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

Final Report for the Energy Modelling Initiative--Initiative de modélisation énergétique

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Abstract

Decarbonized electrification has been identified as the most significant pathway toward achieving deep emissions reduction. The rapid diffusion of demand-side electrification-related innovations allows the demand sectors to reduce their end-use emissions by switching from fossil fuels to clean electricity. However, increasing the dissemination rate of electrification-related demand-side innovations is a challenge. Two types of models were developed to explore (1) the relationship between factors that influence the diffusion of electrification-related demand-side innovations; (2) the relationship between policy or legitimacy support, and disruptive characteristics of electrification-related demand-side innovations. These two models are important for understanding the factors that affect the diffusion of demand-side electrification-related innovations and their potentially disruptive impact on decarbonized electrification. Through correlation analysis, this research found that

- innovations with the potential to lead to decarbonized electrification are associated with lower rates of diffusion.
- innovations with strong economic policy support are associated with higher rates of diffusion.
- innovations with more potential to contribute to decarbonized electrification tend to have less technology-specific economic policy support.
- innovations with more potential to contribute to decentralization and democratization tend to have more legitimacy support. Legitimacy through actors tends to be a precondition to legitimacy through discourse framing.

Résumé

L'électrification décarbonée a été identifiée comme la voie la plus importante pour parvenir à une réduction importante des émissions. La diffusion rapide des innovations liées à l'électrification du côté de la demande permet aux secteurs de la demande de réduire leurs émissions d'utilisation finale en échangeant les combustibles fossiles pour des électricités propres et abordables. Cependant, augmenter le taux de diffusion des innovations liées à l'électrification du côté de la demande reste un défi. Deux types de modèles ont été développés pour explorer (1) la relation entre les facteurs qui influencent la diffusion des innovations liées à l'électrification du côté de la demande ;

(2) la relation entre le soutien politique ou de légitimité et les caractéristiques ruptureuses des innovations liées à l'électrification du côté de la demande. Ces deux modèles sont importants pour comprendre les facteurs qui affectent la diffusion des innovations liées à l'électrification du côté de la demande et leur impact potentiellement perturbateur sur l'électrification décarbonée. Grâce à une analyse de corrélation, cette recherche a révélé que:

- les innovations susceptibles de conduire à une électrification décarbonée sont associées à des taux de diffusion plutôt faibles.
- les innovations bénéficiant d'un fort soutien de la politique économique sont associées à des taux de diffusion plus élevés.
- les innovations ayant plus de potentiel pour contribuer à l'électrification décarbonée ont tendance à bénéficier d'un soutien de politique économique moins concernée par une technologie spécifique
- les innovations ayant plus de potentiel pour contribuer à la décentralisation et à la démocratisation ont tendance à bénéficier d'un soutien plus légitime. La légitimité à travers les acteurs tend à être une condition préalable à la légitimité à travers l'encadrement du discours.

Table of Contents

List of Tables

1 Introduction

Under the 2015 Paris Agreement, Canada committed to reducing its greenhouse gas emissions by 30% below 2005 levels by 2030. Decarbonized electrification has been identified as the most important pathway toward achieving deep emissions reduction in Canada (Bataille et al., 2015; Trottier Energy Future Project, 2016). Improving energy efficiency and deploying renewable energy on the supply side are both important and useful contributions in reducing emissions (Bataille et al., 2015). However, promoting demand-side decarbonization is equally important (Bataille et al., 2015). Numerous studies show that a demand-side transition to electricity plays an important role in deep emission reductions (Bataille et al., 2015; Creutzig et al., 2018; Mundaca et al., 2019; Sakamoto et al., 2021).

Decarbonized electrification on the demand-side can be achieved through the diffusion of demand-side electrification-related innovations (Sakamoto et al., 2021). Demand-side electrification-related innovations are defined as innovations that can enable demand sectors to reduce their end-use emission by switching from fossil fuel end-use innovations (i.e. gas furnace) to electricity end-use innovations (i.e. electric heat pump and electric vehicles) as well as participating in renewable energy generation (Bataille et al., 2015; Sakamoto et al., 2021). However, the extent to which this transformation can be implemented is limited to the disruptive characteristics of the innovation and the diffusion rate of the innovations (Dixon et al., 2018; Wilson, 2018).

Diffusion is the process through which these innovations are communicated through societal channels over time, gaining increasing market share through widespread adoption and continued use (Karakaya et al., 2014). However, there are many research gaps in understanding how quickly multiple demand-side low-carbon innovations can be diffused in an urgent and accelerated time frame. 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. Our research is critical for filling this gap by creating a novel methodology for identifying multiple demand-side innovations and building a more comprehensive understanding of the diffusion of multiple innovations.

Two models were developed. The first model explores the relationship between factors that influence the diffusion of innovations and their dissemination rates. The factors include three characteristics of the innovation (decarbonization, decentralization, democratization), three policy variables (economic, regulatory, knowledge creation and diffusion instruments), and two legitimacy variables (discourse and actors) The first model can help us to understand how to accelerate dissemination of disruptive innovations or clusters of innovations that collectively contribute to a low-carbon energy transition. Second, this paper investigates the relationship between policy or legitimacy support and the characteristics of the innovations. This can help us understand how policy and industry can support the diffusion of innovations that contribute more strongly to decarbonization pathways or clusters of innovations that collectively contribute to decarbonized electrification.

2 Model and Methodology

In sustainability transitions theory, disruptive innovations emerge in the context of socio-technical regimes, the institutional structuring of existing systems that favour path dependence and incremental change (Köhler et al., 2019).

- *Disruptive innovations* create major societal change, including introducing new social values and political beliefs (Dixon et al., 2018; Johnstone et al., 2020; Wilson, 2018).
- *Incremental innovations* refer to improvements to products/services within or outside an existing technological paradigm (Dixon et al., 2018; Wilson, 2018). Incremental innovations offer improved cost-benefits to consumers for products/services in an already established market (Dixon et al., 2018). These innovations do not offer novel attributes to disrupt the socio-technical system.
- *Regime reinforcing innovations* are typically path-dependent and work to stabilize the incumbent socio-technical system by perpetuating system-reinforcing characteristics, such as operating under favorable regulations to the established regime, contributing to large sunk costs in industry investments, benefiting from established economies of scale, and preserving entrenched social norms and behavioral routines that support the incumbent regime (Geels & Johnson, 2018). These types of innovations perpetuate carbon lock-in, the path dependency of complex systems of existing technologies, institutions, and behavioral norms that act in combination to constrain the rate and magnitude of carbon emissions reductions (Seto et al., 2016).

2.1 Model framework

The methodology, analytical framework and lessons learned from a larger research project were applied as empirical analysis for this research paper (Hoicka et al., 2021). The methodology applied in this research paper is focused on electrification-related demand-side innovations while the larger research project investigated all the demand-side low-carbon innovations, which included non-electrification innovations such as, for example, the public bike share scheme.

2.1.1 Sample

The sample of this research paper is 114 electrification-related innovations selected from the dataset of the larger research project. The larger research project had a dataset of 131 low-carbon innovations that had been offered to energy users in the Province of Ontario, Canada, between 1998 and 2018. The dataset was gathered through desk research, a survey of experts across four policy domains of energy, environment, innovation and social innovation sectors, and a survey of the providers of the innovations themselves (Hoicka et al., 2021). Some examples of innovations include: a municipal energy planning program, electric vehicle charging policy incentives, a community energy storage project, energy audits and regional sustainability initiatives.

To focus on decarbonized electrification, the first step of this research was to identify the electrification-related innovations from the larger dataset. Compared to other demand-side low-carbon innovations, electrification-related innovations are those that can allow low-emitting electricity to capture a larger share of total energy use across the different sectors and provide a low-cost pathway for end-users to switch from fossil-fuel based energy system (Bataille et al., 2015). Low-emitting electricity refers to the electricity that is generated with lower amounts of carbon emissions than is emitted from fossil fuel power generation (Bataille et al., 2015). The generation sources of low-emitting electricity include wind power, solar power, hydropower and etc. There are six types of electrification-related innovations identified in our sample:

1. Using renewable energy sources, such as Large Renewable Procurement, a competitive process for procuring large renewable energy projects (Stokes, 2013);
2. Increasing the capacity of electricity storage. The main issue with intermittent renewable energy, such as wind or solar is the lack of dependable capacity they can offer. Electricity storage technologies can store excess energy and release them when wind speed falls or sunshine is limited;
3. Transport electrification, such as rechargeable plug-in hybrid and electric vehicles. The construction of electric vehicle charging stations is also required for transport electrification;
4. Improving the performance of the electricity grid, such as smart grid technology;

5. Reducing electricity use and carbon emissions with energy conservation, energy efficiency and demand-side management, for example, building envelope retrofits (Trottier Energy Future Project, 2016). However, innovations that reinforce the existing fossil fuel regime, like fossil fuel furnaces, were not included because they are path-dependent and work to stabilize the incumbent fossil fuel instead of leading to decarbonized electrification.
6. Fuel switching from a non-electricity carrier to electricity. For example, replacing a natural gas furnace with a heat pump.

Electrification-related innovations were selected if the aim of these innovations falls in the aforementioned types. 114 innovations in the dataset address electrification and 17 do not.

2.1.2 Dissemination rate

The diffusion of the electrification-related innovation has been identified as a key factor that will influence the impact of an innovation on decarbonized electrification (Sakamoto et al., 2021). The dissemination rate variable was used to assess the state of market diffusion for each innovation (i.e. the degree to which an innovation has diffused into a certain population) (Clausen & Fichter, 2019). The formula to calculate the *Dissemination rate* is:

$$Dissemination\ rate = \frac{Uptake\ of\ the\ \ innovation}{Population\ size\ of\ the\ reference\ market}$$

The population size of the reference market is the number of the potential users of this innovation, which is 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 provided in Hoicka et al., (2021).

The uptake of the innovation refers to the number of the innovations that are currently in use (Clausen & Fichter, 2019). Uptake data was identified through desk research and responses from Survey 2. The total number of innovations with available uptake information was 81 out of the total 131 innovations (Hoicka et al., 2021).

In this research paper, since we are only interested in electrification-related innovations, the total number of innovations with available uptake data was 69. Therefore, dissemination rate was calculated for 69 innovations.

2.1.3 Characteristic and support variables

Eight variables that describe the innovation's disruptive characteristics, and the policy and legitimacy supports for the innovation's scale-up. The coding and conceptualization of these variables create the foundation for the 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 decarbonized electrification.

Besides the dissemination rate of the electrification-related innovations, the extent to which decarbonized electrification can be achieved is also limited to the disruptive characteristics of the innovation (Dixon et al., 2018; Wilson, 2018). The two models are concerned with three dimensions of disruption: decarbonization, decentralization, and democratization. Three characteristics of disruption were analysed by developing a coding scale to measure the extent to which the innovation was regime reinforcing, neutral (status quo), incremental, or disruptive (Table 1). Although the scale for each variable was developed independently, Table 1 describes a general coding scale and explanation of each score, from -2 to +2 as they relate to measuring disruption. All scales and details of the code development are provided in detail in Hoicka et al. (2021).

The characteristics of disruption were captured in the variables:

- Decarbonization: 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.
- Decentralization: the degree to which the innovation geographically decentralized from current centralised energy regime

- Democratization: the degree to which the incumbent gains control/market share, or whether citizens or communities gain control of the energy system.

Table 1 Coding Innovations

Score	Scale Definition	Literature
-2	Strongly reinforcing the regime	(Dixon et al., 2018; Geels, 2018; Johnstone et al., 2020; Johnstone & Kivimaa, 2018; Rosenbloom et al., 2016; Wilson, 2018; Wilson & Tyfield, 2018)
-1	Slightly reinforcing the regime	
0	No change to the regime	
1	Incremental change to the regime	
2	Disruptive leading to regime transformation	

Policy instruments can both inhibit or drive scale-up of the innovation. Interlocking systemic forces create socio-technical and policy inertia that sustain the existing regime and prevent the emergence of low-carbon innovations (Unruh, 2000). 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 (Seto et al., 2016). The resistance to adopt new, innovative technologies is due in part to self-reinforcing incentives: path-dependent processes that reinforce positive feedback loops, creating further resistance to regime change among carbon intensive industries and institutions (Seto et al., 2016). 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 (Seto et al., 2016).

Policies that support the scale-up of niche innovation play an important role in influencing socio-technical regime change through the diffusion of disruptive demand-side low-carbon innovations. Three policy variables were constructed to analyze the factors that influence the disruptive characteristics of the electrification-related innovations and the diffusion of the innovation.

- Policy for scale-up: economic instruments: the degree to which economic instruments are used to support or inhibit the scale-up of an innovation. economic instruments are economic incentives or market-based schemes that provide energy users with motivations to adopt innovations. Some examples of economic instruments are tax exemptions, cap and trade, and deployment subsidies.

- Policy for scale-up: regulations: the degree to which regulatory instruments are used to support or inhibit the scale-up of an innovation. Regulatory instruments are direct regulations that aimed at controlling the actions of energy users through command and control, such as the presence or removal of target or commitment for particular sector mentioned in long-term energy plan or climate change plan
- 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. knowledge creation and diffusion are those educational policies, training schemes and labor-market policies that influence knowledge creation, development and diffusion, market formation and resource mobilisation.

Policy instruments can be general or innovation-specific policy instruments (Bergek & Berggren, 2014). General policy instruments aim at providing general support or regulations to an entire industry without pinpointing any particular technology, such as carbon tax and cap-and-trade (Bergek & Berggren, 2014). Technology-specific instruments support specific innovations (Bergek & Berggren, 2014). Regime change is unlikely to occur without innovation-specific policies to support niche innovation (Elzen et al., 2004). If the policy instrument is general, this policy was coded as having incremental impacts on the scale-up of the innovation. If the policy instrument is technology-specific, this policy instrument was coded as having disruptive impacts on the scale-up of the innovation.

Building legitimacy for niche innovations to support their scale-up is a key factor that influences socio-technical system disruption. Based in the literature review, two legitimacy support variables were developed.

- Legitimacy through discourse framing: the degree to which discourse supports or inhibits the scale-up of an innovation. building legitimacy of niche innovations through positive discourse framing or visioning strategies by actors. Some examples of discourse are action plans, annual reports, and 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)

- Legitimacy through actors and networks: the degree to which actors and networks support or inhibit the scale-up of an innovation. The presence or absence of actors (e.g. individuals, organizations, and institutions) with agency will influence the diffusion of niche innovations across multiple scales. 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.

Composite scores were also constructed to measure combined impacts. Composite variables are constructed by aggregating scores on two or more individual variables into an overall score, which allows the measurement of factors that are highly related to one another conceptually or statistically as a whole (Ley, 1972). To investigate the correlations between composite variables and dissemination rate, five composite variables were created based on the eight individual variables.

- Composite characteristics variable: a summation of the three characteristics variables of decarbonization, decentralization, democratization.
- Composite policy variable: a summation of the three policy variables, economic, regulatory, and knowledge creation and diffusion instruments.
- Composite legitimacy support variable: a summation of the two legitimacy variables, legitimacy through discourse framing and legitimacy through actors and networks.
- Composite support variable: a summation of the three policy variables and the two legitimacy supports.
- System innovation score: a summation of all eight variables, the three characteristics, three policy variables, and two legitimacy variables.

2.2 Model accessibility

The model is accessible through the MethodsX paper that publishes in detail each stage of the models' development (Hoicka et al., 2021). It employed four types of software that are accessible:

- *Qualtrics* for developing and distributing surveys;
- *Google docs* for collectively developing scale tables for each variable;
- *Spreadsheets* for data recording, coding and cleaning;
- *SPSS Statistics* for data modeling and analysis.

If this methodology were to be performed in another context, in the case when there is not a list of innovations for a particular energy system, then a sample of demand-side low-carbon innovations must be compiled. The methodology to compile the sample is available in the contextualization section of the Methods X paper that describes the methodology to gather a sample and the dissemination rates through desk research and surveys (Hoicka et al., 2021). In this case, Qualtrics or survey software and spreadsheets are required.

If a complete list of innovations is available for coding, then Qualtrics is not required. When a list of innovations is available, a profile for each innovation must be created to record the necessary information in the spreadsheets (Excel in our case).

Google docs was used for multiple researchers to create scales for each variable at the same time. The scale table for each variable was provided in Hoicka et al., (2021). After finalizing the scale tables, spreadsheets were used to do data coding and cleaning. The scales are described in detail in Hoicka et al. (2021) and can be applied to the sample of innovations.

After finalizing the datasets, data contained in spreadsheets were exported to SPSS Statistics for data modeling and analysis, including calculating Cohen's Kappa coefficient, dissemination rate and Kendall's tau-b correlation coefficient. The details of how this can be done is provided in Hoicka et al., (2021).

2.3 Scenario development process

114 demand-side electrification-related innovations were identified as related to decarbonized electrification. In order to improve our understanding of the potential impact an innovation can have on decarbonized electrification and socio-technical system change, two types of models were developed to explore the disruptive characteristics and diffusion of these 114 innovations.

Kendall's tau-b (t_b) correlation coefficient was selected to measure the relationship between the variables in the models. Kendall's tau-b (t_b) correlation coefficient is calculated based on the ranks of the data, not from their actual values (Akoglu, 2018). Kendall's tau-b correlation coefficient was chosen over other statistics (such as Pearson correlation coefficient) because the scores of certain variables (e.g. Democratization) are clustered around 0 and +1. According to Akoglu (2018), it is more suitable to use Kendall's tau-b correlation coefficient when the same rank is repeated many times in a small dataset. Kendall's tau-b correlation results can be assessed at both the 5% and 1% levels of significance (Table 2). A correlation statistic can provide information about the strength and direction of the relationship between two variables (Akoglu, 2018). The strength or weakness of the correlation between two variables is based on Kendall's tau-b correlation coefficient (Table 3). Correlations can be both statistically significant (Table 2) and have various correlation strengths (Table 3).

Table 2 Interpreting Statistical Significance

Significance Level	Significant	Interpretation
>=5%	Not statistically significant	Occurred by chance
< 5%	Statistically significant	Less than one in twenty chance of being wrong
< 1%	Highly statistically significant	Less than one in a hundred chance of being wrong

Table 3 Kendall's Tau-b correlation strength (McHugh, 2012)

Coefficient	Correlation Strength
$0.0 \leq \tau_b < 0.05$	No correlation
$0.05 \leq \tau_b < 0.20$	Weak correlation
$0.20 \leq \tau_b < 0.50$	Medium correlation
$0.5 \leq \tau_b$	Strong correlation

The first model investigates the relationship between each characteristic and support and the diffusion of innovations. This model can help us to understand how to accelerate dissemination of disruptive innovations or clusters of innovations that collectively contribute to disruptive change. Kendall's tau-b correlation analysis was employed to measure:

- the relationship between each characteristic variable and the dissemination rate; and
- the relationship between each support variable and the dissemination rate.

The second model investigates the relationship between each policy or legitimacy support and each disruptive characteristic. This helps to understand how policy and actors and networks can support the diffusion of disruptive innovations or clusters of innovations to contribute to disruptive change. Kendall's tau-b correlation analysis was run to measure:

- the relationship between each characteristic variable and each support variables;
- relationship between each policy variable and each legitimacy support variable; and
- the relationship between the two legitimacy support variables.

3 Modelling Results and Analysis

3.1 Modelling results

The results of these specific correlations are indicated in Table 4. The key findings are that:

- The correlation between dissemination rate and economic instruments variable (+) is highly statistically significant (1%) and of medium strength.
- The correlation between dissemination rate and decarbonization (-) is statistically significant (5%) and of weak strength.
- Statistically significant effects of other system innovation variables on dissemination rate cannot be found.

Table 4 Kendall's Tau-b Correlation: characteristic, policy and legitimacy variables and dissemination rate

Variables	Relation to dissemination rate
Decarbonization	-.189*
Decentralization	-0.143
Democratization	-0.096
Policy for scale-up: economic instruments	.304**
Policy for scale-up: regulations	-0.003
Policy for scale-up: knowledge creation and diffusion	-0.046
Legitimacy through discourse framing	.173
Legitimacy through actors and networks	0.067

* significant at 5% level, ** significant at 1% level

The results of these specific correlations are presented in Table 5. The key findings of the correlations between composite system innovation variables and dissemination rate are that:

- The correlation between the composite characteristics variable and dissemination rate (-) is statistically significant (5%) and of weak strength.
- The correlation between the composite support variable and dissemination rate (+) is statistically significant (5%) and of weak strength.
- No statistically significant correlation can be found between system innovation score and dissemination rate.

Table 5 Kendall's Tau-b Correlation: system innovation composite variables and dissemination rate

Composite variables	Relation to dissemination rate
System innovation score	0.007
Composite characteristics	-0.194*
Composite support	0.183*

* significant at 5% level, ** significant at 1% level

The results of these specific correlations are presented in Table 6. The key findings of the correlations between characteristics variables and policy or legitimacy variables are:

- The correlation between decentralization and each legitimacy variable and the composite legitimacy variable (+) is highly statistically significant (1%) and of medium strength.
- The correlation between democratization and economic instruments (-) is highly statistically significant (1%) and of medium strength.
- The correlation between decarbonization and economic instruments (-) is statistically significant (5%) and of medium strength
- The correlations between democratization and each legitimacy variable and the composite legitimacy support (+) are statistically significant (5%) and of medium strength
- No statistically significant correlation can be found for any other characteristics and support variables.

Table 6 Kendall's Tau-b Correlation: characteristics and supports

Variables	Decarbonization	Decentralization	Democratization
Policy for scale-up: economic instruments	-0.202*	-0.037	-.250**
Policy for scale-up: regulations	-0.043	0.053	0.069
Policy for scale-up: knowledge creation and diffusion	-0.020	-0.109	-0.052
Composite policy support	-0.146	-0.076	-0.151
Legitimacy through discourse framing	0.105	0.286**	0.281*
Legitimacy through actors and networks	0.156	0.362**	0.234*
Composite legitimacy support	0.129	0.321**	0.275*
Composite support	-0.033	0.123	0.058

* significant at 5% level, ** significant at 1% level

The results of these specific correlations are presented in Table 7. The key findings of the correlations between policy variables and legitimacy support variables are

- The correlation between legitimacy through discourse framing and economic instruments (+) is highly statistically significant (1%) and of medium strength
- The correlation between legitimacy through discourse framing and composite policy support (+) is highly statistically significant (1%) and of medium strength
- The correlation between composite legitimacy support and economic instruments (+) is highly statistically significant (1%) and of medium strength
- The correlation between composite legitimacy support and composite policy support (+) is highly statistically significant (1%) and of medium strength
- The correlation between legitimacy through actors and networks and economic instruments (+) is statistically significant (5%) and of weak strength
- The correlation between legitimacy through actors and networks and composite policy support (+) is statistically significant (5%) and of weak strength
- No statistically significant correlation can be found between regulations and each legitimacy variable and the composite legitimacy support, as well as between policy for scale-up: knowledge creation and diffusion and each legitimacy variable and the composite legitimacy support.

Table 7 Kendall's Tau-b Correlation: policy variable and legitimacy support variable

Variables	Legitimacy through discourse framing	Legitimacy through actors and networks	Composite legitimacy support
Policy for scale-up: economic instruments	0.270**	0.171*	0.243**
Policy for scale-up: regulations	0.100	0.038	0.079
Policy for scale-up: knowledge creation and diffusion	0.101	0.134	0.120
Composite policy support	0.251**	0.192*	0.241**

* significant at 5% level, ** significant at 1% level

Correlation between two legitimacy variables is highly statistically significant and of strong strength (Table 8). The correlation is also positive between these two variables.

Table 8 Kendall's Tau-b Correlation: two legitimacy support variables

Variables	Legitimacy through discourse framing
Legitimacy through actors and networks	0.700**

* significant at 5% level, ** significant at 1% level

3.2 Electrification and decarbonization pathways

The results demonstrate that the innovations that are able to achieve successful diffusion only have the potential to create incremental system change, not the accelerated and transformative change we need. This is demonstrated through the following findings:

- Demand-side low-carbon innovations with the potential to lead to decarbonized electrification pathways are associated with lower rates of diffusion.
- Decarbonization correlates significantly with the dissemination rate and the correlation between these two variables is negative (Table 4), which indicates that electrification-related innovations with disruptive decarbonization characteristics are associated with lower rates of diffusion compared to innovations with incremental decarbonization characteristics.
- The negative association between disruptive decarbonization characteristics and the rate of diffusion signifies a barrier to electrification and decarbonization pathways through the diffusion of existing innovations.

The finding from Table 4 demonstrates that innovations with more technology-specific economic policy instruments are associated with higher rates of diffusion. The positive correlation between dissemination rate and economic instruments are highly statistically significant (1%) and of medium strength (Table 4), meaning that electrification-related innovations with technology-specific policy support through economic instruments are associated with higher rates of diffusion compared to innovations with general economic policy instruments. General economic instruments can only provide general support or regulations to a specific industry without pinpointing any particular technology, such as carbon tax and cap-and-trade, while technology-specific instruments can support specific innovations (Bergek & Berggren, 2014). Without technology-specific policies to support niche innovation, regime change is not likely to occur (Elzen et al., 2004).

Innovations with higher potential to contribute to decarbonized electrification tend to have less technology-specific economic policy support. This is demonstrated by the finding that the correlation between decarbonization and economic instruments is negative (Table 6), This negative correlation indicates that innovations with more disruptive decarbonization potential usually receive less technology-specific economic support compared to innovations that have incremental impacts on the socio-technical regime change. Therefore, more technology-specific economic policy instruments to accelerate dissemination of demand-side electrification-related innovations need to be established.

To illustrate this with an example, electric vehicles are an electrification innovation studied in our research with disruptive decarbonization characteristics (+2). Due to carbon lock-in, it is not easy for electric vehicles to earn more market share than the traditional internal combustion engine models, which are powered by gasoline. 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 (Unruh, 2000).The fossil fuel regime remains locked-in through the complex network of technological, institutional, infrastructural and behavioral 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 (Seto et al., 2016; Unruh, 2000). Policy instruments that support electric vehicles are mostly general instruments, which only have incremental impacts on the scale-up of the innovation. The implementation of technology-specific economic instruments could help electric vehicles to break the carbon lock-in by creating favorable market conditions for electric vehicles, such as providing tax credits towards purchase of electric vehicles.

The findings also show that innovations with more potential to contribute to decentralization and democratization tend to have more legitimacy support in the form of discourse framing and visioning strategies, and in the form of presence of actors facilitating scale-up across multiple scales. innovations with disruptive democratization characteristics are associated with more legitimacy support rather than innovations with incremental democratization characteristics. innovations with disruptive decentralization characteristics are associated with more legitimacy support compared to innovations with incremental decentralization characteristics.

The correlation between the two legitimacy variables indicates that legitimacy through actors and networks tends to be a precondition to legitimacy through discourse framing. Legitimacy requires a strong network of system actors that actively support the innovation across scales (or policy domains).

4 Discussion

4.1 Accessibility and transparency

The models discussed in this paper are accessible and transparent. The details of the models are provided in Hoicka et al., (2021), which is published in an open access journal. The theoretical framework, sampling design, data gathering, codebook design, coding process and interrater reliability test, correlation analysis and results interpretation for the model are all outlined in the aforementioned methods paper.

The software used in this research includes Qualtrics, Spreadsheets, Google docs and SPSS Statistics, which are all accessible online. Alternatives to the software are also easy to access online.

4.2 Usability for policy design

This model has the ability to assist policy-makers in mapping the existing range and combination of policy and legitimacy supports that drive or inhibit system-wide decarbonization within their jurisdictions. This type of analysis can also provide policy insights into which mix of supports can lead to accelerated system change, and which will lead to fossil fuel energy system reinforcement. The methodology, analytical framework and lessons learned from this research can be replicated and applied as empirical analysis by policymakers and practitioners to a variety of contexts to inform the allocation – or reallocation – of resources towards innovations that have the potential to create transformation in the energy system and accelerate system-wide decarbonization. This research can be used to inform policy design in the following ways:

- Initial descriptive statistics of the coding 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.
- Correlation analyses between the individual variables and dissemination rate can be used to examine how to drive or inhibit diffusion of an innovation within a particular context.

- To determine whether, across a mix of innovations in a particular energy system, system reinforcing innovations are receiving more policy and legitimacy support than innovations that support decarbonization and electrification pathways. For example, providing more support for the scale-up of efficient natural gas furnaces compared to deep retrofits of building envelopes coupled with heat pumps.
- To support decision making about how to provide optimal policy and legitimacy support to the right mix of low-carbon innovations to diffuse into markets and support decarbonization and electrification pathways. For example, whether disruptive innovations can decarbonize, decentralize and democratize the energy system; or whether complementary innovations, such as solar and wind power, or electric vehicles and demand response, are receiving similar support for scale-up to achieve optimal outcomes.

4.3 National modelling platform

While this research focuses on the context of Ontario, the analytical framework and lessons learnt from these research models can be applied to other contexts. Since electricity systems are governed and managed by provinces and territories, practitioners or policy makers have to apply these models to each province and territory individually. In the context of Canada, energy systems are controlled and under the authority of provincial governments, and as such, the factors that facilitate the diffusion of low-carbon innovation in the Province of Ontario may differ from those of other Canadian provinces. Moreover, the factors that influence system innovation may also differ depending on market structures, available resources, provincial politics, etc. There is a benefit to conducting this type of analysis at the regional and local level in order to gain context specific insights into how a low-carbon energy transition can be accelerated.

To integrate the research models in a national modeling framework, workshops with practitioners or policy makers from all provinces could guide them through how to do sampling design, data gathering, data coding and interrater reliability test, correlation analysis and results interpretation.

One of the benefits of integrating the research models in a national modeling framework is to increase data accessibility. The major limitation of the models was access to sufficient innovation uptake and population data. Dissemination rates could not be calculated for innovations with missing uptake and population data, which limited the ability of the researchers to conduct statistical analyses and produced limited research findings for the dissemination rate variable. Being integrated in a national modelling platform presents opportunities for future collaboration in filling these data gaps. The integration can also contribute to the improvements and expansion of the research models.

5 Conclusion

Canada committed to reducing its greenhouse gas emissions by 30% below 2005 levels by 2030 under the 2015 Paris Agreement. Decarbonized electrification has been identified as the most important pathway toward achieving deep emissions reduction in Canada. In order to achieve decarbonized electrification, it is crucial to facilitate diffusion of disruptive electrification-related innovations. This research employed the dissemination rate to indicate the state of market diffusion for each innovation. This research also analyzed the disruptive characteristics of the innovation and their correlations with the diffusion of the innovation.

Through correlation analysis, this research found that innovations with the potential to lead to decarbonized electrification are associated with lower rates of diffusion, while innovations with strong economic policy support are associated with higher rates of diffusion. However, innovations with higher potential to contribute to decarbonized electrification tend to have less technology-specific economic policy support. Therefore, technology-specific economic instruments are important to the diffusion of electrification-related innovations and their potential to contribute to low-carbon energy transitions. More technology-specific economic instruments should be implemented to facilitate the diffusion of innovations. This research also found that electrification-related innovations with more potential to contribute to decentralization and democratization tend to have more legitimacy support. Legitimacy through actors tends to be a precondition to legitimacy through discourse framing. Hence building legitimacy is also important to drive or inhabit the potential of an innovation to contribute to electrification and decarbonized pathways.

The analyses described above are a few key examples of the potential applications of the analytical framework. This research 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 any other jurisdictions. This research project is critical for building a more comprehensive understanding of low-carbon innovation diffusion, and also increasing the replicability of the research methodology and broaden potential insights and research applications in this field.

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