Technical Report:

The Interdependency of Transportation Network and Electric Distribution Grid

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1. **Introduction**

Electrification, connectivity, and autonomous driving, as three major transformations in automotive industry, offer great promise to relieve traffic congestion, boost fuel economy, and reduce carbon emission. The U.S. government has also spurred efforts to encourage the utilization of transportation electrification technologies [1, 2]. A fast-growing number of electric vehicles (EV) is recently making a large influence our habits and disrupting transport routines. These changes provide an untraditional view of the transportation network (TN) and the power distribution network (PDN). That is, these two networks studied independently of each other in the literature should be collaboratively managed in order to meet the rising demand of EV charging load [3]. As a result, transportation electrification infrastructure forms an interdependent network of these networks. Either of TN and PDN is a huge and complex system consisting of millions of subnetworks and individual agents. Their “tie point” is critical to the reliability, cost-effectiveness, and relicense of such a complex multi-layered system. As such “tie points”, the emerging deployment of EV charging facilities would complicate the understanding and design of interdependent critical infrastructure systems.

This project aims to model and quantify the interdependency of the transportation network and the power distribution grid. To achieve this objective, the project team has completed three tasks:

1. Completely review the literature studies of the EV charging station (EVCS) planning problem. We survey three major research directions. This EVCS problem used to be analyzed separately in PDN and TN. Recently, these two networks are linked together for PDN offers supplies to the charging demands in TN.
2. Propose a novel EVCS planning model using two-stage mixed-integer stochastic programming. This model allows to design the locations and sizes of EVCS’s and decide the expansion of the existing distribution grid in the here-and-now stage and to control power flows, manage management EV charging operations, and utilize renewable energy in the wait-and-see stage.
3. Develop a fast solution method for the proposed large-scaled model. Depicting the planning and operations of two networks, particularly under the uncertainties of the renewable energy supplies and the EV charging loads, results in the huge complexity.
4. **Literature Review**

The EVCS planning problem used to be analyzed separately in PDN and TN. In power distribution network, the system operation and security constraints, i.e., power flow constraints, voltage limit constraints and thermal limit constraints, need to be considered in detail while the driving patterns of EV are usually simplified. A two-step EV charging stations planning method in PDN is proposed in [4] where the optimal sites for EVCS is identified in the first stage, with consideration of environmental factors and service radius, and the optimal sizing of EVCS is determined in the second stage using a modified primal-dual interior point algorithm. A life cycle cost based optimal EVCS planning model is proposed in [5] which includes the location and sizes of EVCS, as well as the charging strategies of battery storage system.

In transportation network, the traffic flow is modeled in detail using traffic assignment problem (TAP) models and the impact of EV on power distribution system is usually neglected. Most research work in TN focuses on including EV in current TAP models [6]. Optimal electric vehicle charging station placement in transportation network is discussed in [7-10]. [7] proposes a multiple-recharging-station-location model based on a vehicle-refueling logic with set coverage and maximum coverage concept. [8] focuses on human factors to make sure every EV can access a charging station within driving capacity. Drives' spontaneous adjustments and interactions of travel and recharging decisions are considered in [9]. Transportation demand forecasts and travel survey data is used to produce mobility patterns in [10] with drives' competition and behaviors captured. Dynamics in the transportation network topological structure is captured in [11] where a multi-period model is proposed to expand EVCS network. The transportation network expansion problem is discussed in [12, 13]. The network performance is optimized by links expansion with Wardrop user equilibrium (UE) constraint [12] and a discrete network expansion model is formulated in [13] to determine optimal link addition and link capacity.

The interdependency of transportation network and power distribution network brought by EV behaviors shows the importance of considering TN and PDN simultaneously when dealing with EV problems. The operation equilibrium of TN and PDN is identified by iteratively solving a TAP and OPF problem in [14] where a multi-community UE model is proposed considering driving patterns, electricity prices and fast charging stations. The traffic flow information is sent to PDN and the electricity price is sent to TN until a fixed point is reached. An optimal traffic-power flow model with Wardrop UE constraints is proposed in [15] to identify optimal coordinated operation of TN and PDN. Optimal planning of EV charging station in coupled transportation network and power distribution network is discussed in [16-23]. A multi-objective planning method is proposed in [16] which ensures charging service while reduces power losses and voltage deviation. A battery capacity-constrained EV flow capturing location model is proposed to maximize EV traffic flow. An equilibrium model is proposed in [17] that captures interactions among availability of public charging opportunities, electricity prices and destination and route choices of PHEVs. A user equilibrium (UE) based traffic assignment model is incorporated in [18] to capture the traffic flow pattern and the objective is to minimize overall annual investment cost and energy losses and maximize annual captured traffic flow at the same time. A planning framework for different types of PEV charging facilities is proposed in [19] where the charging demand is generated by a forecasting method. Vehicle travel patterns are used in [20] to capture charging demand and a capacitated-flow refueling location model is proposed in [21] to evaluate EV charging demand on TN. [22] uses dynamic OD traffic flow on TN to model time-varying PEV charging demand and proposes a stochastic mixed-integer SOCP model to site and size fast EVCS. FISK's stochastic traffic assignment model is used to model traffic flows in [23] and the investment and operation costs of PDN is minimized and the annually captured traffic flow is maximized simultaneously. Both power distribution system operation constraints and traffic flow constraints are considered in these literature, but system expansion is not taken into discussion.

An expansion planning model of urban electrified transportation networks is proposed in [24] which determines the best investment strategies for TN and PDN simultaneously, including sites and sizes of new lanes, charging facilities, distribution lines and local generators. Nesterov user equilibrium (NUE) is used to model traffic flow in the TN and linearized BFM is used to model PDN. The power demand of on-road charging facility is assumed to be proportional to the traffic flow it carries. The model is formulated as a mixed-integer nonlinear program with NUE constraints and transformed into an equivalent mixed-integer convex program through duality theory and techniques of integer algebra. [25] also proposes an expansion planning model where the traffic flow is captured by an unconstrained traffic assignment model (UTAM) with road capacity constraints being relaxed, and the PDN is also modeled with linearized BFM. Different from [24], the EV charging demands and interdependency of TN and PDN are characterized by EV charging station location model in [25], in which constraints on EV driving range and traffic flow equilibrium are explicitly incorporated. A mixed-integer linear programming (MILP) is formulated for the coordinated planning model and a global optimal solution can be retrieved. Both [24] and [25] formulate the expansion planning model without consideration of system operation uncertainties. In [26], a multi-year expansion planning method for growing EV is proposed with a dual-stage optimization framework, where the first-stage deals with the optimal investment for network reinforcement and second-stage examines system performance under various operating situations. The system planning decision-making and operation simulations are combined in [26], but the transportation network is totally ignored. To our understanding, there is no paper which deals with EV charging station planning problem in coupled transportation and power distribution network with system expansion and system operation included at the same time.

1. **Nomenclature**

|  |  |
| --- | --- |
| **Sets** |  |
|  | Set of TN nodes |
|  | Set of PDN nodes |
|  | Set of PDN lines |
|  | Set of opening locations of EVCS’s |
|  | where “ is a dummy station |
|  |  |
| **Parameters** |  |
|  | Fixed cost of building a charging station at location j |
|  | Cost of building a unity of capacity at location j |
|  | Cost of each PDN line . |
|  | Unit penalty cost for unsatisfied demands.  Unit benefit for fulfilled utility. |
|  | Utility of EV owners at region i choosing station j for charging at scenario . |
|  | Threshold utility value below which EV owners do not make charging. |
|  | Demand at TN node at scenario . |
|  | Real load at PDN node at scenario if it is positive; otherwise real flow generated from electrical supplies. |
|  | Reactive load at PDN node at scenario if it is positive; otherwise real flow generated from electrical supplies. |
|  | Capacity of allowed real power flow at PDN line . |
|  | Capacity of allowed reactive power flow at PDN line . |
|  | Upper bound of voltage. |
|  | Lower bound of voltage. |
|  | Resistance of PDN line . |
|  | Reactance of PDN line . |
|  | Real power needed for each unit of charging load. |
|  | Charging power factor. |
|  |  |
| **Variables** |  |
|  | Binary variable indicating whether location j is selected |
|  | Charging capacity at station j |
|  | Binary variable indicating whether the line should be added to PDN line |
|  | Unsatisfied demands at station j |
|  | Charging loads from region i to station j |
|  | Real power flow passing PDN line |
|  | Reactive power flow passing PDN line |
|  | Voltage power at node m. |

1. **Problem Description and Model**

This project considers an EVCS planning problem under the interdependency of TN and PDN. There are four questions which need to be addressed:

1. How many EV fast charging stations should be built?
2. Where and how large should each station be built?
3. How is the existing PDN expanded to satisfy the potential charging loads?
4. How are the constructed EVCS used to serve EV charging demands?

Questions (a)-(c) considers the long-term planning strategy of building EVCS and expanding PDN. On this basis, question (d) is to seek the optimal policy to operate the constructed charging stations to serve

EV charging demand during a short-term period. This feature of the hierarchical structure motives us to specify a two-stage stochastic programming model, of which the first here-and-now stage is to study questions (a)-(c) and the second wait-and-see one is to answer question (d).

The first stage of the model is described as

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| *s.t.* |  |  |
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The objective of the first-stage minimizes the costs incurred from the selection of locations and sizes of EVCS’s, the expansion of PDN, and the penalty for unsatisfied demand, on average, in the second-stage.

In the second stage, the PDN acts as a supplier which needs to best satisfy the charging demands of EV’s in TN. The charging demands are generated at certain regions in TN and each EV is decentralized. Owners are able to makes charging decision to maximize its individual utility (see [27]). We characterize the preference as the following exponential utility function of charging cost and traffic time:

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where is the utility value of EV in region charging at station at scenario and the charging cost and traffic time both varies in scenario. We set a dummy station () for drivers decide not to charge their EV’s, and let which is a given threshold. Now the largest utility value tells the station that an owner prefers to go. Hence, if we have decided the locations and sizes of charging stations, the user-choice assignment model [27] is formulated as follows:

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Constraint (1) depicts capacity requirement on each built EVCS, constraint (2) ensures EV owners select EVCS that they prefer, and constraint (3) is for assigning charging demands to different EVCS’s.

We now integrate the EV charging demand into the PDN model as follows:

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Constraints (4)-(5) formulates the power flow to satisfy all loads including EV charging . Note that Constraints (4)-(5) also take in account the supplies from the renewable energy with a negative . Constraints (6)-(12) are voltage requirement to ensure charging quality. Constraints (13)-(14) specify the capacity restriction of power flows.

Combining the TN and PDN constraints, we have the second-stage model as

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|  | s.t. TN constraints (1)-(3) and PDN constraints (4)-(14). |  |

In the second stage, we minimize the penalty cost resulting from unmet charging demand for the restriction to the capacities of the constructed EVCS’s and expanded PDN decided in the first stage.

1. **Solution Method**

The aforementioned model aggregates TN and PDN. Either is a huge and complex system consisting of millions of subnetworks and individual agents. Moreover, the uncertainties of the renewable energy supplies and the EV charging loads bring a large number of scenarios into the model and further increase the complexity. We develop a fast algorithm based on the Bender decomposition method.

For the sake of brevity, let us define the following function

By this definition, the dual problem of the second-stage model is given as

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We now describe the algorithm. First solve a sequence of master problems

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| *s.t.* |  |  |
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Let be an optimal solution at the current iteration. Then we solve to general a new cut into the master problem

The algorithm repeats these iterations until the optimal value of the master problem converges.

1. **Case Study**

**Test Network**

We consider the autonomous EV’s charging problem. This problem has become core business for Ford, Uber, and Amazon. Autonomous EV fleet is different from human-driven EV fleet for Autonomous EV’s obey the systematic optimal charging management. This advantage immensely promote charging economy.

We test our model on 34-node test feeder [] and Sious Falls transportation network []. The model is implemented in Python and IBM’s CPLEX 12.9. In our case study, the inner loop of TN is assumed to be the urban and outer loops are assumed to be the suburban, and we use three loops. The cost of building a charging station in inner loop is higher than the outer loop. We assume the inner loop building cost is $1,000,000, middle loop building cost is $500,000, and the outer loop building cost is $200,000.

A screenshot of a cell phone

Description automatically generated

A picture containing text, map, light, street

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**Model Performance**

Compared with regular human-driven EV always choosing charging station with the highest utility, we adjust the tolerance level () on utility which following the systematic optimal charging management. In order to evaluate the performance of our model, we assume the expanding capacity is 2, and plot three values as the tolerance level changes. We notice that with limited capacity of expanding the PDN, if we can adjust the tolerance level, we can fulfill a lot of extra demand. On the other hand, the building cost will not increase a lot and the utility will not decrease a lot.

Since there is big jump between and We want to investigate these two cases in detail.

Table

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| --- | --- | --- | --- |
| Tolerance () | Location | Capacity () | PDN line () |
| 5 | ( 2,5,10,11,13,19,20,21 ) | (﻿143.0, 181.0, 195.0, 195.0, 120.0, 156.0, 168.0, 181.0) | (2,3)-1; (3,4)-2;  (9,13)-2; (10,11)-2  (15,16)-2; (17,19)-1;  (20,23)-2; (23,25)-2;  (26,27)-2; (31,32)-2; |
| 0 | ( 2,5,11,13,19,20,21) | (﻿143.0, 181.0, 195.0, 120.0, 156.0, 130.0, 180.0) | (2,3)-1; (3,4)-2; (10,11)-2;  (15,16)-2; (17,19)-1;  (20,23)-2; (23,25)-2;  (26,27)-2; (31,32)-2; |

The table 1 shows that if we increase the tolerance level, we can build more station to fulfill more demand. The new location we build is in location 10 which is the inner loop. The reason behind this is that if we build a station in 10 when the consumer always choose the largest utility location, a lot of consumer will only charge in location 10. However, with the limit of capacity in 10, a lot of demand cannot be fulfilled, which causes a very high penalty cost. Thus, we will next to investigate the case when we can build large capacity station. We choose the expanding PDN capacity (K) to be 5.

Now, if we change the PDN expanding capacity to 50. We notice that changing the tolerance level will not save cost for us. Only two large stations in urban will fulfill all demand in the town.

Table

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| --- | --- | --- | --- | --- |
| Tolerance () | Location | Capacity () | Cost | PDN line ( |
| 0 | ( 2,5,13,20,21 ) | (330,400,194,260,246) | $ ﻿﻿1463000.0 | (2,3)-1; (3,4)-5;  (10,11)-5; (17,19) -2;  (26,27)- 4; (31,32)-3 |
| 5 | (2,13,20,21) | (362,310,358,400) | $ ﻿﻿1268000.0 | (2,3)-1; (3,4)-5;  (17,19) -4;(20,23)-5;  (23,25)- 5; (31,32)-5; |

Under the Autonomous EV assumption, we can move the inner loop demand to outer loop. Instead of building small charging station in inner loop, we may build larger station in urban area. In the case of table 1, we can build less stations to save fixed cost. The saved cost is $ 195,000 which is smaller than $500,000 the fixed cost to build in the middle loop, because we need to expand PDN in order to build a station with larger capacity.

Now, if we change the PDN expanding capacity to 50. We notice that changing the tolerance level will not save cost for us. Only two large stations in urban will fulfill all demand in the town.

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| Tolerance () | Location () | Capacity () | Cost | PDN line ( |
| 0 | ( 2,11,21 ) | (280,634,516) | $ ﻿ ﻿1063000 | (2,3)-1; (3,4) -4;  (15,16) -8; (31,32)-7; |
| 5 | ( 2,11,21 ) | (280,634,516) | $ ﻿﻿1063000 | (2,3)-1; (3,4) -4;  (15,16) -8; (31,32)-7; |

**Computation Power**

To test the computation efficiency, in our cases studies, we simulated daily demand for one month with 30 days.

1. **References**

[1] C. C. Chan, "The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE,* vol. 95, *(4),* pp. 704-718, 2007.

[2] E. Ungar and K. Fell, "Plug In, Turn On, and Load Up," *IEEE Power and Energy Magazine,* vol. 8, *(3),* pp. 30-35, 2010.

[3] M. E. El-Hawary, *Introduction to Electrical Power Systems.* Hoboken, NJ: Wiley, 2008.

[4] Z. Liu, F. Wen and G. Ledwich, "Optimal planning of electric-vehicle charging stations in distribution systems," *IEEE Trans. Power Del.,* vol. 28, *(1),* pp. 102-110, 2012.

[5] Y. Zheng, Z. Y. Dong, Y. Xu, K. Meng, J. H. Zhao and J. Qiu, "Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning," *IEEE Trans. Power Syst.,* vol. 29, *(1),* pp. 221-229, 2013.

[6] W. Wei, W. U. Danman, W. U. Qiuwei, M. Shafie-Khah and J. P. Catalao, "Interdependence between transportation system and power distribution system: a comprehensive review on models and applications," *Journal of Modern Power Systems and Clean Energy,* vol. 7, *(3),* pp. 433-448, 2019.

[7] Y. Wang and C. Lin, "Locating multiple types of recharging stations for battery-powered electric vehicle transport," *Transportation Research Part E: Logistics and Transportation Review,* vol. 58, pp. 76-87, 2013.

[8] A. Y. Lam, Y. Leung and X. Chu, "Electric vehicle charging station placement: Formulation, complexity, and solutions," *IEEE Transactions on Smart Grid,* vol. 5, *(6),* pp. 2846-2856, 2014.

[9] F. He, Y. Yin and J. Zhou, "Deploying public charging stations for electric vehicles on urban road networks," *Transportation Research Part C: Emerging Technologies,* vol. 60, pp. 227-240, 2015.

[10] C. J. Sheppard, A. Harris and A. R. Gopal, "Cost-effective siting of electric vehicle charging infrastructure with agent-based modeling," *IEEE Transactions on Transportation Electrification,* vol. 2, *(2),* pp. 174-189, 2016.

[11] S. Li, Y. Huang and S. J. Mason, "A multi-period optimization model for the deployment of public electric vehicle charging stations on network," *Transportation Research Part C: Emerging Technologies,* vol. 65, pp. 128-143, 2016.

[12] C. Li, H. Yang, D. Zhu and Q. Meng, "A global optimization method for continuous network design problems," *Transportation Research Part B: Methodological,* vol. 46, *(9),* pp. 1144-1158, 2012.

[13] D. Z. Wang, H. Liu and W. Y. Szeto, "A novel discrete network design problem formulation and its global optimization solution algorithm," *Transportation Research Part E: Logistics and Transportation Review,* vol. 79, pp. 213-230, 2015.

[14] W. Wei, L. Wu, J. Wang and S. Mei, "Expansion planning of urban electrified transportation networks: A mixed-integer convex programming approach," *IEEE Transactions on Transportation Electrification,* vol. 3, *(1),* pp. 210-224, 2017.

[15] W. Wei, S. Mei, L. Wu, M. Shahidehpour and Y. Fang, "Optimal traffic-power flow in urban electrified transportation networks," *IEEE Transactions on Smart Grid,* vol. 8, *(1),* pp. 84-95, 2016.

[16] G. Wang, Z. Xu, F. Wen and K. P. Wong, "Traffic-constrained multiobjective planning of electric-vehicle charging stations," *IEEE Trans. Power Del.,* vol. 28, *(4),* pp. 2363-2372, 2013.

[17] F. He, D. Wu, Y. Yin and Y. Guan, "Optimal deployment of public charging stations for plug-in hybrid electric vehicles," *Transportation Research Part B: Methodological,* vol. 47, pp. 87-101, 2013.

[18] W. Yao, J. Zhao, F. Wen, Z. Dong, Y. Xue, Y. Xu and K. Meng, "A multi-objective collaborative planning strategy for integrated power distribution and electric vehicle charging systems," *IEEE Trans. Power Syst.,* vol. 29, *(4),* pp. 1811-1821, 2014.

[19] H. Zhang, Z. Hu, Z. Xu and Y. Song, "An integrated planning framework for different types of PEV charging facilities in urban area," *IEEE Transactions on Smart Grid,* vol. 7, *(5),* pp. 2273-2284, 2015.

[20] N. Shahraki, H. Cai, M. Turkay and M. Xu, "Optimal locations of electric public charging stations using real world vehicle travel patterns," *Transportation Research Part D: Transport and Environment,* vol. 41, pp. 165-176, 2015.

[21] H. Zhang, S. J. Moura, Z. Hu and Y. Song, "PEV fast-charging station siting and sizing on coupled transportation and power networks," *IEEE Transactions on Smart Grid,* vol. 9, *(4),* pp. 2595-2605, 2016.

[22] H. Zhang, S. J. Moura, Z. Hu, W. Qi and Y. Song, "A second-order cone programming model for planning PEV fast-charging stations," *IEEE Trans. Power Syst.,* vol. 33, *(3),* pp. 2763-2777, 2017.

[23] S. Wang, Z. Y. Dong, F. Luo, K. Meng and Y. Zhang, "Stochastic collaborative planning of electric vehicle charging stations and power distribution system," *IEEE Transactions on Industrial Informatics,* vol. 14, *(1),* pp. 321-331, 2017.

[24] W. Wei, L. Wu, J. Wang and S. Mei, "Network equilibrium of coupled transportation and power distribution systems," *IEEE Transactions on Smart Grid,* vol. 9, *(6),* pp. 6764-6779, 2017.

[25] X. Wang, M. Shahidehpour, C. Jiang and Z. Li, "Coordinated Planning Strategy for Electric Vehicle Charging Stations and Coupled Traffic-Electric Networks," *IEEE Trans. Power Syst.,* vol. 34, *(1),* pp. 268-279, 2018.

[26] B. Zeng, J. Feng, J. Zhang and Z. Liu, "An optimal integrated planning method for supporting growing penetration of electric vehicles in distribution systems," *Energy,* vol. 126, pp. 273-284, 2017.

[27] W. Yang, "A user-choice model for locating congested fast charging stations," *Transportation Research Part E,* vol. 110, pp. 189-213, 2018. Available: <https://www.sciencedirect.com/science/article/pii/S1366554517305100>.