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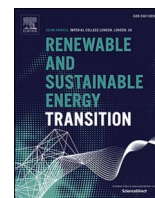
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## Diffusion of demand-side low-carbon innovations and socio-technical energy system change

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### ABSTRACT

To mitigate climate change in an accelerated time frame, more research is needed to understand how to achieve effective large-scale diffusion of low-carbon innovations. The conceptualization of sectoral socio-technical system transitions requires extending beyond an economic and technological focus, towards a wider system view that combines societal, behavioural, and institutional elements alongside the natural environments and infrastructures. Any socio-technical system reconfiguration will be shaped by the diffusion of multiple innovations. This study employs a novel empirical and quantitative framework that integrates considerations of system actors, behaviours, innovations, and infrastructure simultaneously. Based on a review of socio-technical literature, the framework scores demand-side, low-carbon innovations on a scale from regime reinforcing to disruptive across the dimensions of decarbonization, democratisation and decentralisation. It also scores the innovations according to the policy (economic, regulatory, informational) and legitimacy (actors, discourse) factors that support or inhibit their diffusion. This allows for the investigation of the relationship between the diffusion of innovations and socio-technical energy system change, including whether a relationship exists, its strength, and direction. In analysing 80 innovations that diffused to the demand-side between 1998-2018 in Ontario, Canada, diffusion is found to be negatively correlated with system disruption and decarbonization. Although economic supports tend to be a focus of mainstream policymaking, this study found that economic instruments, legitimacy through discourse, and combined policy and legitimacy supports are important to the systemic diffusion of demand-side low-carbon innovations.

### 1. Introduction

The 2022 IPCC Working Group 3 report on climate change mitigation reaffirms the world must reduce greenhouse gas (GHG) emissions substantially for which rapidly decarbonizing the global energy supply and addressing energy demand is critical to this endeavour [1]. The involvement of the demand-side of the energy system – a broad range of energy users, that includes households, organisations and industry – is critical to reaching ambitious carbon reduction goals. Demand-side low-carbon innovations are products or services targeted at reducing carbon emissions from demand side response (flexibility), demand reduction and distributed energy (localised energy production) [7]. This can include new, or significantly improved, products, processes, marketing methods, organisational structures and institutional arrangements, which can alter behaviour and consumption patterns and result

in lower carbon emissions compared to established technologies [8,9]. Diffusion is the process through which market-ready innovations are communicated through societal channels over time, gaining increasing market share through widespread adoption and continued use [2]. Extensive analysis demonstrates that the rapid diffusion of demand-side low-carbon innovations is a key strategy for decarbonizing energy systems to maintain average global temperature rise at or below 1.5°C [3–6].

In fact, many of the low-cost and commercially viable low-carbon innovations required to meet global mitigation targets already exist [10], yet demonstrate slow rates of diffusion [11], including on the demand-side [12]. Research has found that innovations with an environmental focus tend to experience slow rates of diffusion [8,12–14]. Only one third of environmental product and service innovations achieve over 15% of market share, due to lack of attention and investment

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from both public and private sectors [15]. For example, among 38 technologies that are market ready and fundamental to achieving a 2°C target, only four – solar PV, energy efficient lighting, data centres and networks, and electric vehicles – are sufficiently penetrating markets [11].

There are long-standing arguments that the broader challenge to decarbonization is disrupting the systemic lock-in of path dependent, carbon intensive energy systems [16–18] which requires understanding the energy system as a socio-technical system and involving energy users in the transition to alternative low-carbon innovations [19]. Even among more conservative projections, decarbonization strategies employ exponential increases in renewable energy [20], whose infrastructure is inherently more physically decentralised [21–24]. Within this, there are also arguments that dramatic diffusion of renewable energy to replace fossil fuels requires political decentralisation, or democratisation, of energy production [25–27].

Deep changes to energy demand and the dramatic increase of renewable energy are both associated with the implementation of clusters of innovations. For example, deep energy retrofits that reduce building energy use by up to 80% require the upgrade of the building envelope as well as upgrades to mechanical systems, often simultaneously [28]. Increasing reliability of renewable energy, that has the greatest potential across landscapes, is strongly associated with clustering types of renewable energy, alongside flexibility (demand response, prosumership, storage), coupled with the innovation of bidirectional electricity flows [29–31].

Therefore, the diffusion of a *range* of low-carbon innovations is deeply connected to unlocking the path dependence of energy systems in the form of decarbonization, physical decentralisation and democratisation. Low-carbon innovations can influence the socio-technical system in different ways; they can be disruptive, incremental or reinforce socio-technical regimes [32,33]

- **Disruptive** innovations incorporate new features, which disrupt the existing technological paradigm and lead to broader system change, including the emergence of new actors in low-carbon energy production and supply, regulatory interventions, and the introduction of new social values and political beliefs [9,32,34,35].
- **Incremental** innovations are improvements to products and/or services within or outside an existing technological paradigm [9,32], offering improved cost-benefits to consumers for products or services in already established markets [32].
- **Regime reinforcing** innovations are path-dependent and work to stabilise the incumbent socio-technical system [33,36].

Any socio-technical system reconfiguration will be shaped by the diffusion of multiple, not singular innovations. Diffusion research should, therefore, focus on a range of innovations [15,37] and energy transitions research should focus on the diffusion of disruptive, rather than incremental or regime reinforcing innovations [19].

Socio-technical system transitions are shaped by a complex set of policies, regulations, legislation, markets, societal behaviour, values, and individual actors [38,39]; understanding how these transitions materialise is a major challenge to interdisciplinary and socio-technical systems research [40]. The diffusion of low-carbon innovations is known to be affected by a range of factors [14,35]. The conceptualization of sectoral socio-technical systems requires going beyond an economic and technological focus, towards a wider system view that combines societal, behavioural, and institutional elements alongside the natural environments and infrastructures [40]. More research is needed to understand what kind of institutional frameworks and governance tools are required to achieve effective large-scale diffusion at a stage when technologies are commercially available and new demand-side actors become involved [41].

However, there are a range of limitations and areas where contributions can be made in research about the diffusion of low-carbon

innovations and their relationship to socio-technical energy system change. For example, diffusion research has tended to focus on a single sector, or single technology case study, and on a small scope of factors that influence innovation diffusion [15]. Analysing the characteristics of a single innovation independently limits the potential insights and the applicability of the research findings in other contexts [15]. Furthermore, energy modelling studies are criticised for having a limited representation of socio-political considerations and system actors, limiting the ability to appropriately analyse socio-technical system change [40]. Transition frameworks, premised on sustainability transition theories, that account for system actors and socio-technical system change are considered complementary to energy modelling studies. However, sustainability transition theories that attempt to explain socio-technical system change tend to take a sectoral focus, for example, focusing on energy supply, buildings, and transport sectors separately [40], even though all these sectors impact energy system changes. Socio-technical energy transition' (STET) models attempt to capture the variety of factors covered in socio-technical transitions theory quantitatively “where formal quantitative energy models are developed that also capture the elements of socio-technical transitions, including societal actors and the co-evolutionary nature of policy, technology and behaviour.” [40]. In a review of STET models, Li et al. [40] point out that because transition frameworks are often conceptual, it is difficult to operationalize the complex elements of transitions in quantitative analysis to meet the needs of policy development and decision making without over simplifying [40]. Therefore, there are substantial gaps in research and knowledge surrounding how quickly multiple low-carbon innovations can be diffused to the demand-side in an accelerated time frame, as well as their potential to influence disruptive, incremental or regime-reinforcing socio-technical system change.

Three critical questions around the role of energy users and demand-side low-carbon innovations include:

- How do we classify and evaluate innovations that are diffusing into markets, in terms of their potential to contribute to energy system change?
- What is the relationship between the disruptive potential of an innovation and diffusion? And,
- To what extent do policies and legitimisation support or inhibit the diffusion of low-carbon innovations?

In the context of an urgent timeframe to address climate disruption [42], the objective of this study is to provide a better understanding of how to accelerate the diffusion of demand-side low-carbon innovations that influence socio-technical energy system change. The contribution of this study is in the research application of an energy system-wide analysis that offers a better understanding of how to achieve effective large-scale diffusion, and whether the innovations that are being diffused are reinforcing or disruptive to the socio-technical regime. This study addresses these dimensions by formulating a transition framework, based in socio-technical transition theory literature, that is both empirical and quantitative and integrates considerations of system actors, behaviours, innovations and infrastructure simultaneously. As such, this study, while contributing a framework rather than an energy model, contributes to the emerging literature on STET models [40]. Many STET models concentrate on “representing one type of actor, typically generic consumers, rather than a broader spectrum of actors” [40].

## 2. Materials and methods

The contribution of this study is in the development of what Li et al. [40] consider to be a STET framework, which can be incorporated into future models and offers a better understanding of the nuances of the role of diffusion of innovations in socio-technical energy system change. While this framework does not explore economic trade-offs or measure

price/costs (transition feasibility) typically offered by STET models, it does consider how economic instruments (subsidies, loans, grants, etc.) influence innovation diffusion and it can be linked to other models to extend the overall analysis boundaries using the “landscape of models” approach [40,43].

To understand how to encourage the diffusion of innovations that accelerate energy system change, this methodology relies on two key components: a literature review of evidence and factors that inhibit or encourage the diffusion of low-carbon innovations; and, the use of Kendall’s tau-b correlation coefficient, a correlation statistic that can provide information about the strength and direction of the relationship between two variables, allowing the results to be assessed for significance and strength. While correlations do not allow empirical claims about the causation of diffusion for each explanatory variable examined, the extensive supporting evidence based in peer-reviewed literature supports any inferences made about the direction of attribution.

Researchers in Germany have undertaken a comprehensive and detailed cross-sector analysis of the drivers and barriers to the diffusion of environmental product and service innovations, identifying six fields of influence: product-; adopter-; supplier-; sector-; government-; and path-related factors, which are relevant (though not all statistically significant) to the diffusion of these innovations using both literature review of causal factors and Kendall’s Tau-b correlations [15,44,45]. This paper uses a similar methodology to explore the diffusion of innovations and system change.

## 2.1. Framework and variables

The framework presented in this study is based on an extensive literature review of socio-technical transition theories to identify factors that encourage or inhibit the diffusion of innovations that might be regime reinforcing, incremental or disruptive (more details and background information provided in the Theory section). As such, it addresses the clear gaps in the literature by incorporating socio-political and institutional elements, such as a broad spectrum of actors (from energy users to regime actors and networks), legitimacy, and policy instruments, thereby quantifying the impact these factors have on both innovations and socio-technical system change. This is done by measuring the elements that relate to the demand-side and socio-technical energy system change:

- 1 **Innovation impact on system change:** the framework scores innovations according to their characteristics of disruption – whether they have potential to be regime reinforcing, incremental or disruptive. The three dimensions of disruption are decarbonization, decentralisation and democratisation. A scale of -2 to + 2 was employed for each score to represent the range from system reinforcing to incremental to disruptive. A composite disruption score as defined in Table 1 is the aggregation of scores of decarbonization, decentralisation and democratisation. The composite disruption score measures the disruption dimensions as a whole.
- 2 **Policy influence on diffusion:** the framework scores innovations according to the presence of policies from within and across regimes that support or impede their diffusion. The three types of policy instruments measured are economic, regulatory, and knowledge creation and diffusion. A scale of -2 to + 2 was employed for each score to represent the range of support from inhibiting to strongly supporting an innovation’s diffusion.
- 3 **Legitimacy influence on diffusion:** the framework scores innovations according to the presence of system actors/networks within and across regimes that support or impede their diffusion. The types of legitimacy measured were support from system actors/networks and discourse framing. A scale of -2 to + 2 was employed for each score to represent the range of support from inhibiting to strongly supporting an innovation’s diffusion.

**Table 1**  
Definition of variables.

Variables	Definition
Decarbonization	The potential for an innovation to contribute to energy system decarbonization, as an indicator of the innovation’s potential to disrupt the fossil fuel regime.
Decentralisation	The potential for an innovation to contribute to infrastructure decentralisation, disrupting the established centralised energy regime.
Democratisation	The potential for an innovation to contribute to citizens and/or communities gaining an increasing share of control and/or ownership of the energy system, disrupting incumbent ownership and control.
Policy for scale-up - economic instruments	The degree to which economic instruments are used to support or inhibit the scale-up of an innovation.
Policy for scale-up - regulations	The degree to which regulatory instruments are used to support or inhibit the scale-up of an innovation.
Policy for scale-up - knowledge creation and diffusion	The degree to which knowledge creation and diffusion instruments are used to support or inhibit the scale-up of an innovation.
Legitimacy through discourse	The degree to which discourse supports or inhibits the scale-up of an innovation.
Legitimacy through actors	The degree to which actors and networks support or inhibit the scale-up of an innovation.
Composite disruption score	The aggregation of scores of decarbonization, decentralisation and democratisation for each innovation.
Composite policy and legitimacy support score	The aggregation of scores of three policy instruments and two legitimacy supports for each innovation.

4 **Composite policy and legitimacy support:** the framework scores the aggregation of scores of the three policy instruments and two legitimacy supports, as defined in Table 1, which measures the combined institutional and legitimacy influence on diffusion as a whole.

5 **Diffusion to demand-side actors:** Drawn from Clausen and Fichter [15], this variable measures an innovation’s dissemination rate among potential users (reference market). [15]

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

All variables are defined in Table 1. The scores for each variable are described in detail in Table 2. The scores were developed as a framework; the method of development is outlined in detail in a Methods X paper [37].

## 2.2. Sample and context

The methodology for sampling, variable and scale development, interrater reliability for data coding, and measurement of dissemination rates are described in detail in the Methods X article provided as supplementary materials [37], which also provides the full list of innovations. A summary of the Methodology of this study is provided in Fig. 1.

A sample of 131 low-carbon innovations that were offered to energy users in the Province of Ontario, Canada, between 1998 and 2018 was analysed. It is now understood that multi-level policy mixes influence the diffusion of low-carbon innovations [46]. To identify the relevant policies in a particular context requires the identification of the relevant policy regimes (domains) that contain the institutions, actors and networks [e.g., 46]. For this reason, the sample of innovations was derived through a combination of desk research, surveys of experts and information from the providers of the innovations themselves– e.g.,

**Table 2**  
Scoring and Innovation's Potential to Contribute to System Change [adapted from 37].

Variable/ Score	System Reinforcing			Incremental Change	Disruptive Change
	-2	-1	0	+1	+2
Decarbonization potential	Strongly reinforces the fossil fuel regime and strengthens path-dependencies: creates new demand for fossil fuels; fuel switch from lower to higher intensity carbon.	Slightly reinforces the fossil fuel regime and strengthens path dependencies: fuel switch from higher intensity to lower intensity carbon; increase efficiency of fossil fuel use.	No / unknown effect on the fossil fuel regime.	Incremental system change towards decarbonization: decrease in fossil fuel use; efficiency improvement relevant to both fossil fuels and renewable energy.	System disruption towards decarbonization. Fuel switch away from or removal of fossil fuel; contributes to system building of renewable/ non carbon energy.
Decentralisation potential	Strongly reinforces centralised grid. E.g., Build new connections for energy users to the centralised grid.	Slightly reinforces centralised grid. E.g., Switch particular use to a more centralised option.	No / unknown effect on the grid.	Incremental system change towards decentralisation: switch use to off-grid or single actor grid.	System disruption potentially leading to system decentralisation: switch use off main grid to multi-actor grid or increased flexibility.
Democratisation potential	Incumbent gains all or nearly all control and/or a controlling share of ownership. Examples of near monopolies and oligopolies for incumbents, as seen in multinationals	Incumbent gains more control and/or gains an increased share of ownership. E.g. renting solar power from incumbent (incumbent gaining market share)	No / unknown change in ownership and/ or control.	Individuals and/or communities gain more control and/or increased share of ownership. E.g. Municipal Energy Plan (community provides input)	Individuals and/or communities gain all or nearly all control and/or a controlling share of ownership. E.g. cooperative ownership of renewable energy
Policy for innovation scale-up: Economic instruments	Strongly weaken support for scale-up through removal of technology-specific economic instruments that influence diffusion; or presence of policies that strongly contradict scale-up.	Slightly weaken support for scale-up through removal of general economic instruments that influence diffusion; or presence policies that slightly contradict scale-up.	No / unknown effect on scale-up.	Slightly support scale-up through implementation of general economic instruments that influence diffusion. E.g., economic support for specific industry, such as tax exemptions, cap and trade and feed-in tariffs	Strongly support scale-up through implementation of technology-specific economic instruments that influence diffusion. E.g., economic support for specific technology, such as deployment subsidies and low-interest loans
Policy for innovation scale-up: Regulatory instruments	Strongly weaken support for scale-up through removal of technology-specific regulations that influence diffusion; or policies that strongly contradict scale-up.	Slightly weaken support for scale-up through removal of general regulations that influence diffusion; or policies that slightly contradict scale-up.	No / unknown effect on scale-up.	Slightly support scale-up through general regulations that influence diffusion. e.g., 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)	Strongly support scale-up through technology-specific regulations that influence diffusion. E.g., higher design standards (a particular technology's usage) and mandatory requirements for specific technology
Policy for innovation scale-up: Knowledge Creation and Diffusion	Strongly weaken support for scale-up through removal of policies that strengthen networks and create and diffuse knowledge.	Slightly weaken support for scale-up through removal of policies that create and diffuse knowledge at the niche-level.	No/ unknown impact on scale-up.	Slightly support scale-up through policies that create and diffuse knowledge at the niche-level. E.g. educational policies, educational campaigns, training schemes, labour-market policies, secondment of expertise and workshops that provide niche-level support to knowledge diffusion	Strongly support scale-up through policies that establish new networks and create and diffuse knowledge. E.g., 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, support organisations that aim at connecting local user initiatives.
Legitimacy through discourse	Strongly weaken legitimacy support for scale-up through removal of supportive plans/ strategies delivered by system actors; or plans/ strategies spanning policy domains that strengthen the incumbent regime.	Slightly weaken legitimacy support through weakening of supportive plans/ strategies; or plans/ strategies limited to a single policy domain that strengthens the incumbent regime.	No/ unknown impact on scale-up.	Slightly strengthen legitimacy support through plans/ strategies that create positive discourse framing within a single policy domain.	Strengthen legitimacy support through plans/ strategies that create positive discourse framing across policy domains.
Legitimacy through actors and networks	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.	Presence of incumbent regime actors operating within a single policy domain to constrain scale-up.	Silo of niche-level actors operating within a single policy domain facilitating scale-up. Impact negligible.	Presence of intermediaries without presence of regime-level actors operating across policy domains facilitating scale-up. This includes regime-level actors within a single policy domain or niche-level actors operating across policy domains.	Strong network of regime-level actors and intermediaries operating across policy domains facilitating scale-up.

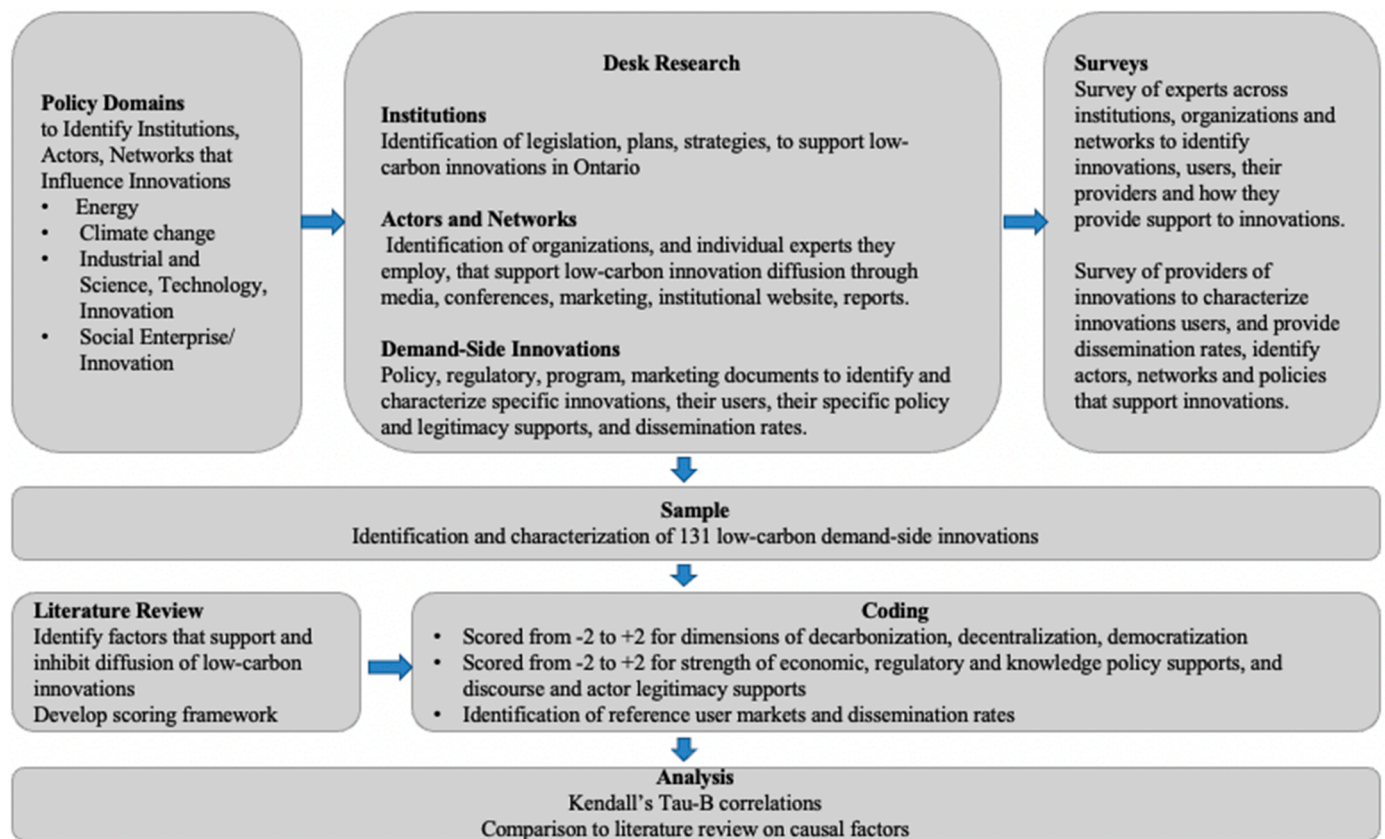


Fig. 1. Summary of Methodology [adapted from 37].

governments, utilities, not-for-profits, businesses— across the dominant regimes that influence the diffusion of low-carbon innovations within Ontario’s energy system. Examples of the innovations that were identified are outlined in Table 3, and a full list of innovations, descriptions and their users, is provided in supplementary materials.

The energy system of the Province of Ontario was selected due to proximity to the researchers as well as their deep existing knowledge of climate change and demand-side energy policy in Ontario. Between 2003 and 2018, the Province of Ontario pursued numerous decarbonization strategies that included aspirations and policies to provide energy users with options to participate in a low-carbon energy transition [37]. These included the implementation of smart-metres and availability of time-based energy consumption data by customer, long term demand side management strategies for the natural gas sector delivered by the provinces two main gas utilities, and aggressive electricity conservation to support the cessation of coal-fired power generation, and a long-term energy plan. Strategic and policy plans across the four policy

Table 3

Type of innovation.

Type	Number	Examples
Product	12	Natural gas appliance Residential solar power Electric vehicle Electric vehicle charger Smart thermostat
Service	68	Local bicycle sharing service Carbon trading service Energy efficiency assessment on residential natural gas appliances Renewable energy co-operatives Knowledge hub for renewable energy and GHG knowledge Energy audit

domains were developed at both the federal and provincial levels of government over the study’s timeframe, that were used to inform the multilevel analysis of policy and legitimacy factors that influence the diffusion of innovations.

A provincial boundary was selected because energy and natural resources are under provincial jurisdiction in Canada. Ontario’s energy system spans most of the province (remote regions in the North have independent systems) and at the time was comprised of two natural gas distribution companies providing 8.7 billion cubic metres of natural gas for over 3 million residential customers and 17.9 billion cubic metres natural gas for 155,703 commercial and industrial customers in 2019 [47,48]. A province-wide electricity transmission system company and Independent Electricity System Operator (IESO) manages the electricity market. The electricity system capacity in 2020 was 38,644 MW, made up of 13% nuclear, 29% fossil fuels, and 37% renewable energy [49]. Canadians are high energy users and among the highest greenhouse gas emitters at 19.4 tonnes per capita [50].

The dissemination rate measured the uptake of each innovation by energy users across its reference market (the number of potential users of a particular innovation). The types of reference markets identified in the sample include homeowners, tenants, Indigenous communities, individuals, firms, governments, and not-for-profits. These reference markets and their population size are in [37]. Dissemination rates for 81 innovations were found.

In order to provide scores to all innovations on their potential impact on system change, as well as the policy and legitimacy factors that influence them, a coding guide was developed in order to assign scores outlined in Table 2 to each of the 131 innovations. Information on the characteristics, users, and inhibiting and supporting factors that was used to assign the score was drawn from the surveys of experts, and document analysis (Fig. 1). To ensure consistency and limit subjectivity when assigning scores in the analysis, interrater reliability was employed and a substantial level of agreement was established.

### 2.3. Correlations

Correlations were used to examine the relationship between variables which tend to occur together in a way not expected by chance alone [51]. A correlation statistic can provide information about the strength and direction of the relationship between two variables [52]. The variables in our sample did not meet the assumptions of Pearson's correlations. Kendall's tau-b correlation coefficient was determined to be a more suitable metric of association between the variables in this analysis, as it is a non-parametric alternative [52]. Kendall's tau-b ( $t_b$ ) correlation coefficient is calculated based on the ranks of the data, not from their actual values [51] and results can be assessed for significance (Table 1 in supplementary materials) and strength (Table 4).

While multivariate and ordinary least squares regressions could test causation, because STET models tend to be difficult to operationalise, and the objective of this research was to understand relationships between diffusion and system change, the dataset did not meet the criteria for these causal regressions (see Supplementary Materials for a detailed account). One outlier was removed; the final sample size was  $n=80$ .

In order to explore the relationship between the disruptive potential of an innovation and diffusion, we ran a correlation analysis between each dimension of disruption and the dissemination rate, as well as between the composite disruption score (the aggregation of scores of decarbonisation, decentralisation and democratisation) and dissemination rate.

In order to explore the relationship between factors that encourage or inhibit the diffusion of innovations, we ran a correlation analysis between each type of support (policy instruments and legitimacy) and the dissemination rate, as well as between the composite policy and legitimacy support score (the aggregation of scores of three policy instruments and two legitimacy supports) and dissemination rate.

## 3. Theory

The scores outlined in "Materials and Methods" are derived from a literature review of evidence and factors that inhibit or encourage the diffusion of low-carbon innovations. As part of the literature review, three relevant dimensions of low-carbon socio-technical system change were identified as decarbonisation, physical decentralisation, democratisation. Three types of relevant policy instruments found were economic, regulatory and knowledge creation and diffusion instruments. Legitimation by actors and networks as well as in discourse were also found to be relevant variables to encourage or inhibit innovations. The following literature review outlines the rationale for the selection of these variables based on an extensive review of socio-technical transitions and diffusion of innovations literatures.

### 3.1. Innovations and socio-technical system change

Most technological innovations are never adopted by mainstream markets due to dominant and rigid socio-technical regimes, particularly for innovations that require changes in consumer behaviours or are incompatible with existing technological and physical infrastructure [53]. Radical or disruptive innovations diffuse more slowly than conventional innovations due to the lack of compatibility with the established socio-technical system [53,54].

A sustainability transition is the transformation of socio-technical

systems, including the transitions of technologies, user behaviours, industrial sectors, infrastructures and institutions towards environmental sustainability [55]. A socio-technical system is made up of embedded and interconnected configurations of society and technologies, which fulfil societal functions [56]. The Multi-Level Perspective theorises that the niche, regime, and landscape are the three interconnected layers that comprise a socio-technical system [57]. The small and flexible niche is where various innovations are created, researched and tested [55]. The socio-technical regime is the stable environment of established technology, practices, regulations and networks that reinforce the existing technological system and influence the direction of innovation [53,58,59], where dominant technologies and user practices are locked-in; and the stable macroeconomic, environmental, social, and macro-political landscape that provides both the foundation for regime stability and the necessary pressures forcing the existing regime to change (e.g. price developments, demographic trends, environmental changes, etc.) [26–28]. Socio-technical transitions arise from the culmination of landscape pressures, and the readiness of niche innovations to break through and disrupt the incumbent regime [62]. Therefore, sustainability transitions are achieved through the diffusion of niche innovations [57].

Disruptive innovations incorporate new features, which disrupt the existing technological paradigm and lead to broader system change, including the emergence of new actors in low-carbon energy production and supply, regulatory interventions, the introduction of new social values and political beliefs [9,32,34,35]. For disruptive innovations to lead to system change, it requires the upscaling or diffusion of disruptive innovations. Elements of the system also need to change, such as encouraging and allowing new types of business models, markets, actors and networks, removing policy and regulatory barriers, and encouraging the wider distribution of power and ownership of infrastructure and resources [63].

Incremental innovations are improvements to products and/or services within or outside an existing technological paradigm [9,32], offering improved cost-benefits to consumers for products or services in already established markets [32]. The diffusion of incremental innovations leads to only minor adjustments within the established patterns of the existing regime, without having to compromise its core structures, institutions, and actors [64,65].

Regime reinforcing innovations are path-dependent and work to stabilise 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 [36].

To increase the rate of diffusion of low-carbon innovations, the system level barriers that prevent actors and institutions from participating in their adoption need to be addressed [12]. The scale-up of innovations involves increasing the number of a particular niche innovation and their geographical distribution, by demonstrating niche innovations; expanding social networks through the encouragement of more actors to support the niche innovation, and increasing the social acceptance of the visions behind the niche innovations [66,67]. Landscape developments may facilitate the scale-up of innovations by creating transformation pressures on the incumbent regimes [56]. However, lock-in mechanisms of the existing regime, such as existing actors and networks in the fossil fuel sector, matured infrastructure for the dominant technologies and lack of investments in the new infrastructure may prevent the expansion of the niche [68].

### 3.2. Relevant dimensions of socio-technical system change

#### 3.2.1. Decarbonisation

In order to avoid the worst impacts of climate change, decarbonisation is a critical dimension of energy system disruption. Energy

**Table 4**  
Characteristics of Kendall's Tau-b [15].

Coefficient	Correlation Strength
$0.00 < t_b < 0.05$	No correlation
$0.05 < t_b < 0.20$	Weak correlation
$0.20 < t_b < 0.50$	Medium correlation
$0.50 < t_b$	Strong correlation

systems are responsible for roughly 80% of emissions globally [69] and this means that fossil fuel based energy uses must be replaced by no-carbon emitting sources of energy. A low-carbon energy transition requires building a new socio-technical system by reducing emissions in the production and consumption of energy, which requires a reconfiguration of current technologies, institutions, and user practices [57]. Carbon lock in, is a state in which the combination of systemic multi-scalar forces work together to support the dominant fossil fuel regime through the complex network of technological, institutional, infrastructural and behavioural systems that support the continued use of carbon intensive technologies that constrains the diffusion and adoption of alternative low-carbon innovations [16,17]. Path dependency is the continued use of an innovation due to favourable market conditions and first mover advantages, despite the existence and availability of more efficient, alternative technologies [17].

### 3.2.2. Infrastructure decentralisation

Infrastructure decentralisation is another important dimension of socio-technical energy system change that is extensively debated in energy transitions literature. Energy infrastructure systems have historically been designed for large-scale centralised generation technologies that deliver energy over long distances, in one direction, to high demand centres [70]. While energy decentralisation often refers to the entry of new actors with agency over the energy system [e.g., 23], it starts with a shift in technical infrastructure [21] that includes distributed supply, end use technology and the determinants of demand [71]. That is, physical decentralisation is a shift in the technologies, services, and architecture of the energy system That include flexibility enhancements to electricity distribution systems, such as energy conservation, efficiency, demand response, storage, aggregators, combining renewable energy technologies (complementarity), connectivity, and proximity [72–74]. Decentralisation is required for the diffusion of low-carbon innovations, such as electric vehicles and renewable energy, that are important to low-carbon energy transitions that are needed to replace a fossil-fuel based energy system.

Path dependency of centralisation inhibits the diffusion of decentralised technologies. For example, the absence of decentralised small-scale energy grids has been shown to inhibit the development and diffusion of renewable energy sources, technologies that are incompatible with large-scale centralised energy generation regimes [74].

Despite dramatic decreases in prices in renewable energy technologies, particularly solar and wind [75], renewable energy still only accounts for 11% of total final energy consumption globally [76] with only 2,500 GW of installed renewable energy [77]. Distributed renewable energy generation accounts for only 1% of electricity generation across the globe, although its uptake is accelerating [76,78].

### 3.2.3. Democratisation

Democratisation is another important dimension of disruption to energy systems identified in debates about socio-technical energy transitions. Democratisation involves infrastructure, rules, regulations and actors. The Sustainability Transitions Research Network (STRN) recently argued that a new research agenda for sustainability transitions requires a focus on distributive and participatory struggles within sustainability transitions [79].

Energy systems have been predominantly operated by centralised incumbent actors, such as vertically and horizontally bundled energy utilities [80]. Incumbent actors benefit from the existing institutional and infrastructural configurations, and advocate for policies and regulations that support their interests and reinforce their industry dominance [81]. New actors have been entering the energy sector to make decisions about how energy is sited, produced, consumed and managed [21] for example, through prosumership, cooperatives, community trusts, Indigenous economic development corporations, local authorities, and renewable energy communities [73,82,83]. Rescaling decision-making is disruptive as it brings in many new actors operating

smaller scale innovations, challenging the interests of incumbent actors [84–86]. While there are many examples of democratised energy around the world, it is still a small share of ownership of renewable energy production, and has reached market share in few places. There are close to 3,500 European renewable energy cooperatives [87]. Diffusion of democratic forms of energy are only in the tens in Brazil and Australia [77], and the hundreds in Canada and New Zealand [82,83]. Mainstream market share has been reached in Nepal, where roughly 15% of electricity is produced by community-owned micro-hydro installations and in Costa Rica, where four energy cooperatives with over 180,000 members control almost 15% of the energy market [77].

## 3.3. Scale-up and diffusion of innovations

A literature review of the empirical evidence on driving and inhibiting factors to the scale-up and diffusion of disruptive innovations identified five important variables: economic policy instruments, regulatory policy instruments, knowledge creation and diffusion policy instruments, legitimacy through discourse and legitimacy through actors, all of which are included in the model.

### 3.3.1. Policy instruments

Policy instruments are tools applied by policymakers that support or inhibit the development, market formation, scale-up and diffusion of sustainable innovations [88]. Technology-push and demand-pull policies are used to address the under-provisioning of technologies that are viewed as a public good, and in their absence, such technologies would remain under-provisioned by market forces [89,90]. A key challenge is that incumbent governments and institutional arrangements can undermine these policies [90].

A combination of supportive policies (policy mix) [55], is needed to facilitate the diffusion of emerging technologies [91,92]. General policy instruments can support a range of technologies to achieve broader sustainability objectives and are associated with the diffusion of incremental innovations, while technology-specific policy instruments target support to a particular technology and are necessary for the diffusion of disruptive innovations [93], which is why they were assigned a score of +2 in Table 2. Based on literature [55,94], herein, policy instruments are separated into three main categories for supporting or inhibiting innovation diffusion: economic, regulatory, and knowledge creation and diffusion.

**3.3.1.1. Economic policy instruments.** The diffusion of environmental innovations will be inhibited if they are not able to compete economically with conventional innovations [15]. Economic instruments provide demand-side energy users with incentives to adopt technologies [93]. General economic instruments do not target specific technologies. These include carbon taxes, feed-in tariffs, emissions trading schemes, and tradable renewable certificate systems, are associated with incremental innovation and the diffusion of established technologies [93,95]. Fiscal instruments, such as removal of subsidies for fossil fuel-based technologies, can support low-emissions innovations to compete economically with incumbent technologies, leading to their adoption and diffusion [11]. Technology-specific economic instruments, such as deployment subsidies, low-interest loans, tax credits, grants and rebates for specific technologies, and public procurement of specific technologies, are necessary to support the development and diffusion of disruptive innovations [93].

For example, in the case of decentralisation of energy systems, empirical evidence shows that the rapid diffusion of renewable energy technologies in Germany and the Netherlands is primarily attributed to economic instruments which improved their financial advantages [15, 96]. The lack of investments and subsidies for renewable energy technologies have been shown to have a negative effect on their diffusion and implementation [96].

**3.3.1.2. Regulatory policy instruments.** Regulatory instruments directly control and regulate the adoption of innovations [93]. General regulatory instruments include broad targets or commitment for a particular sector, emissions regulations and performance standards setting, but not for specific technologies [93]. Technology-specific instruments can set higher design technological standards (i.e. prescription of a certain equipment or technology), identification of Best Available Techniques or mandatory requirements such as technology-specific rules for permits, land-use etc. [93].

Governments use regulatory policy instruments to influence the diffusion of innovations by improving the selection environment [89, 92]. However, the findings from empirical analyses are mixed. General regulatory instruments can contribute to the diffusion of incremental innovation or regime-reinforcing innovations but not to development and diffusion of disruptive innovations [93]. For example, Dutch building regulations were found to encourage more adoption of conventional water heating technologies with improvement in energy efficiency, but did not contribute to the diffusion of heat pumps [93]. Technology-specific regulatory instruments had a positive impact on the development and first market introduction of disruptive innovations, such as electric vehicles, but limited impact on further development and diffusion [93]. A technologic-specific Eco-design Directive had a strong positive effect on diffusion of energy efficiency products [15].

Establishing technology-specific regulations is a challenge for regulatory authorities since they pose knowledge demands. The impact of regulations on diffusion of cleaner technologies can be negative if inappropriate regulations are enforced in certain conditions, for example, if regulatory authorities don't have enough knowledge, the regulations may promote "yesterday's" innovations [97]. Furthermore, the lack of long-term regulations, and contradictory regulations (e.g., across agriculture and energy), have been shown to hamper the development and diffusion of renewable energy technologies [98].

**3.3.1.3. Knowledge creation and diffusion instruments.** Knowledge creation and diffusion policy instruments contribute to embedding new practices in the incumbent socio-technical regime, and include educational policies, training schemes, information and education campaigns, media, coordination of intellectual property rights and reference guidelines for best available technologies [55,94]. Diffusion of innovations depends on the creation and diffusion of knowledge along networks to compete with other systems [99].

Policy can contribute to improving the degree of the connectivity in knowledge networks so that knowledge can be widely diffused [99]. Empirical study shows that knowledge development (such as R&D) and diffusion (such as workshops and conferences) have a positive influence on the development, diffusion and implementation of biomass digestion in the Netherlands [96]. Fichter and Clausen [45] found that information-based instruments can be very helpful in accompanying strong regulations and economic instruments in a policy mix, but they are "not at all sufficient as stand-alone measures"(p.48). In the case of decarbonisation, a deficit of knowledge, education and human capital can reduce the willingness to adopt low and/or no carbon innovations [90].

### 3.3.2. Legitimacy

Institutional theory suggests that building acceptance for a novel innovation and challenging the incumbent institution depends heavily on the creation of legitimacy [100]. Legitimacy is created through a series of intentional actions and strategies deployed by system actors (actors with agency) to build and favourably shape support for a specific technology or practice [101]. Legitimacy supports niche innovation scale-up and diffusion through resource mobilisation, market formation, and actors gaining political strength [102–104]. Building an innovation's legitimacy for socio-technical system disruption requires the

presence of positive discourse framing and visioning strategies by actors and the presence of actors with agency facilitating the diffusion of niche innovations across multiple scales [101,102,105,106].

**3.3.2.1. Legitimacy through discourse.** Niche or regime actors, or networks of actors, develop storylines (discourse) that frame innovations in a particular way (positively or negatively) to influence the context within which the innovation is diffused [107]. Positive discourse framing is the articulation of a favourable vision or expectation through connecting it to the broader regime or landscape environment, and builds legitimacy for certain innovations, influencing their diffusion [101,107]. Policies, visioning strategies and public statements create legitimacy [104], and the collective visioning and discourse framing by system-level actors influences the development and diffusion of niche technologies [101,107].

Empirically, the diffusion of renewable energy technology is attributed to legitimacy through discourse through long term goals and targets [96,108], societal interest and acceptance [103], public concerns about climate change and positive visions of renewables [102], lobbying, and public debate [109], that stimulate investment and allocation of resources, and appeal to technology users [96]. The relative rate at which innovations diffuse is important as it affects the business case for adoption. For example, in Japan, solar-wind hybrid systems were impeded due to industry lobbying effects [110].

**3.3.2.2. Legitimacy through actors.** A system disruption requires the presence of institutions, agencies, and actors with agency (that can influence the regime) in facilitating the diffusion of niche innovations across scales [60,61,101,102,106]. Innovation intermediaries assist niche-level actors in scaling-up technology diffusion and market adoption and assist regime actors in the creation of political and institutional space within the regime [61,107]. "Prime movers" are key actors in the creation of new technological systems and in the creation and diffusion of knowledge.

The absence of an aligned or coordinated network of system actors is a challenge for diffusion [41,98]. Innovation intermediaries also facilitate innovation adopters [41]. In examining the factors that influence the diffusion of low-carbon innovations, there tends to be a supply side bias, even though diffusion is mostly influenced by demand-side actors, such as adopters and intermediaries [41]. In a study of 130 environmental product and service innovations, supplier-related factors (e.g. renown and reputation of suppliers) and sector-related factors (e.g. degree of support by industry trade associations) correlated highly significantly with medium strength with the dissemination rate [15].

Empirically, the diffusion of renewable energy technologies is attributed to the legitimacy through actors experience from a "sister" technology innovation systems [109] – a competent supplier industry and coordinated actors and networks that improve the functioning of the market [99]. The diffusion of decentralised technologies is also attributed to grassroots actors providing legitimacy and other forms of support [111].

### 3.4. Combined supports

According to the literature review, scale up of decentralisation and democratisation are influenced by multiple factors.

For example, challenges along the centralisation-decentralisation scale include regulatory issues, such as institutional barriers, market structure and lack of grid access, economic issues such as financing, and the legitimacy influence of connectivity of actors in the system [34,41]. There are many factors that encourage the diffusion of decentralised innovations, such as regulatory and physical infrastructure (e.g., markets and flexible energy systems) [78], knowledge creation and diffusion of community sense-making and mental models related to innovations [112], potential for legitimacy through clusters of smaller firms

organised in new networks [99], economic instruments and supplier related factors [113], providing feed-in-tariffs [114], and the consideration of combined costs of clusters of innovations rather than singular innovations, and forms of local participation [72,115].

Drivers of scale-up and diffusion of democratisation of energy innovations include a supportive institutional context [116,117], the local capital goods industry [99,117,118], legitimacy, grassroots learning and experimenting [111], local framing as multiple problems and institutional learning [117], capacity to manage risks, shared ownership or partnerships between public and community-based projects [119], being able to move forward with lower financial returns than the thresholds for private industry [118] cooperative size, cooperative organisation, feed-in-tariffs and direct policies [114,120] and the presence of intermediaries to address capacity issues [41]. Inhibitors to diffusion of democratised low-carbon innovations include auction-based mechanisms, higher process and transaction costs of smaller scale projects [119], the ability to raise capital [120], geographic dispersion impedes knowledge sharing [121] and that different values and expectations of niche actors make it difficult to de-contextualise, scale up and translate those niche practices to mainstream contexts [111,121,122].

4. Results

Fig. 2 provides a visualisation of dissemination rate and composite disruption score for the 80 innovations (for which dissemination rates were available). According to Fig. 2:

- 1 61 innovations had characteristics of system disruption (i.e., composite disruption score above 0), of which 5 had a dissemination rate above 15%, and 56 below. A number of these were electricity based innovations.
- 2 16 innovations had no characteristics of system disruption (i.e. composite disruption score equals 0), of which 6 had a dissemination rate above 15%, and 10 below. Many of these, particularly those with very high dissemination rates, were innovations that extend the use of natural gas, a fossil fuel.
- 3 1 innovation had system reinforcing characteristics (i.e. composite disruption score below 0). This innovation continues the use of natural gas, a fossil fuel.

Tables 5 and 6 present a summary of the central tendency and dispersion results from each of the disruption, policy and legitimacy variable scores and the composite scores of the innovations. Legitimacy through actors and networks has the highest average score (+1.66), while knowledge creation and diffusion policy instruments have the lowest average score (+0.37) (Table 5). The average composite disruption score is +1.93, while the average composite policy and legitimacy support score is +5.40 (Table 6).

Table 7 presents the results of the correlations outlined in Section 2.3, for which five statistically significant correlations were found (Table 7).

Disruption and diffusion:

The findings indicate that innovations with characteristics of system disruption are associated with lower rates of diffusion, and innovations that are regime reinforcing are associated with higher diffusion rates, which is also shown visually in Fig. 2.

- A medium and highly statistically significant negative correlation relationship was found between decarbonization and dissemination rate ( $t_b = -0.232$ ).

Table 5 Summary of disruption, policy and legitimacy supports statistics (n=80)

Variable	Mean Score	Standard Deviation	Score Frequency				
			-2	-1	0	+1	+2
Decarbonization	+0.71	1.02	0	18	2	45	15
Decentralisation	+0.98	0.60	0	4	4	64	8
Democratisation	+0.31	0.52	0	0	57	21	2
Policy for Scale-up: Economic	+0.87	0.80	0	5	16	43	16
Policy for Scale-up: Regulations	+0.88	0.46	0	0	14	62	4
Policy for Scale-up: Knowledge creation and diffusion	+0.37	0.58	0	1	51	25	3
Legitimacy through discourse	+1.61	0.70	1	0	4	19	56
Legitimacy through actors and networks	+1.66	0.69	0	1	7	10	62

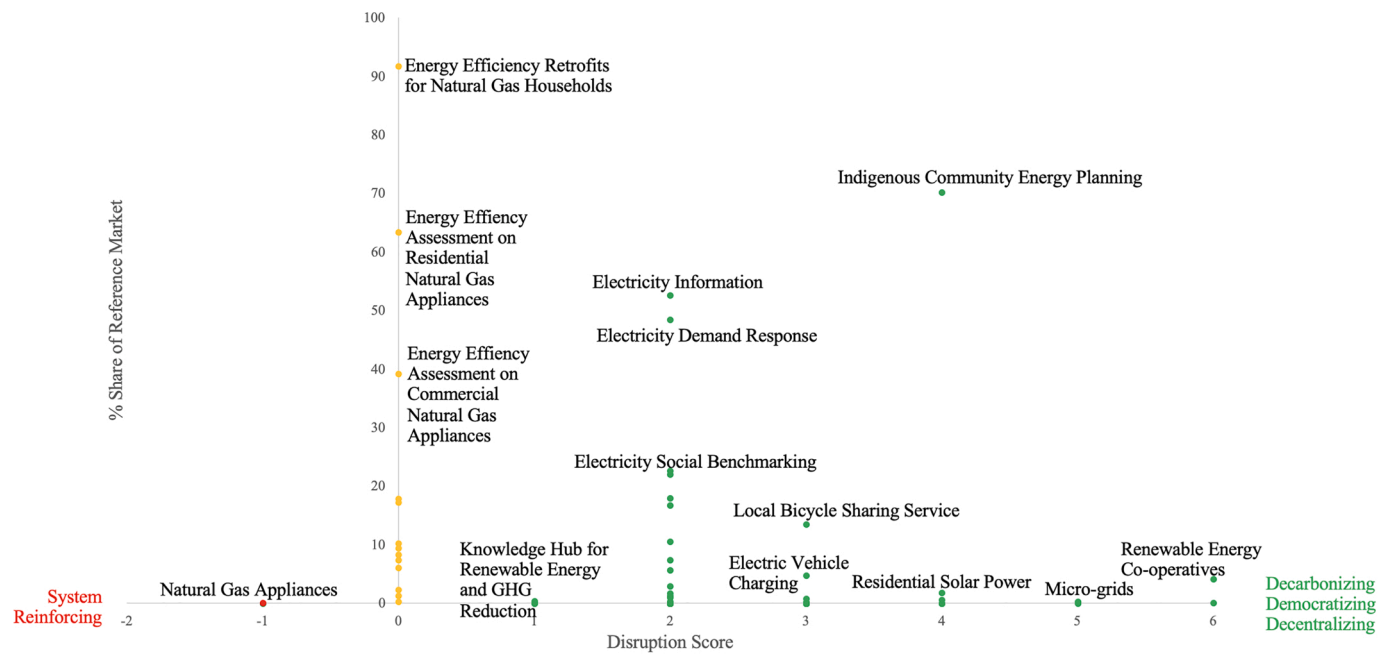


Fig. 2. dissemination rate and composite disruption score for innovations (n=80).

**Table 6**  
Summary of composite variables statistics (n=80)

Variables	Mean Score	Mode Score	Standard Deviation	Observed Range	Possible Range
Composite Disruption Score	+1.93	+2	1.682	(-2 – +6)	(-6 – +6)
Composite Policy and Legitimacy Support Score	+5.40	+7	1.920	(0 – +8)	(-10 – +10)

**Table 7**  
Correlation Results (n=80)

Variable	Dissemination Rate Correlation Coefficient
Decarbonization	-0.232**
Decentralisation	-0.121
Democratisation	-0.116
Economic Instruments	+0.276**
Regulatory Instruments	+0.054
Knowledge creation and diffusion instruments	-0.132
Legitimacy through discourse	+0.178*
Legitimacy through actors	+0.104
Composite Disruption Score	-0.222**
Composite Policy and Legitimacy Support Score	+0.161*

\*\* Significant at the 1% level (2-tailed).

\* Significant at the 5% level (2-tailed).

- A medium and highly statistically significant negative correlation relationship was found between composite disruption score and dissemination rate ( $t_b = -0.222$ ).

*Supports and diffusion:*

The findings indicate that each of the economic policy instruments, legitimacy through discourse and a combination of all policy and legitimacy supports are associated with low-carbon innovation diffusion.

- 1 A medium and highly statistically significant positive correlation between economic policy instruments and dissemination rate ( $t_b = +0.276$ ).
- 2 A weak and statistically significant positive correlation between legitimacy through discourse framing and dissemination rate ( $t_b = +0.178$ ).
- 3 A weak and statistically significant positive correlation between composite policy and legitimacy support scores and dissemination rate ( $t_b = +0.161$ ).

All other correlations are not statistically significant.

Given that economic policy instruments are found to be relatively important, **Table 8** outlines the breakdown of the economic policy instruments by instrument type for the innovations that were analysed. The most common type of economic policy instruments are incentives (46%), and the most common type of economic incentives are rebates (16%), followed by grants (14%). Financing is the second most common type of economic instrument (6%), with a fairly even spread across bonds, loans, local improvement charges, and other (or not specific). There are four non-material incentives observed across the innovations, and only one disincentive. These findings demonstrate that there is a strong emphasis on material incentives for economic policy instruments supporting the scale-up and diffusion of the innovations, and less emphasis on financial incentives for the innovations.

**Table 8**  
Types of Economic Instruments and their distribution (n=80).

Type of Economic Instrument	Frequency	Percent of Total Economic Instrument (%)	
Material Incentives	Payment for electricity produced	5	6
	Grant	11	14
	Pay per performance	0	0
	Rebate	13	16
	Tax credit	3	4
	Other/not specified	5	6
	Total (Material Incentives)	37	46
Non-Material Incentives	Pro-environmental behaviours (e.g. choosing a zero carbon mode of transportation for commuting)	4	5
	Disincentives	Price on carbon (cap and trade)	1
Financing	Bonds	2	3
	Loans	0	0
	Local improvement charges	2	3
	On-bill	0	0
	Other/not specified	1	1
Total (Financing)	5	6	

**5. Discussion**

The findings indicate that economic instruments, legitimacy through discourse, as well as combined policy and legitimacy supports all encourage the diffusion of low-carbon innovations to demand-side energy users in Ontario, while the the potential for decarbonization and of combined disruption dimensions are inhibiting. The key finding of this study is that, in a context where economic supports tend to be a focus of mainstream policy [126], combined supports for innovations are found to be important, which agrees with a similar previous research project by Clausen and Fichter [15] and Fichter and Clausen [45,132].

*5.1. Dissemination and disruption*

The correlation between decarbonization and dissemination rate confirms and measures this tendency towards the diffusion of fossil-fuel regime reinforcing innovations in Ontario’s energy system, reflecting, in empirical measurement, the theories, analyses and findings presented by Seto et al. [81], Unruh [16,18] and Wilson [9]. Until recently, the Province of Ontario, has been on a path of continued promotion of a breadth of policies supporting diffusion of natural gas efficiency innovations, rather than decarbonized sources of energy and fossil fuel replacing innovations. These policies were very successful in supporting natural gas innovations to achieve high market shares (see Fig. 2). For example, many energy efficiency policies offered competing rebates for heat pumps (disruptive on the decarbonization scale) as well as to natural gas furnaces (regime reinforcing), meaning that energy users had equal incentive to select either innovation. Other fossil fuel replacements, such as electric vehicles, also still had very low market share and lower support (Fig. 2). Although the scoring framework originates to the innovations found in Ontario, it is likely that it can be usefully applied to other jurisdictions in order to select low-carbon innovations to promote. For example, it is not unique to Ontario for policies to favour efficiency, rather than elimination fo natural gas for households—the 2022 attacks on Ukraine has revealed the continued dependence of European states on natural gas exported from Russia.

The relationship between the composite disruption score (the aggregation of scores of decarbonization, decentralisation and democratisation) and the dissemination rate shows a tendency for innovations to be system reinforcing, and reflects findings in the literature about strained relationships between incumbent, centralised energy systems, and new actors and technologies entering the socio-technical system.

Due to a legacy of a monopolistic electricity and gas system, Ontario's energy system is strongly controlled by incumbents [85]. An energy justice analysis using the same dataset found that 68% of innovations measured were offered by governments, utilities and the centralised planner (IESO), while the remaining innovations were offered by non-profit organisations and private businesses [123]. In the case of democratisation, the findings indicate that the demand-side innovations being offered to energy users do not put pressure on the disruption of control within the energy system. Similarly, in the case of physical decentralisation, no relationship between disruption and diffusion was found. The majority of innovations ( $n=64$ ) were found to have the potential for an incremental system change towards decentralisation, and very few innovations ( $n=8$ ) were disruptive. Ontario removed coal fired generation but continues to use mainly nuclear energy as a power source, the lack of flexibility measures available to energy users on the demand-side limits the dissemination of renewable energy technologies and the broader potential for decarbonization of the energy system, such as for the electrification of heating and transportation. Between 2012 and 2017, there was consumer adoption of renewables on the distribution grid [124], which in this study is measured as incremental change to infrastructure. The electricity system operator (IESO), despite having aspirations of localised smart energy systems, has only now begun to develop white papers for distributed generation, consumer preferences and choices, and enhancing distributed level products and services in 2019 [125], all of which would lead to disruptive change. Again, although these scoring scales were developed in Ontario, they can be usefully applied to other jurisdictions to understand if the degree of democratisation or decentralisation are different.

#### 5.1.1. Future research on dissemination and disruption

Future analyses can measure what combinations of incremental or disruptive innovations have the potential to change the strength and direction of these relationships. In order to achieve a strongly positive correlation between disruption and dissemination rate, there would need to be higher diffusion of radically disruptive innovations, and much lower diffusion of regime reinforcing innovations. In addressing the demand-side contribution to climate change, it would be helpful to address how to increase the diffusion of innovations with the potential for disruption along different dimensions, and how to decrease the diffusion of system reinforcing innovations. Furthermore, the right blend of optimal supports for low-carbon innovations can be investigated by analysing the relationships between the supports and the disruptive potential of the innovations.

#### 5.2. Supports and dissemination

The composite policy and legitimacy support score (the aggregation of scores of three policy instruments and two legitimacy supports) has an important impact on the diffusion of environmental innovations [45]. This study's findings reflect this, as innovations with higher combined policy and legitimacy supports had higher rates of diffusion, whereas those that lacked composite policy and legitimacy supports are associated with lower rates of diffusion.

The relationship between economic policy instruments and dissemination rate is expected. Economic policy instruments are often attributed as important to the diffusion of innovations [89,90,126]; the absence of such instruments have a negative effect on their diffusion and implementation [15,93,96]. While most of the innovations ( $n=59/80$ ) had economic instrument support, only 16 had technology-specific economic instruments (Table 5). The types of economic instruments employed in Ontario were varied, including payment for electricity produced, grant, pay per performance, rebate, tax credit, bonds, loans, local improvement charges and on-bill [127].

The literature review found mixed results in terms of whether regulatory instruments support the diffusion of innovations. For example, Negro et al. [96]'s analysis showed that the influence of regulations on

the diffusion of innovations can be either positive or negative and Bergek and Berggren [93] found that both general and specific regulatory instruments do not necessarily result in the development or diffusion of disruptive innovations. The findings of this study appear to reflect this, as relationships between regulatory instruments and dissemination rate were not found, although there was a relationship between combined policy supports and dissemination rate. Ontario policy tended to rely on broad targets and commitments in their long-term energy and climate change plans. For example, Ontario had a commitment to build a clean energy system that is more than 90% free of greenhouse gas emissions in its long term energy plan [128]. As a result, 62 innovations had general regulatory instrument support while only 4 innovations had technology-specific regulatory instrument support (Table 5).

Although knowledge creation and diffusion support the diffusion of low-carbon innovations [99], the lack of relationship found between knowledge creation and diffusion policy instruments and dissemination rate may be explained by multiple reasons. For example, Fichter and Clausen's [45] analysis showed that information-based instruments require strong regulations and economic instruments in a policy mix in order to be effective. Furthermore, although the influence of knowledge creation and diffusion on innovation diffusion is expected to be positive, other systemic factors, such as institutional or actor and network weaknesses, can weaken the diffusion of knowledge and information [99]. Jacobsson and Johnson [99] found that the amount of information and knowledge that is diffused in the system depends on the degree of connectivity (trust and collective identity) in the existing system, and the formation of connectivity relies on bridging institutions, actors and networks. The outcomes are, therefore, more nuanced. Across the sample, few of the innovations were found to be supported by knowledge creation and diffusion policy instruments; only 25 innovations had general support and only 3 had technology-specific knowledge support (Table 5). Ontario should be increasing supports for knowledge creation and diffusion, and the findings agree with Fichter and Clausen [45] that policy mix with balanced use of instruments are important and information-based instruments, such as public labelling schemes, can be very helpful in accompanying regulations and economic incentives. For example, despite the rise in electricity prices [124], the GreenButton program that provided standardised information to Ontario consumers had little uptake [37], demonstrating the price may not have been an important enough driver. Meanwhile, Ontario's natural gas prices remained relatively flat and low [124], so there may not have been enough drive to use information to reduce natural gas usage.

The literature states that both legitimacy through discourse and through actors are important to facilitate the diffusion of innovations [60,61,96,100–103,106–109]. Overall, the results demonstrate that there is generally strong legitimacy support across the sample of low-carbon innovations compared to the policy supports (see Table 5). Therefore, we would have expected to see a relationship between each of legitimacy through discourse and legitimacy through actors and dissemination rate, although only legitimacy through discourse and combined policy and legitimacy supports were found to be significant. Most of the innovations ( $n=75$ ) have legitimacy support through some degree of positive discourse framing and the vast majority ( $n=72$ ) have support from a network of actors and intermediaries (Table 5). Most of the innovations ( $n=62$ ) had a strong network of regime-level actors and intermediaries operating across policy domains (Table 5). At the same time, only 12 innovations were above 15% dissemination rate, and 68 below. The results indicate that legitimacy is a permitting factor, reinforcing the importance of combined supports.

#### 5.2.1. Future research on supports and dissemination

With regard to optimal supports for low-carbon innovations, one strength of Ontario's system revealed by this investigation is the high level of legitimacy support for many low-carbon innovations through both actors and networks and discourse, while weaknesses include emphasis on supporting regime-reinforcing innovations and weak

regulatory and knowledge creation and diffusion supports (see Table 5).

Immediate further research using this dataset describing Ontario could also explore the relationships between supports to identify how to enhance the blend of policy support and pathways to support the diffusion of disruptive innovations. This is supported by the literature, which indicates relationships between the supports themselves. For example, actors and networks of competing technology systems are known to strengthen knowledge creation and diffusion [99], and the mobilisation of policy support through realignment of institutions [130]. The legitimacy of an innovation and its actors are strongly related to institutional frameworks, and one important institutional alignment is the “redirection of science and technology policy in order to generate a range of competing designs” [130].

In the case of decentralisation, clusters and combinations of innovations adopted by the demand-side are increasingly important [72–74]. Further analysis could examine whether a relevant measure is the comparison of supports for diffusion across similar users of these complementary innovations that are required in infrastructure decentralisation [110,131].

### 5.3. Study limitations

A limitation of the study is the lack of information about the innovations required for analysis. While this did not affect the statistical analyses, it can affect policy decisions for particular innovations. This was not surprising, and one of the reasons for using surveys of stakeholders to gather information, as lack of energy data has long been an acknowledged problem in Canada [129]. The main issue is that dissemination rate variables for 51 innovations (over one third of the innovations studied) were not available. To gather uptake rates, the researchers contacted stakeholders through online and telephone surveys [37]. Many stakeholders were contacted to find population statistics, such as government entities (e.g. municipal economic development agencies), academic institutions and/or non-government organisations (e.g. environmental groups). During this time, the provincial conservative government elected in 2018 ended the government’s open data policy, and even less data was publicly available. Other information about the innovations that were required for coding, was more complex for some variables than for others. For example, the difference between the determination of a general or technology-specific economic instrument compared to determining legitimacy through actors score, which often required looking at networks and associations, funders, actors involved in the development and delivery of the innovation, information that was located in a variety of documents and the surveys. Despite these limitations, coding inter rater reliability was used in six rounds, and the level of agreement was “almost perfect” for all variables [37].

Furthermore, our data did not meet the criteria for causal regressions so this study cannot make empirical claims about the factors that *cause* diffusion. However, for all the factors analysed, we referenced the literature to understand their proven relationships with disruption and diffusion. We therefore have extensive supporting evidence based in the peer-reviewed literature to support our inferences about the direction of attribution.

## 6. Conclusion

One of the most important societal questions related to climate change is how to increase the diffusion of disruptive innovations and decrease the diffusion of system reinforcing innovations. Research is needed to discern the institutional frameworks and governance tools needed to achieve effective large-scale diffusion at a stage when technologies are commercially available and new demand-side actors become involved [41]. However, going beyond economic and technical analyses to understand how socio-technical transitions unfold is an interdisciplinary research challenge [40].

The main novelty of this study is identifying multiple demand-side

innovations within a specific energy system context (Ontario), characterising each innovations’ potential for socio-technical energy system change and the policy and legitimacy factors that drive or inhibit its diffusion. This framework incorporates demand-side actors, the niche innovation, the regime actors and the socio-technical system, demonstrating how a transition framework that is both empirical and quantitative and can integrate considerations of system actors, behaviours, innovations and infrastructure simultaneously. The contribution of this study goes beyond the diffusion of innovations, with a focus on the relationships between diffusion and system change, and the focus on system-wide analysis, with the articulation and measurement of three elements of disruption, developed to understand the potential for innovations to impact broad system change, and the articulation of five support variables to measure the system’s impact on the scale-up of these innovations, using a broad sample of innovations across the province’s energy system, users. This allows empirical measurement of the direction and strength of relationships between diffusion and system change, and offers a clearer understanding of whether innovations that are being diffused are reinforcing or disruptive to the socio-technical regime along the dimensions of decarbonization, decentralisation, and democratisation. It also evaluates the specific policy (economic, regulatory, informational) and legitimacy (actors, discourse) factors that drive or inhibit an innovation’s diffusion. The scores and correlation analyses, combined with an extensive literature review on causal factors, allowed for the measurement of whether a relationship exists, its strength, and direction. A key indicator of a transition would be a positive change in the relationship between disruption and diffusion, which our framework explicitly measures. This offers future researchers, policy-makers and system actors the ability to evaluate the various factors that either support or inhibit the diffusion of a range of innovations within a particular energy system.

The key finding of this study is that, in a context where economic supports tend to be a focus of mainstream policy [126], combined supports for innovations are found to be important. In the context of Ontario, innovations with disruptive and decarbonization potential are negatively associated with diffusion; economic policy instruments and legitimacy through discourse and combined supports are all positively associated with diffusion of low-carbon innovations on the demand-side. How to increase these supports is an important question, and further research should address the relationships between supports, for example, between legitimacy and policy instrument support. The findings confirm what the literature, including studies of the diffusion of singular innovations, have shown regarding the relationships between an innovation’s disruptive characteristics and diffusion, the relationship between economic policy and legitimacy through discourse and diffusion, and the range of combined supports on the diffusion of low carbon innovations.

While the scoring system and research originates in and focuses on the context of Ontario, the issue of the diffusion of low-carbon innovations and system change is a global concern, and therefore generalizable to other contexts. This transition framework and lessons learned can be applied to other contexts and energy systems this framework can be employed to predict and optimise diffusion, as the questions of impact and diffusion of innovations are currently important in the global need for carbon mitigation. The scoring system of the framework, and methodologies of this and suggested future research can be applied to the suite of demand-side low-carbon innovations in other jurisdictions in order to measure similar relationships through correlations and explore the same research questions. This would require identifying low-carbon innovations and their users within a particular jurisdiction. Some jurisdictions may have this information already gathered, while others may require gathering a dataset unique to the jurisdiction, to which Hoicka et al. [37] sampling methodology can be applied with the identification of the regimes and policy domains that influence the diffusion of low-carbon innovations in that jurisdiction. Finally, in the broader goal of developing transition frameworks that incorporate the

nuances of complex socio-technical system change, this framework can be incorporated into other models through what Li et al. terms a “landscape of models” approach, which bridges models and frameworks together.

### CRedit authorship contribution statement

**Christina E. Hoicka:** Conceptualization, Methodology, Investigation, Resources, Writing - Original Draft, Reviewer Response, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding Acquisition; **Yuxu Zhao:** Conceptualization, Data Curation, Methodology, Validation, Formal analysis, Investigation, Visualization, Writing - Original Draft, Reviewer Response, Writing - Review & Editing; **Maria-Louise McMaster:** Conceptualization, Data Curation, Methodology, Validation, Investigation, Writing - Original Draft, Reviewer Response, Writing - Review & Editing; **Runa R. Das:** training students in correlation method.

### Declaration of Competing Interest

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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