Integrated planning, operation and optimization of coupled transportation and energy systems

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Editorial

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1. Transportation electrification: challenges and policy significance

The growing need to reduce the greenhouse emissions from transportation systems has gained attention toward sustainable transportation by deploying electric vehicles (EVs) including private and public vehicles (Sheldon et al., 2023). As per reports, electric car sales grew by 55% and showed a new record of over 10 million EVs sale in 2023 (International Energy Agency, 2023). On the other side, battery electric buses are increasingly utilized for their low operation cost in comparison to the traditional fuel-based buses (Pragaspathy et al., 2022). Several European countries, for instances, Belgium, Norway and Switzerland, and also non-European country including China achieved sales shares of electric buses over 50% in 2023 (International Energy Agency, 2023). These pieces of evidence of the global need for using EVs indicate an urgent need to expand the charging infrastructures. Furthermore, EVs also create new challenges for energy systems due to the massive charging demand from the widespread deployment of EVs, in terms of required electricity for supporting charging demands as well as the mitigation of their adverse impacts on energy systems.

A standalone transportation research or energy research is insufficient to precisely understand the interactions between these two domains. To effectively address the challenges posed by their coupling, it is essential to examine multiple contexts, encompassing both short-term (operational) and long-term (planning) policies, to ensure safe and reliable transportation and energy systems. A prerequisite is to understand the right impact of transportation systems on energy systems. The realization of the right impact can assist in figuring out the proper planning and operation of charging infrastructure. The current studies mostly have focused on various, and individual aspects of coupling transportation and energy systems, including estimation of charging demands, the impact of transportation systems on energy systems, planning of charging stations as well as bidirectional interaction of transportation systems and energy systems. Fig. 1 illustrates the coupling between transportation and energy systems. In the transportation system, various modes such as electric buses and electric cars carry out their daily trips, requiring charging to continue their operations. Charging stations serve as the connection point between transportation and energy systems, where charging demands impose additional loads on the energy system. The energy system, in turn, operates on daily, hourly, or even intra-hourly intervals, supported by various energy sources, with assets and resources planned based on these demands. Therefore, increased charging demands necessitate adjustments to the energy system to accommodate the electrification of mobility. From the transportation perspective, planning involves expanding infrastructure for charging stations. It is important to note that successful and precise planning of transportation and energy systems can be achieved by integrating the scheduling of EVs with the short-term operations of energy systems. In the next two sections, we investigate the current studies to assess the challenges as well as the future research directions to include the elusive gaps.

2. Existing studies on coupled transportation and energy systems

The rapid increment of EV adoption and the consequent increase in charging demands of EVs necessitates optimizing the charging infrastructure planning and management of energy systems to host these spatiotemporal new demands. Many studies are dedicated to modeling and forecasting these spatiotemporal patterns in EV charging demand. For example, residential consumers often use slow chargers (so-called level 1) overnights which can increase the electricity consumption up to 50% (Brouwer et al., 2013). On the contrary, commercial or public fast chargers (level 2 or 3) impact energy systems seriously, particularly during peak hours (Xu et al., 2017). A long-term charging demand estimation is a prerequisite for strategizing and planning charging infrastructures. The long-term estimations are categorized into two main groups: system-dynamic and agent-based models. The system-dynamics model offers a comprehensive top-down framework, by highlighting the structure and feedback loops within the system, while the agent-based model employs a bottom-up framework, simulating each individual agent's behavior (Parishwad and Jia, 2023).

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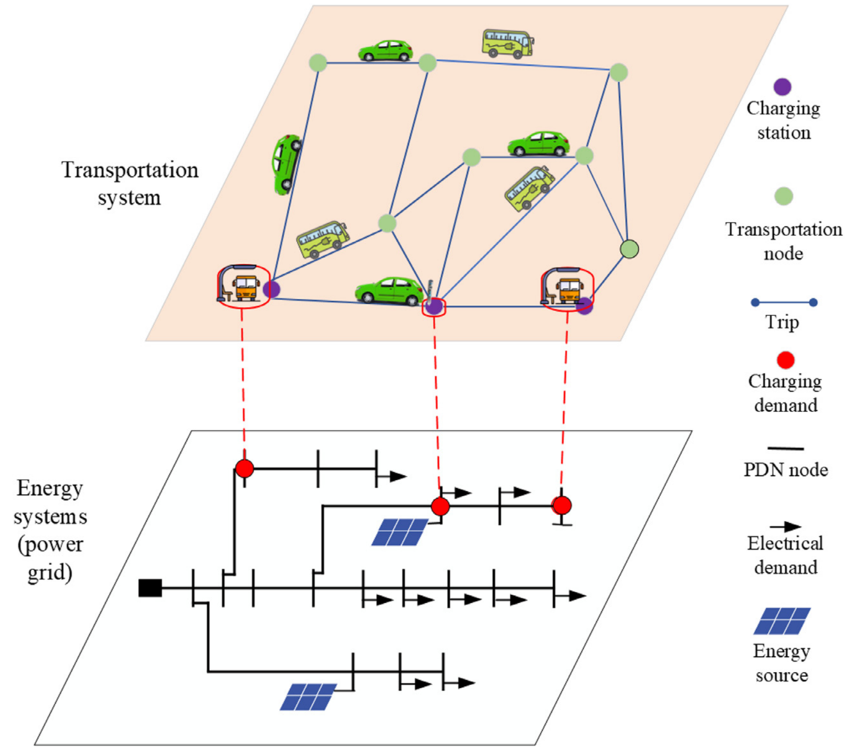

Fig. 1. Minimum obtained voltage during whole planning horizon.

To fully understand the research in each sector (transportation or energy), it is crucial to first recognize the importance of studying these systems in an integrated manner, rather than investigating them independently. The large-scale integration of EVs into energy systems impacts various aspects of the energy grid, making the management of power flow and operational constraints more complex. For example, high levels of EV integration into the power grid-particularly in distribution networks-can lead to increased current levels in grid branches (cables, wires, and transformers), causing voltage drops at customer connection points (Zhang et al., 2024; 2023). As a result, violations of grid constraints and asset overloads may occur, necessitating the reinforcement of power grid components such as transformers, generation capacity, conductors, and switches. It is also worth mentioning that the integration of EVs into energy systems presents potential benefits. For instance, bidirectional interactions through vehicle-to-grid (V2G) technology can enable EVs to act as temporary mobile power sources, enhancing the resilience of energy systems during extreme events, outages, and disasters (Zhang et al., 2023).

One of the primary challenges in coupled transportation and energy systems is to model the impact of the selfish behavior of the drivers on the location of charging stations connected to energy systems. The location of charging stations may affect the route choice and consequently the road traffic congestion. Several studies have explored these mutual impacts by mostly focusing on the energy side (Li et al., 2023). Some studies have investigated stationary charging infrastructure (Li et al., 2023), while others have examined wireless (dynamic) charging for electric vehicles (EVs) (Najafi et al., 2024). Stationary and wireless charging differ significantly in terms of travel time, primarily due to congestion and waiting times. Stationary charging infrastructure can increase congestion near charging locations, whereas wireless charging offers a seamless charging experience during travel, eliminating the need to wait in a charging queue. Hence, the optimization objectives differ with respect to the type of charging. From a mathematical perspective, stationary charging is more accurately modeled by precisely measuring the energy received by EVs at the specific locations of the energy systems. This allows the impact of the received energy to be simulated within an optimization framework. In contrast, wireless charging demands are treated as a coefficient related to the flow of vehicles, which often overlooks charging efficiency. The biased focus on the energy side has caused an oversimplification in modeling transportation systems by overlooking the dynamic nature of road traffic in the existing studies. That is, only a single-time sample was considered to represent the traffic flow of vehicles on roads. However, since traffic flow is dynamic, a static framework cannot accurately capture it. Consequently, energy resources were coordinated only for that specific time sample, while the accurate actions in energy systems may differ if we consider the dynamic nature of traffic flow. However rare, some studies have addressed the impact of charging demands of transportation systems on energy systems by considering the power grid operation with the existence of charging demands (Najafi et al., 2024; Qiao et al., 2022). As summarized by Unterluggauer et al. (2022), the excessive stress on the energy system from escalating shares of EVs can bring various challenges, such as overloading of transformers and branches in energy systems, power and energy losses, voltage drops, as well as phase unbalances.

Vehicle-to-grid (V2G) introduces some flexibility in the operation of energy systems by enabling bidirectional power transfer between the energy systems and electric vehicles. The EV batteries work as an energy storage by charging during off-peak hours (price or electricity demand), and discharge during peak hours. Furthermore, by deploying the time-of-use electricity prices, EV owners can reduce their costs by charging at lower electricity prices and discharging at higher prices, when the EVs are plugged in for longer periods for harvesting V2G benefits. A pre-condition to using the energy of EVs is to ensure that their energy can satisfy the mobility demands, and only the surplus part of the energy is traded with the energy system (Niu et al., 2024). Utilizing surplus energy can provide some flexibility in the operation of energy systems e.g., offsetting variability of renewable energy sources (RESs). However, the biased energy research only focuses on providing flexibility by EVs, overlooking the primary duty of EVs as a mobility service (Sevdari et al., 2022). For instance, Wei et al. (2022) considered Vehicle-to-Grid (V2G) technology within an integrated energy system, where home charging allows EVs to charge or discharge when plugged in. The presence of EVs was modeled using a probability distribution function. The study's results demonstrate the benefits of EVs in effectively shaping electricity demand on the power grid. However, there is no guarantee that EV owners will leave home with the required amount of charge for mobility purposes, or that their acceptance is considered in plugging in their EVs. Therefore, the optimization problem in V2G can aim to reduce electricity procurement costs on the energy side or increase profits for EV owners in the interaction with energy systems. Furthermore, several studies have explored EV users' willingness to pay or accept charging costs by designing and conducting surveys, followed by extracting insights using data-driven methods (Baumgartner et al., 2022; Visaria et al., 2022). These surveys are designed based on factors that influence users' decisions regarding whether to accept or pay for charging. Such research helps bridge the gap by moving beyond viewing EV users as passive participants in the real market.

The planning of charging infrastructures for public transit systems differs in various aspects compared to private cars. The public transit should adhere to a predetermined timetable within a day which implies tight charging scheduling between consequent trips. The integrated planning and scheduling of the public transit system specifies the size, location of chargers, and short-term decisions of charging/discharging scheduling (Duan et al., 2023). Therefore, the objective functions mainly include the total cost of charging infrastructure planning and optimization of charging scheduling. Electric buses can be charged in depots by slow chargers or en route by fast chargers. Slow chargers range from 50–150 kW, while the fast chargers vary from 150–600 kW. Obviously, the fast chargers affects energy systems more seriously due to their capacity (Hu et al., 2022). However, most existing studies on charging infrastructure planning focus primarily on addressing issues related to the transportation side alone. For example, Zhou et al. (2022) identified the optimal deployment of en-route chargers, charging schedules, and the configuration of electric bus batteries, with the latter referring to the determination of the optimal battery size. The effect of more accurate energy consumption of electric buses on charging infrastructure planning and charging scheduling has also been explored in Gairola and Nezamuddin (2023). The current coupled system studies have concentrated on the economic aspects of the interaction with energy systems by including the time-of-use pricing in charging infrastructure planning problem, by focusing on specifying the size and locations for charging infrastructures in depots and en route (He et al., 2022). Nevertheless, some studies have investigated the multi-stage planning of charging infrastructure, considering the growth of charging demands over time. In these studies, charging infrastructure is planned in various stages while being integrated with energy systems. Although this approach looks toward future perspectives, it oversimplifies the problem due to the lack of sufficient information on spatiotemporal demands (Lin et al., 2019).

3. Assessment of current studies and future research direction

A comprehensive solution for coupled transportation and energy systems requires a thorough understanding of both domains. Estimating charging demands is the first step in planning charging infrastructure, as it highlights the new demand placed on energy systems. Accurately capturing both the spatial and temporal characteristics of these demands is essential for effectively locating charging infrastructure within transportation systems and assessing the impact on energy systems. While several studies have explored the effects of transportation systems on various aspects of energy systems to answer the question, "How can charging demands impact the energy system?", none of them have introduced a multimodal framework to accurately determine potential impacts. It is clear that considering demand from only a single mode fails to reflect the true impact on the energy system.

Although various studies explore the interaction between transportation and energy systems for private cars, they often overlook the dynamic nature of traffic flow, focusing instead on static models that do not reflect the reality of traffic dynamics. In addition, in terms of the public transit system, current practices emphasize careful planning of infrastructure, including various decisions such as charging scheduling, battery size, and effect of energy consumption on optimal location and size of charging infrastructure and charging scheduling (Gairola and Nezamuddin, 2023; Zhou et al., 2022). However, the optimal sizing and placement of charging infrastructure can only be achieved by considering the energy system to ensure the optimal functioning of these coupled systems.

Moreover, the bidirectional interaction between transportation and energy systems can yield benefits for both. For transportation systems, the benefits are primarily economic (as discussed in Section 2), while for energy system operators, the benefits are mainly technical, such as increased operational flexibility. Nevertheless, the current studies lack a balanced view in exploring the various features and benefits of the coupled systems. Although some studies have investigated EV users willingness to pay or accept charging costs, further exploration is needed, particularly in the context of mobility regulations specific to each country. Lastly, there is one overlooked aspect in the current studies regarding the support of charging demands in energy systems. Specifically, it is crucial for developing sustainable solutions to mitigate the adverse impacts of charging demands on energy systems, e.g., voltage drops, transformers overload, etc. The deployment of RESs increases the generation capacity of energy systems to help balance supply with the rising demands. Since RESs can be installed locally, such as at charging infrastructure locations, they not only compensate for charging demands but also assist in the operation of the power grid such as regulating voltage and reducing power grid losses (Fu et al., 2023).

Considering the aforementioned gaps, we propose the following future research directions to bridge them:

- The current practice lacks a comprehensive long-term spatiotemporal estimation of charging demands necessary to determine the size and location of new infrastructure within coupled transportation and energy systems. Further research is needed to advance beyond the current state of the art by incorporating "long-term, spatial, and temporal" aspects into the estimation of charging demands.
- Effective multimodal modeling of transportation systems, coupled with more nuanced modeling of the energy systems, can help address the adverse impacts of high charging demands. Current practices often overlook either detailed modeling of the energy system alongside transportation systems for multimodal transportation. Such integrated multimodal modeling is essential to ensure that transportation systems do not impose additional stress on energy systems.
- A potential future approach could bridge the existing gap in accurately modeling traffic flow including dynamic behavior for private cars, leading to more precise calculations of the infrastructure required to support vehicle charging demands and enhance energy system infrastructure.
- To counterbalance the excessive demands from transportation systems, deploying sustainable solutions such as RESs still needs more attention. Integrated planning of charging infrastructure and RESs not only mitigates the negative impact of charging demands on energy systems but also enhances overall sustainability from a systemic perspective.
- Current studies often disregard the preconditions for utilizing EV energy, which is primarily intended for mobility, as well as limitations imposed by transportation systems. A promising future research direction is to optimize coupled systems by considering these constraints, thereby maximizing the benefits of integrated transportation and energy systems.
- Although there are current practices using data-driven methods to develop policies that consider EV users, it remains important to examine the influencing factors across different cities to assess EV users' willingness to participate in bidirectional interactions between transportation and energy systems.

In summary, the planning and expansion of e-mobility must be accompanied by a corresponding expansion of energy systems. The expansion in energy systems may include increasing the capacity of electricity generation, and improving the capacity of assets with the new loads e.g. transformers, cables, etc. Standalone optimization of isolated systems fail to provide a realistic understanding of their interconnected nature. To achieve a more comprehensive understanding of planning and expansion in transportation systems, an integrated solution is required. Future research should focus on developing an integrated planning and optimization framework that considers both transportation and energy systems, with particular attention to their interactions and mutual influences.

Declaration of Competing Interest

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

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Arsalan Najafi: Writing – original draft, Writing – review & editing, Project administration, Investigation, Formal analysis. **Kun Gao:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization. **Omkar Parishwad:** Writing – review & editing, Investigation, Formal analysis. **Mahdi Pourakbari-Kasmaei:** Writing – review & editing, Investigation, Formal analysis. **Radu-Emil Precup:** Writing – review & editing, Formal analysis. **Raul-Cristian Roman:** Writing – review & editing, Formal analysis.

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