Representation and evaluation of deployment scenarios for electric vehicle charging facilities, coupling Agent-Based Modeling (MATSim) and LCA

Context

With zero tailpipe emissions and high energy conversion rate compared to conventional vehicles (ICEV) (1.5 km per mega joule vs .28 km/mj) (Nie and Ghamami, 2013) electric vehicles (EV) are becoming popular mobility solutions to both consumers and policy makers for minimizing carbon emission. With improved battery technology and in the midst of increasing demand, vehicle electrification appears to be the main objective of the automotive industry in the upcoming decade. The national EV survey for Canada reveals that electric vehicle ownership from 2015 to 2018 increased of about 6 times. With government incentives in the form of tax exemptions, priority lanes and free charging opportunities, this number is likely to get even higher. Quebec's govt. expects to have around 40% EV penetration by 2030.

The development of electric mobility raises several challenges however. The technological development and deployment of batteries and charging infrastructure are dynamically connected, and determines the environmental potential of vehicle electrification: battery technology modifies the need for charging, thus chargers. Nowadays, the lack of charging facilities has shown to be a major brake to EV adoption (Mutarraf et al. 2022). Thus, the density of chargers on the territory, but also their respective charging speed, impact the adoption of the different EV technologies by households and organizations, as well as user travel routes and more generally travel patterns. Building these charging infrastructures, replacing ICEV by EV, and modifying travel patterns, modify the environmental performance of the transportation system, and modeling these impacts requires coupling different tools.

Research proposal and methodological overview

We have two main research questions. The first is: "Which deployment strategy of EV charging infrastructure should we chose towards a fast sustainable carbon neutrality?". The second is: what is the order of magnitude of the environmental impacts due to EV charging infrastructure life cycle, depending on the technology, and compared to the sole EV or ICEV life cycle. In order to investigate these questions, this research proposal includes two separate but interrelated projects:

1. A first project focuses on exploring the issue of locating charging facilities to mass-market the shift from ICE to EV mobility
2. A second project focuses on assessing the environmental outcomes of project's 1 shifting scenarios using consequential life cycle assessment (CLCA)

The two projects are complementary as the environmental evaluation developed in part 2 will allow to compare different scenarios in terms of charging station location developed in part 1, as showcased by Querini and Benetto (2017). Methodologically, the idea is to couple the agent-based approach, that allows to model human behavior in Project 1, to CLCA, that enables to estimate environmental consequences of human behavioral changes in Project 2. Overall, the methodology allows capturing and measuring burden-shifting due to mobility policy (Hicks 2022) and in particular different deployment strategies for EV chargers.

Project 1: Equitable Sequential Charging Facility Location Estimation in Urban Land Use Setting

State of the art

For several reasons, not every potential EV owner will be able to install a charger at home, therefore, the unavailability of sufficient and conveniently located public chargers is the foremost deterrent behind EV adoption (EV ownership survey 2018). Additionally, it is also a key reason for inefficient EV usage, as users might have to take long detours and waste time waiting in queues due to long charging time. With an increased number of EVs, charger location choices become trivial as queuing is likely to increase substantially in busy areas of the network. Researchers have tackled the problem of charger location estimation using two design principles, demand-based charger allocation (Dashora et al., 2010; Frade et al., 2011; Sweda and Klabjan, 2011; Chen, Kockelman and Khan, 2013) and flow-capturing charger allocation (Kuby and Lim, 2005, 2007; Wang and Lin, 2009; Lim and Kuby, 2010; Mak, Rong and Shen, 2013). In demand-based allocation, the charging request locations are estimated from travel data or simulation and chargers are allocated by minimizing the overall distance between the requests and charger locations. In flow capturing charging facility allocation scheme, chargers are allocated in facilities that can capture flows from the maximum number of OD pairs. settings, people tend to charge their vehicles while performing activities, requiring modification to the existing design logic for charger location estimation. Recently, Zhang et al. (2020) proposed using the K-mean clustering algorithm to determine chargers' location in the San Francisco area. The authors did use an activity-based traffic model (ABM) named "Beam". However, the simulation is used only to generate charging requests in an electric ridesharing fleet context. The authors iteratively increased the number of clusters in the k-means algorithm and evaluated the resulting charging request from the underlying activity-based model, until a maximum distance threshold with a 95% confidence interval between chargers and request locations is reached. This translates to the minimum number of chargers, given an arbitrary maximum distance between any charging request and the closest charger. However, as the K-means algorithm minimizes the summation of distance between cluster centroids i.e., chargers and charging requests, other potential charging performance indicators such as queue at the chargers, number of unique requests served, total energy served, duration of connections etc. are not optimized. The authors proposed to determine the number of plugs at each charger to minimize queuing, however, often the maximum number of plugs possible at a location is limited by specific local circumstances (size of the space available, type of land use, etc.).

Proposal

We propose a modified charger location estimation framework that combines both the demand-based and flow maximization approach while considering the urban land use pattern and subsequent charging behavior. The framework employs a two-step approach where in the first step, a set of candidate charger locations is chosen by maximizing the capture of agent activity locations and corresponding activity duration. It is possible to vary weights for activity locations and durations for EV and non-EV users, as well as consider different EV and charger technologies, that allows, for example, evaluating transition paths toward different future EV scenarios. Then we employ a modified clustering algorithm, where we determine a set of new cluster centroids (i.e., chargers) with a set of existing non-movable clusters (chargers) (sequential charger employment) from the set of candidate locations. Additionally, we propose a modified distance measure, which considers the weighted distance between the cluster centroids and the candidate points, average queue and total electricity served at charging locations so that these performance measures are all considered for the charger locations. We propose polynomial or interpolation-based metamodels for the estimation of the average queue and electricity served while performing the clustering algorithm. The number of total agents' trajectory through the cluster, the typical duration of the activity performed in the charging facility and the capacity of the charger are used as the explanatory variable in the metamodel while determining queuing time and energy served at a charger location. The two steps are computed iteratively, each time improving the metamodel estimation and increasing the number of clusters until a certain threshold value for all the performance indicator is reached for all clusters within 95% confidence interval. Figure 1 shows the framework of our proposed charger facility location estimation algorithm.

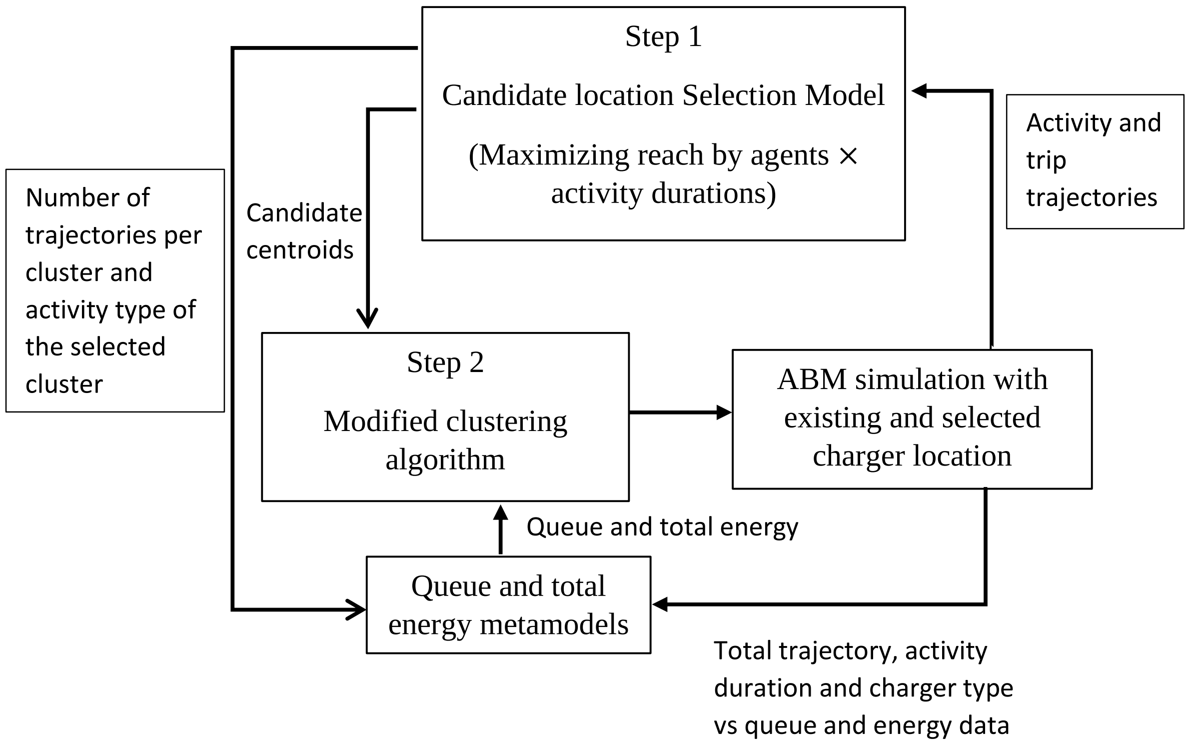

Figure 1: Schematics of charger location estimation algorithm

Contribution

Compared to the existing literature, our contributions are the following,

- The proposed framework combines both demand-based and flow maximized schemes of allocating chargers where the first step maximizes the reach of agents and the second step ensures the chargers will captures similar amounts of charging requests.
- The charger candidate location selection algorithm incorporates the activity location and duration pattern that are determinants of charging behavior in urban land use settings.
- The modified clustering algorithm allows finding optimal new charger locations while considering existing chargers in place, which is a more realistic problem to solve than from-scratch planning, given the current path toward high EV penetration rates in the future.
- The modified clustering algorithm has multiple objectives as it takes into account queuing time, weighted distance and power supplied over all chargers, ensuring similar level of usage for all charging facilities.

Project 2: Environmental evaluation of electric mobility scenarios using life cycle assessment

State of the art

The world faces a severe triple planetary crisis: climate change, biodiversity loss, and pollution (Hellweg et al. 2023). Transportation plays a significant role in exacerbating the triple planetary crisis, as it is a major contributor to greenhouse gas emissions, pollution, landscape fragmentation, and the loss of habitats. Consequently, there is a growing body of literature focusing on mobility and its environmental implications.

In particular, LCA of EVs has gained considerable attention, as the electrification of vehicles is viewed as a technological solution with the potential to achieve road mobility carbon neutrality by mid-century. Many studies examine the environmental potential of mobility electrification using LCA, but they fail to consider charging infrastructure within their system boundaries. Yet, individual studies specifically assess the environmental impacts of charging facilities using LCA (Zhao et al. 2021; Nansai et al. 2001; Horesh, Zhou, et Quinn 2023; Konrad, Bernt, et Hofmann 2023; Zhang et al. 2019). Among the studies specifically at dynamic aspects around EV charging, a study by Tang et al. considered the environmental impacts of charging EV depending on dynamic life cycle inventories (LCIs), i.e., when the electricity is consumed (Tang et al. 2021). Carra et al. also developed a list of 102 key indicators of sustainable locations for EV charging facilities, combining Analytical Hierarchy Process, an algorithm and Monte Carlo simulation (Carra, Maternini, et Barabino 2022). But their understanding of the life-cycle impact of charging facilities is extremely limited. Xu et al. looked at the carbon footprint of different charging technologies, but they failed at understanding the link between charging facilities and EV penetration (Xu et al. 2020). Finally, the dynamics of charging facility deployment with EV penetration has never been coupled to an LCA approach, while such a systemic approach is required to correctly sketch future dynamics and their environmental outcomes – including burden-shifting - at a large scale."

Proposal

This second study builds upon the expertise of the CIRAIG (Interuniversity Research Centre for the Life Cycle of Products, Processes, and Services) in LCA and aligns with ongoing collaborations with Prof. Guillaume Majeau-Bettez, focusing on integrating traffic modeling with LCA.

TASK 1 - Critical Literature Review on LCAs of Charging Infrastructure

- A comprehensive review of the existing literature will be conducted to gather insights on LCAs of charging infrastructure, specifically pertaining to various technologies and other relevant parameters. This analysis will help establish a solid foundation and identify knowledge gaps in the field.

TASK 2 - Development of an LCI Database on Charging Infrastructure in the Montreal Context

- A customized LCI database will be developed to capture the life cycle impacts of charging infrastructure within the specific context of Montreal. This database will encompass the complete life cycle stages, ranging from raw material extraction to end-of-life scenarios, and will facilitate a holistic assessment of the environmental burdens associated with charging infrastructure.

TASK 3 - Recommendations on Developing a Similar Database for French Contexts

- Based on the experience gained from developing the LCI database for Montreal, recommendations will be provided for creating a similar database tailored to the specific requirements of Paris or other French contexts. These recommendations will consider regional variations in charging infrastructure, technological preferences, and other relevant factors.

TASK 4 - Adaptation of Existing LCIs for Electric Vehicles (EVs) and Internal Combustion Engine Vehicles (ICEVs) in Montreal

- Existing LCIs for EVs and ICEVs will be adapted to the Montreal context to account for local parameters, such as electricity grid characteristics, transportation patterns, and fuel supply chain. Recommendations for adapting these LCIs to the French context will also be provided, considering variations in markets and local conditions.

TASK 5 - Calculation of Environmental Impacts for Scenarios Generated in Project #1

- Utilizing the LCI database developed in Tasks 2 and 4, environmental impacts associated with different charging infrastructure scenarios developed in Project 1 will be quantified. These scenarios will incorporate various technologies, charging configurations, and infrastructure deployment strategies, allowing for a comparative assessment of their environmental performance.

TASK 6 - Analysis of Potential Burden-Shifting:

- The project will explore potential burden-shifting phenomena that may arise due to different deployment scenarios of charging infrastructure and provide insights on strategies to mitigate such unintended consequences.

Contribution

Through this research project, the aim is to advance the understanding of the environmental implications of charging infrastructure deployment. The tasks outlined above will enable the development of a comprehensive LCI database, facilitate comparative assessments of different scenarios, and provide recommendations for adapting the research to French contexts. Ultimately, the findings will contribute to informed decision-making processes in sustainable transportation planning and infrastructure development. More specifically, project #2 will:

- Providing a comprehensive understanding of the environmental impacts due to EV charging infrastructure:
  - Highlighting main factors of variability of these impacts
  - Making recommendation on the system boundaries and accurate LCA modeling of these infrastructure
- Incorporating the environmental impacts of charging infrastructure in the assessments of electrification scenarios considering the dynamics between charging facilities and EV penetration, depending on technologies

Application & transfer

The methodology will be developed on the Montreal model first as a proof of concept. The team of Polytechnique Montréal (PM) will then assist Ecole des Ponts ParisTech (ENPC) to transfer the methodology to the Paris model, with a stay of a member of PM at ENPC (or conversely) to these ends. This will help ENPC to implement EV in their MATSim Paris model for studies on this topic and to couple life cycle environmental impacts to these simulations.

Conditions

Duration: 12 months (6 months for project 1, 6 months for project 2)

Start planned for around September-October 2023.

Funding request

90 k€ : recruitment + international conference + exchange with ENPC (trips & stay)

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