical explorations of energy justice, and the range of indicators across various actor types, justice is best coded as “presence” or “lack of presence” of justice. The innovations were coded according to the following indicators to show the presence of justice, not the degree of it and binary coding was used for determining presence (or lack of presence) of the justice indicators.

Variable 3: innovation adoption

Energy user participation is critical to a low-carbon energy transition [15,81,89]. To mitigate climate change, individuals, households and organizations are expected to engage in multiple activities that co-evolve with institutions and infrastructures [89]. Low-carbon energy transitions depend on the engagement of energy users with demand-side innovations and, in this context, it is specifically this engagement that is of interest. How energy behaviours, practices and decisions can be influenced has been an area of study for decades [1,54,55,103], especially as demand for energy and the services it provides continue to rise [44]. According to a review study, decision

Table 19
Energy justice indicators.

Indicator	Coding approach for assessing indicator	Principle	Definition of principle
Availability	This indicator assesses whether or not the innovation intends to improve availability of supply, infrastructure, energy efficiency, conservation, transportation, storage and/or distribution of energy.	Availability	Broadly, availability draws from the idea that "people deserve sufficient energy resources of high quality" ([93], p. 14). Sovacool and Dworkin [92] emphasize concerns related to supply and reliability, as well as technological innovations enhancing conservation, transportation, storage and distribution of energy, including investment in such factors.
Affordability	This indicator assesses whether or not the innovation intends to reduce cost of supply, infrastructure, conservation, transportation, storage and/or distribution of energy for each user type.	Affordability	Affordability draws from the idea that "the provision of energy services should not become a financial burden for consumers, especially the poor" ([93], p. 14). Furthermore, affordability concerns energy bills that do not overly burden consumers, as well as stable and equitable prices [92].
Information	This indicator assesses whether or not the innovation provides targeted information about supply, infrastructure, conservation, transportation, storage and/or distribution of energy for each user type.	Good governance	Sovacool and Dworkin [92] identify "good governance" as a principle of energy justice, where access to information about energy and the environment is a central element of "good governance."
Involvement	This indicator assesses whether or not each type of actor was involved (through engagement and consultation efforts) in the development of the innovation.	Due Process	Due process, for the purposes of this research, draws primarily from the idea that "communities must be involved in deciding about projects that will affect them" ([92], p. 439).

making surrounding energy use is dependant on myriad factors/variables [113]. The adoption of energy efficiency measures varies according to several characteristics, including demographics [17]. Despite many studies that have examined correlates and predictors in this area generally known as pro-environmental behaviour [2,24,52,72,79,104], what constitutes environmental behaviour varies and problematically many studies have failed to explicitly provide a definition of it. Jorgenson et al. [50] define pro-environmental behaviour as "private-sphere environmental action at the level of individual persons"(p. 164).

Recently, studies have begun to examine a diverse range of participation and public engagement such as activism, community action, behaviour change, consultation, surveys, workshops and practices [81]. Jorgenson et al. [50] present a framework that captures a broader range of behaviours by a broad range of actors that can impact system change. Their framework distinguishes between public/private; individual/collective; direct/indirect environmental actions by individuals or organizations [50]. The environmental action that our study focuses on is the adoption of innovation(s), be it a behaviour, a technological innovation, or a new practice. Our variable Innovation Adoption is broader than pro-environmental behaviour, and narrower than the participation and public engagement defined by Pallet et al. [81] or environmental action defined by Jorgenson et al. [50], as we are specifically addressing innovations that address the energy system as a socio-technical system.

We have, in this dataset, captured some of these potential variables related to innovation adoption; these were not all determined a priori. Innovation adoption related variables were determined and, in some cases constructed, after data collection. It should be noted that the presence or lack of these characteristics is not equivalent to the demonstration of Innovation Adoption. In fact, these factors are what is deemed to contribute (potentially) to Innovation Adoption and is what [61] (above) notes as the correlates and predictors of pro-environmental behaviour.

Table 20
Innovation adoption variables (all are measured as binary variables).

Overarching variable grouping area	Variable	Justification for use
Incentives	Payment for electricity produced Grant Pay per performance Rebate Tax credit Other/not specified Non-material incentives	Behaviour may be altered through offering financial or other material incentives. [1,103]
Financing	Bonds Loans Local improvement charges On-bill Other/not specified	Behaviour may be altered through offering specific type of monetary rewards [1,103]
Feasibility of participation	Availability Affordability Information Involvement	Demand side can be dependant on information [1,80,92] Our energy justice variable measures feasibility of participation [60,92,103].
Type of behaviour intervention	Antecedent intervention Consequence intervention	Antecedent influence prior to behaviour, consequence is after. [1]
Impact	Decarbonization Decentralization Democratization	When looking at pro-environmental behaviour or environmental action it is important to know the impact it will have (a way to know its significance) [50,61,81]. Our decarbonization, decentralization, democratization variables can be used as a proxy for measuring impact.
Type of service	Policy Program Product Project Service	Innovations when applied to the demand side, to a specific program [57] or policy goal (e.g., [86] Type of policy can make a difference to adoption of an innovation [104]

Table 20 identifies the Innovation Adoption variables and their justification, through the literature that they are based in. The variables contribute to better understanding of Innovation Adoption in the context of innovation diffusion and incorporate various types of variables to explain a significant environmental behaviour [104]. Innovations were coded according to these factors for the presence or lack of presence of them and so all are coded in binary form.

Recontextualization

The first step in the coding process was to locate information about the innovations that were identified. Profiles of the innovations were constructed by combining the findings from the desk research contained in Table 1, the survey results, and additional desk research specific to the innovation. Website pages, reports, and relevant documents pertaining to the innovation were identified and used to find the following information for each innovation:

1. Who provided the innovation (organization name and type);
2. How the innovation was provided to energy users (e.g. material incentives, informational mechanisms);
3. The aim of the innovation (e.g. energy efficiency, demand-side management);
4. The part of the energy system the innovation addresses (e.g. electricity, natural gas);
5. If the innovation flexibility, complementarity, inter connectivity and bi-directionality);
6. Who uses the innovation (e.g. individuals, households, private businesses);
7. How the innovation influences user behaviour (e.g. antecedent interventions, consequence interventions);

Table 21
Cohen's Kappa reference table. McHugh, M. L. (2012). Interrater reliability: the kappa statistic. Biochemia medica, 22(3), 276-282.

Score Range	Degree to Agree
Less than or equal to 0	no agreement
0.01 – 0.20	none to slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 1.00	almost perfect

8. Who was involved in the development, delivery, and funding of the innovation (e.g. governments, non-profits, intermediaries, utilities).
9. Prominent networks (e.g. industry and trade associations);
10. Strategies, reports and planning documents (e.g. energy and environmental plans);
11. Policies, regulations, and relevant legislation.

Some of the documents consulted included Electricity Conservation Reports; Natural Gas demand-side management program reports; Cap and trade program and revenue recycling reports; Green Energy and Green Economy Act (2009); and the Ontario Long-term energy plans (all years).

Based on this information, the information relevant for coding each specific innovation was written into a coding log. For example, the coder retrieved the original documents and innovation profile for more detailed information about the specific coding category. If more information was required to determine a value, the coder retrieved the original survey response or conducted additional desk research as needed, which included internet searches and the review of policy documents not captured in the above-mentioned coding resources.

Once the necessary information about an innovation was compiled in the coding log, the researchers systematically coded each innovation for all eight variables in accordance with the *system innovation* coding framework. Codes were initially recorded in the coding logs and then transferred to Excel codebooks.

System innovation

In this study, two coders were responsible for coding 131 demand-side low-carbon innovations. In order to ensure a significant level of agreement (consistency) between the two coders, Cohen's Kappa statistic was employed to measure interrater reliability. Interrater reliability measures the extent to which members in the coding team assign the same value to the same variable [69]. The Cohen's Kappa statistic is frequently used to indicate the interrater reliability [69]. The formula to calculate Cohen's Kappa coefficient is:

$$K = \frac{P_0 - P_e}{1 - P_e}$$

P_0 is the "relative observed agreement amongst raters", and P_e is the "hypothetical probability of chance agreement" ([14], p. 39). The Cohen's Kappa statistic hypothesizes that if the result of the test is higher (closer to 1), then the two researchers had more agreement on the values assigned to a set of variables. If the Cohen's Kappa coefficient is closer to zero, there is less agreement between researchers; if the coefficient is closer to one, there is a higher level of agreement between researchers. The Cohen's Kappa reference table can be found in Table 21, which demonstrates the six-score range of Cohen's Kappa statistic and the degree of agreement each of them represents. The aim was to ensure that there was, at minimum, substantial agreement between the researchers coding the innovations.

Interrater reliability was assessed in six rounds, all identified in Table 22. In the first round, two coders coded the eight system innovation variables for 20 low-carbon demand-side innovations and

Table 22
Results of Cohen's Kappa calculation.

Variable	1st round	2nd round	3rd round	4th round	5th round	6th round
Decarbonization	0.467	0.528	0.818			
Decentralization	0.368	0.455	1			
Democratization	0.783	0.715	0.905			
Policy for scale-up: economic instruments	0.623	0.633	0.931	0.9	0.9	
Policy for scale-up: regulation	0.219	0.643	0.779	0.75	1	
Policy for scale-up: knowledge	0.405	0.706	0.891			0.882
Legitimacy through discourse framing	0.697	0.702	0.935			
Legitimacy through actors and networks	0.671	0.605	0.860			

interrater reliability was assessed. To improve the level of agreement between the two researchers, additional steps were taken.

In the second round, for variables that received a Kappa score below 0.6 in the first round, the two coders reviewed each other's coding logs to assess the reasoning behind any disagreement and recoded the same 20 cases. For the variables that received a score above 0.6, the two coders coded 5 additional innovations. The scores for variables Decarbonization and Decentralization were still below 0.6. Some of the other variables were still between 0.6 and 0.8.

In the third round, a meeting was scheduled to go through the logic for the Decarbonization and Decentralization variables carefully and in detail. The two coders recoded these variables for the same 20 innovations and coded an additional 5 innovations. For the other variables with Kappa scores between 0.6 and 0.8, the coders compared only the specific innovations that they had coded differently. They discussed the logic and information used for coding these variables in order to resolve any remaining differences in coding strategies. The two coders recoded the same 25 innovations for the variables policy for scale up: economic instruments, legitimacy through discourse framing, and legitimacy through actors. For these variables, the researchers recoded the same 20 innovations and an additional 5 innovations for the variables policy for scale up: regulations and knowledge creation and diffusion. These scores revealed substantial agreement for regulations and almost perfect agreement for the remaining seven variables. It was determined that this level of agreement between researchers was appropriate and interrater reliability was confirmed. Following these three rounds of interrater reliability tests, the two coders continued to code the remaining 106 low-carbon demand-side innovations independently, which were divided evenly between the two coders.

After producing a descriptive analysis of the results of variable distributions across innovation cases, it was determined that the documents required for coding of all three policy variables (economic, regulations, and knowledge creation and diffusion) were not comprehensive. The team clarified the examples in the coding scale tables, and gathered additional documents. These policy variables for 131 innovations were recoded by one coder. In the fourth, fifth and sixth rounds of interrater reliability, the second coder recoded the policy variables for 20 innovations based on the new coding scale tables and information in order to improve the Kappa scores. Between rounds four and five the two researchers discussed their coding logic to improve the score of the regulation variable.

Energy justice variable

Coding was completed by one author, with support from all co-authors, using information provided by survey respondents, as well as desk research obtained through publicly available information, primarily from websites associated with the identified innovations.

Innovation adoption

Coding was completed by one author, with support from the co-author with expertise in pro-environmental behaviour using information provided by survey respondents, as well as desk research obtained through publicly available information, primarily from websites associated with the identified innovations.

Conclusion

The research framework presented in this paper describes a novel approach for identifying multiple demand-side low-carbon innovations, and for predicting their impact on socio-technical systems change. This methodology directly addresses the tendency of diffusion research to focus on a single technology and a small scope of factors that influence innovation diffusion by instead identifying multiple innovations and a range and combination of system factors. This methodology contributes to the field of sustainability transitions and carbon lock-in, and can be applied by policy makers and practitioners focused on problems at the intersection of energy users, energy systems, and climate disruption to empirical data in their jurisdictions. While this research focuses on the context of Ontario, the methodology and lessons learned can be applied to other contexts.

This research project is critical for building a comprehensive understanding of low-carbon innovation diffusion, and will contribute to broadening insights and research applications in this field. The analytical framework presented in this paper can respond to a variety of research questions through quantitative analysis of univariate, bivariate and multivariate observations and relationships.

Initial descriptive statistics can be used to inform the distribution, variability, and dispersion of the innovation characteristics and supports, as well as the attributes (qualities) of the innovations themselves. Describing the data in this way can, based on our analytical framework, provide a roadmap for more complex analyses. For example, bivariate analyses between the individual system innovation variables and dissemination rate can be used to examine various relationships, such as how the decarbonization potential of an innovation (disruptive, incremental, system reinforcing) is associated with an innovation's rate of diffusion. Bivariate analysis can be used to explore the relationship between two specific system innovation variables. For example, researchers can determine whether or not there is a relationship between decarbonization potential and regulatory policy supports. With the use of multivariate analyses, such as regression analysis, more predictive analyses can result, such as predicting system innovation based on other variables in the dataset or even predicting innovation dissemination based on system innovation as one of the inputs in a larger model. These types of analyses enable researchers to understand and measure the influence of one or more system variables on the rate of innovation diffusion.

The analytical framework presented in this paper also allows researchers to compare the relationship between innovation attributes and the factors that influence innovation diffusion and system change. Innovation attributes include the aim of the innovation (e.g. energy efficiency), the mechanism through which the innovation is provisioned (e.g. material incentives), the types of users (e.g. households), amongst others. Measuring associations between the inherent qualities of the innovations and their disruptive potential can offer insights into whether or not innovation attributes influence their diffusion. In future analyses, the adoption of innovations can be examined by looking at the factors that may be able to predict the dissemination rate.

The analyses described above are a few key examples of the potential applications of the analytical framework. This framework can be replicated and applied to regional and local empirical studies in order to quantify and inform the range and combination of factors that drive or act as a barrier to system change. Industry experts and professionals can use this type research to map the current landscape of low-carbon innovations being offered to energy users.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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