Lake Michigan Electric Vehicle Circuit

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Table of Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

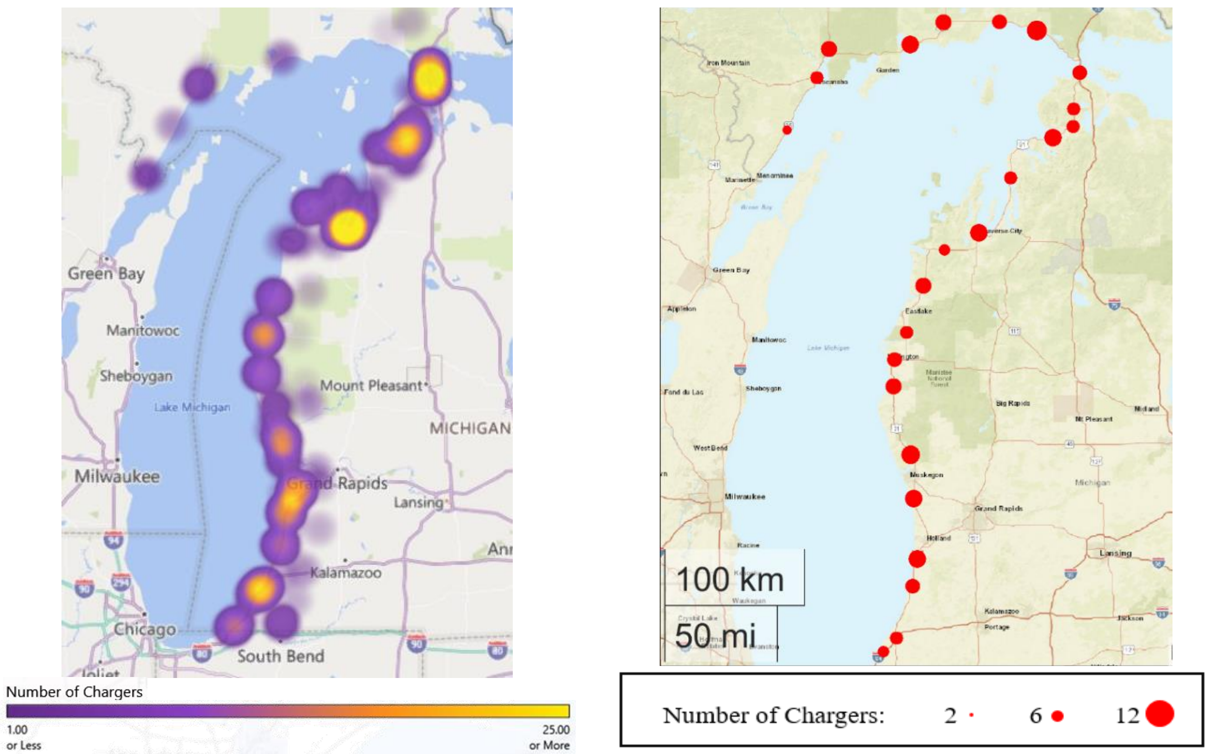
This comprehensive study is focused on the strategic development of electric vehicle (EV) charging infrastructure in the Lake Michigan Circuit area. Its primary objective is to facilitate convenient and efficient charging options, particularly for tourists, within this geographical region. The study encompasses key sections, each contributing to a nuanced understanding of the charging network, its optimization, budgetary implications, and its integration into the broader transportation landscape. The Lake Michigan Circuit area is a prime location for ecotourism and the overarching goal of the study is to devise an integrated, cost-effective, and user-friendly charging network. The methodology section offers a detailed roadmap for how the study approaches the complex task of planning and optimizing charging infrastructure. It introduces the Level-2 and Direct Current Fast Charging (DCFC) modeling frameworks, which serve as the foundation for the study's analysis. The Level-2 framework consists of various stages, including trip generation, trip distribution, EV and energy demand estimation, and charger allocation, all of which are meticulously explained. The DCFC modeling framework also introduces novel elements, such as the concept of a charging buffer range and the algorithm for assigning electric vehicles to charging stations, making the study's approach exceptionally nuanced and sophisticated.

The study's results and discussions unveil the outcomes of the Level-2 network analysis. It employs both heuristic and optimization approaches to determine the optimal location of Level-2 charging stations under diverse scenarios. It is revealed that the optimization approach excels in minimizing overall user inconvenience, albeit with longer solution runtimes, compared to the heuristic approach. The scenarios demonstrate the intricate trade-offs between capital investment, budget constraints, and user costs. Moreover, the analysis explores the impact of charging power and budget constraints on infrastructure allocation, providing insights into cost-effectiveness and user experience. The optimal configuration of DCFC stations addresses budgetary limitations and travel feasibility. It is clear that budget constraints significantly influence the feasibility and user convenience of the DCFC network. The study's results indicate that budget limits below $4 million lead to stranded energy demand and unserved EVs. The importance of ensuring EV trip feasibility over minimizing user delay is underscored, and the budget allocation is identified as a crucial factor. The results showcase the location and scale of the optimal charging infrastructure under varying budget constraints, offering a robust foundation for strategic decision-making. Finally, a combined network that integrates Level-2 and DCFC infrastructure is developed and analyzed. This integrated approach, operating under a total budget of $20 million, accommodates different budget allocations between the two networks. Remarkably, it effectively serves the entire energy demand in most budget allocation scenarios. However, the study identifies an exception when only 20% of the budget is allocated to the DCFC network, leading to significantly increased average DCFC queuing times. This finding highlights the importance of allocating at least 30% of the budget to the DCFC network to maintain an acceptable level of user costs. Comparing the results shows that the lowest total cost occurs when 60% of budget is allocated to Level-2 and 40% to DCFC. Meanwhile all scenarios have the same investment cost, this scenario has the lowest user

costs (delays). Thus, it is the most cost-efficient configuration as shown in Figure below.

Optimal Charging Infrastructure Results for Interconnected Network Under Different Budget Allocations

Budget Allocation	20%	80%	30%	70%	40%	60%	50%	50%	**60%**	**40%**	70%	30%	80%	20%
Network	Level-2	DCFC	Level-2	DCFC	Level-2	DCFC	Level-2	DCFC	**Level-2**	**DCFC**	Level-2	DCFC	Level-2	DCFC
Number of New Stations	74	14	106	11	138	11	187	11	**206**	**12**	232	9	285	9
Number of New Chargers	376	177	502	158	631	132	788	104	**867**	**78**	952	61	1,080	35
Level-2 Unserved Demand Served by DCFC (MWh)	-	133.6	-	106.1	-	78.5	-	46.6	**-**	**33.3**	-	19.7	-	2.9
Level-2 Unserved EVs Served by DCFC	-	5,128	-	4,061	-	2,993	-	1,781	**-**	**1,278**	-	759	-	116
Ave. Level-2 Detour (min)	8.42	-	8.24	-	6.65	-	6.07	-	**4.67**	**-**	4.48	-	2.63	-
Ave. DCFC Refueling (min)	-	10.14	-	9.76	-	9.49	-	8.92	**-**	**8.69**	-	8.26	-	8.01
Ave. DCFC Queueing (min)	-	0.74	-	0.54	-	0.86	-	0.93	**-**	**2.18**	-	4.67	-	34.20
Ave. DCFC Detour (min)	-	1.99	-	1.57	-	1.61	-	1.78	**-**	**1.76**	-	2.31	-	1.78



(a) (b)

Optimal Charging Infrastructure Distribution with a $20 Million Total Investment Budget (a) Level-2 ($12 million) (b) DCFC ($8 million)

In conclusion, this study provides a rich and insightful exploration of the planning and optimization of charging infrastructure within the Lake Michigan Circuit area. The results yield practical recommendations for decision-makers and stakeholders, emphasizing the significance of balancing budget constraints, charging power, and user satisfaction. Ultimately, the study equips the region with valuable insights to develop a robust and user-centric charging network that aligns with sustainable transportation goals and enhances the experience of travelers, particularly those engaged in tourism activities around the Lake Michigan.

INTRODUCTION

Over the past few years, there has been a noticeable rise in the adoption of electric vehicles (EVs). However, the pace of this growth differs from one state to another. In the case of Michigan, the increase is noteworthy, but it remains below the national average. By the end of 2022, Michigan has 0.4% EV market share among all vehicles, compared to 2.5% EV market share of California ("Alternative Fuels Data Center: TransAtlas," 2022). The rising trend in EV adoption, among other factors, can be attributed to their energy efficiency and zero tailpipe emissions; however, other factors, including fuel costs, purchase prices, and demographic factors, also influence the market share of alternative fuel vehicles like EVs (He et al., 2013; Nie and Ghamami, 2013). Recent research has emphasized that the presence of a well-distributed network of charging stations is the most crucial factor driving the increased adoption of EVs (Fakhrmoosavi et al., 2021b; Liu et al., 2023).

Planning the charging infrastructure requires distinct considerations for intracity and intercity travel (Lim and Kuby, 2010). When it comes to intracity trips, the distances involved typically align with the driving range of EVs, thus considering factors such as activities and chain of trips is essential (He et al., 2015; Kavianipour et al., 2023). However, for intercity trips, the driving distances may exceed the battery capacity of a fully-charged EV. Consequently, the design of charging infrastructure is primarily geared towards ensuring feasibility and comprehensive coverage across the network (He et al., 2013). The Society of Automotive Engineers (SAE) has categorized charging infrastructure into three levels (as shown in **Figure 1**): Level-1 (slow charging, using a regular wall outlet, typically overnight), Level-2 (currently most prominent, requiring a few hours to fully charge), and Level-3 or DCFC (the fastest type, charging up to 80% in 30 minutes or less, suitable for long-distance travels) (Khan et al., 2018). There is a growing demand for DCFC stations to support longer trips made by EV users. While DCFC effectively reduce charging time and enable long-distance travel for EVs, their implementation is hindered by the high costs involved. In contrast, Level-2 chargers take more time to charge but come with significantly lower user and implementation expenses (Fakhrmoosavi et al., 2021a; Mastoi et al., 2022). Furthermore, the use of DCFC results in higher currents and temperatures, both of which are known to exert additional stress on batteries and accelerate their deterioration. Therefore, it is advisable to prioritize charging through lower-power chargers, whenever there is sufficient time to do so, to promote better battery health (Geotab USA, 2020). In summary, Level-2 chargers are the preferred choice for locations where vehicles will be parked for an extended period, while DCFC stations are suitable for instant recharging during the long-distance trips.

Charger Type	Primary Use	Charging Power	Charger Cost	Charging Time	Charging Price
Level-1	Residential	1.2 – 1.9 kW	$0.2K - $1.5K	8 – 16 hours	0.02 – 0.06 $/mile
Level-2	Residential & Public	2.6 – 19.2 kW	$0.5K – $5K	4 – 8 hours	0.02 – 0.06 $/mile
Level-3 DCFC	Public	50 – 350 kW	$28K - $140K	20 – 30 minutes (80%charge)	0.12 – 0.25 $/mile

Figure 1. Summary of Charging Infrastructures for EVs.

Recently, the adoption of EV technology has emerged as an effective strategy to promote sustainable ecotourism and boost economic growth in areas renowned for their tourist attractions (LaMonaca and Ryan, 2022). Prior research has emphasized that the presence of charging stations at tourist destinations significantly influences the decision of EV users to embark on their trips (Csiszár et al., 2019). These advancements not only foster the widespread adoption of EVs but also extend their utility to cater to various individual needs, extending beyond daily commuting. In light of these considerations, there is a pressing need to develop a comprehensive framework that identifies the optimal location, quantity, and charging levels for stations within regions known for their tourist attractions, while encompassing all the components discussed in this project.

In 2022, Michigan, Wisconsin, Illinois, and Indiana collaboratively entered into the "Lake Michigan EV Circuit Tour" agreement. The purpose of this agreement is to establish an EV charging route that traverses the Lake Michigan coastline, ensuring a seamless EV trip. The goals of the agreement encompass (1) accelerating vehicle electrification and EV adoption, (2) elevating economic growth, and (3) promoting EV ecotourism around Lake Michigan (“Lake Michigan EV Circuit,” 2022). **Figure 2** illustrates Lake Michigan and its neighboring states. The provision of charging infrastructure for EVs is indispensable in facilitating ecotourism by offering sustainable and convenient travel options. As the popularity of EVs continues to surge among tourists, the presence of charging stations along travel routes and at tourist hotspots has grown increasingly crucial.

Figure 2. Miles of Lake Michigan shoreline by state ("Lake Michigan shoreline by state," 2023).

The Michigan Department of Environment, Great Lakes, and Energy (EGLE) initiated the investment in an analytical approach to find the optimum location and number of chargers for the long-distance tourism trips of the EV users. This study aims to introduce a framework for charging planning. The proposed approach considers the intercity trips of EV users, existing charging infrastructure capacity, and costs associated with building an interconnected network of charging stations to find the optimum investment strategy, while ensuring the feasibility of trips for ecotourism in Michigan.

EGLE facilitated a series of stakeholder meetings with communities, utility companies, charging station companies, and the State of Michigan departments. These meetings enabled the data collection process and refinement of the assumptions for the analytical approach.

For the remainder of this report, the problem statement, literature review, methodology including the modeling framework, and the solution approach are presented. Finally, the results for each charging level are presented followed by the conclusion section.

PROBLEM STATEMENT

This research presents a comprehensive framework for optimizing the charging infrastructure, considering both Level-2 chargers at tourist destinations near Lake Michigan's coastline in the state of Michigan and DCFC stations along its main corridor (a.k.a. Lake Michigan Circuit). The Level-2 modeling framework encompasses four steps of trip generation, trip distribution, energy demand estimation, and charger allocation. The Level-2 framework has a dual focus: (1) determine the optimal locations and quantities of Level-2 chargers at potential destinations within the study area and (2) establishing a seamless connection between the Level-2 and DCFC networks to ensure any unserved energy demand from Level-2 network will be fulfilled by the DCFC network, all while minimizing user inconveniences. Candidate points for Level-2 chargers are selected based on their tourist appeal and visitor duration, with a focus on lodging locations. The primary aim of the model is to minimize the overall system costs, which encompass capital expenditures, including charger, utility, and land acquisition expenses. Additionally, the model seeks to mitigate user inconveniences, such as delays and cost disparities that may arise when users are compelled to charge at a DCFC station due to the lack of Level-2 chargers at their destination. It's crucial to emphasize that maintaining trip feasibility remains a critical constraint throughout the problem-solving process.

On the other hand, DCFC framework initiates a corridor-level optimization for charging infrastructure, aiming to minimize costs for both users and system providers. The framework accounts for stochastic queuing delays at charging stations while ensuring the feasibility of EV trips and adhering to budgetary constraints. Furthermore, a distinctive solution methodology is proposed, incorporating simulated annealing (SA), dynamic penalties for handling constraints, and a two-stage decision-making process to separately determine charging station locations and quantities. Within this approach, an algorithm is developed to accurately model EV charging behaviors by considering multiple charging station options during EV intercity trips. By analyzing the interaction between Level-2 and DCFC frameworks, this research aims to provide valuable insights into the effective deployment and usage of charging infrastructure, facilitating wider EV adoption.

LITERATURE REVIEW

Charging infrastructure planning is at the forefront of advancing the widespread adoption of EVs, addressing critical concerns such as range anxiety, accessibility, renewable energy integration, and economic growth. In this section, we delve into the intricacies of EV charging infrastructure optimization, with a specific focus on two key components: Level-2 charging and DCFC. To provide a comprehensive perspective, we commence by examining the distinct considerations associated with intracity and intercity travel in the realm of charging infrastructure needs.

Charging infrastructure planning necessitates distinct considerations for intracity and intercity travel (Lim and Kuby, 2010). In intracity trips, the distances typically align with the driving range of EVs, requiring a focus on traveler activities and trip sequencing (He et al., 2015).

The optimization of EV charging station placement for long-distance trips has been a subject of extensive research (Jing et al., 2017; Kavianipour et al., 2021a). Early models, such as Flow-Capturing Location Models (FCLM), focused on the idea that a single charging facility on a path could capture traffic flow, but this assumption did not consider the need for multiple recharging stops (Shen et al., 2019; Upchurch et al., 2009). To address this limitation, Flow Refueling Location Models (FRLM) were developed, with objectives ranging from maximizing coverage and level of service to minimizing infrastructure costs while ensuring comprehensive EV flow coverage (Nourbakhsh and Ouyang, 2010). Notably, Ghamami et al. (2016) contributed to this area by developing an optimization model that explored EV travel along a 150-mile corridor and assessed the tradeoff between investing in charging stations and batteries to provide an acceptable level of service.

Alternatively, charging demand may concentrate at specific stations, potentially exceeding station capacity and leading to queuing delays (Ghamami et al., 2016; Wang et al., 2019). Researchers like Ghamami et al. (2020) developed models to investigate optimum charging infrastructure configurations while considering deterministic queuing in intercity networks. More recently, Kavianipour et al. (2021b) devised a modeling framework for urban charging infrastructure planning, incorporating deterministic and stochastic queuing delays based on relative arrival and service rates. Additionally, due to the substantial infrastructure investments required for EV charging stations and limited initial budgets, studies have started incorporating budget constraints into the optimization problem (Bao and Xie, 2021). Wang et al. (2018) investigated the siting and sizing problem of fast charging stations in a highway network, considering a limited budget for station construction.

Level-2 chargers offer advantages such as lower installation and maintenance costs and reduced battery deterioration, making them suitable for tourist destinations with extended stays, such as hotels and motels. They provide versatile charging for various EV models, offering convenient options for daily use and benefiting from an established infrastructure network. Therefore, installing Level-2 chargers in locations associated with extended stays could reduce the total system costs, with charging time being less critical for users. However, there is limited research on the integration of Level-2 and DCFC infrastructures within an interconnected network, where EVs effectively utilize both publicly available Level-2 and DCFC in mutual interaction. In this context, Level-2 chargers primarily serve as destination chargers, offering cost-effective solutions with slower charging speeds, while DCFC stations are preferred for rapid charging during intercity travel or when nearby Level-2 chargers are unavailable.

In conclusion, Level-2 chargers are well-suited for destinations with extended stays, while DCFC stations excel in meeting the rapid charging needs of intercity travel. However, a significant research gap exists in integrating Level-2 and DCFC infrastructures within a network, hindering their effective mutual utilization. Bridging this gap is essential to fully leverage the benefits of both charger types.

DATA COLLECTION

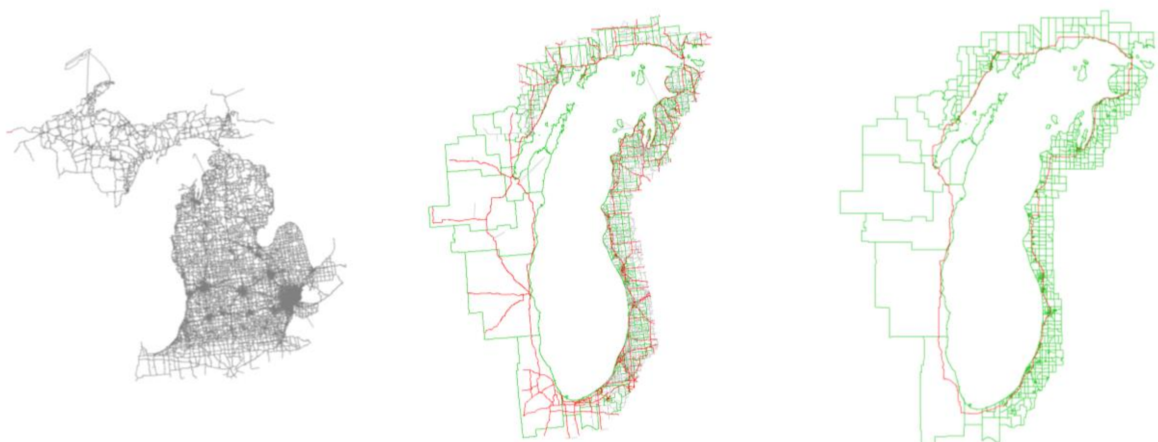
Charging infrastructure planning has a wide array of stakeholders. In this project, we conducted extensive meetings with these stakeholders to acquire their valuable insights and viewpoints. Furthermore, during these engagements, pertinent data were gathered, which will be employed as inputs for our modeling framework. This section offers an overview of the data procured for development of Level-2, DCFC and the integrated frameworks.

Study Area and Road Network

The designated study area, referred to as the Lake Michigan Circuit (LMC) area, encompasses the area within 10-mile distance from the shoreline of Lake Michigan. The road network was obtained from the 2015 updated and calibrated Michigan network provided by Michigan Department of Transportation (MDOT). Within the MDOT data, the state of Michigan is divided into smaller geographical regions referred to as Traffic Analysis Zones (TAZ). Michigan encompasses a total of 4,461 TAZs, with 626 TAZs situated either entirely or partially within the LMC area. LMC area has an approximate of 10,000 nodes and 32,000 links. Each TAZ is represented by a centroid pinpointed by specific geographical coordinates. Visual representations of the road network in Michigan and the LMC area can be found in **Figure 3 (a)** and **Figure 3 (b)**, respectively.

Corridor Structure

The main objective of the DCFC framework is to propose an EV charging corridor equipped with a fast-charging infrastructure, facilitating convenient road trips for EV users within the LMC area. Consequently, the proposed corridor should be positioned in close proximity to the shoreline and ensures accessibility to tourist attractions and amenities surrounding the lake. Moreover, it should encompass major arterial roads and expressways known for their high-speed limits and capacity. Thus, the study advocates for the establishment of an EV charging corridor that encompasses the interstates I-94 and I-196, as well as the highways US-31 in the Lower Peninsula (LP) and US-2 and US-35 in the Upper Peninsula (UP). This corridor covers approximately 600 miles of roadways. A visual representation of the proposed charging corridor within the LMC area can be observed in **Figure 3 (c)**.



(a) state of Michigan network (b) Lake Michigan network (c) Lake Michigan corridor

Figure 3. Road networks originally provided by MDOT

Candidate Points

The primary objective of this study revolves around establishing a network that effectively supports EV tourism. Consequently, any attraction or business engaged in tourism activities within the LMC area is regarded as a potential site for the installation of EV chargers. These candidate points are categorized based on their business type and the average duration of visitors' stays:

1. Short-term stay locations, where tourists typically spend less than 2 hours on average, encompass places like retail stores, restaurants, and gas stations.

2. Mid-term stay locations, where tourists spend an average of 2-6 hours, include venues such as parks, shopping malls, movie theaters, and stadiums.
3. Long-term stay locations, where tourists typically spend more than 6 hours on average, comprise accommodations like hotels, motels, and rental cabins.

Given that Level-2 chargers have a slower charging rate compared to DCFCs, it is most suitable to install them at long-term stay destinations. As illustrated in **Figure 4**, within LMC area, out of a total of 7,074 candidate points, 964 locations are classified as long-term stay destinations.

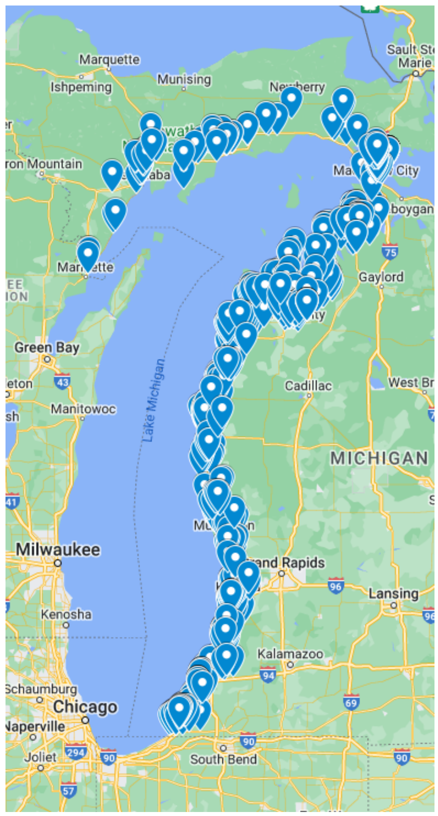
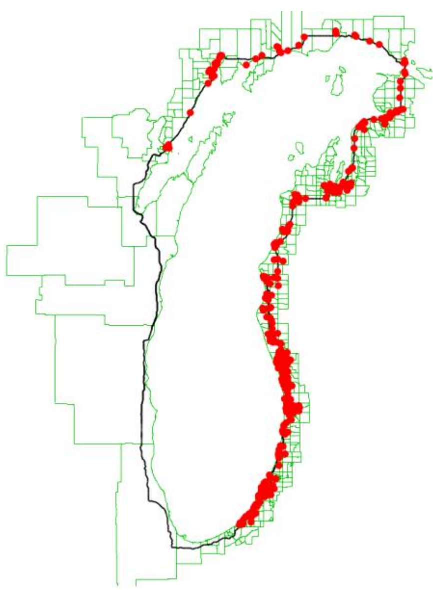
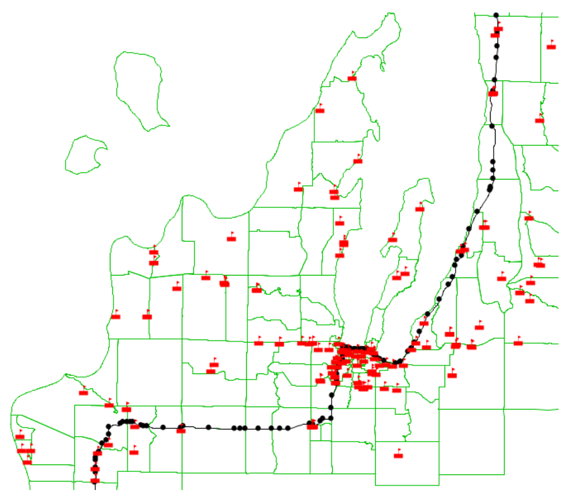


Figure 4. Level-2 candidate points

Additionally, short-term stay locations emerged as the most suitable choices for DCFC site placement due to their average visit duration, which aligns with the typical refueling time at a DCFC station, ranging from 15 to 60 minutes. In total, 640 candidate DCFC locations were pinpointed within the LMC area, as illustrated in **Figure 5 (a)**. Subsequently, the DCFC candidate points were linked to the nearest access point along the main corridor. To estimate the detour travel distances, the shortest path from the main corridor exit to each candidate DCFC point was recorded. **Figure 5 (b)** illustrates the distribution of DCFC candidate points around the main corridor. A total of 219 DCFC candidate locations were mapped to access points on the main corridor. As shown in **Figure 5 (c)**, the majority of DCFC points were closely distributed, with an average distance between adjacent nodes of less than 3 miles. However, in specific areas such as UP, where infrastructure and land development are limited, the distance between consecutive candidate points could extend up to 24 miles. Efficiently evaluating the optimal charging infrastructure configuration among 219 candidate locations can be a time-consuming task, especially when some of these locations are in close proximity to each other. Given the dense distribution of DCFC candidate locations around major cities and attractions, it is practical to work with representatives from each group of candidate locations. To address this, hierarchical clustering was adopted to streamline the problem and propose the final set of candidate locations. The algorithm initially treats each data point as a cluster and gradually merges the two closest clusters into a larger one. This process continues until the distance between adjacent cluster centroids exceeds a predefined threshold of 5 miles. Ultimately, the centroids of these clusters serve as corridor node representations. The outcome of this clustering technique results in the consideration of 58 nodes along the LMC corridor, as depicted in **Figure 5 (d)**. It is important to note that these final 58 nodes serve as both candidate locations for constructing the charging infrastructure and demand hubs for generating and attracting EV trips.



(a)



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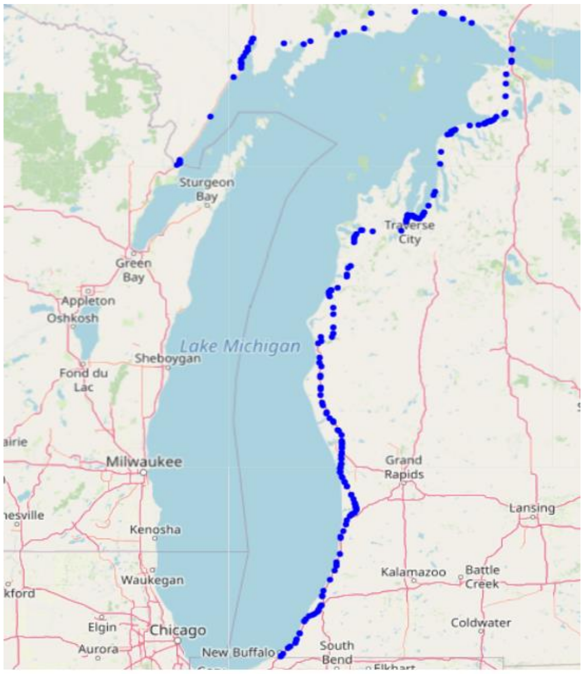
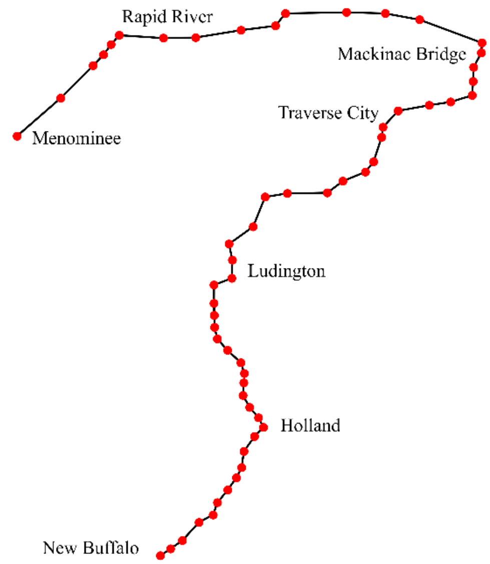


(c)



(d)

Figure 5. Corridor Node Identification Process: (a) DCFC Candidate Locations (b) Distribution of Candidate Locations (c) Corridor Access Points for Candidate Locations (d) Final LMC Corridor Nodes

Travel Demand

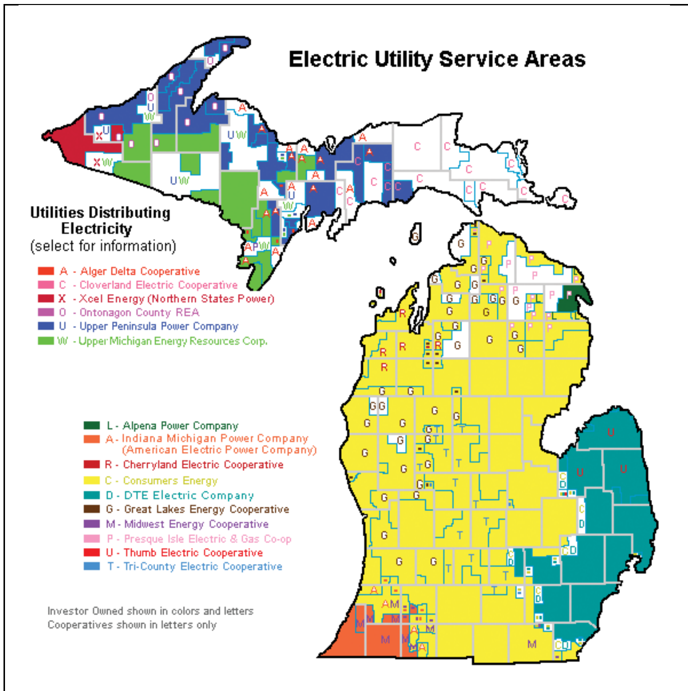
The study leveraged the Michigan origin-destination (OD) demand table provided by MDOT. This OD demand table encompasses a dimension of 4,461 by 4,461, offering insights into the volume of trips to and from each TAZ. However, specific data for tourism-related trips is not readily available, necessitating the adoption of an alternative approach to estimate tourism demand. Further details regarding this estimation process are elaborated upon in the Level-2 Modeling Framework section.

Following the identification of the final 58 corridor nodes, the subsequent task involves assessing the travel demand along the LMC corridor. To determine the segment of trips passing through the LMC corridor nodes, the OD demand matrix of Michigan was analyzed. The LMC corridor demand can be categorized into two primary groups: (1) demand generated and attracted within the LMC area and (2) demand passing through the LMC. For the first group, the study assigned the origin and destination to the nearest of the 58 corridor nodes, effectively converting the Michigan TAZ demands into corridor demands. For the second group, the shortest path algorithm was applied to all OD pairs to identify trips traversing the LMC area. The first and last trajectory points within the LMC along the shortest path were then matched to the nearest corridor node. Out of the 19.7 million daily trips in the state of Michigan, 1.3 million trips were recognized as moving between the specified corridor nodes, indicative of the travel demand along the LMC.

Utilities

As depicted in **Figure 6**, Michigan is segmented into various regions, each under the jurisdiction of different utility providers. These providers have furnished cost estimates for delivering electricity at specific power levels to specified locations within their respective domains. For this assessment, five distinct energy levels were considered for Level-2 and DCFC stations separately. These utility costs encompass a range of expenses, including the acquisition, installation, and maintenance of the power grid infrastructure needed to meet the power demands of the charging stations. Given the diverse land development and environmental characteristics across the study area, spanning from rural to densely urban regions, the utility costs reported by companies in the LMC area exhibited significant variability. While some locations exhibit consistent costs regardless of the energy level, others experience significant cost increase as the energy demand increases. These escalations are largely attributable to the need for technological upgrades or enhancements in grid capacity. To account for this variability, our study devised a step function that captures utility costs corresponding to different ranges of hourly energy demand. **Figure 6** presents the utilities' average costs for Level-2 infrastructure in Michigan.

Utility cost data for all 640 initial DCFC candidate points were also acquired. For each of the final 58 corridor nodes, the utility cost was calculated as the average of the utility costs associated with the originally aggregated DCFC candidate points at that location. **Figure 7** visually represents the distribution of utility costs across corridor nodes for each energy demand level.



Energy Provided Hourly (kWh)	Michigan Utilities Average Estimate (k$)
< 70	16.94
70 - 150	25.14
150 - 300	294.31
300 - 500	575.83
500 <	640.35

Figure 6. Electric utility service areas and average utility upgrade cost in Michigan

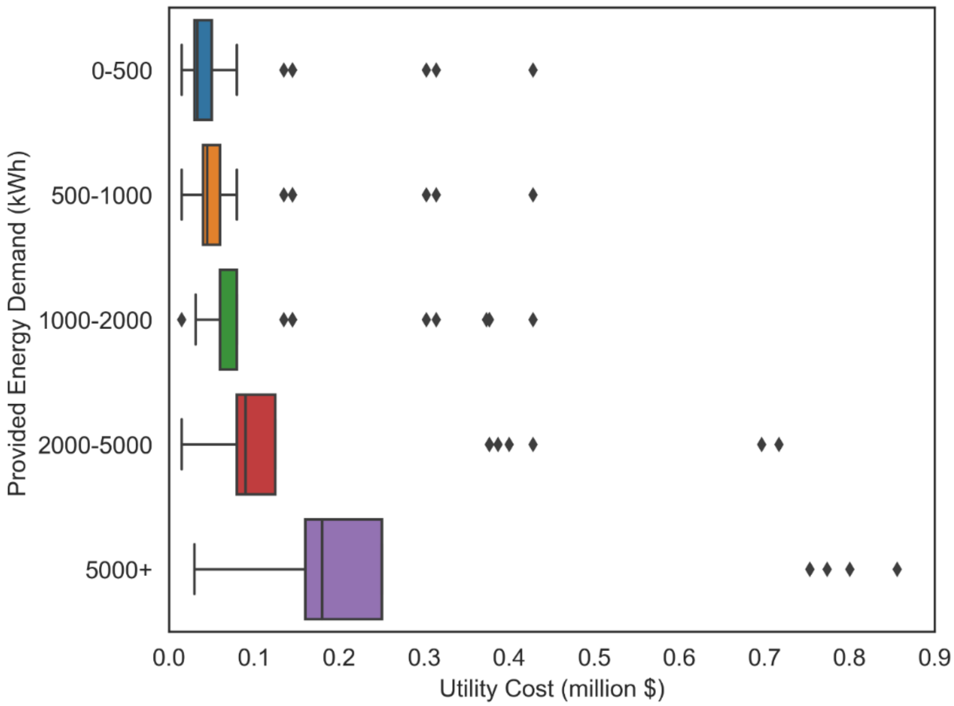


Figure 7. Utility cost distribution across energy demand steps

Current charging infrastructure

Incorporating the influence of existing chargers in the LMC area is crucial because they currently fulfill a portion of the energy demand. This inclusion allows for a more comprehensive and realistic evaluation of the charging infrastructure needs.

Existing Level-2 Chargers

The Alternative Fuel Data Center (AFDC) provides nationwide data on the locations of EV charging stations, facilitating easy access to information about charging stations in Michigan. For the LMC area, an existing Level-2 charger is considered accessible if it falls within a 0.5-mile radius of a candidate point. Consequently, a total of 230 existing Level-2 chargers are accounted for within the LMC area.

Figure 8 illustrates the distribution of existing Level-2 chargers among the TAZs in LMC area.

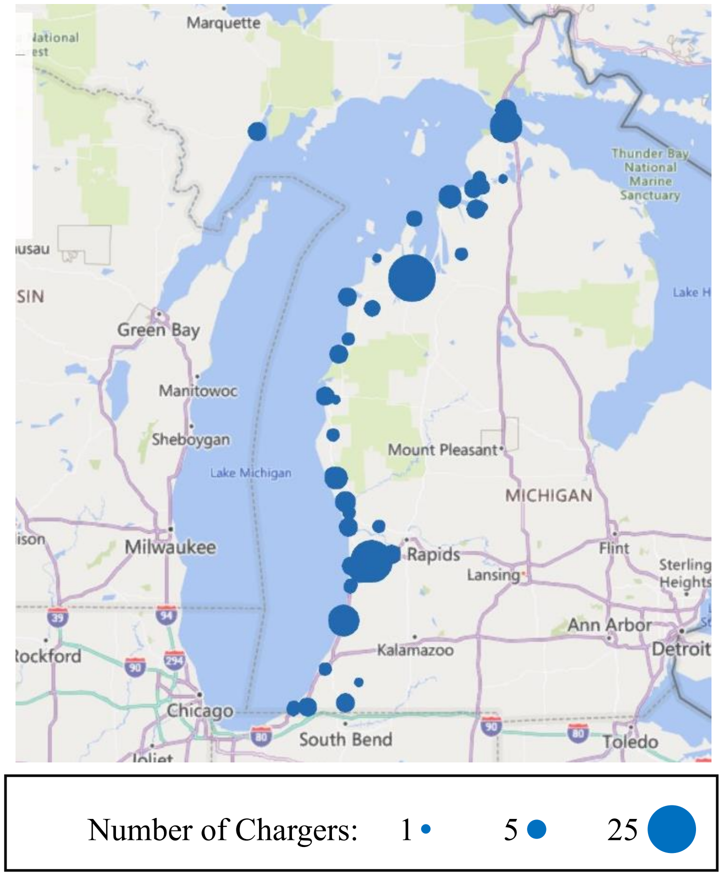
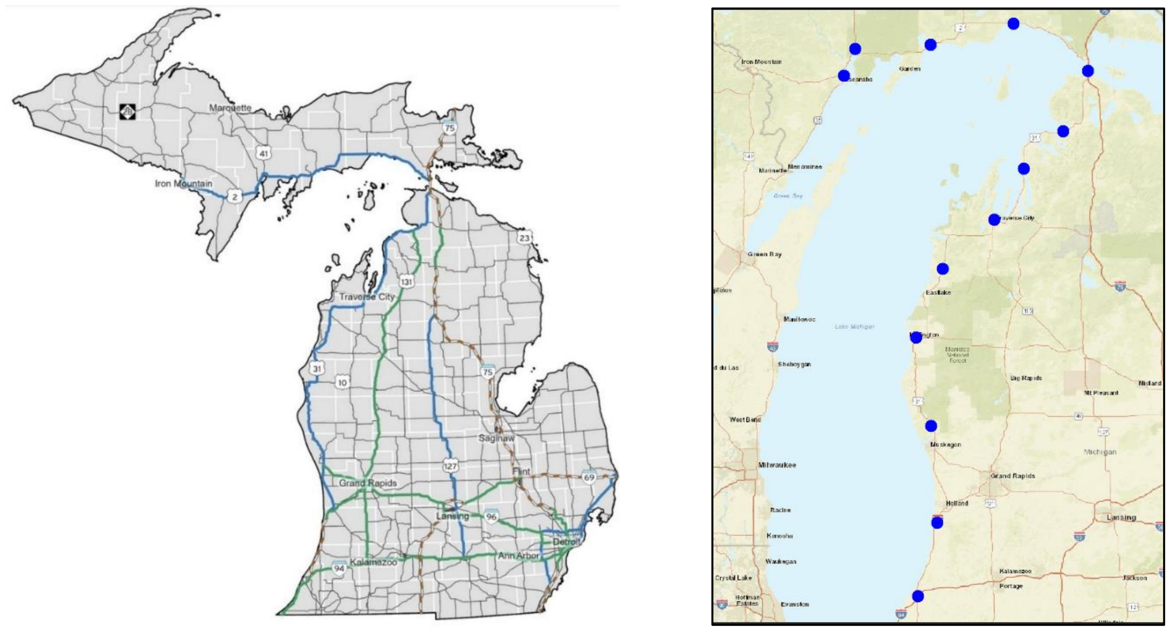


Figure 8. Existing public Level-2 chargers

Existing DC Fast Chargers

As part of the National Electric Vehicle Infrastructure (NEVI) Formula Program, funding is provided to the state of Michigan to establish a network of fast chargers to support EV intercity trips across the state (HNTB et al., 2022). The NEVI program requires the installation of at least four 150-kW chargers along the state's designated Alternative Fuel Corridors (AFCs), as depicted in **Figure 9 (a)** (HNTB et al., 2022). In this study, we analyzed the proposed NEVI network to identify any charging facilities that can be used as current charging infrastructure. This process identified 13 charging stations along the LMC corridor that, based on the NEVI plan, are supposed to have at least four chargers by the end of the year 2026, resulting in a total of 52 current/planned chargers in the LMC analyses depicted in the **Figure 9 (b)**. The NEVI-planned chargers will accommodate a portion of the fast-charging demand as well as a portion of unmet energy demand in the Level-2 network.



(a) (b)

Figure 9. Current EV charging infrastructure in LMC corridor - (a) Michigan alternative fuel corridors, (b) Identified NEVI chargers on LMC corridor

METHODOLOGY

Level-2 Modeling Framework

As illustrated in **Figure 10**, the proposed modeling framework for Level-2 charging infrastructure consists of four primary stages, each accompanied by various subsidiary steps: (1) trip generation, which involves the calculation of the number of trips generated at each location, (2) trip distribution, which is the process of determining the destinations for the trips generated at each of the previously analyzed locations, (3) EV and energy demand estimation, and (4) charger allocation. These stages collaboratively lead to the determination of the optimal locations and quantities for Level-2 chargers.

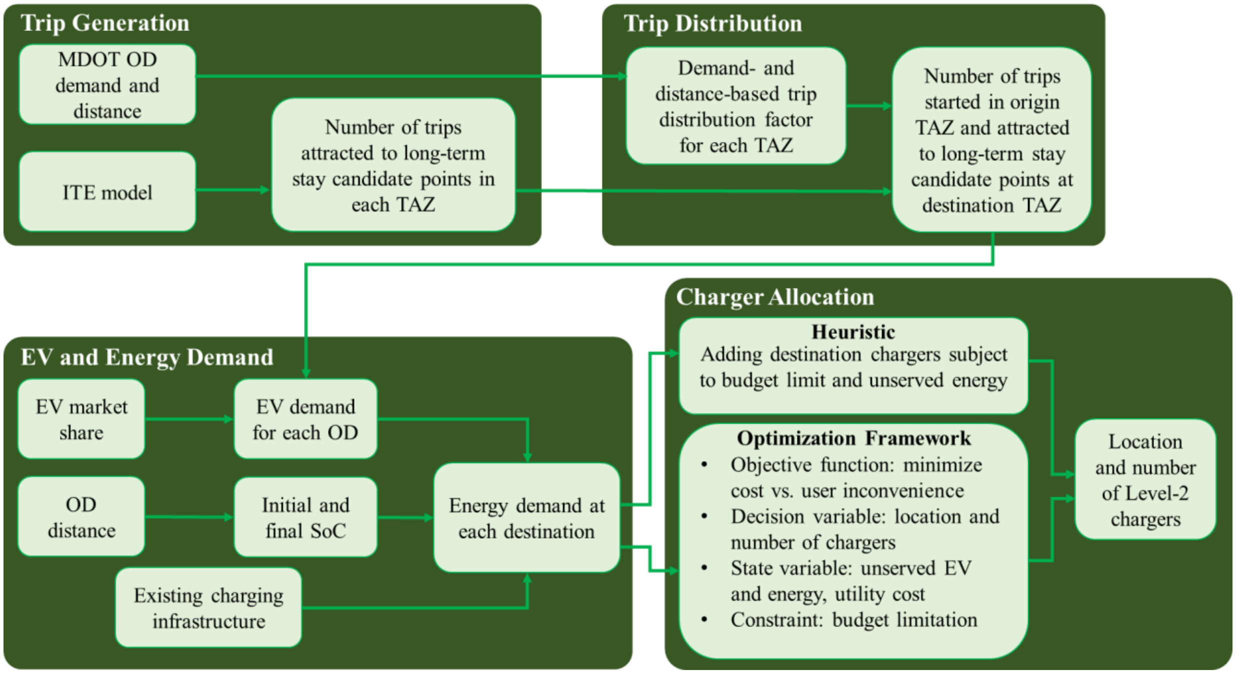


Figure 10. Level-2 modeling framework

Trip Generation

After the allocation of Level-2 candidate points to their respective TAZs, the total number of trips attracted to each TAZ is computed using trip generation rates reported in the Trip Generation Manual by the Institute of Transportation Engineers (ITE) (*Trip Generation Manual*, 2012). The manual provides trip generation rates for various land use categories based on specific estimator variables, such as facility gross area or employee count. By aligning the business types associated with the candidate points with the land use categories specified in the manual, it becomes feasible to estimate the number of trips attracted by each candidate point, and subsequently, by each TAZ. For instance, when examining long-term stay locations (hotels and motels) as potential candidate points for Level-2 chargers, the manual specifies an average of 14.34 trips and 12.80 trips generated per employee per day for hotels and motels, respectively. Applying the manual's recommended 50-50 ratio for entering and exiting trips, we arrive at estimated numbers of 7.17 and 6.40 trips per employee per day attracted to hotels and motels, respectively.

Trip Distribution

Once the number of trips attracted by each TAZ is computed, it is essential to determine the origin of these trips due to the significant influence of distance on the state of charge (SoC) of EVs. Longer trips result in lower SoC upon reaching the destination, sometimes necessitating recharging en-route to ensure the trip's completion. Moreover, trips originating from more distant locations are more likely to conclude at long-term stay locations, such as hotels. Therefore, an appropriate trip distribution factor should account for these factors. Conversely, TAZs situated at greater distances from each other tend to exchange fewer trip compared to those in closer proximity. As a result, the trip distribution factors must be balanced to reflect the impact of OD demand. The calculation of the trip distribution factor for each TAZ destination, excluding trips shorter than 85 miles, as they are less likely to terminate at long-term stay locations, is as follows:

$$P_{ij}\left(j \in D_i \middle| d_{ij} \geq 85\ mi\right) = \frac{\frac{q_{ij}}{\sum_j q_{ij}} * \frac{d_{ij}}{\sum_j d_{ij}}}{\sum_i \left(\frac{q_{ij}}{\sum_j q_{ij}} * \frac{d_{ij}}{\sum_j d_{ij}}\right)}$$

The likelihood of TAZ i being the origin of trips attracted to TAZ j (P_{ij}) is directly related to two factors. Firstly, it depends on the demand ratio between zones i and j (q_{ij}) in comparison to the overall demand attracted by zone j. Secondly, it considers the ratio of the distance between zones i and j (d_{ij}) relative to the total distance between any zone and zone j. By multiplying these two ratios during the trip distribution process, we account for the collective impact of both travel demand and distance.

EV and Energy Demand Estimation

This stage encompasses the processes illustrated in **Figure 11**. By following this procedure, it calculates the initial SoC, mid-trip DCFC, and final charging at the destination, all while considering the desired SoC and total energy demand within the LMC area. When there are no budget constraints and no need for integration with a DCFC network, the required number of Level-2 chargers at each destination can be computed using the provided process. However, if there are budget constraints or a necessity for integration with a DCFC network, additional steps become necessary. This stage explores two mathematical approaches, namely a heuristic method and an optimization model, which will be discussed in the subsequent section.

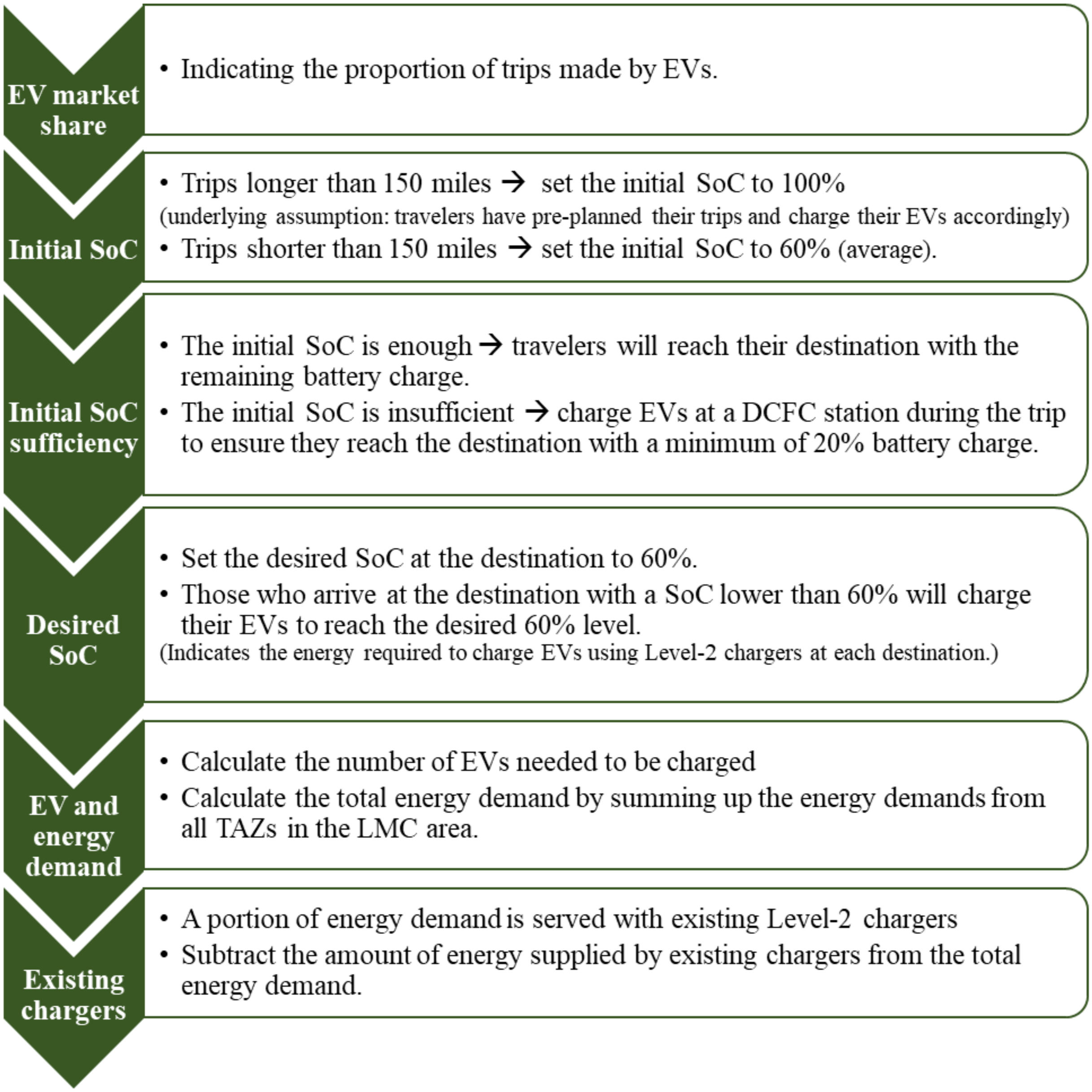


Figure 11. EV and energy demand estimation process

Charger Allocation

This stage presents two methods for allocating chargers. The heuristic approach focuses on producing a practical solution within a reasonable timeframe, while the optimization approach entails a systematic selection of input values from an allowable set to either maximize or minimize a real function, followed by the computation of the function's value.

<u>*Heuristic Approach*</u>

In scenarios where a budget constraint exists and must be distributed between the Level-2 and DCFC networks, situations may arise where there are insufficient funds to install all the required Level-2 chargers. In such instances, a portion of the energy demand must be met by the DCFC network. Therefore, the connection between the two frameworks becomes crucial. Priority should be given to the installation of Level-2 chargers in destinations that are farther from a DCFC station. To achieve this, information about the location of DCFC stations is integrated into the Level-2 framework, enabling the calculation of the distance from each destination to its nearest DCFC station. By assuming an average speed, the detour time from a destination to its corresponding DCFC station can be determined. This detour time forms the basis for prioritizing destinations in the allocation of Level-2 chargers. The following flowchart (**Figure 12**) outlines the approach for installing Level-2 chargers when a budget constraint is in place.

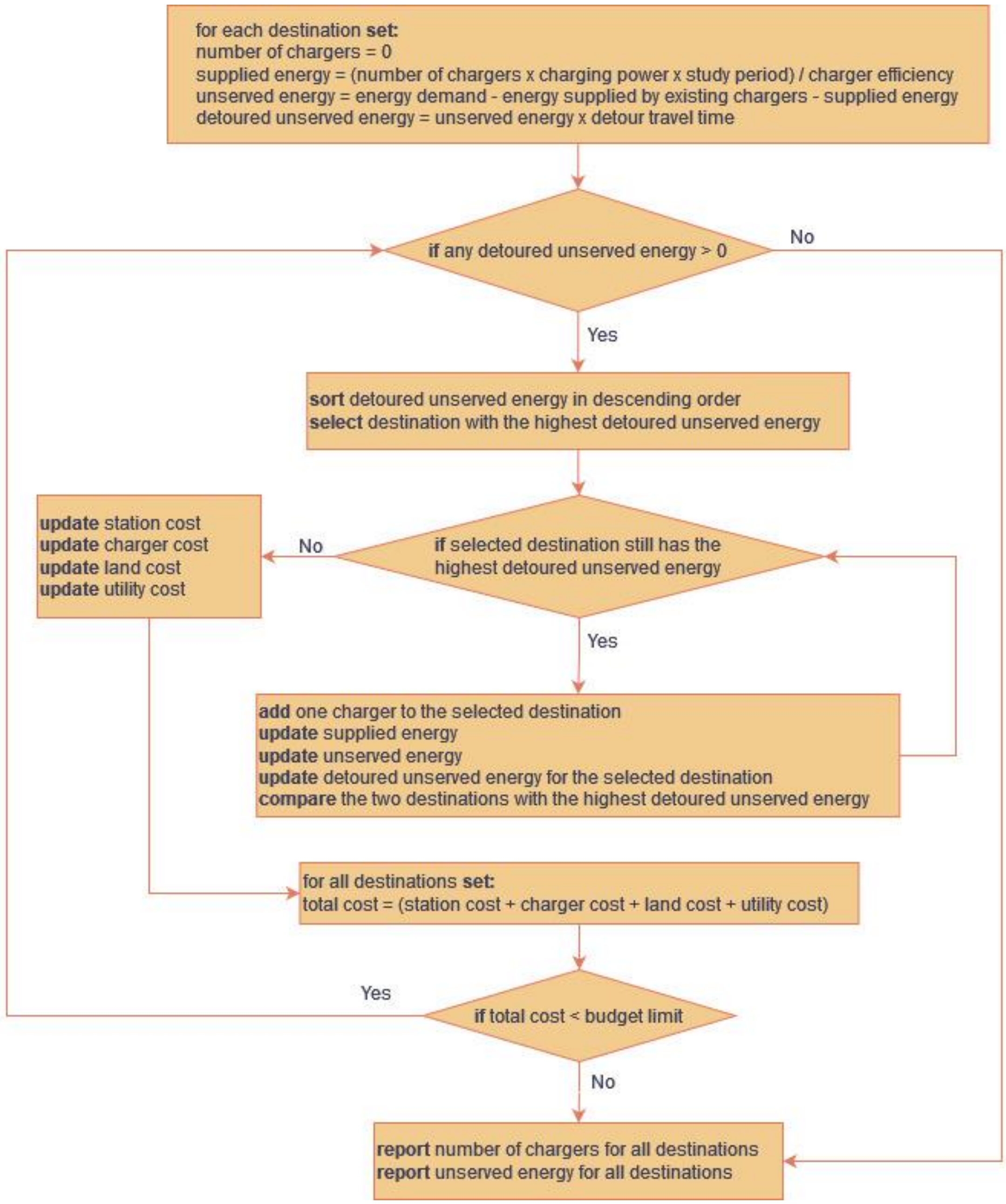


Figure 12. Flowchart of heuristic approach for Level-2 charger allocation

After allocating Level-2 chargers up to the point where the total cost reaches the budget limit, any excess unserved energy from each destination is aggregated and directed towards the respective DCFC station.

Optimization Model

While the heuristic approach can account for the budget limit and reroute unserved energy demand to DCFC stations, it lacks the ability to simultaneously address user inconvenience and optimize based on variable costs like utility cost. To this end, an optimization model is proposed and formulated using mixed-integer programming. The objective function aims to minimize the total system cost, encompassing capital expenditures (e.g., charger, utility, and land acquisition costs) and user inconveniences (e.g., detour travel time and cost differences when requiring charging at a DCFC station due to the absence of Level-2 chargers at the destination) as follows:

$$\min \frac{1}{k}\sum_{j\in J}(C_s x_j + PC_c z_j + C_{l_j} x_j + C_{u\,j}) + \gamma \sum_{j\in J}(TT_j^d EV_j^{unserved}) + \lambda \sum_{j\in J} E_j^{unserved}$$

The objective function comprises three main components. The first component represents the infrastructure cost, including the fixed cost of constructing each Level-2 charging station (C_s), the variable cost based on the number of chargers installed at each destination (C_c), land acquisition expenses (C_{l_j}), and utility upgrade costs ($C_{u\,j}$). The second component accounts for the total delay (γTT_j^d) cost incurred by EVs that must take detours due to the absence or inadequacy of Level-2 chargers at their destinations ($EV_j^{unserved}$). The third component quantifies the inconvenience cost, indicating the additional expenses users bear when opting for DCFC station charging instead of using Level-2 chargers. Constraints ensure that capital expenditures remain within the budget limit, determine the necessary utility upgrades based on the number of chargers and subsequently compute the associated utility costs, and calculate unserved energy. The problem is formulated as mixed-integer programming with linear constraints. Commercial optimization software (CPLEX solver using AMPL) is employed to solve the problem.

DCFC Modeling Framework

The main decision variables in the DCFC placement problem are determining the optimal charging station locations and the appropriate number of chargers at each station. The primary constraints encompass budget limitations and path feasibility. Budget constraints may be imposed by system providers due to various reasons, such as the unavailability of necessary funding or a phased development and investment approach. Furthermore, a feasible charging corridor for EVs is one that can adequately support charging facilities to accommodate EV movement between different OD pairs. This ensures that EVs do not run out of energy during their trips**.** The primary objective function in DCFC framework seeks to design an EV charging corridor that minimizes infrastructure costs (including land, utility, and equipment costs) and user delay costs (comprising queuing, charging, and detour time). Simultaneously, it ensures path feasibility and compliance with budget constraints. **Figure 13** illustrates the DCFC modeling framework.

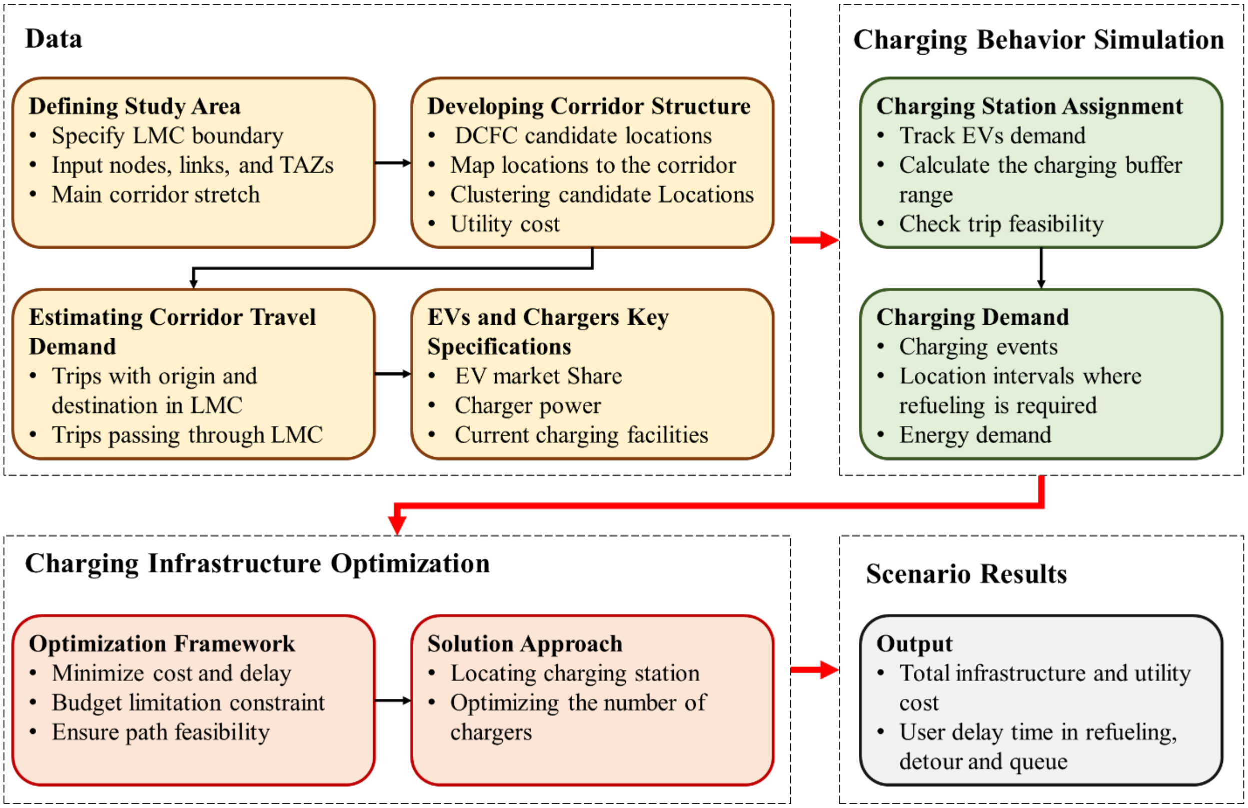


Figure 13. DCFC modeling framework

To formulate the problem, DCFC framework suggests a set of nodes which serve as potential locations within the corridor where charging stations can be constructed. These nodes are utilized by a set of OD pairs representing travel movements along the corridor. The framework considers various user classes each characterized by specific EV attributes, such as initial SoC or battery performance. For each user class-OD pair combination, distinct attributes are defined, including predefined origin, destination, trip length, initial SoC, and a sequence of consecutive nodes that are visited by a known travel demand. Additionally, each user class may feature unique minimum SoC, maximum SoC, and SoC threshold, which influence the timing of their search for charging stations. The objective function is as follows:

$$min \sum_{i \in I}(C_i^s x_i + U_i^S x_i + C_i^p z_i) + \gamma \times (\sum_{i \in I} R_i + \sum_{i \in I} \pi_i + \sum_{i \in I} TTD_i)$$

The objective function consists of two primary components with the goal of minimizing both the overall infrastructure cost and the user delay cost. The first term computes the total daily cost encompassing charging station costs C_i^s, utility cost U_i^S, and chargers C_i^p. This calculation is based on the availability of charging stations x_i and the quantity of chargers z_i at each location i. The second term quantifies the monetary value of the user's time spent during the charging process. It does so by considering the total user refueling R_i, queuing π_i, and detour time TTD_i, using a factor denoting the value of time γ.

Constraints update SoC at each node, verify the feasibility of EV trips, define budgetary limitations, define the utility cost at each station as a function of charging power and the number of chargers, calculate the total incoming travel demand and energy demand for each station, and estimate the total refueling time and waiting time at each station.

Solution Approach

A Modified Constraint Simulated Annealing (MCSA) algorithm is designed to address the intricate Mixed Integer Nonlinear Programming problem outlined in the DCFC modeling framework. MCSA incorporates a dynamic penalty approach, efficiently managing constraints through this metaheuristic method. Additionally, we delve into a framework for modeling EV charging behavior during intercity trips, followed by the introduction of an algorithm for assigning EVs to charging stations while considering multiple charging location options within a specified buffer range. Lastly, we outline a charger allocation procedure that determines the optimal number of chargers at each station, accounting for user experience delay and various budget constraints.

Modified Constraint Simulated Annealing

The proposed problem in DCFC framework belongs to the category of Mixed Integer Nonlinear Programming (MINL). This problem exhibits high nonlinearity due to constraints related to stochastic queuing and path feasibility. Furthermore, the presence of a stepwise utility cost function, reflecting the realistic nature of utility upgrades, makes the problem non-convex. While commercial solvers may offer solutions, they often demand significant computational time and do not guarantee a global optimum. To tackle these complexities, the modeling framework introduces a novel approach based on Simulated Annealing (SA), dynamic penalty mechanisms for constraint management, and a two-stage decision-making process aimed at optimizing charging station locations and charger quantities separately.

EV Charging Behavior Modeling

This section outlines the assumptions incorporated into the DCFC modeling framework to better simulate the charging behavior of EV users during intercity trips. Initially, the framework assumed that all EVs traveling between an OD pair would be assigned to a specific charging station. However, for a more realistic representation of EV charging behavior, this section introduces the concept of a charging buffer range. This range encompasses a set of potential charging stations that EVs can choose from. Furthermore, an algorithm is proposed to monitor the movements of EV users and assign them to appropriate charging stations, thus estimating their charging demand along the corridor.

During intercity trips, EV owners prefer to charge their vehicles before their SoC falls below a certain minimum level, typically to alleviate range anxiety. They begin searching for charging stations early on to identify charging options along their route. However, EV users also aim to minimize the number of charging events and, therefore, avoid charging too early to prevent additional stops. As a result, each EV requiring charging has a buffer range within which they can select an available charging station without the risk of necessitating extra charging stops later on. If there are no charging stations within this buffer range, the EV trip becomes infeasible. This modeling assumes that the choice of EV charging stations is not influenced by detours or queuing at the stations. Therefore, it posits that travel demand will be evenly distributed among the available charging stations within the buffer zone. However, it's important to note that the modeling framework can be adapted to accommodate different behavioral models if needed.

Figure 14 illustrates an EV trip from node A to H, starting with a 60% battery charge. The EV initiates its search for a charging station when the charge level drops below 40%, aiming to locate a charging station before it reaches 20%. The buffer range narrows down the candidate nodes to three options (D to F), effectively avoiding the need for additional charging events later in the trip. A path is deemed feasible if at least one charging station exists within the buffer range.

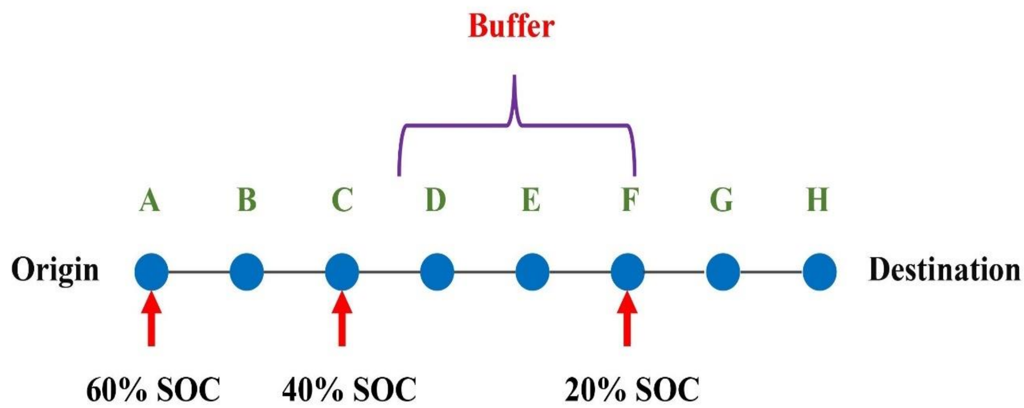


Figure 14. An Illustrative Example Demonstrating the Purpose of the Buffer Range

The amount of charging required for EVs at charging stations is contingent on several factors, including their current SoC, remaining trips, and minimum SoC thresholds. When a charging event represents the final one needed to complete their trip, EVs opt to charge their vehicles just enough to reach their destination with the minimum SoC required. However, in cases where EVs undertake long-distance trips, possess limited battery capacity, or encounter suboptimal battery performance, they may necessitate multiple charging events. In such instances, EVs fully charge their vehicles up to their maximum SoC, with the exception of the last charging event, where the objective is to reach the destination with a single refueling while maintaining the required minimum SoC.

Monitoring the movements of EVs throughout the corridor while simulating their charging behaviors and accounting for multiple charging options presents a complex challenge. This complexity is especially pronounced when EVs require multiple charging events, as the selection of charging stations hinges on prior charging location decisions, rendering the problem highly nonlinear. To address this complexity, the DCFC modeling framework introduces an EV station selection assignment algorithm. This algorithm calculates the buffer range for charging, identifies available charging stations within this buffer area, assigns vehicles to suitable charging stations, and segments trips with multiple charging events into smaller individual segments.

Charger Allocation

Upon finding charging events and energy demand for each group of charging stations the problem can be formulated to determine the optimal number of chargers per station. The proposed approach finds the optimal number of chargers per station while considering the trade-off between utility cost, charger cost, and user experienced delays. This problem is a non-convex Mixed Integer Nonlinear Programming (MINP) and is subject to budget constraints.

RESULTS AND DISCUSSIONS

This section presents the numerical results, including optimal solutions for Level-2 and DCFC frameworks independently, along with a set of results for the interconnected network combining both Level-2 and DCFC infrastructure.

Level-2 Network

The optimum location and number of level-2 chargers are determined using both heuristic and optimization approaches. The base case scenario represents the expected condition in 2030. Two distinct scenarios are examined within the context of the base case: one presumes no budgetary constraint on capital expenditures, while the other enforces a $10 million budgetary limit. The default parameter values, gathered through numerous stakeholder meetings, are detailed in **Table 1**. However, specific parameters that vary with geographical location, such as land cost and energy demand, are omitted from this listing due to the extensive array of their values.

Table 1. Level-2 Base Case Parameters

Description	Value
EV market share	0.25
Battery efficiency (mile/kWh)	3.5
Battery Capacity (kWh)	70
Charger efficiency	1.18
Study period (hour)	24
Value of time ($/hour)	18.00
Total EV demand (vehicles)	9,254
Total energy demand (MWh)	241.63
Total energy from existing Level-2 chargers (MWh)	33.12
DCFC to Level-2 charging cost differential ($/kWh)	0.25
Infrastructure Lifetime (years)	10
Level-2 charging power (kW)	11
Level-2 station cost per location ($)	5,465.00
Level-2 charger cost per charger per power ($/kW)	403.93

Evaluation of Solution Approaches

Table 2 displays the results of both heuristic and optimization (CPLEX) approaches for the two base case scenarios, namely Scenario 1 and Scenario 2. Across both scenarios, it is evident that the CPLEX solution excels in finding a lower cost solution compared to the heuristic approach, underscoring its superior performance in terms of optimization. Nevertheless, it is noteworthy that the heuristic approach delivers significantly shorter solution runtimes for both scenarios. Although CPLEX remains an acceptable choice for this statewide network, it is essential to recognize that for larger and more complex networks, such as combined network of Level-2 and DC fast chargers, the heuristic approach may become a more practical option due to its reasonable solution times, even if its performance is somewhat inferior.

In Scenario 1, the heuristic approach considers 325 stations with a total of 1,156 chargers, necessitating a capital expenditure of $18 million, a sum sufficient to fulfill the entire energy demand. Conversely, the optimization approach results in the construction of 285 stations, equipped with 1,112 chargers, at a cost of $16 million. However, this requires some EVs to detour to a DCFC station for recharging. The rationale behind this lies in the cost-effectiveness perspective of the CPLEX solution, opting for some unserved EVs, compared to greedy approach in the heuristic method accommodating the entire energy demand.

Moving on to Scenario 2, with a $10 million budget limit, CPLEX manages to a lower cost solution, even though it adds more stations and chargers compared to the heuristic approach. While the average detour delay is higher in the CPLEX solution, fewer EVs require these detours, resulting in lower overall user inconvenience. The comparison between Scenario 1 and Scenario 2 highlights the importance of factoring in user inconvenience when planning for charging infrastructure. Scenario 1 demands a larger capital investment but ultimately results in a lower total cost (including user cost). On the contrary, charging infrastructure projects are often bound by the budgetary constraints, and the optimization approach excels significantly in such scenarios. It effectively considers these constraints and assesses the inconvenience experienced by users. After a thorough comparison of heuristic and optimization results across the base case scenarios, this study advocates the utilization of the optimization approach when investigating standalone Level-2 infrastructure due to its precision and effectiveness. Conversely, for the examination of Level-2 infrastructure within an interconnected network involving DCFCs, the heuristic approach is recommended, primarily owing to its notable advantage in terms of efficiency.

Table 2. Comparison of Heuristic and CPLEX Results for Base Case Scenarios

Scenario	1: Unlimited Budget		2: $10M Budget Limit	
	Heuristic	CPLEX	Heuristic	CPLEX
Number of Stations	325	285	154	215
Number of Chargers	1,156	1,112	678	972
Average Detour Delay (min)	0	18.13	3.8	12.17
Unserved Energy (MWh)	0	0.25	69.15	18.82
Unserved EV (veh.)	0	10	2,635	719
Infrastructure Cost (m$)	17.97	16.06	10.00	10.00
Station Cost (m$)	*1.78*	*1.56*	*0.84*	*1.17*
Charger Cost (m$)	*5.14*	*4.94*	*3.01*	*4.32*
Land Acquisition Cost (m$)	*0.70*	*0.61*	*0.33*	*0.46*
Utility Cost (m$)	*10.35*	*8.95*	*5.82*	*4.05*
Total investment and User Cost ($/day)	4,919.08	4,514.35	23,029.01	10,070.80
Solution Time (s)	0.78	26.34	0.14	24.99

Scenarios Encompassing Various Charging Power and Budgetary Constraints

This section encompasses a range of analyses designed to assess the impact of potential budget constraints and changes in charging power on the optimum allocation, while keeping other parameters consistent with the base case. **Table 3** offers a summary of the results for all scenarios among which 7 kW chargers without a budget constraint displaying the lowest total cost (highlighted in bold). As expected, an increase in the available budget results in a lower cost solution (including user costs), as depicted in **Figure 15**.

According to **Table 3**, for scenarios with no budget limit, the number of stations remains consistent, regardless of the charging power, as they guarantee trip feasibility for nearly all users. However, when the charging power is increased, the number of chargers decreases due to enhanced throughput capacity. It is important to note that, with a fixed charging power, an increase in budget results in a reduced total detour delay. Conversely, with a fixed budget, increasing the charging power leads to a longer total detour delay (as shown in **Figure 16**). This underscores the fact that, under specified budgetary limitations, investing in more costly technologies like higher charging power may result in relatively greater inconvenience for users.

Table 3. Results for Scenarios Encompassing Several Budget and Charging Power

Charging Power	7 kW			11 kW			19 kW		
Budget Limit	$5M	$10M	No limit	$5M	$10M	No limit	$5M	$10M	No limit
Number of Stations	97	221	285	93	215	285	92	200	285
Number of Chargers	1,013	1,490	1,656	653	972	1,112	376	592	729
Unserved EV Avg. Detour Delay (min)	13.72	11.48	31.92	14.57	12.17	18.13	14.68	12.68	10.00
All EV Avg. Detour Delay (min)	4.33	0.84	0.03	4.59	0.95	0.02	4.81	1.20	0.03
Unserved Energy (MWh)	76.45	17.71	0.27	76.36	18.82	0.25	79.48	22.84	0.83
Unserved EV (veh.)	2,919	676	10	2,914	719	10	3,035	874	32
Infrastructure Cost (m$)	5.00	10.00	15.31	5.00	10.00	16.06	5.00	10.00	16.76
Station Cost (m$)	0.53	1.21	1.56	0.51	1.17	1.56	0.50	1.09	1.56
Charger Cost (m$)	2.86	4.21	4.68	2.90	4.32	4.94	2.88	4.54	5.59
Land Acquisition Cost (m$)	0.21	0.47	0.61	0.20	0.46	0.61	0.20	0.43	0.61
Utility Cost (m$)	1.40	4.11	8.46	1.39	4.05	8.95	1.41	3.94	9.00
Total investment and User Cost ($K/day)	32.49	9.50	**4.36**	33.19	10.07	4.51	34.60	11.78	4.90
Solution Time (s)	23.27	24.73	21.98	22.71	24.99	26.34	24.86	23.97	23.15

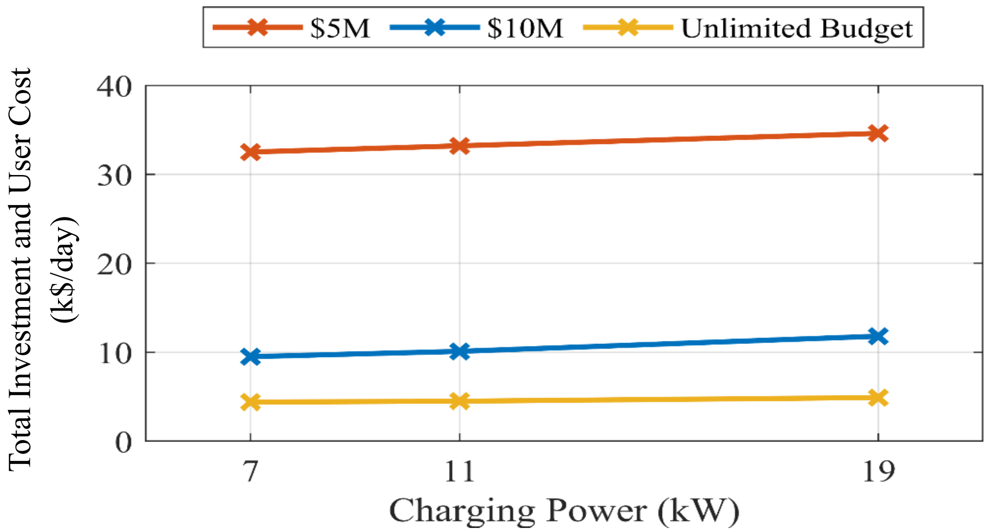


Figure 15. Total investment and user cost per charging power for different budget limits

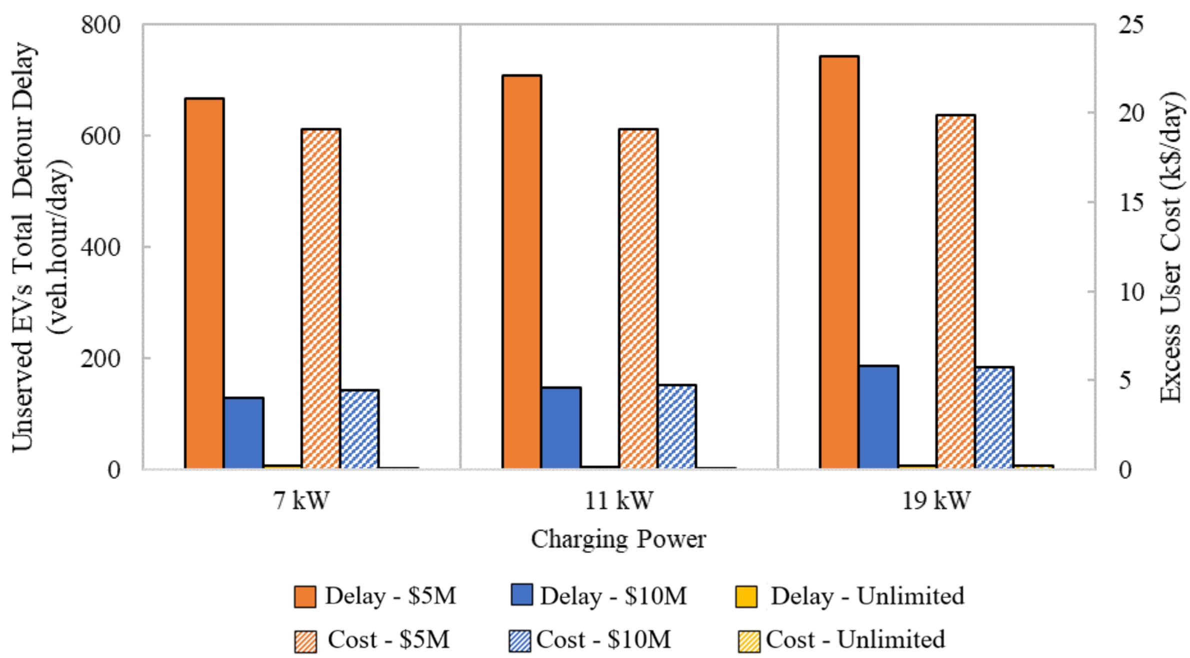


Figure 16. Users' inconvenience per charging power for different budget limits

Figure 17 presents heat maps that depict the spatial distribution of Level-2 chargers within the LMC area for all scenarios, based on the results obtained by CPLEX. Notably, across all scenarios, the heat maps reveal a significant concentration of chargers in popular tourist destinations within the LMC area, including Traverse City, Mackinaw City, and Holland. This concentration of chargers aligns with the core objective of the study, which is to facilitate EVs' tourism travel by ensuring the availability of charging infrastructure in key points of interest. This deliberate allocation underscores the project's goal to meet the charging requirements of electric vehicle users visiting renowned attractions in the state of Michigan. By doing so, the Level-2 framework contributes to enhancing the overall experience of these travelers and promoting ecotourism.

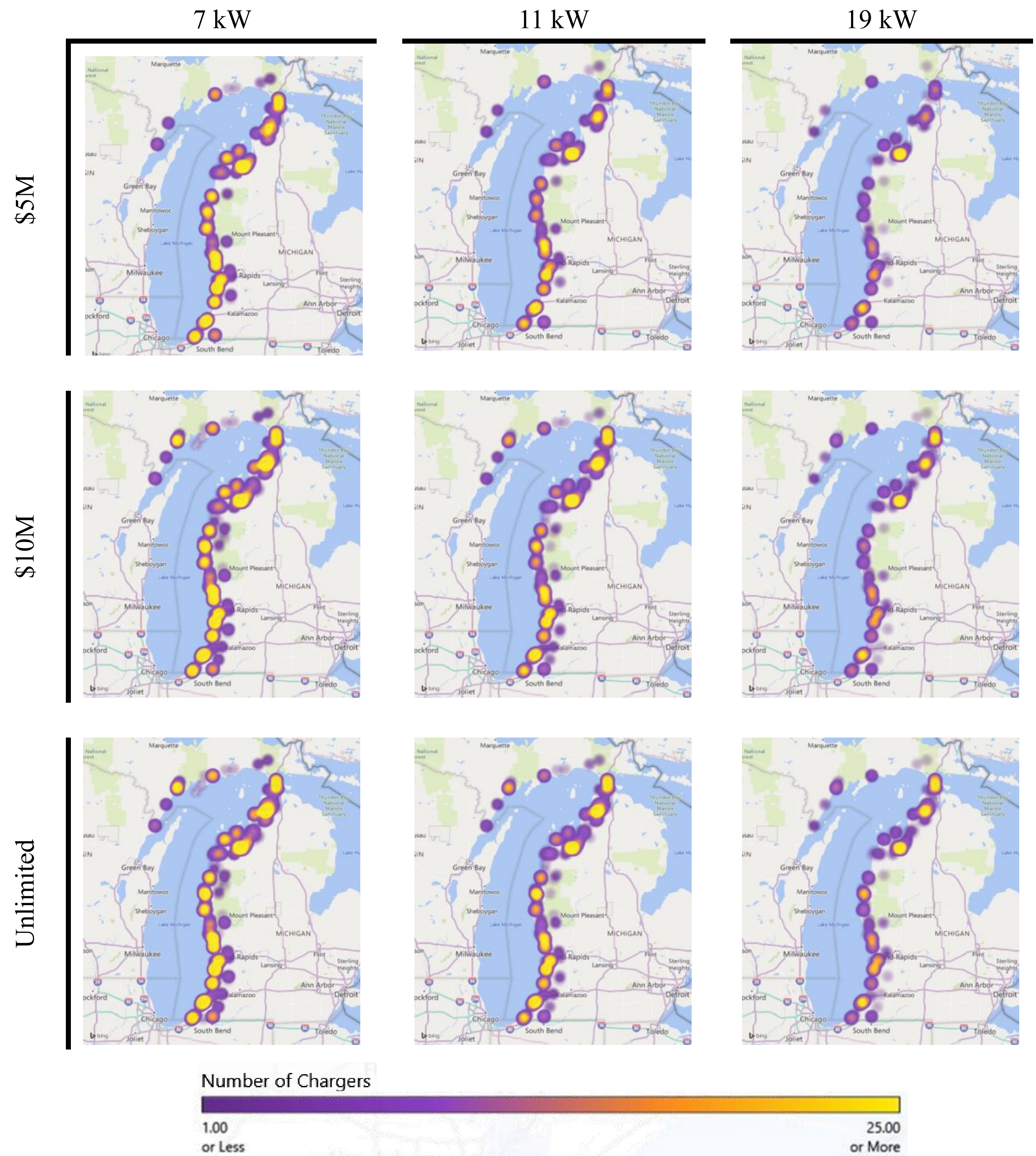


Figure 17. Distribution of Level-2 chargers in LMC area for different budget limits and charging powers

DCFC Network

This section presents the optimal configuration of DCFC stations along the LMC corridor under various budgetary limitations. **Table 4** shows the assumptions and default parameters used in the DCFC framework.

Table 4. DCFC Parameters

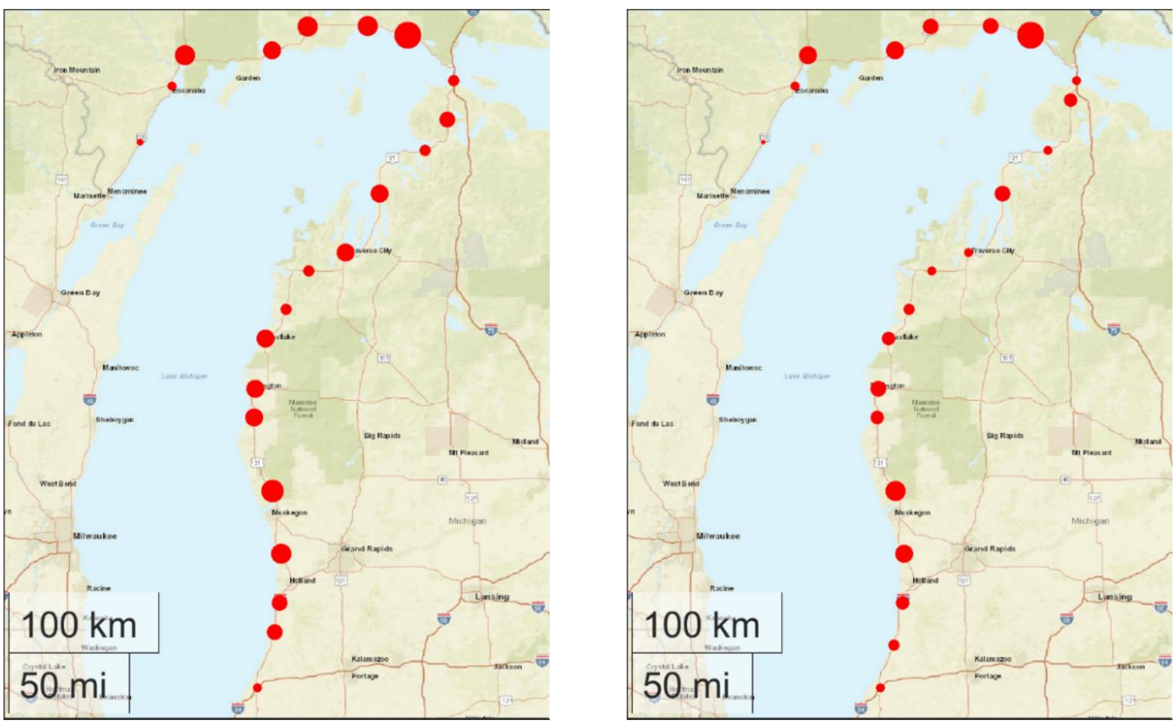
Description	Value
EV market share	0.25
Battery efficiency (mile/kWh)	3.5
Battery Capacity (kWh)	70
Minimum SoC (%)	20
Charger efficiency	1.33
Value of time ($/hour)	18.00
Infrastructure Lifetime (years)	10
DCFC charging power (kW)	150
DCFC station cost per location ($)	80,125.00
DC fast charger cost per charger ($)	76,250.00

Table 5 summarizes the optimal charging infrastructure configurations under different budget constraints. It is crucial to emphasize that budget limits below $4 million lead to infeasible paths for EV travel, resulting in stranded energy demand and unserved EVs. The table reveals that the current NEVI charging infrastructure investment can cater to a significant portion of the charging demand within the LMC area. However, to support convenient intercity trips along the lake shorelines, additional charging stations and chargers are necessary. Beyond the $6.18 million already invested by the NEVI program, an additional budget of approximately $10 million is required to construct a charging infrastructure configuration that ensures both the feasibility of EV travel along the LMC corridor and the provision of high-quality service. Furthermore, **Table 5** shows that budget allocations ranging from $10 million to $4 million still lead to a viable EV charging facility that offers trip feasibility. However, lower budget levels increase user delay. Additionally, **Table 5** indicates that the average detour delay and refueling time are more influenced by station location and distribution. In contrast, since the allocated budget determines the charger capacity at each station, a decrease in the budget can result in significantly longer waiting times.

Figure 18 illustrates the location and scale of the optimal charging infrastructure under varying budget constraints, including no budget limits and three discussed budget limitations. The figure shows that reducing the budget significantly decreases the number of chargers, while the number of stations and their distribution remain relatively stable. Ensuring the feasibility of all EV trips takes precedence over minimizing user delay. Therefore, even at very low budget levels, a minimum distribution of charging stations is necessary. The figure also demonstrates that as the budget decreases, the number of chargers at all stations declines. However, stations located in the UP, which are more widely dispersed and distant from each other, maintain a higher charger count due to higher energy demand per station. Stations in the LP, situated near high-traffic areas with significant charging demand, also maintain more chargers in low-budget scenarios compared to other stations.

Table 5. Optimal Charging Infrastructure Results Under Different Budgetary Limitations

Budget limit (million $)	**No limit**	**8**	**6**	**4**
Charging power (kW)	150	150	150	150
Number of charging events	8,135	8,135	8,135	8,135
Total daily EV energy demand (MWh)	124.87	124.87	124.87	124.87
Number of current stations	13	13	13	13
Number of current chargers	52	52	52	52
Number of new stations	9	10	10	9
Number of new chargers	106	83	60	35
Total number of stations	22	23	23	22
Total number of chargers	158	135	112	87
Total current infrastructure cost (million $)	6.18	6.18	6.18	6.18
Land investment cost (million $)	0.13	0.11	0.08	0.06
Utility cost (million $)	0.82	0.62	0.48	0.46
New stations investment cost (million $)	1.56	1.44	1.30	1.20
New charger’s investment cost (million $)	8.29	6.49	4.69	2.74
Total new infrastructure Cost (million $)	9.85	7.93	5.99	3.94
Average refueling Time (min)	7.98	7.97	7.94	7.87
Average queuing time (min)	0.15	0.52	1.64	32.66
Average detour time (min)	1.38	1.43	1.98	1.89



(a) (b)

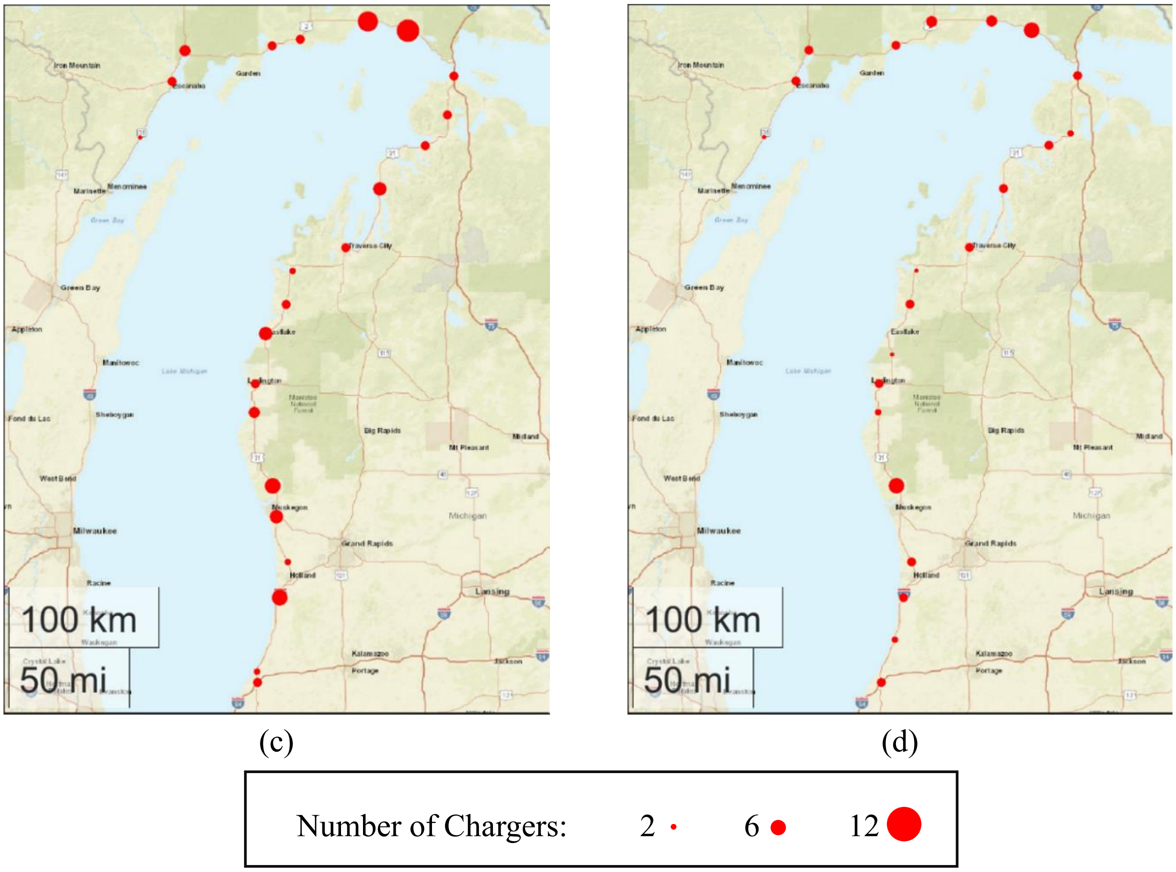
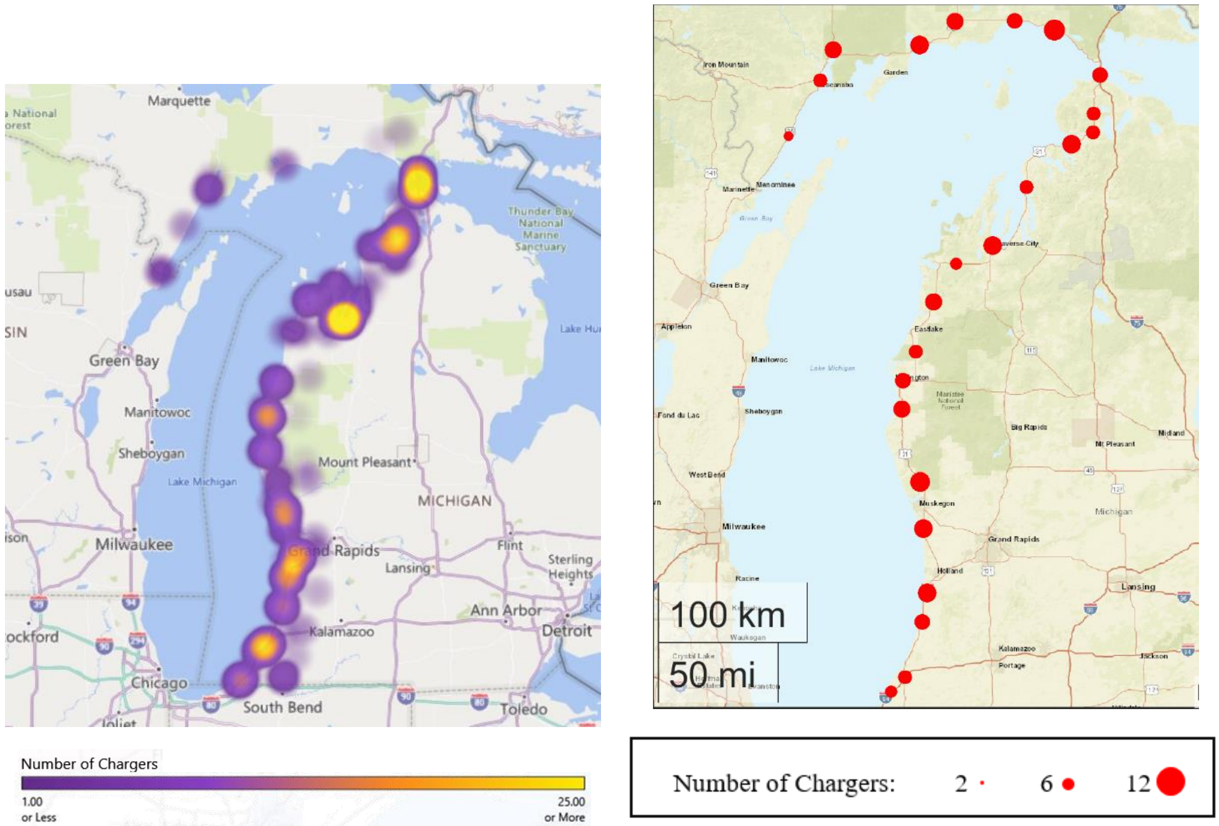


Figure 18. Optimal charging infrastructure configuration under (a) No budget limitation (b) $8 million budget (c) $6 million budget (d) $4 million budget

Level-2 and DCFC Interconnected Network

This section presents the results of a combined network where both Level-2 and DCFC infrastructure work together. A total budget of $20 million is assumed with different allocation scenarios between Level-2 and DCFC networks. All parameters and assumptions remain the same as the base cases of both Level-2 and DCFC networks, presented in **Table 1** and **Table 4**. The heuristic approach is selected to solve the Level-2 portion due to its better performance in a larger network (compared to a standalone Level-2 network). The framework considers that any EV that cannot find a Level-2 charger at its LMC destination detours to the nearest DCFC station. **Table 6** presents the optimal results for an interconnected network of Level-2 and DCFC stations. A notable observation is that the interconnected infrastructure effectively serves the entire LMC EV demand, regardless of the budget allocation between Level-2 and DCFC networks. This implies that, in most budget allocation scenarios, the interconnected infrastructure provides an acceptable level of service. However, there is an exception: when only 20% of the budget ($4 million) is allocated to DCFC network. In this case, the average DCFC queuing time increases significantly to 34 minutes. Thus, to maintain an acceptable level of service, it is crucial to allocate at least 30% of budget to the DCFC network. Comparing the results shows that the lowest total cost occurs when 60% budget is allocated to Level-2 and 40% to DCFC. Meanwhile all scenarios have the same investment cost, this scenario has the lowest user costs (delays). Thus, it is the most cost-efficient configuration. **Figure 19** illustrates the optimal distribution of interconnected Level-2 and DC fast chargers for the 60%-40% budget allocation scenario (columns in bold in **Table 6**).



(a) (b)

Figure 19. Optimal charging infrastructure distribution with a $20 million total investment budget (a) Level-2 ($12 million) (b) DCFC ($8 million)

Table 6. Optimal Charging Infrastructure Results for Interconnected Network Under Different Budget Allocations

Budget Allocation	20%	80%	30%	70%	40%	60%	50%	50%	**60%**	**40%**	70%	30%	80%	20%
Network	Level-2	DCFC	Level-2	DCFC	Level-2	DCFC	Level-2	DCFC	**Level-2**	**DCFC**	Level-2	DCFC	Level-2	DCFC
Number of New Stations	74	14	106	11	138	11	187	11	**206**	**12**	232	9	285	9
Number of New Chargers	376	177	502	158	631	132	788	104	**867**	**78**	952	61	1,080	35
Level-2 Unserved Demand Served by DCFC (MWh)	-	133.66	-	106.05	-	78.46	-	46.56	**-**	**33.29**	-	19.73	-	2.95
Level-2 Unserved EVs Served by DCFC	-	5,128	-	4,061	-	2,993	-	1,781	**-**	**1,278**	-	759	-	116
Ave. Level-2 Detour (min)	8.42	-	8.24	-	6.65	-	6.07	-	**4.67**	**-**	4.48	-	2.63	-
Ave. DCFC Refueling (min)	-	10.14	-	9.76	-	9.49	-	8.92	**-**	**8.69**	-	8.26	-	8.01
Ave. DCFC Queueing (min)	-	0.74	-	0.54	-	0.86	-	0.93	**-**	**2.18**	-	4.67	-	34.20
Ave. DCFC Detour (min)	-	1.99	-	1.57	-	1.61	-	1.78	**-**	**1.76**	-	2.31	-	1.78

CONCLUSION

In this project, a comprehensive analysis of EV charging infrastructure was conducted, focusing on both Level-2 and DCFC networks as well as their interconnection to support ecotourism. The primary objective was to optimize the placement and sizing of charging stations while considering budget constraints and user inconvenience. The study employed a combination of heuristic and optimization approaches to address the complexity of the problem and provide valuable insights into the development of EV charging infrastructure.

Level-2 Charging Infrastructure

The analysis of Level-2 charging infrastructure indicated that the optimization approach outperformed the heuristic approach when the network is evaluated independently, especially under budget constraints. However, the heuristic approach is recommended when the Level-2 network is evaluated within an interconnected network, involving DCFCs, due to its notable advantage in terms of efficiency. Key findings from the results and analyses include:

- Increased capital investment from $5 million to $10 million can lead to a significant reduction in user inconvenience, with lower total cost, shorter average detour delays, and fewer unserved EVs.
- Charging power plays a crucial role in infrastructure optimization. Switching to higher charging power reduces the number of required stations and chargers, but it comes at a higher cost per piece. In this study, 7 kW chargers exhibited the least total cost for Level-2 network.
- Balancing budget allocation and charging power is essential. Higher budgets with fixed charging power reduce user inconvenience, while limited budgets with increased charging power result in longer delays. Therefore, considering both cost and user inconvenience is vital when investing in Level-2 charging infrastructure.

DCFC Charging Infrastructure

This framework focused on providing charging facilities along a main corridor around the Lake Michigan, aiming to support ecotourism and EV adoption. The research yielded insights into the requirements for DCFC infrastructure. Key findings from this analysis include:

- An optimal DCFC charging infrastructure would require a total cost of $10 million. However, it was demonstrated that viable charging stations could be achieved with a lower budget, albeit with increased user waiting times during the charging process.
- Budget constraints significantly impact the number of chargers and user waiting times, underscoring the importance of budget allocation for EV charging infrastructure.

The main contribution of this infrastructure is to facilitate EV travels along the LMC through DCFC stations. Future research opportunities include assessing factors such as user delay time, charging pricing, and tourism attractions that influence charging station selection.

Interconnected Infrastructure

The interconnected network of Level-2 and DCFC stations demonstrated the adaptability in addressing the diverse demands of EV users in LMC area. Considering a $20 million budget limit, this project explored various budget allocation scenarios between Level-2 and DCFC networks. The interconnected charging infrastructure, operating under different budget allocation schemes, consistently proves to be a robust solution for meeting the EV charging demands within the LMC area. This observation underscores the flexibility and reliability of this integration in accommodating the charging requirements of EV users.

However, it is crucial to highlight an exception to this overall success. When only 20% of the budget is allocated to the DCFC network, a significant increase in the average DCFC queuing time is observed. This finding suggests that maintaining an acceptable level of user costs and minimizing inconvenience necessitates allocating a minimum of 30% of the total $20 million budget to the DCFC network.

In summary, the combined Level-2 and DCFC infrastructure, supported by varying budget allocations, offers a versatile solution that can effectively serve the LMC EV demand, contributing to the promotion of sustainable transportation practices and enhancing the EV user experience throughout the LMC area. Appendices provide detailed results for each network as well as the interconnected network.

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Fakhrmoosavi, F., Kavianipour, M., Shojaei, M. (Sam), Zockaie, A., Ghamami, M., Wang, J., Jackson, R., 2021b. Electric Vehicle Charger Placement Optimization in Michigan Considering Monthly Traffic Demand and Battery Performance Variations: Transportation Research Record: Journal of the Transportation Research Board 2675. https://doi.org/https://doi.org/10.1177/0361198120981958

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APPENDIX A: INDEPENDENT LEVEL-2 NETWORK

Table 1A presents the detailed results of the Level-2 independent network solved by CPLEX. It includes the ID and coordinates of the centroid for each Traffic Analysis Zone (TAZ) in the Lake Michigan Circuit (LMC) area along with the number of chargers installed under each charging power and budget limit scenario.

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
46.202244	-86.865724	0	1	1	0	1	1	0	1	1
44.636049	-86.233122	6	6	6	4	4	4	2	2	2
44.552900	-86.183034	0	0	1	0	0	1	0	0	1
44.556695	-85.877686	0	1	1	0	1	1	0	1	1
42.103589	-86.473766	0	0	2	0	0	2	0	0	1
42.100509	-86.487408	0	8	8	0	5	5	0	3	3
42.089630	-86.481457	0	0	2	0	0	2	0	0	1
42.064405	-86.477494	0	6	6	0	4	4	0	2	2
42.019917	-86.428909	0	0	1	0	0	1	0	0	1
41.939656	-86.565203	0	0	1	0	0	1	0	0	1
41.828495	-86.365565	0	0	1	0	0	1	0	0	1
41.821261	-86.243215	17	17	17	11	11	11	7	7	7
41.836135	-86.201354	0	2	2	0	1	1	0	1	1
45.299837	-85.080234	0	0	1	0	0	1	0	0	1
46.216113	-84.925904	4	4	4	3	3	3	2	2	2
45.782254	-87.080079	0	8	8	0	5	5	0	3	3
46.008707	-87.062141	0	0	1	0	0	1	0	0	1
45.690950	-86.638500	0	2	2	0	1	1	0	1	1
45.377026	-84.948043	0	0	2	0	0	1	0	0	1
45.680307	-84.792184	5	5	5	3	3	4	2	2	2
45.593931	-84.791827	4	4	4	0	3	3	0	2	2
45.507571	-84.791519	4	4	4	0	3	3	0	2	2
44.762864	-85.600646	11	11	12	7	7	8	4	4	5
44.729354	-85.543835	64	64	64	41	41	41	24	24	24
43.945531	-85.979654	0	1	1	0	1	1	0	1	1
44.119543	-85.862712	0	1	1	0	1	1	0	1	1
44.032421	-85.981005	0	1	1	0	1	1	0	0	1
44.910436	-85.873808	0	1	1	0	1	1	0	0	1
46.065372	-85.740592	2	2	2	0	2	2	0	1	1
46.075674	-85.008414	0	1	1	0	1	1	0	1	1
46.149150	-85.156366	3	4	4	2	2	3	1	2	2
46.056440	-84.852492	0	1	1	0	1	1	0	1	1

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
44.473288	-86.214138	0	2	2	0	2	2	0	1	1
44.470710	-85.999542	0	1	1	0	1	1	0	1	1
44.284403	-85.950335	4	4	4	3	3	3	2	2	2
43.961294	-86.444635	0	3	3	0	2	2	0	1	2
44.123843	-86.356167	0	0	1	0	0	1	0	0	1
44.033360	-86.099889	0	2	2	0	1	1	0	1	1
45.481313	-87.351919	7	7	7	5	5	5	3	3	3
43.236085	-86.253158	6	6	6	4	4	4	2	3	3
43.253322	-86.235002	0	0	1	0	0	1	0	0	1
43.223010	-86.240711	6	6	6	4	4	4	2	3	3
43.228482	-86.274032	0	0	1	0	0	1	0	0	1
43.412634	-86.300525	10	12	12	6	8	8	3	5	5
43.343194	-86.342078	0	3	3	0	2	2	0	1	1
43.268948	-86.336397	8	8	8	5	5	5	3	3	3
43.268209	-86.287861	0	0	1	0	0	1	0	0	1
43.251685	-86.271403	0	0	1	0	0	1	0	0	1
43.220637	-86.164559	0	1	1	0	0	1	0	0	1
43.278618	-86.111030	0	0	2	0	1	1	0	0	1
43.685093	-86.458454	21	21	23	13	13	15	7	7	9
43.598063	-86.098882	0	0	1	0	0	1	0	0	1
42.779611	-86.115970	0	0	1	0	0	1	0	0	1
43.082778	-86.224021	0	2	2	0	1	1	0	1	1
43.065872	-85.934096	0	0	1	0	0	1	0	0	1
42.771264	-86.171509	0	0	1	0	0	1	0	0	1
46.052709	-85.929414	2	2	2	0	2	2	1	1	1
42.531924	-85.861080	5	5	5	3	3	3	2	2	2
42.526304	-85.835138	0	1	2	0	1	1	0	1	1
42.523785	-85.878435	0	2	2	0	1	1	0	1	1
42.465564	-85.878098	2	2	2	1	2	2	0	1	1
42.656345	-86.199553	21	21	27	13	13	17	7	7	10
42.645016	-86.209489	21	21	21	13	13	13	7	7	7
42.615839	-86.180298	0	2	2	0	1	1	0	1	1
42.663349	-86.173069	18	19	19	11	12	12	7	7	7
42.703349	-86.150158	0	4	4	0	3	3	0	2	2
42.761507	-86.079991	0	2	2	0	1	1	0	1	1
42.565876	-85.721565	0	1	1	0	1	1	0	1	1
42.580278	-86.075704	0	2	2	0	1	1	0	1	1
42.564214	-86.181444	5	6	6	3	4	4	2	2	2
42.518507	-86.202296	0	0	1	0	0	1	0	0	1

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
42.459662	-86.222410	0	1	1	0	1	1	0	0	1
42.462642	-86.158399	0	2	2	0	1	1	0	1	1
45.077292	-85.241021	0	4	4	0	3	3	0	2	2
45.091548	-85.351459	0	0	1	0	0	1	0	0	1
45.028958	-85.338858	0	6	6	0	4	4	0	2	3
45.164710	-85.321933	0	0	1	0	0	1	0	0	1
45.162047	-85.243503	0	0	1	0	0	1	0	0	1
44.876361	-85.407408	8	9	9	6	6	6	3	3	4
44.915524	-85.388970	0	4	4	0	2	3	0	2	2
44.867320	-85.335456	0	1	1	0	1	1	0	1	1
44.962868	-85.259884	0	2	2	0	2	2	0	1	1
45.005465	-85.250955	0	4	4	0	3	3	0	2	2
44.968313	-85.146452	0	2	2	0	1	1	0	1	1
44.914661	-85.264331	0	0	1	0	0	1	0	0	1
44.884954	-85.260787	0	2	2	0	1	1	0	1	1
44.923864	-85.151448	0	2	2	0	1	2	0	1	1
44.728984	-86.082574	0	1	1	0	1	1	0	0	1
44.691729	-86.171841	3	4	4	2	2	3	1	2	2
44.664149	-86.085652	5	6	6	4	4	4	2	2	2
44.615479	-86.095503	4	4	4	3	3	3	2	2	2
44.648154	-86.016354	6	6	6	4	4	4	2	3	3
44.643837	-85.966170	0	1	1	0	1	1	0	0	1
44.753945	-85.872641	0	1	1	0	1	1	0	1	1
42.074374	-86.503040	0	6	6	0	4	4	0	2	3
42.085523	-86.493037	0	0	2	0	0	2	0	0	1
42.119561	-86.445235	0	0	3	0	0	2	0	0	1
42.097949	-86.420692	36	36	36	23	23	23	13	14	14
42.069020	-86.445371	19	19	19	12	12	12	7	7	7
42.171050	-86.384504	0	0	1	0	0	1	0	0	1
42.183392	-86.254731	0	6	6	0	4	4	0	2	3
42.220407	-86.249618	0	0	2	0	0	2	0	0	1
42.205662	-86.285257	0	0	2	0	0	2	0	0	1
42.036231	-86.519321	28	29	29	18	18	18	11	11	11
41.967349	-86.480976	0	0	1	0	0	1	0	0	1
42.087858	-85.931065	0	0	1	0	0	1	0	0	1
41.784916	-86.749198	5	5	5	3	3	3	2	2	2
41.799203	-86.742562	0	2	2	0	2	2	0	1	1
41.793467	-86.732951	18	18	18	12	12	12	7	7	7
41.779466	-86.698519	0	0	1	0	0	1	0	0	1

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
41.768084	-86.748350	8	8	8	5	5	5	3	3	3
41.812383	-86.696769	10	10	10	6	6	6	4	4	4
41.775909	-86.786649	0	1	1	0	0	1	0	0	1
41.847797	-86.658142	7	7	7	4	5	5	3	3	3
41.879558	-86.618479	0	0	1	0	0	1	0	0	1
41.785902	-86.476973	0	0	2	0	0	1	0	0	1
41.785960	-86.260897	0	0	2	0	0	1	0	0	1
41.975157	-86.125915	0	0	2	0	0	1	0	0	1
41.992765	-86.106201	0	5	5	0	3	3	0	2	2
42.042860	-86.162253	0	0	1	0	0	1	0	0	1
42.042764	-86.078094	0	0	1	0	0	1	0	0	1
45.309152	-85.260137	9	10	10	6	6	6	4	4	4
45.319342	-85.244996	0	6	7	0	4	4	0	3	3
45.207593	-85.022234	5	5	5	3	4	4	2	2	2
45.207997	-84.990290	5	5	5	3	4	4	2	2	2
45.336318	-85.234228	0	5	5	0	3	3	0	2	2
45.158950	-85.135834	0	0	1	0	0	1	0	0	1
45.237635	-84.942354	6	6	7	4	4	4	2	3	3
45.738478	-84.688457	8	9	9	5	6	6	3	3	4
45.777194	-84.727961	21	71	98	13	45	62	7	26	36
45.415467	-84.690147	0	0	1	0	0	1	0	0	1
45.740599	-87.090102	0	13	13	0	8	9	0	5	5
45.756502	-87.083990	0	14	14	0	9	9	0	5	6
45.768367	-87.074708	0	0	1	0	0	1	0	0	1
45.723514	-87.094107	0	2	2	0	1	1	0	0	1
45.863747	-87.029546	0	3	3	0	2	2	0	1	2
45.842369	-87.044495	0	3	4	0	2	2	0	2	2
45.799974	-87.101045	0	2	2	0	1	1	0	1	1
45.916458	-86.973696	0	0	1	0	0	1	0	0	1
45.905983	-86.937441	0	0	1	0	0	1	0	0	1
45.802343	-86.508657	0	2	2	0	1	1	0	1	1
45.369344	-84.942143	0	12	12	0	8	8	0	5	5
45.372533	-84.973889	0	7	7	0	4	4	0	3	3
45.366937	-84.966270	0	20	20	0	13	13	0	7	7
45.361268	-85.036682	21	21	30	13	13	19	7	7	11
45.357569	-84.962288	0	21	26	13	13	16	7	7	10
45.730054	-84.915968	6	6	6	4	4	4	2	3	3
45.443203	-84.941204	0	0	1	0	0	1	0	0	1
45.439633	-84.882469	0	3	3	0	2	2	0	1	2

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
45.484738	-84.937346	14	14	14	9	9	9	5	6	6
45.460757	-84.997864	0	3	3	0	2	2	0	1	1
45.433596	-84.981560	0	1	1	0	1	1	0	0	1
45.429577	-84.996554	0	4	5	0	3	3	0	2	2
45.440139	-84.818085	0	1	1	0	1	1	0	0	1
45.427865	-84.757427	0	4	4	0	3	3	0	2	2
45.370042	-84.894404	9	9	9	6	6	6	3	3	4
45.319557	-84.950686	0	0	1	0	0	1	0	0	1
45.402400	-84.883478	10	14	14	6	9	9	5	5	6
45.346554	-85.072851	0	5	5	0	3	3	0	2	2
45.325477	-84.794455	0	0	1	0	0	1	0	0	1
44.778277	-85.650733	0	2	2	0	2	2	0	1	1
44.770424	-85.581131	5	5	6	3	4	4	2	2	2
44.758150	-85.584116	42	42	42	27	27	27	15	16	16
44.756040	-85.629260	0	3	3	0	2	2	0	1	1
44.756122	-85.619870	0	1	1	0	1	1	0	1	1
44.750955	-85.603953	0	2	2	0	1	2	0	1	1
44.850201	-85.543985	0	2	2	0	1	1	0	1	1
44.925711	-85.521702	0	1	1	0	1	1	0	0	1
44.812659	-85.441728	13	14	14	9	9	9	5	5	5
44.755334	-85.472176	5	5	5	3	4	4	2	2	2
44.764940	-85.722306	0	1	1	0	1	1	0	0	1
44.733591	-85.651782	21	21	21	13	13	14	8	8	8
44.738531	-85.606981	0	1	1	0	1	1	0	0	1
44.619529	-85.789909	0	1	1	0	1	1	0	1	1
44.644168	-85.730811	6	6	6	4	4	4	2	3	3
44.674236	-85.791553	0	1	1	0	1	1	0	1	1
44.557782	-85.785692	0	1	1	0	0	1	0	0	1
44.750366	-85.567056	14	14	14	9	9	9	5	5	6
44.723690	-85.480810	0	2	2	0	1	2	0	1	1
44.699152	-85.544181	0	0	1	0	0	1	0	0	1
43.922276	-85.875307	0	0	1	0	0	1	0	0	1
44.119183	-85.952802	0	2	2	0	1	1	0	1	1
44.123662	-86.011794	0	1	1	0	1	1	0	1	1
45.076689	-85.635981	0	1	1	0	1	1	0	1	1
45.017934	-85.729655	4	4	4	3	3	3	2	2	2
44.971444	-85.676177	5	5	5	3	4	4	2	2	2
45.017387	-85.650847	12	12	12	8	8	8	4	5	5
44.820435	-85.967155	1	1	1	0	1	1	0	1	1

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
44.820229	-86.034827	2	2	2	1	1	1	1	1	1
44.896014	-85.951957	24	24	24	15	15	15	9	9	9
44.885207	-86.031853	3	3	3	2	2	2	1	1	1
44.839801	-85.676077	0	0	1	0	0	1	0	0	1
44.936374	-85.761802	0	2	2	0	1	1	0	1	1
44.891082	-85.762479	0	1	1	0	1	1	0	1	1
44.907882	-85.679570	0	2	2	0	1	1	0	1	1
44.913560	-85.642461	0	1	1	0	1	1	0	1	1
44.849324	-85.746326	5	5	5	3	3	3	2	2	2
45.860874	-84.722812	10	11	11	7	7	7	4	4	4
45.884404	-84.730661	21	42	56	13	27	36	7	15	21
46.138922	-85.558612	0	0	1	0	0	1	0	0	1
46.203202	-85.797616	0	1	1	0	1	1	0	1	1
45.871152	-84.779912	0	1	1	0	0	1	0	0	1
44.254897	-86.327039	13	14	14	9	9	9	5	5	5
44.247255	-86.315687	3	4	4	2	3	3	0	2	2
44.237284	-86.313233	6	6	6	4	4	4	2	3	3
44.238751	-86.331299	5	5	5	3	4	4	2	2	2
44.199414	-86.292156	6	6	6	4	4	4	2	3	3
44.215233	-86.122227	0	0	1	0	0	1	0	0	1
44.350377	-86.225830	0	3	3	0	2	2	0	1	1
44.391016	-86.207905	0	0	1	0	0	1	0	0	1
44.416231	-86.120949	0	2	2	0	1	1	0	1	1
44.372977	-86.121680	0	0	1	0	0	1	0	0	1
44.490952	-85.878120	0	1	1	0	1	1	0	1	1
44.386740	-86.036995	0	0	1	0	0	1	0	0	1
44.208470	-86.007952	0	2	2	0	2	2	0	1	1
44.209675	-85.887796	0	1	1	0	1	1	0	0	1
43.966023	-86.455244	0	7	8	0	5	5	0	3	3
43.961014	-86.433478	0	10	10	0	6	6	0	3	4
44.034768	-86.250446	0	0	1	0	0	1	0	0	1
44.005843	-86.448816	8	8	8	5	5	5	3	3	3
44.046119	-86.448490	6	7	7	4	4	4	2	3	3
44.036615	-86.370189	0	0	1	0	0	1	0	0	1
43.952005	-86.412191	21	21	37	13	13	24	7	7	14
43.852282	-86.418905	0	0	1	0	0	1	0	0	1
43.969499	-86.097078	0	3	3	0	2	2	0	1	1
45.137791	-87.608826	0	1	1	0	1	1	0	1	1
45.149746	-87.621452	2	2	2	1	1	1	1	1	1

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
45.121397	-87.614150	10	10	11	6	7	7	4	4	4
45.671041	-87.388019	0	1	1	0	1	1	0	1	1
45.416716	-87.590546	0	1	1	0	0	1	0	0	1
43.196349	-86.233422	7	7	7	5	5	5	3	3	3
43.194195	-86.248714	5	5	5	3	3	3	2	2	2
43.437757	-86.370850	0	1	1	0	1	1	0	0	1
43.360419	-86.177309	0	0	1	0	0	1	0	0	1
43.197960	-86.261587	7	7	7	5	5	5	3	3	3
43.197766	-86.214899	6	6	6	4	4	4	2	2	2
43.184127	-86.217295	0	4	4	0	2	2	0	2	2
43.160089	-86.218832	15	15	15	10	10	10	6	6	6
43.195061	-86.270410	0	4	4	0	2	2	0	2	2
43.463402	-85.965113	6	6	6	4	4	4	2	3	3
43.471467	-85.959511	0	2	2	0	1	1	0	1	1
43.474331	-85.937543	0	2	2	0	1	1	0	1	1
43.462293	-85.938098	0	0	1	0	0	1	0	0	1
43.597261	-86.009435	0	2	2	0	2	2	0	1	1
43.498498	-86.438085	0	0	1	0	0	1	0	0	1
43.793651	-86.415541	8	8	8	5	5	5	3	3	3
43.698069	-86.358717	0	1	1	0	1	1	0	0	1
43.686975	-86.386629	8	8	8	5	5	5	3	3	3
43.513738	-86.311011	6	7	7	4	4	4	2	3	3
42.786649	-86.102328	6	7	7	4	4	4	2	3	3
42.777593	-86.089340	7	7	7	4	5	5	3	3	3
43.069800	-86.227358	7	7	7	4	5	5	3	3	3
43.042811	-86.203274	0	2	2	0	1	1	0	1	1
43.051401	-86.233660	0	2	2	0	1	1	0	1	1
43.062995	-86.210022	9	9	9	6	6	6	3	4	4
43.059815	-86.224004	0	3	3	0	2	2	0	1	1
42.980335	-86.166691	0	0	1	0	0	1	0	0	1
43.005739	-86.214360	0	1	1	0	1	1	0	1	1
42.962808	-86.198657	0	1	1	0	0	1	0	0	1
43.038168	-86.223943	21	21	21	13	13	14	7	7	8
43.018276	-86.176544	0	2	2	0	2	2	0	1	1
42.964994	-85.890360	6	6	6	4	4	4	2	3	3
42.819280	-86.124742	0	3	3	0	2	2	0	1	1
42.815627	-86.083824	21	42	42	13	27	27	7	15	15
42.820707	-86.158743	0	0	1	0	0	1	0	0	1
42.790158	-86.194512	6	6	6	4	4	4	2	2	3

TAZ Centroid		Number of Chargers								
		7 kW			11 kW			19 kW		
Latitude	Longitude	$5M	$10M	No Limit	$5M	$10M	No Limit	$5M	$10M	No Limit
42.785993	-86.153436	0	2	2	0	1	1	0	1	1
42.857758	-85.864151	5	5	5	3	3	3	2	2	2
42.896199	-85.891913	0	1	1	0	1	1	0	1	1
45.960241	-86.260689	0	3	3	0	2	2	0	1	1
45.957885	-86.239179	20	20	21	13	13	13	7	7	7
45.872426	-86.380051	0	1	1	0	0	1	0	0	1
46.114637	-86.396105	0	1	1	0	1	1	0	1	1
45.953979	-86.433519	0	2	2	0	1	1	0	1	1
46.169743	-86.544165	0	1	1	0	1	1	0	1	1
42.409114	-86.245498	18	18	18	12	12	12	7	7	7
42.408736	-86.269460	16	16	16	10	10	10	6	6	6
42.388113	-86.279349	0	3	3	0	2	2	0	1	2
42.385008	-86.248580	0	2	2	0	1	1	0	1	1
42.412787	-86.255211	0	2	2	0	1	2	0	1	1
42.397126	-86.196743	3	4	4	2	2	2	1	2	2
42.397240	-86.052477	0	1	1	0	1	1	0	1	1
42.220625	-86.023391	0	5	6	0	4	4	0	2	2
42.318303	-86.045188	0	0	1	0	0	1	0	0	1
42.200562	-86.162786	0	0	1	0	0	1	0	0	1

APPENDIX B: INDEPENDENT DCFC NETWORK

Table 1B to **Table 4B** present the detailed results of the DCFC independent network for different budget constraints. Each table includes the number and coordinates of the nodes along the main corridor in the LMC area as well as the number of total required stations and chargers and the number of existing (planned in NEVI) stations and chargers at each node. Subtracting the number of existing stations/chargers from the number of total required stations/chargers gives the number of new stations/chargers to be installed in the network.

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
41.77804	-86.7276	0	0	0	0
41.8337	-86.6639	0	0	0	0
41.89918	-86.5906	0	0	0	0
42.04383	-86.4876	0	0	0	0
42.1349	-86.3681	1	4	1	4
42.20099	-86.3727	0	0	0	0
42.30165	-86.3086	0	0	0	0
42.39784	-86.2556	0	0	0	0
42.47929	-86.2224	1	7	0	0
42.6574	-86.1835	1	7	1	4
42.72667	-86.1423	0	0	0	0
42.79952	-86.0867	0	0	0	0
42.87553	-86.1174	0	0	0	0
42.95797	-86.1721	1	9	0	0
43.05348	-86.2148	0	0	0	0
43.15256	-86.2092	0	0	0	0
43.22797	-86.2049	0	0	0	0
43.3388	-86.2443	1	10	1	4
43.41211	-86.3101	0	0	0	0
43.50264	-86.3736	0	0	0	0
43.5941	-86.3905	0	0	0	0
43.68996	-86.3926	0	0	0	0
43.78586	-86.3944	1	8	0	0
43.95597	-86.3845	1	8	1	4
43.98486	-86.2841	0	0	0	0
44.13023	-86.2799	0	0	0	0
44.25737	-86.301	1	8	0	0
44.43046	-86.1289	1	5	1	4
44.63135	-86.0767	0	0	0	0
44.66043	-85.9381	1	5	0	0
44.66489	-85.6902	0	0	0	0
44.76893	-85.6342	1	8	1	4

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
44.83064	-85.4536	0	0	0	0
44.91241	-85.4031	0	0	0	0
45.11612	-85.3502	1	8	1	4
45.18622	-85.345	0	0	0	0
45.31682	-85.2503	0	0	0	0
45.36125	-85.0574	0	0	0	0
45.37015	-84.9708	1	5	1	4
45.43968	-84.7908	0	0	0	0
45.551	-84.7845	1	7	0	0
45.66393	-84.7813	0	0	0	0
45.7792	-84.7334	1	5	1	4
45.85741	-84.7294	0	0	0	0
46.04138	-85.117	1	12	0	0
46.0947	-85.4469	1	9	1	4
46.10092	-85.5715	0	0	0	0
46.09139	-85.9508	1	9	0	0
45.99313	-86.0118	0	0	0	0
45.9529	-86.2449	1	8	1	4
45.89989	-86.5079	0	0	0	0
45.89541	-86.7085	0	0	0	0
45.9267	-86.975	1	9	1	4
45.84448	-87.0333	0	0	0	0
45.74582	-87.0797	1	4	1	4
45.67615	-87.1455	0	0	0	0
45.41793	-87.3465	1	3	0	0
45.11572	-87.6177	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
41.77804	-86.7276	0	0	0	0
41.8337	-86.6639	1	2	0	0
41.89918	-86.5906	0	0	0	0
42.04383	-86.4876	0	0	0	0
42.1349	-86.3681	1	4	1	4
42.20099	-86.3727	0	0	0	0
42.30165	-86.3086	0	0	0	0
42.39784	-86.2556	1	5	0	0
42.47929	-86.2224	0	0	0	0
42.6574	-86.1835	1	6	1	4
42.72667	-86.1423	0	0	0	0
42.79952	-86.0867	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
42.87553	-86.1174	0	0	0	0
42.95797	-86.1721	1	8	0	0
43.05348	-86.2148	0	0	0	0
43.15256	-86.2092	0	0	0	0
43.22797	-86.2049	0	0	0	0
43.3388	-86.2443	1	9	1	4
43.41211	-86.3101	0	0	0	0
43.50264	-86.3736	0	0	0	0
43.5941	-86.3905	0	0	0	0
43.68996	-86.3926	0	0	0	0
43.78586	-86.3944	1	6	0	0
43.95597	-86.3845	1	7	1	4
43.98486	-86.2841	0	0	0	0
44.13023	-86.2799	0	0	0	0
44.25737	-86.301	1	6	0	0
44.43046	-86.1289	1	5	1	4
44.63135	-86.0767	0	0	0	0
44.66043	-85.9381	1	4	0	0
44.66489	-85.6902	0	0	0	0
44.76893	-85.6342	1	4	1	4
44.83064	-85.4536	0	0	0	0
44.91241	-85.4031	0	0	0	0
45.11612	-85.3502	1	7	1	4
45.18622	-85.345	0	0	0	0
45.31682	-85.2503	0	0	0	0
45.36125	-85.0574	0	0	0	0
45.37015	-84.9708	1	4	1	4
45.43968	-84.7908	0	0	0	0
45.551	-84.7845	0	0	0	0
45.66393	-84.7813	1	6	0	0
45.7792	-84.7334	1	4	1	4
45.85741	-84.7294	0	0	0	0
46.04138	-85.117	1	12	0	0
46.0947	-85.4469	1	7	1	4
46.10092	-85.5715	0	0	0	0
46.09139	-85.9508	1	7	0	0
45.99313	-86.0118	0	0	0	0
45.9529	-86.2449	1	8	1	4
45.89989	-86.5079	0	0	0	0
45.89541	-86.7085	0	0	0	0
45.9267	-86.975	1	8	1	4

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
45.84448	-87.0333	0	0	0	0
45.74582	-87.0797	1	4	1	4
45.67615	-87.1455	0	0	0	0
45.41793	-87.3465	1	2	0	0
45.11572	-87.6177	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
41.77804	-86.7276	0	0	0	0
41.8337	-86.6639	0	0	0	0
41.89918	-86.5906	0	0	0	0
42.04383	-86.4876	0	0	0	0
42.1349	-86.3681	1	4	1	4
42.20099	-86.3727	1	3	0	0
42.30165	-86.3086	0	0	0	0
42.39784	-86.2556	0	0	0	0
42.47929	-86.2224	0	0	0	0
42.6574	-86.1835	1	7	1	4
42.72667	-86.1423	0	0	0	0
42.79952	-86.0867	0	0	0	0
42.87553	-86.1174	1	3	0	0
42.95797	-86.1721	0	0	0	0
43.05348	-86.2148	0	0	0	0
43.15256	-86.2092	1	6	0	0
43.22797	-86.2049	0	0	0	0
43.3388	-86.2443	1	7	1	4
43.41211	-86.3101	0	0	0	0
43.50264	-86.3736	0	0	0	0
43.5941	-86.3905	0	0	0	0
43.68996	-86.3926	0	0	0	0
43.78586	-86.3944	1	5	0	0
43.95597	-86.3845	1	4	1	4
43.98486	-86.2841	0	0	0	0
44.13023	-86.2799	0	0	0	0
44.25737	-86.301	1	6	0	0
44.43046	-86.1289	1	4	1	4
44.63135	-86.0767	1	3	0	0
44.66043	-85.9381	0	0	0	0
44.66489	-85.6902	0	0	0	0
44.76893	-85.6342	1	4	1	4
44.83064	-85.4536	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
44.91241	-85.4031	0	0	0	0
45.11612	-85.3502	1	6	1	4
45.18622	-85.345	0	0	0	0
45.31682	-85.2503	0	0	0	0
45.36125	-85.0574	0	0	0	0
45.37015	-84.9708	1	4	1	4
45.43968	-84.7908	0	0	0	0
45.551	-84.7845	1	4	0	0
45.66393	-84.7813	0	0	0	0
45.7792	-84.7334	1	4	1	4
45.85741	-84.7294	0	0	0	0
46.04138	-85.117	1	10	0	0
46.0947	-85.4469	1	9	1	4
46.10092	-85.5715	0	0	0	0
46.09139	-85.9508	0	0	0	0
45.99313	-86.0118	1	4	0	0
45.9529	-86.2449	1	4	1	4
45.89989	-86.5079	0	0	0	0
45.89541	-86.7085	0	0	0	0
45.9267	-86.975	1	5	1	4
45.84448	-87.0333	0	0	0	0
45.74582	-87.0797	1	4	1	4
45.67615	-87.1455	0	0	0	0
45.41793	-87.3465	1	2	0	0
45.11572	-87.6177	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
41.77804	-86.7276	0	0	0	0
41.8337	-86.6639	0	0	0	0
41.89918	-86.5906	0	0	0	0
42.04383	-86.4876	0	0	0	0
42.1349	-86.3681	1	4	1	4
42.20099	-86.3727	0	0	0	0
42.30165	-86.3086	0	0	0	0
42.39784	-86.2556	1	3	0	0
42.47929	-86.2224	0	0	0	0
42.6574	-86.1835	1	4	1	4
42.72667	-86.1423	0	0	0	0
42.79952	-86.0867	0	0	0	0

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
42.87553	-86.1174	1	4	0	0
42.95797	-86.1721	0	0	0	0
43.05348	-86.2148	0	0	0	0
43.15256	-86.2092	0	0	0	0
43.22797	-86.2049	0	0	0	0
43.3388	-86.2443	1	7	1	4
43.41211	-86.3101	0	0	0	0
43.50264	-86.3736	0	0	0	0
43.5941	-86.3905	0	0	0	0
43.68996	-86.3926	0	0	0	0
43.78586	-86.3944	1	3	0	0
43.95597	-86.3845	1	4	1	4
43.98486	-86.2841	0	0	0	0
44.13023	-86.2799	1	2	0	0
44.25737	-86.301	0	0	0	0
44.43046	-86.1289	1	4	1	4
44.63135	-86.0767	1	2	0	0
44.66043	-85.9381	0	0	0	0
44.66489	-85.6902	0	0	0	0
44.76893	-85.6342	1	4	1	4
44.83064	-85.4536	0	0	0	0
44.91241	-85.4031	0	0	0	0
45.11612	-85.3502	1	4	1	4
45.18622	-85.345	0	0	0	0
45.31682	-85.2503	0	0	0	0
45.36125	-85.0574	0	0	0	0
45.37015	-84.9708	1	4	1	4
45.43968	-84.7908	1	3	0	0
45.551	-84.7845	0	0	0	0
45.66393	-84.7813	0	0	0	0
45.7792	-84.7334	1	4	1	4
45.85741	-84.7294	0	0	0	0
46.04138	-85.117	1	7	0	0
46.0947	-85.4469	1	5	1	4
46.10092	-85.5715	0	0	0	0
46.09139	-85.9508	1	5	0	0
45.99313	-86.0118	0	0	0	0
45.9529	-86.2449	1	4	1	4
45.89989	-86.5079	0	0	0	0
45.89541	-86.7085	0	0	0	0
45.9267	-86.975	1	4	1	4

Latitude	Longitude	Total Stations	Total Chargers	Existing Stations	Existing Chargers
45.84448	-87.0333	0	0	0	0
45.74582	-87.0797	1	4	1	4
45.67615	-87.1455	0	0	0	0
45.41793	-87.3465	1	2	0	0
45.11572	-87.6177	0	0	0	0

APPENDIX C: INTERCONNECTED NETOWRK OF LEVEL-2 AND DCFC

Table 1C presents the detailed results of the Level-2 portion in the integrated network solved by the heuristic algorithm for different budget allocated to Level-2 network. It includes the ID and coordinates of the centroid for each TAZ in the LMC area along with the number of chargers (11kW) required under each allocated budget.

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
46.202244	-86.865724	0	0	0	1	1	1	1
44.636049	-86.233122	1	3	3	4	4	4	4
44.552900	-86.183034	0	0	0	0	0	0	1
44.556695	-85.877686	0	0	0	0	0	1	1
42.103589	-86.473766	0	0	0	1	1	1	2
42.100509	-86.487408	2	3	4	4	4	5	5
42.089630	-86.481457	0	0	0	1	0	1	1
42.064405	-86.477494	1	2	3	3	2	4	4
42.019917	-86.428909	0	0	0	0	0	0	1
41.939656	-86.565203	0	0	0	0	0	1	1
41.828495	-86.365565	0	0	0	1	1	1	1
41.821261	-86.243215	10	11	11	11	11	11	11
41.836135	-86.201354	0	1	1	1	1	1	1
45.299837	-85.080234	0	0	0	0	0	0	1
46.216113	-84.925904	2	2	2	2	3	3	3
45.782254	-87.080079	0	0	2	3	4	4	5
46.008707	-87.062141	0	0	0	0	0	1	1
45.690950	-86.638500	0	1	1	1	1	1	1
45.377026	-84.948043	0	0	0	0	0	0	1
45.680307	-84.792184	1	0	2	3	3	3	3
45.593931	-84.791827	0	0	0	1	2	2	3
45.507571	-84.791519	0	2	0	1	2	2	3
44.762864	-85.600646	0	0	2	4	5	6	7
44.729354	-85.543835	37	38	39	40	40	41	41
43.945531	-85.979654	0	0	1	1	1	1	1
44.119543	-85.862712	0	0	1	1	1	1	1
44.032421	-85.981005	0	0	0	1	1	1	1
44.910436	-85.873808	0	0	0	0	1	1	1
46.065372	-85.740592	0	1	1	1	1	1	2
46.075674	-85.008414	0	0	0	0	0	0	1
46.149150	-85.156366	0	1	1	2	2	2	2
46.056440	-84.852492	0	0	0	0	1	1	1

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
44.473288	-86.214138	0	0	0	1	1	1	2
44.470710	-85.999542	0	0	0	0	0	0	1
44.284403	-85.950335	1	2	2	2	3	3	3
43.961294	-86.444635	0	0	0	0	1	1	2
44.123843	-86.356167	0	0	0	0	0	0	1
44.033360	-86.099889	0	0	1	1	1	1	1
45.481313	-87.351919	0	1	3	3	4	4	5
43.236085	-86.253158	1	2	3	3	4	4	4
43.253322	-86.235002	0	0	0	0	0	0	1
43.223010	-86.240711	0	2	3	4	4	4	4
43.228482	-86.274032	0	0	0	0	0	0	1
43.412634	-86.300525	4	5	6	7	7	7	8
43.343194	-86.342078	0	0	0	1	1	1	2
43.268948	-86.336397	2	3	4	5	5	5	5
43.268209	-86.287861	0	0	0	0	0	0	1
43.251685	-86.271403	0	0	0	0	0	0	1
43.220637	-86.164559	0	0	0	1	1	1	1
43.278618	-86.111030	0	0	0	0	1	1	1
43.685093	-86.458454	12	13	12	13	15	15	15
43.598063	-86.098882	0	0	0	0	0	1	1
42.779611	-86.115970	0	0	0	0	0	1	1
43.082778	-86.224021	0	0	0	1	0	1	1
43.065872	-85.934096	0	0	0	0	1	1	1
42.771264	-86.171509	0	0	0	0	0	0	1
46.052709	-85.929414	0	0	0	1	0	2	2
42.531924	-85.861080	2	3	3	3	3	3	3
42.526304	-85.835138	0	0	1	1	1	1	1
42.523785	-85.878435	0	1	1	1	1	1	1
42.465564	-85.878098	1	1	1	1	1	1	2
42.656345	-86.199553	0	0	6	10	13	14	17
42.645016	-86.209489	1	5	8	10	12	12	13
42.615839	-86.180298	0	0	0	0	0	0	1
42.663349	-86.173069	0	0	0	3	7	8	11
42.703349	-86.150158	0	0	0	1	2	2	3
42.761507	-86.079991	0	0	0	1	1	1	1
42.565876	-85.721565	0	0	1	1	1	1	1
42.580278	-86.075704	0	0	0	1	1	1	1
42.564214	-86.181444	1	2	2	3	3	3	4
42.518507	-86.202296	0	0	0	0	0	1	1

Allocated Budget		$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
42.459662	-86.222410	0	0	0	0	0	1	1
42.462642	-86.158399	0	0	0	0	0	1	1
45.077292	-85.241021	0	1	1	2	2	3	3
45.091548	-85.351459	0	0	0	0	0	0	1
45.028958	-85.338858	1	2	3	3	3	4	4
45.164710	-85.321933	0	0	0	0	0	0	1
45.162047	-85.243503	0	0	0	0	0	0	1
44.876361	-85.407408	5	5	5	5	6	6	6
44.915524	-85.388970	1	1	2	2	2	2	2
44.867320	-85.335456	0	0	1	1	1	1	1
44.962868	-85.259884	0	0	1	1	1	1	2
45.005465	-85.250955	1	1	2	2	2	2	3
44.968313	-85.146452	0	0	1	1	1	1	1
44.914661	-85.264331	0	0	0	0	0	0	1
44.884954	-85.260787	0	0	1	1	1	1	1
44.923864	-85.151448	0	1	1	1	1	1	1
44.728984	-86.082574	0	0	0	0	0	1	1
44.691729	-86.171841	0	2	2	2	2	2	2
44.664149	-86.085652	0	3	3	3	3	4	4
44.615479	-86.095503	0	2	2	2	2	3	3
44.648154	-86.016354	0	3	2	4	3	4	4
44.643837	-85.966170	0	0	0	0	0	1	1
44.753945	-85.872641	0	0	0	1	1	1	1
42.074374	-86.503040	2	2	3	3	2	4	4
42.085523	-86.493037	0	0	0	1	0	1	2
42.119561	-86.445235	0	0	0	0	1	1	2
42.097949	-86.420692	18	19	21	22	22	22	23
42.069020	-86.445371	9	10	11	11	11	12	12
42.171050	-86.384504	0	0	0	0	0	0	1
42.183392	-86.254731	1	2	3	3	3	4	4
42.220407	-86.249618	0	0	1	1	1	1	2
42.205662	-86.285257	0	0	0	1	1	1	2
42.036231	-86.519321	17	17	18	18	16	18	18
41.967349	-86.480976	0	0	0	0	0	1	1
42.087858	-85.931065	0	0	1	1	1	1	1
41.784916	-86.749198	3	3	2	3	3	3	3
41.799203	-86.742562	1	1	0	1	1	2	2
41.793467	-86.732951	11	11	10	11	11	12	12
41.779466	-86.698519	0	0	0	0	1	1	1

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
41.768084	-86.748350	5	5	4	5	5	5	5
41.812383	-86.696769	6	6	2	6	6	6	6
41.775909	-86.786649	0	1	0	1	1	1	1
41.847797	-86.658142	4	4	0	4	4	5	5
41.879558	-86.618479	0	0	0	0	0	1	1
41.785902	-86.476973	0	1	0	1	1	1	1
41.785960	-86.260897	0	1	1	1	1	1	1
41.975157	-86.125915	0	0	0	0	0	0	1
41.992765	-86.106201	0	0	1	1	1	1	1
42.042860	-86.162253	2	2	3	3	3	3	3
42.042764	-86.078094	0	0	0	0	1	1	1
45.309152	-85.260137	0	0	0	0	0	1	1
45.319342	-85.244996	0	5	5	6	6	6	6
45.207593	-85.022234	0	3	3	4	4	4	4
45.207997	-84.990290	2	2	3	3	3	3	4
45.336318	-85.234228	2	2	3	3	3	3	4
45.158950	-85.135834	0	2	2	2	3	3	3
45.237635	-84.942354	0	0	0	0	0	0	1
45.738478	-84.688457	2	3	3	4	4	4	4
45.777194	-84.727961	0	2	3	4	5	5	6
45.415467	-84.690147	0	13	32	43	50	53	60
45.740599	-87.090102	0	0	0	0	0	1	1
45.756502	-87.083990	0	0	0	0	3	4	8
45.768367	-87.074708	0	0	0	2	4	6	8
45.723514	-87.094107	0	0	0	0	0	0	1
45.863747	-87.029546	0	0	0	0	0	0	1
45.842369	-87.044495	0	0	1	1	2	2	2
45.799974	-87.101045	0	0	1	2	2	2	2
45.916458	-86.973696	0	0	0	0	0	1	1
45.905983	-86.937441	0	0	0	0	0	0	1
45.802343	-86.508657	0	0	1	1	1	1	1
45.369344	-84.942143	0	0	1	4	5	6	7
45.372533	-84.973889	0	0	0	0	0	0	2
45.366937	-84.966270	0	0	0	0	1	4	11
45.361268	-85.036682	13	5	10	13	18	18	19
45.357569	-84.962288	0	1	7	10	13	13	16
45.730054	-84.915968	2	2	3	4	4	4	4
45.443203	-84.941204	0	0	0	0	0	0	1
45.439633	-84.882469	0	0	1	1	2	2	2

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
45.484738	-84.937346	7	8	8	9	9	9	9
45.460757	-84.997864	0	0	1	1	1	2	2
45.433596	-84.981560	0	0	0	0	0	0	1
45.429577	-84.996554	0	0	1	2	2	2	3
45.440139	-84.818085	0	0	0	0	0	1	1
45.427865	-84.757427	0	2	2	2	1	3	3
45.370042	-84.894404	1	2	4	5	5	5	6
45.319557	-84.950686	0	0	0	0	0	0	1
45.402400	-84.883478	5	6	7	8	9	9	9
45.346554	-85.072851	0	0	0	0	3	3	3
45.325477	-84.794455	0	0	0	0	0	0	1
44.778277	-85.650733	0	0	0	0	0	0	1
44.770424	-85.581131	0	0	0	1	2	3	3
44.758150	-85.584116	19	21	24	25	26	26	27
44.756040	-85.629260	0	0	0	0	0	0	1
44.756122	-85.619870	0	0	0	0	0	0	1
44.750955	-85.603953	0	0	0	0	0	0	1
44.850201	-85.543985	0	0	0	0	1	1	1
44.925711	-85.521702	0	0	0	0	1	1	1
44.812659	-85.441728	7	7	8	8	8	9	9
44.755334	-85.472176	1	2	3	3	3	3	4
44.764940	-85.722306	0	0	0	0	0	0	1
44.733591	-85.651782	6	8	10	11	12	13	13
44.738531	-85.606981	0	0	0	0	0	0	1
44.619529	-85.789909	0	0	0	0	0	0	1
44.644168	-85.730811	2	0	3	2	4	3	4
44.674236	-85.791553	0	0	0	0	1	1	1
44.557782	-85.785692	0	0	0	0	0	0	1
44.750366	-85.567056	3	5	7	8	8	8	9
44.723690	-85.480810	0	0	0	1	1	1	1
44.699152	-85.544181	0	0	0	0	0	0	1
43.922276	-85.875307	0	0	0	0	1	1	1
44.119183	-85.952802	0	0	1	1	1	1	1
44.123662	-86.011794	0	0	0	0	1	1	1
45.076689	-85.635981	0	0	0	1	1	1	1
45.017934	-85.729655	2	2	2	3	3	3	3
44.971444	-85.676177	2	3	3	3	3	3	4
45.017387	-85.650847	7	7	7	7	8	8	8
44.820435	-85.967155	0	0	0	1	1	1	1

Latitude	Longitude	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers (Allocated Budget)						
44.820229	-86.034827	0	1	1	1	1	1	1
44.896014	-85.951957	14	15	15	15	15	15	15
44.885207	-86.031853	1	2	2	2	2	2	2
44.839801	-85.676077	0	0	0	0	0	0	1
44.936374	-85.761802	0	0	1	1	1	1	1
44.891082	-85.762479	0	0	0	0	1	1	1
44.907882	-85.679570	0	0	0	1	1	1	1
44.913560	-85.642461	0	0	0	1	1	1	1
44.849324	-85.746326	1	2	2	3	3	3	3
45.860874	-84.722812	0	5	6	6	7	7	7
45.884404	-84.730661	25	34	35	35	35	35	36
46.138922	-85.558612	0	0	0	0	0	0	1
46.203202	-85.797616	0	0	0	1	1	1	1
45.871152	-84.779912	0	0	0	0	0	1	1
44.254897	-86.327039	0	0	2	8	9	9	9
44.247255	-86.315687	0	0	0	2	2	2	2
44.237284	-86.313233	0	0	0	3	4	4	4
44.238751	-86.331299	0	0	0	3	3	3	4
44.199414	-86.292156	0	1	2	3	4	4	4
44.215233	-86.122227	0	0	0	0	1	1	1
44.350377	-86.225830	0	0	1	1	1	1	2
44.391016	-86.207905	0	0	0	0	0	1	1
44.416231	-86.120949	0	0	0	0	0	0	1
44.372977	-86.121680	0	0	0	0	0	0	1
44.490952	-85.878120	0	0	0	0	1	1	1
44.386740	-86.036995	0	0	0	0	0	0	1
44.208470	-86.007952	0	1	1	1	1	2	2
44.209675	-85.887796	0	0	0	1	1	1	1
43.966023	-86.455244	0	1	2	3	4	4	5
43.961014	-86.433478	0	0	3	4	5	5	6
44.034768	-86.250446	0	0	0	0	0	0	1
44.005843	-86.448816	1	2	3	4	4	5	5
44.046119	-86.448490	2	2	3	4	4	4	4
44.036615	-86.370189	0	0	0	0	0	0	1
43.952005	-86.412191	9	13	17	20	21	22	23
43.852282	-86.418905	0	0	0	0	0	1	1
43.969499	-86.097078	0	0	1	1	2	2	2
45.137791	-87.608826	0	0	1	1	1	1	1
45.149746	-87.621452	1	1	1	1	1	1	1

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
45.121397	-87.614150	6	6	7	7	7	7	7
45.671041	-87.388019	0	0	0	1	1	1	1
45.416716	-87.590546	0	0	0	0	0	0	1
43.196349	-86.233422	0	3	4	4	4	5	5
43.194195	-86.248714	0	2	3	3	3	3	3
43.437757	-86.370850	0	0	0	0	1	0	1
43.360419	-86.177309	0	0	0	0	0	0	1
43.197960	-86.261587	0	3	4	4	4	5	5
43.197766	-86.214899	0	2	3	3	4	4	4
43.184127	-86.217295	0	1	2	2	2	2	2
43.160089	-86.218832	0	9	9	9	9	10	10
43.195061	-86.270410	0	1	2	2	2	2	2
43.463402	-85.965113	3	3	4	4	4	4	4
43.471467	-85.959511	0	0	1	1	1	1	1
43.474331	-85.937543	0	0	1	1	1	1	1
43.462293	-85.938098	0	0	0	1	1	1	1
43.597261	-86.009435	1	1	1	1	2	2	2
43.498498	-86.438085	0	0	0	0	1	0	1
43.793651	-86.415541	4	0	4	5	2	5	5
43.698069	-86.358717	0	0	0	0	0	1	1
43.686975	-86.386629	2	3	0	0	5	5	5
43.513738	-86.311011	2	3	4	4	4	4	4
42.786649	-86.102328	0	3	4	4	4	4	4
42.777593	-86.089340	0	3	4	4	4	4	5
43.069800	-86.227358	1	3	4	4	2	4	4
43.042811	-86.203274	0	0	0	1	0	1	1
43.051401	-86.233660	0	0	0	0	0	1	1
43.062995	-86.210022	3	4	5	5	1	5	5
43.059815	-86.224004	0	0	1	1	0	2	1
42.980335	-86.166691	0	0	0	0	0	0	1
43.005739	-86.214360	0	0	0	0	0	0	1
42.962808	-86.198657	0	0	0	0	0	0	1
43.038168	-86.223943	12	12	13	13	11	14	14
43.018276	-86.176544	0	0	0	0	1	1	2
42.964994	-85.890360	3	3	3	4	4	4	4
42.819280	-86.124742	0	0	1	1	2	2	2
42.815627	-86.083824	9	26	26	26	27	27	27
42.820707	-86.158743	0	0	0	0	0	0	1
42.790158	-86.194512	0	2	3	3	4	4	4

	Allocated Budget	$4M	$6M	$8M	$10M	$12M	$14M	$16M
TAZ Centroid		Number of Chargers						
Latitude	Longitude							
42.785993	-86.153436	0	0	0	1	1	1	1
42.857758	-85.864151	2	2	3	3	3	3	3
42.896199	-85.891913	0	0	0	1	1	1	1
45.960241	-86.260689	0	0	0	0	0	0	1
45.957885	-86.239179	0	0	0	0	5	7	12
45.872426	-86.380051	0	0	0	0	0	1	1
46.114637	-86.396105	0	0	0	1	1	1	1
45.953979	-86.433519	0	0	0	1	1	1	1
46.169743	-86.544165	0	0	0	1	1	1	1
42.409114	-86.245498	11	0	2	11	11	12	11
42.408736	-86.269460	9	0	2	9	10	10	10
42.388113	-86.279349	1	0	0	2	2	2	2
42.385008	-86.248580	0	0	0	1	1	1	1
42.412787	-86.255211	0	0	0	0	1	1	1
42.397126	-86.196743	1	0	0	2	2	2	2
42.397240	-86.052477	0	0	0	1	1	1	1
42.220625	-86.023391	3	3	3	3	4	4	4
42.318303	-86.045188	0	0	0	1	1	1	1
42.200562	-86.162786	0	0	0	1	1	1	1

Table 2C presents the detailed results of the DCFC portion in the integrated network for different budget allocated to DCFC network. It includes the number and coordinates of the nodes along the main corridor in the LMC area as well as the number of required new stations and new chargers at each node. The number of existing stations and chargers are not included in this table as they remain the same as what presented in **Table 1B** to **Table 4B**. In the table the total number of required stations and chargers are noted as T.S. and T.C., respectively.

Node		$16M		$14M		$12M		$10M		$8M		$6M		$4M	
Latitude	Longitude	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.
41.77804	-86.7276	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41.8337	-86.6639	0	0	0	0	1	4	0	0	0	0	0	0	0	0
41.89918	-86.5906	0	0	0	0	0	0	1	2	1	2	0	0	0	0
42.04383	-86.4876	0	0	0	0	0	0	0	0	1	3	0	0	0	0
42.1349	-86.3681	1	7	1	8	1	5	1	4	1	4	1	4	1	4
42.20099	-86.3727	1	5	0	0	0	0	0	0	0	0	1	3	0	0
42.30165	-86.3086	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42.39784	-86.2556	0	0	1	10	1	9	0	0	0	0	0	0	1	3

Node		$16M		$14M		$12M		$10M		$8M		$6M		$4M	
Latitude	Longitude	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.
42.47929	-86.2224	0	0	0	0	0	0	1	6	1	5	0	0	0	0
42.6574	-86.1835	1	13	1	15	1	12	1	9	1	7	1	8	1	4
42.72667	-86.1423	1	6	0	0	0	0	0	0	0	0	0	0	0	0
42.79952	-86.0867	1	9	0	0	0	0	0	0	0	0	0	0	0	0
42.87553	-86.1174	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42.95797	-86.1721	0	0	1	11	1	9	1	8	0	0	1	5	0	0
43.05348	-86.2148	0	0	0	0	0	0	0	0	1	7	0	0	1	5
43.15256	-86.2092	1	15	0	0	0	0	0	0	0	0	0	0	0	0
43.22797	-86.2049	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43.3388	-86.2443	1	8	1	13	1	9	1	8	1	8	1	5	1	4
43.41211	-86.3101	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43.50264	-86.3736	0	0	0	0	0	0	0	0	0	0	1	4	0	0
43.5941	-86.3905	1	7	0	0	0	0	0	0	0	0	0	0	1	3
43.68996	-86.3926	0	0	0	0	1	6	1	8	0	0	0	0	0	0
43.78586	-86.3944	0	0	1	6	0	0	0	0	1	6	0	0	0	0
43.95597	-86.3845	1	11	1	11	1	10	1	9	1	5	1	8	1	4
43.98486	-86.2841	0	0	1	5	0	0	0	0	0	0	0	0	0	0
44.13023	-86.2799	0	0	0	0	0	0	1	5	1	4	1	4	1	4
44.25737	-86.301	1	10	1	10	1	9	0	0	0	0	0	0	0	0
44.43046	-86.1289	1	6	1	6	1	5	1	6	1	6	1	6	1	4
44.63135	-86.0767	1	6	0	0	0	0	0	0	0	0	0	0	0	0
44.66043	-85.9381	0	0	0	0	1	6	0	0	1	3	0	0	0	0
44.66489	-85.6902	0	0	1	6	0	0	1	7	0	0	1	3	1	2
44.76893	-85.6342	1	16	1	9	1	11	1	6	1	7	1	6	1	4
44.83064	-85.4536	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44.91241	-85.4031	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.11612	-85.3502	1	9	1	8	1	7	1	4	1	4	1	4	1	4
45.18622	-85.345	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.31682	-85.2503	1	5	0	0	0	0	0	0	0	0	0	0	0	0
45.36125	-85.0574	0	0	1	5	1	6	1	5	0	0	0	0	0	0
45.37015	-84.9708	1	16	1	13	1	10	1	8	1	7	1	6	1	4
45.43968	-84.7908	0	0	0	0	0	0	0	0	1	4	0	0	0	0
45.551	-84.7845	1	6	0	0	1	5	1	7	1	4	1	6	0	0
45.66393	-84.7813	0	0	1	6	0	0	0	0	0	0	0	0	1	4
45.7792	-84.7334	1	15	1	13	1	10	1	7	1	5	1	4	1	4
45.85741	-84.7294	1	4	0	0	0	0	0	0	0	0	0	0	0	0
46.04138	-85.117	1	11	1	12	1	12	1	10	1	9	1	8	1	7
46.0947	-85.4469	1	8	1	10	1	7	1	10	1	5	1	6	1	4
46.10092	-85.5715	0	0	0	0	0	0	0	0	0	0	1	6	0	0
46.09139	-85.9508	1	8	0	0	1	7	0	0	1	6	0	0	1	4

Node		$16M		$14M		$12M		$10M		$8M		$6M		$4M	
Latitude	Longitude	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.	T.S.	T.C.
45.99313	-86.0118	0	0	1	4	0	0	1	6	0	0	0	0	0	0
45.9529	-86.2449	1	10	1	11	1	9	1	9	1	7	1	6	1	5
45.89989	-86.5079	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.89541	-86.7085	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.9267	-86.975	1	6	1	9	1	8	1	5	1	6	1	5	1	4
45.84448	-87.0333	1	4	0	0	0	0	0	0	0	0	0	0	0	0
45.74582	-87.0797	1	6	1	7	1	6	1	5	1	4	1	4	1	4
45.67615	-87.1455	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45.41793	-87.3465	1	2	1	2	1	2	1	2	1	2	1	2	1	2
45.11572	-87.6177	0	0	0	0	0	0	0	0	0	0	0	0	0	0