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Charging infrastructure for electric vehicles in Multi-Unit Residential Buildings: Mapping feedbacks and policy recommendations

Diana Lopez-Behar[a], Martino Tran[b,*], Thomas Froese[a], Jerome R. Mayaud[b,*], Omar E. Herrera[c], Walter Merida[c]

[a] Department of Civil Engineering, University of British Columbia, 2002-6250 Applied Science Lane, Vancouver, BC, Canada V6T 1Z4

[b] Centre for Interactive Research on Sustainability, School of Community and Regional Planning, University of British Columbia, 6333 Memorial Road, Vancouver, BC, Canada V6T 1Z2

[c] Department of Mechanical Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, BC, Canada V6T 1Z4

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ABSTRACT

Achieving meaningful reductions in greenhouse gas emissions from the global transportation sector will rely on a large-scale transition to electric vehicles (EVs). Many governments aim to encourage the uptake of EVs in cities, because urban areas are well suited to EV driving ranges and stand to benefit hugely from reduced local emissions. In the Canadian province of British Columbia (BC), where clean renewable electricity sourcing makes EV deployment an attractive proposition, over a quarter of residents live in Multi-Unit Residential Buildings (MURBs), most of which are not equipped with EV charging infrastructure. In a related study, Lopez-Behar et al. (accepted) explored the challenges and decision-making processes involved in the installation of EV charging infrastructure in MURBs in BC, from the perspective of different stakeholders. Here, we build on those findings to map out and analyze feedback loops within this system using a Causal Loop Diagram (CLD). We then present potential demand-focused policy interventions to address the issues raised by our modelling results, grouped into three categories: financial/fiscal, regulatory and information/awareness measures. Financial/fiscal policy measures include creating incentives for EV owners and extending them to the building owners, and programs to incentivize and provide financial aid for building owners to develop building retrofit plans. Regulatory policy measures include addressing the rights and obligations of the stakeholders and making mandatory the installation of charging stations in new MURBs. Information/awareness policy measures include expanding the existing guidelines and informing the development of a long-term EV charging infrastructure plan. Our policy recommendations are designed to inform the interventions of municipal and provincial governments in BC, but could also be relevant to many urban EV markets worldwide.

1. Introduction

With the Paris Agreement aiming to maintain global average temperature rise to below 2 °C (United Nations, 2016), achieving meaningful reductions in greenhouse gas (GHG) emissions is a stated priority for most countries and many large cities (C40 Cities and ARUP, 2016). A recent report by McKinsey and C40 Cities (2017) suggests that 'next-generation mobility' measures – of which vehicle electrification is an important component – could contribute 20–45% of total planned emissions reductions. Electric vehicles (EVs) can reduce fossil fuel dependency in the transportation sector, as long as they are powered with sustainable sources of electricity such as solar or hydropower (Bradley and Frank, 2009; Williams et al., 2012; Tran et al., 2013). The increasing availability and affordability of EVs means they are rapidly becoming viable alternatives to traditional fossil fuel vehicles (Egbue and Long, 2012; Tran et al., 2012; Impey, 2013). Indeed, worldwide EV sales increased by 40% between 2016 and 2017, with more than 2 million EVs now on the road (IEA, 2017). This increase is mainly attributable to market growth in developed and industrializing countries, with the largest contributions to absolute global sales coming from China (~ 330,000 new EVs in 2016) and the US (155,000 new EVs in 2016). National EV market shares vary significantly across developed countries, from 0.9% in the US and 1.4% in the UK to 6.4% in the Netherlands and 28.8% in Norway (IEA, 2017). However, conventional fossil fuel vehicles maintain a significant market lead relative to EVs, in a case that could be described as technological lock-in (Cowen and

* Corresponding authors.
E-mail address: martino.tran@ubc.ca (M. Tran).

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Hulten, 1996). Increased EV uptake could be achieved via several mechanisms, an important one of which is active governmental support to help accelerate change through reasonable policy prescriptions.

Policy instruments such as regulation, taxation, subsidies and incentives will be key for accomplishing a large-scale EV transition (Tran et al., 2012). Strong governmental support is needed through a combination of supply-focused and demand-focused policies (Brand et al., 2013; Wolinetz and Axsen, 2017). Supply-focused policies incentivize vehicle suppliers to develop and sell more efficient EVs, and to increase the models available to potential buyers. In California, low carbon fuel standards and a zero-emissions vehicle mandate have put the onus for electrification on vehicle and fuel suppliers (van der Steen et al., 2015). Governments can also provide R&D funding to further support the development of EV technology and infrastructure (Ahman, 2006).

Demand-focused policies, on the other hand, seek to directly increase consumer interest in EVs through purchase subsidies, making available charging infrastructure and other non-financial incentives. For instance, several US states propose tax credits and rebate programs to help EV buyers offset the costs associated with installing charging infrastructure, as well as regulatory initiatives that include permit streamlining and building code revisions. Norway has introduced aggressive demand-focused policies, including vehicle tax exemptions, perks such as free municipal parking and toll-free roads and ferries, and the deployment of public charging stations on all main roads to cover long-distance trips (EV Norway, 2018). Demand management also involves decreasing the relative appeal of conventional vehicles: EV-only driving lanes and zero- or low-emissions zones prohibiting high-emission vehicles are being implemented in over 220 cities across 14 European countries (Urban Access Regulations, 2018). Whilst economic incentives and subsidies have somewhat boosted EV market shares, they are most effective when maintained over longer time periods (~ 15 years). However, governmental support programs usually only last between two and five years (Wolinetz and Axsen, 2017). It has been argued by Axsen et al. (2016) and others that stringent, long-term policies at multiple scales of government are needed to ensure continued EV uptake.

Canada has set ambitious goals for EV deployment as it attempts to decarbonize its transport sector, which accounted for 24% of GHG emissions in 2015 (ECCC, 2017). EVs have been shown to meet 90% of Canadians' daily driving needs, particularly in urban areas where driving ranges are generally smaller (Bloomberg New Energy Finance, 2017). Canadian federal, provincial and territorial governments are therefore jointly developing a national Zero-Emissions Vehicle Strategy with an unbinding target to achieve 30% EV sales by 2030 (Government of Canada, 2017). Currently, reaching this target relies mainly on demand-oriented programs, with EV subsidies being made available in the provinces of British Columbia (BC), Quebec and Ontario. In BC, for instance, rebates of up to $5000 are available to cover the cost of a new EV. Supply-oriented incentives are also being trialed, such as Quebec's recent policy requiring manufacturers and car dealers to ensure a certain proportion of available stock are zero-emission vehicles. However, despite the policies currently in place, EVs accounted for only 0.6% of total car sales in Canada in 2016 (Clean Energy Canada, 2017). In a Canada-wide 'EV Policy Report Card', which analyzed current and proposed EV supportive policies, Axsen et al. (2016) found that all provinces will fall short of the national EV target, and EV market share in the majority of provinces will not exceed 10% by 2040.

BC is an interesting case study for EV deployment in Canada. Around 85% of its electricity is sourced from large hydropower (National Energy Board, 2016), and the province has a zero-emissions electricity standard in its Clean Energy Act that requires at least 93% of total generation be met by clean or renewable resources (SBC, 2010). As a result of BC's electricity grid mix, widespread EV usage could cut GHG emissions by 80–98% in the province (Axsen et al., 2015). BC has 'passable' policies for encouraging EV market share, according to Axsen et al.'s (2016) Report Card, including the highest carbon tax in Canada ($30/tonne) and a requirement to target a reduction in carbon emissions from transportation fuels. Moreover, current residential electricity rates in BC are low enough to make home-charging of an EV about seven times more economical than fueling a conventional vehicle with gasoline (Axsen et al., 2015). Whilst these factors contributed to a 48.6% increase in EV sales between 2016 and 2017 in BC (FleetCarma, 2017), total EV market share remains at ~ 2%, and may not exceed 10% by 2040 (Axsen et al., 2016).

In efforts to further incentivize EV uptake across the province, the BC government and a number of municipal city governments have highlighted the major strategic importance of expanding access to charging infrastructure (e.g. City of Vancouver, 2016; PlugIn BC, 2017). The reliance of EVs on grid electricity means that 80–90% of charging takes place at home where it is most convenient for drivers (Plug'n Drive & CCIT, 2014; Axsen et al., 2015). Deploying more home-charging infrastructure could therefore encourage EV adoption amongst city residents without the need for an expensive high-density public charging network (Peterson and Michalek, 2013; Yilmaz and Krein, 2013; Greene et al., 2014).

Any home-charging infrastructure strategy will have to consider Multi-Unit Residential Buildings (MURBs: buildings with three or more dwelling units and shared common interior and exterior spaces), which account for 28.6% of households in BC (Plug'n Drive & CCIT, 2014). Most existing MURBs in BC are not equipped with adequate EV charging infrastructure, and the challenges associated with installing new charging stations can become barriers to EV uptake (Axsen et al., 2015). A study by Lopez-Behar et al. (accepted), which is related to the present study, identified four main problem domains in the context of MURBs: charging infrastructure installation, building limitations, governance issues and parking availability. By mapping the main stakeholders and decision-making criteria and outcomes for each domain, the authors showed that communication between EV owners, other MURB residents and building owners will be key for developing comprehensive, future-proof infrastructure and retrofit investment plans. What is still lacking in the literature is a full map of the causal relations that exist within this complex system, including the feedbacks that could serve to accelerate, or hinder, EV uptake among MURB residents.

In this study we aim to build on our previous analysis of the EV charging infrastructure installation system in MURBs (Lopez-Behar et al. (accepted)), by mapping the causal relations that link the system's entities and identifying potential demand-focused policy interventions. We concentrate our analysis on the main metropolitan areas of BC, since they are home to the majority of MURBs in the province and concentrate 70% of the light-duty vehicle fleet that could be replaced by EVs (Impey, 2013). The high densification and mobility challenges experienced in BC's urban areas is illustrative of the challenges faced by many modern cities, so we seek to outline policies that could be relevant to many EV markets around the world.

2. Methods

In a related study (Lopez-Behar et al. (accepted)), we conducted a three-part analysis of stakeholder dynamics in the installation of EV charging in MURBs in BC. We outlined the problem system, identified potential barriers to installation of charging infrastructure, and mapped the main stakeholders and decision-making criteria within the system. We now advance this analysis by evaluating the interdependencies and causal links connecting the problem domains using Causal Loop Diagrams. We then propose policy measures to address the barriers and feedbacks identified by our modelling framework. Our study only considers EVs that can be partially or fully fueled by grid electricity. This includes Battery Electric Vehicles (BEVs), which are powered exclusively by grid electricity, and Plug-in Hybrid Electric Vehicles (PHEVs), which can be powered by both gasoline and grid electricity. Non-plug-in Hybrid Electric Vehicles (NPHEVs) are excluded from our analysis, because they use recaptured kinetic energy rather than grid electricity.

A Causal Loop Diagram (CLD) is a conceptual modelling framework used to identify and explain feedback loops and to visualize the interrelation of variables in a system. The CLD framework was originally developed within the Systems Dynamics approach, which seeks to represent and simulate the dynamic, non-linear behavior of complex systems (Rogers et al., 2005), often with a focus on policy analysis and design (Morecroft, 2015). System Dynamics modelling is a versatile tool for simulating technology and product diffusion, so has been used to study the uptake of alternate fuel vehicles (AFVs) (e.g. Leaver et al., 2009; Shafiei et al., 2015). While many of these studies are based on quantitative models predicting the evolution of AFV market share over time (Shepherd, 2014), a few studies have used Causal Loop Diagrams to qualitatively assess the potential policy implications of supporting the diffusion of high-efficiency vehicles (e.g. Stepp et al., 2009).

The methodological basis for CLDs differs from traditional event-oriented linear approach, where solutions are designed to fix a problematic event, sometimes without questioning the underlying cause of the problem or the potential effects of the solutions (Morecroft, 2015). Instead, CLDs emphasize the linkages between problems and solutions in a system via a series of causal links that form feedback loops (Shepherd, 2014). In our case, installing EV charging infrastructure in existing residential buildings can be considered a complex system involving two separate industries (vehicle manufacturing and residential building development) and a wide variety of stakeholders, including EV owners, building residents and building owners. By mapping the system's entities and exploring the feedbacks that maintain them, the CLD framework allows us to identify key leverage points, as well as the potential effects of intervention strategies.

In our CLD (built using Vensim PLE v.7.1 software), the causal links between entities can have different polarities: positive (noted as '+' in the diagram) or negative ('-'). A positive polarity means an increase in the first entity causes an increase in the second entity, while a negative polarity means an increase in the first entity causes a decrease in the second entity. A series of causal links can then form feedback loops, which are either reinforcing (noted as 'R' in the diagram) or balancing ('B'). Reinforcing loops serve to amplify reactions in the system, whereas balancing loops oppose change and growth. A system composed of balancing and reinforcing loops may eventually reach dynamic equilibrium, whilst reinforcing loops left unchecked by balancing loops can lead to exponential growth (Shepherd, 2014). In this way, CLD analysis can help to identify potential sources of policy synergy from reinforcing loops and policy resistance from balancing loops. It can also highlight the unintended consequences that interventions aimed at one part of the system may generate in other parts of the system (Stepp et al., 2009).

3. Mapping system interdependencies

The full CLD mapping out the system of charging infrastructure installation in MURBs is displayed in Fig. 1. We examine each of the system's three reinforcing loops (R1, R2 and R3) and single balancing loop (B1), and the interrelationships between them where appropriate.

3.1. Loop R1: Infrastructure and EV adoption

Reinforcing loop R1 describes the positive effects of infrastructure installation in MURBs on EV adoption (Fig. 2). An increase in the availability of charging in MURBs results in greater EV interest among residents. Interest in EVs can also be spurred by a variety of external factors, such as public charging availability, perceived societal affinity to EVs, and other exposure types to EVs (e.g. marketing campaigns and word of mouth from both users and non-users) (Struben and Sterman, 2008). Increased interest drives up EV adoption among MURB residents; these new users will have a motivation to install charging infrastructure in their homes, thus boosting installation and closing the reinforcing loop. The availability of home charging depends on the amount of charging infrastructure already installed within a MURB, but also on off-street parking availability. Minimum parking requirements established by municipal bylaws and BC's provincial codes rarely require the provision of parking stalls for 100% of MURB residents, and many 'green' building rating systems actively suggest minimizing parking availability to reduce automobile dependence among residents (e.g. USGBC, 2017). Parking availability is also dictated by building ownership: high-end apartments for sale are likely to include parking for most residents, while economic purpose-rental units may not. Limited parking availability for some MURB residents may restrict their interest in purchasing an EV.

3.2. Loop B1: Building limitation implications

Balancing loop B1 describes the negative effects of the limitation in a building's power distribution system, as well as the financial implications of these effects (Fig. 2). The installation of charging stations within a MURB increases the building's base load because of the extra requirements imposed on its power distribution system. The base load increment depends on the number of charging stations installed, but also on their charging level, which in residential settings is usually either 'Level 1′ (slower) or 'Level 2′ (faster). Local regulatory requirements for allocating new loads to existing power systems also affect the base load increment. Higher charging levels and more stringent allocation codes generally result in greater building base loads.

At the same time, increased building base loads will result in increased building system limitations. As the number of installations increases, the class of work needed to upgrade the power distribution system will also increase, which has cost implications for the investing stakeholder. Charging infrastructure installation in existing buildings is likely to be undertaken in steps, such that only a limited number of stations will be installed simultaneously (Impey, 2013). As demand grows, the building base load will increase with each installation step, meaning that more components will require upgrades to prevent overloading of the building's electrical system. More numerous and larger charging stations will require more frequent and expensive changes to the building power system. Greater upgrade costs and upgrade investments have other causal links to reinforcing loops R2 and R3 (see Section 3.4).

The difference between the user investment required to upgrade the building system and a user's investment budget is termed the 'investment acceptability'. Investment acceptability is therefore determined by the costs of the physical power system upgrades, the purchase and installation of the Electrical Vehicle Supply Equipment (EVSE) (the equipment serving as an intermediary between the power source and the vehicle's charging port), and the permits required for installation. Whilst investment acceptability usually consists of a range, each user will have a limit beyond which they are not prepared to invest in new charging infrastructure. This entity does not tend to decrease (charging stations are rarely removed from the building at this stage), but it will not increase if the investment acceptability limit is reached. The negative polarity of the link between a user's upgrade investment and their investment acceptability makes this a balancing loop.

An additional factor to consider is a building's physical constraints, including the configuration and layout of the power systems. For instance, the location of parking stalls relative to the building's main electrical room could become problematic as the number of charging stations grows. As the complexity of the building configuration increases, physical constraints are likely to negatively impact the installation of charging infrastructure. This phenomenon is independent of other technical constraints, as it cannot be easily solved with a building upgrade and would require a fundamental change in the building configuration.

Loop B1 is connected to loop R1 via the charging infrastructure installation entity. Loop R1 acts to drive up EV adoption and charging

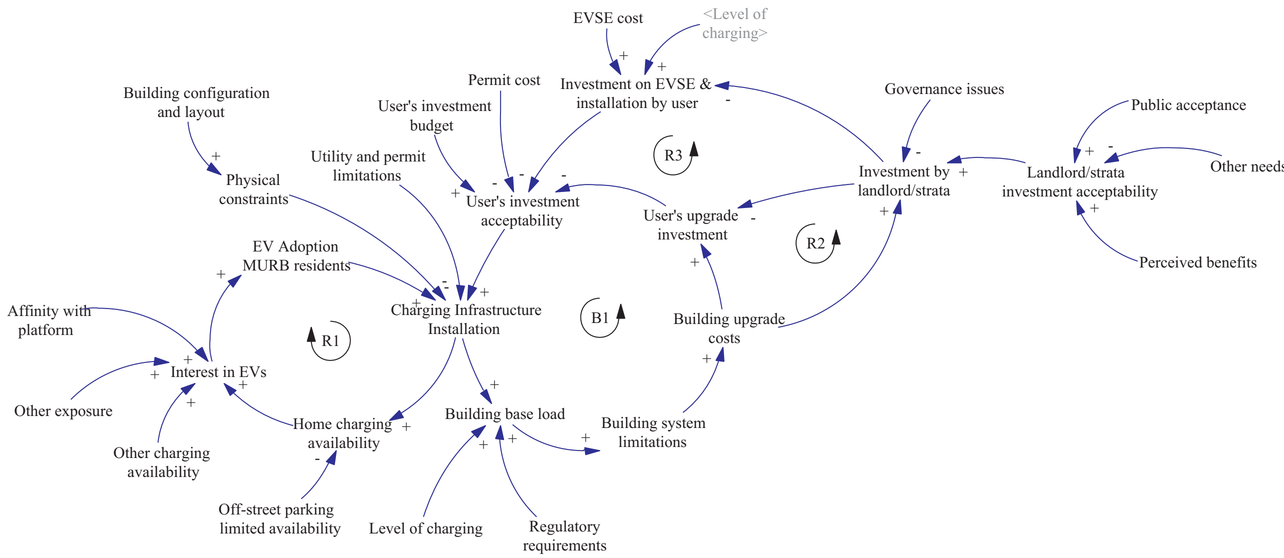

Fig. 1. Causal Loop Diagram (CLD) of the entire system of charging infrastructure installation in MURBs.

infrastructure availability in MURBs, and thus uptake by new users. However, with greater interest from residents, additional loading on the building's power system will raise upgrade costs, and the investment needed for each new installation increases. Ideally, the system would reach its limit by means of saturation (i.e. 100% of parking stalls becoming EV-ready), but if investment acceptability is breached, a portion of interested residents may not have access to home charging whilst their neighbors do. This may be deemed unfair and lead to governance issues.

3.3. Loops R2 and R3: Financial support from building owners

Reinforcing loops R2 and R3 refer to the support that the building owner(s) can provide to EV users by fully or partially funding building upgrades and EVSE installation (Fig. 3). Two principal types of MURB ownership exist in BC: (i) purpose-built rental buildings, which are in most cases entirely owned by a single organization and administered by property managers; and (ii) strata buildings, where owners own individual strata lots and together own the common property and assets as a strata corporation. In both purpose-built rental and strata corporation buildings, the landlord or strata council might agree to pay for the upgrades and the charging station, since they keep the benefits of the investments once the tenant moves out or the apartment owner sells their unit.

In the case of generous financial support for upgrades and equipment from the landlord or strata council, individual EV users must invest less from their own funds. Decreased user investment result in increased investment acceptability, which promotes charging infrastructure installation. As discussed in Section 3.2, this increases the building base load and thus the ensuing upgrade costs. Consequently, an expense considered by the landlord or strata council to be a one-off may become an unanticipated repeating (and increasing) form of financial support.

The financial support that the building owners are willing and able to provide depends on two factors: the owner investment acceptability and governance issues. Owner investment acceptability will increase if public acceptance and perceived benefits of charging stations increase, but will decrease if other financial needs are perceived to be of greater

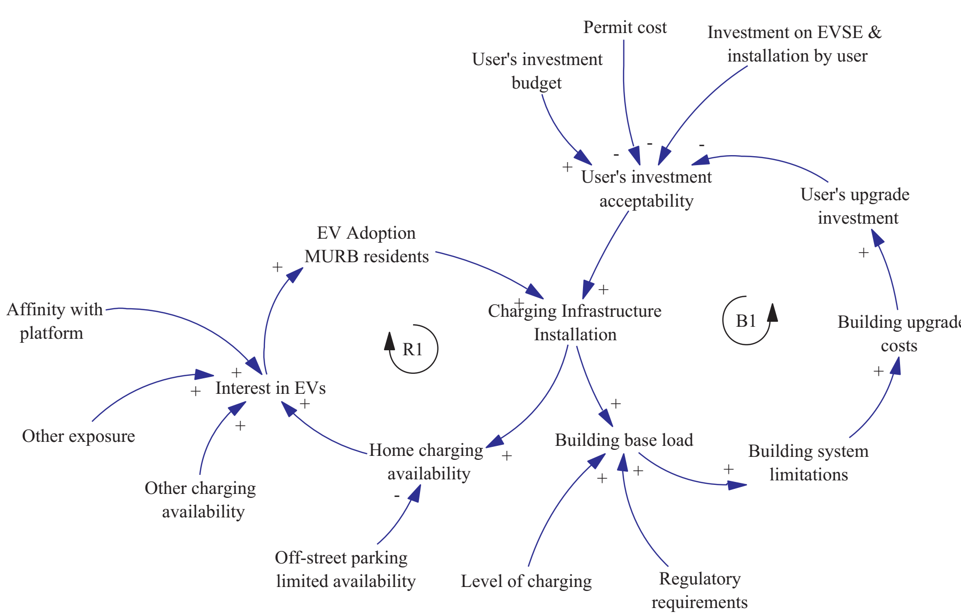

Fig. 2. Reinforcing loop R1 and balancing loop B1 from the main Causal Loop Diagram.

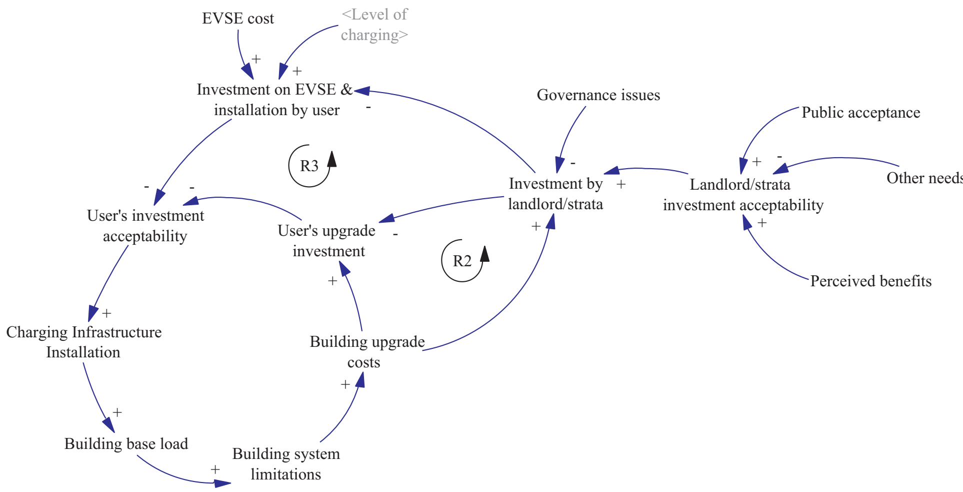

Fig. 3. Reinforcing loops R2 and R3 from the main Causal Loop Diagram.

priority, such as building maintenance and administrative and insurance costs. If a building owner deems an installation to cause numerous governance issues, this may negatively influence their decision to provide, or permit, the installation of charging infrastructure. In the case of installation, building owners may require that the EVSE remain fixed so that it can remain building property if an EV user decides to move out of the MURB.

4. Policy recommendations

We now provide a number of policy recommendations to address the issues raised in our CLD analysis and the barriers identified in the related study of Lopez-Behar et al. (accepted). The recommendations are divided into three categories: financial/fiscal, regulatory and information/awareness. The policy recommendations are discussed in more detail below and summarized in Table 1, as well as explicitly mapped in an overarching CLD (Fig. 4). The CLD highlights the ways in which the policy recommendations can influence the system, by showing whether they act to reinforce EV uptake and promote the installation of charging stations, or act to remove barriers and limitations. The investment implications for different stakeholders in the system are also considered.

4.1. Financial and fiscal policies

Financial barriers and implications play a significant role in the system. The main financial barriers consist of the additional investment that EV users or building owners must pay to cover the costs of purchasing and installing EVSEs, and of upgrading the building's power distribution system. As shown in the CLD, such barriers directly influence the decision to pursue installation, which in turn has repercussions on the decision to acquire an EV over a conventional fossil-fuel vehicle. Fiscal and financial instruments such as subsidies, cash rebates, capital grants, tax incentives and discounted loans are the most appropriate policy interventions in this case (Browne et al., 2012).

Cash rebates or discounted loans from the government can help EV users to cover the costs of the EVSE and its installation. Such a policy was implemented in BC in 2013 and 2017 through the 'Multi-Unit Residential Building Charging Program', whereby MURB residents could apply for a 75% rebate of the cost of acquisition and installation

Table 1
Summary of policy recommendations.

Policy category	Policy title	Recommendations
Financial & Fiscal	Cash rebates/discounted loans	Incentives such as cash rebates or discounted loans, offered by the provincial government, to aid EV users in partially covering the costs of the EVSE and its installation, as well as the required building upgrade costs.
	Conditional financial aid to building owners	Extend the financial aid to strata councils and landlords, and condition it to a minimum number of charging stations.
	Incentivize development of retrofit plans	Within the following decade, municipal and provincial governments should plan and implement a program to incentivize and financially aid strata councils and landlords to develop a retrofit plan, and to upgrade their building's power distribution system sufficiently to accommodate future charging needs of their residents.
Regulatory	Revise regulatory requirements	Revise and constantly update the regulatory requirements from codes and standards to reflect the current technological advances and avoid being over conservative, which can lead to unnecessary oversizing of electrical equipment.
	Regulate rights and obligations of stakeholders	Regulate the rights and obligations of EV users, building residents, strata councils, and landlords, regarding the installation and use of charging stations within MURBs to avoid future situations of unfairness and inequality among them.
	Make charging station installation mandatory in new MURBs	Make it mandatory, at a provincial level, for new MURBs to provide charging stations for a proportion of all parking stalls, and to be technically prepared to accommodate charging stations in all parking stalls in future.
Information and awareness	Guidance on key issues	Expand the existing guidelines to provide clear guidance and solutions on technical and governance issues, such as charging infrastructure cost responsibility and ownership.
	Guidelines for long-term EV charging infrastructure plans	Develop a program or guideline to inform and guide strata councils and landlords on how to develop a long-term EV charging infrastructure plan that will guide and dictate present and future charging infrastructure deployment in their building, the infrastructure upgrade needs, and governance and ownership considerations.

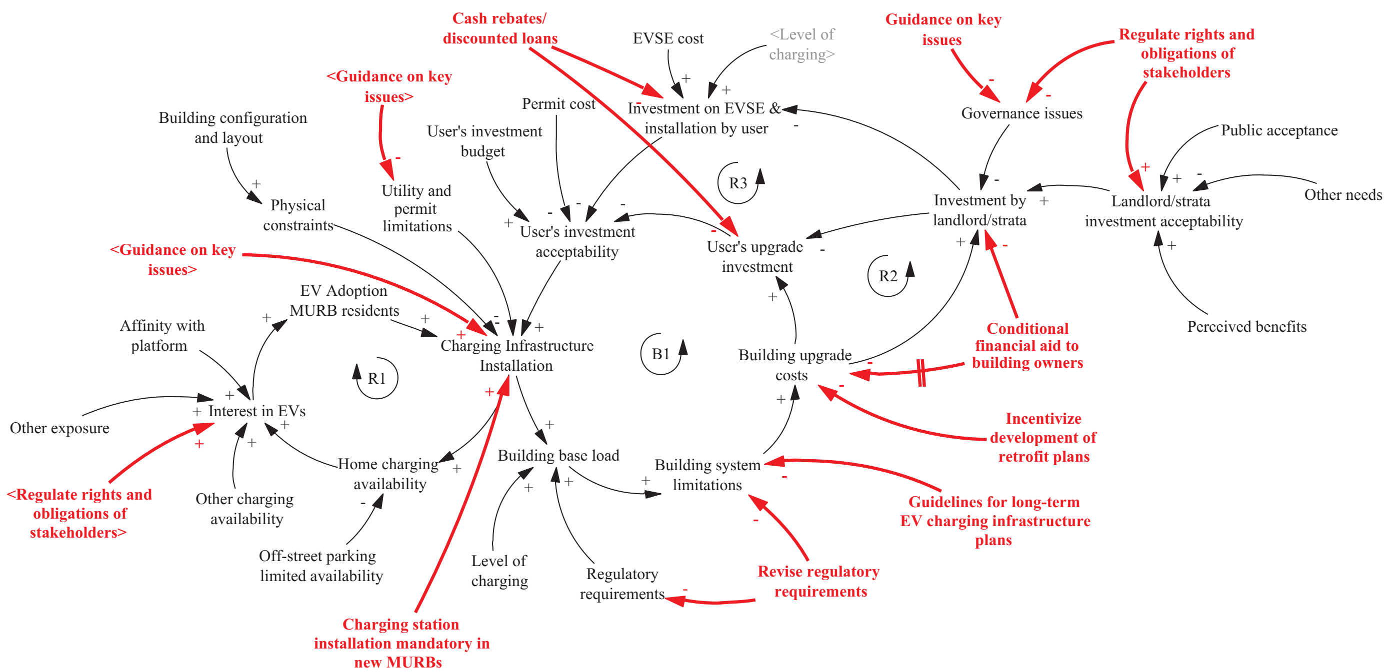

Fig. 4. CLD of entire system, highlighting how the policies proposed in this paper (in red) map into the system and affect specific variables.

of one Level 2 charging station (PlugIn BC, 2017). However, investment in building upgrades can in some cases be costlier than station installation, meaning the equipment rebate may not be sufficiently attractive to potential EV adopters. Governments should therefore consider extending the rebate or loan to cover a proportion of the associated building upgrade costs.

It is crucial to consider the beneficiaries of such financial aid. Directing financial aid to single EV users promotes installation on a case-by-case basis, which, as previously discussed, raises the cost of installation per station. Instead, making financial aid accessible to strata councils and landlords, and setting a minimum number of charging stations that must be installed in the MURB, would encourage installation requests to be grouped into single larger projects, thus decreasing costs on a per-station basis over time. This would increase the value for money of such an incentive, and the availability of extra stations would promote EV adoption among other residents.

As seen in the interaction between loop R1 and loop B1 (Section 3.2), incentivizing charging station installation in existing MURBs could make additional installations more expensive in the long run due to power system constraints. For this reason, governments should consider directing financial aid to building owners for upgrading power distribution systems sufficiently to accommodate their residents' future charging needs. Anticipating future installation needs avoids temporarily patching the power system, which may have safety implications, or investing in equipment that will soon be rendered obsolete as demand further exceeds capacity. Education and awareness measures are important for guiding building owners through the appropriate planning processes (see Section 4.3).

4.2. Regulatory policies

Barriers relating to legal, institutional or public acceptability issues can be addressed through a variety of regulatory policy instruments, including technology-forcing mandates and standards, mandatory codes and bylaws, and voluntary certifications (Browne et al., 2012).

Lopez-Behar et al. (accepted) identified conservative regulatory requirements as a significant barrier to EV uptake in the BC context. Specifically, several contingencies in Section 8 and Section 86 of the Canadian Electrical Code (CEC) are designed to prevent overloading of electrical systems when new charging infrastructure is installed in a building. However, the unrealistic constant electrical loading assumed in its demand calculations can result in unnecessary and costly upgrades to a building's power distribution system (Impey, 2013). The methodology for load calculations in the CEC should therefore be revised to account for realistic EV charging patterns and actual building loads, as well as advances in charging technology.

Policy measures should also be targeted at regulating the rights and obligations of EV users, other residents, strata councils and landlords with regards to the installation and use of charging stations in MURBs. This would help avoid a multitude of potential governance issues and perceptions of unfairness between residents. As previously discussed, the fact that building upgrades generally become more comprehensive and expensive as more charging stations are installed, could result in some residents paying higher costs than their neighbors for the same service. If a building owner provides financial support for installing charging stations for a group of EV users at a given time, future EV users may also expect the same, or even higher, support to cover the increased building upgrade costs. Other complications may arise if it becomes financially or technically unfeasible to keep installing charging station in the building, as the sharing of existing infrastructure may be impractical or unpopular depending on the agreed financing structure within the MURB. Regulating the rights and obligations of users may provide more security and mitigate the perceived and actual risks for potential EV users; in turn, this could help to promote interest in EVs and uptake among MURB residents. Strata councils and landlords should be given freedom to decide on certain issues relating to their MURBs, but it will be important for the government to provide clear regulatory frameworks to avoid unfair situations from developing between residents, especially as EV uptake continues to increase.

Whilst complex issues surround retrofitting existing MURBs, municipal and provincial governments should consider proactively mandating that all new MURBs provide a certain proportion of 'EV-ready' parking-stalls. This should be accompanied by mandated provisions in buildings' electrical systems to install full capacity in the future. For instance, the City of Vancouver has already implemented a bylaw to the provincial 2012 BC Building Code, requiring 20% of all parking stalls in new MURBs to be EV-ready and technical considerations to be made to eventually reach 100%. This form of legislative future-proofing would be a significant step in boosting EV uptake amongst MURB residents.

4.3. Education and awareness policies

Many barriers we identified in our two related studies could be addressed relatively simply and cost-effectively using education and awareness policy measures. Relevant barriers include governance issues, public acceptability issues such as lack of support and technical understanding, and regulatory issues arising from limited technical guidance.

Within BC, several resources from both non-governmental associations and government already exist that deal with some of the issues we have highlighted. The Condominium Home Owners Association of BC has published a guide explaining the options and procedures for strata corporations looking to install charging stations on common property and within strata lots (CHOA, 2014). It provides guidance on technical and non-technical aspects relevant to both new and existing MURBs. The Building Owners and Managers Association of BC created a guide covering charging levels, parking space considerations, power and transformer requirements, metering, cost, maintenance, and safety (BOMA BC, 2013). A deployment guidelines document by CEATI (2014) provides technical guidance for residential charging, including a section on the additional constraints for multi-family dwellings such as siting requirements and the installation process. Finally, Metro Vancouver maintains an online guide providing information relevant to homeowners, tenants and strata councils on EV charging in condominiums and apartments, including several tools and resources (Metro Vancouver, 2018). The website also has a registry of EV-friendly strata for public consultation.

These resources provide valuable, open-source information to guide a variety of stakeholders, and certainly are helping to close some knowledge gaps amongst interested parties. However, uncertainty remains with regards to some governance issues, particularly those regarding cost responsibilities and equipment ownership. There is also a notable lack of guidance on how best to develop a long-term EV charging infrastructure plan that will dictate present and future charging infrastructure deployment within a MURB. Specific government-led policies aimed at increasing awareness and access to technical and non-technical information would help to overcome perceived and actual barriers to infrastructure installation.

5. Conclusion and policy implications

Boosting EV uptake to achieve meaningful GHG emissions reductions in BC will require new, innovative policy interventions. Indeed, BC's current policies and incentives are not likely to support an EV market share much higher than 10% by 2040 (Axsen et al., 2016), far below the national government's stated aim of 30% by 2030. In this study, we analyzed the issues surrounding EV charging infrastructure installation in MURBs, because they are home to a significant proportion of the province's potential EV users. We developed a causal loop diagram (CLD) to map the relations that exist between the system's main entities and showed that installation is constrained by dynamically linked problems with various technical, financial, social and regulatory facets. Four causal loops were identified, three that reinforce EV uptake and the infrastructure installation process, and one that balances the growth due to technical building limitations and their implications for investment.

Based on our modelling results and the potential barriers identified by Lopez-Behar et al. (accepted), we developed a set of demand-focused policy recommendations that could be implemented to address the challenges of charging infrastructure installation. Our proposed financial/fiscal policy measures include providing cash rebates or discounted loans for equipment purchase and building upgrades, providing financial aid to building owners with minimum installment conditions, and incentivizing the development of future-proof retrofit plans. Regulatory policy measures include revising regulatory requirements (e.g. conservative electrical codes), regulating the rights and obligations of different stakeholders within MURBs, and making charging station installation mandatory in new MURBs. Information/awareness policy measures, which could be relatively simple and cost-effective to implement, include expanding guidelines for long-term charging infrastructure plans and providing extra guidance on key governance and fairness issues.

Our policy recommendations are designed to inform the interventions of municipal and provincial governments in BC but are also likely to be relevant to many urban EV markets worldwide. Cities are responsible for ~ 70% of CO_2 emissions (C40 Cities, 2018) and generate ~ 80% of global GDP (McKinsey, 2011), so they are set to play a critical role in addressing climate change. As vehicle electrification continues to be rolled out in a variety of urban contexts, challenges associated with the provision of private and public charging infrastructure will increasingly come to the fore. Policies that account for the decision-making processes and dynamics of stakeholders in a holistic, systematic way will ensure a smoother and more rapid transition to EVs.

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