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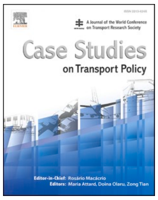

The costs and challenges of installing corridor DC Fast Chargers in California

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ABSTRACT

A national network of DC Fast Charging infrastructure (DCFC) corridors can facilitate connectivity and long-distance travel using battery electric vehicles (BEVs). Optimal locations of such facilities are where BEV drivers have easy access to charging where drivers will not have to make any deviation from their pre-planned trips. Such optimally located corridor DCFCs are usually in remote, underserved communities and immediately next to a highway where they lack the advantages of shared utility infrastructure in an urban setting. Therefore, we find that other studies and industry knowledge of infrastructure investments do not apply to corridor DCFC locations. This study evaluates the full project costs of installing and commissioning 54 DC Fast Chargers in 36 sites located in major transportation corridors in California and finds significant variation in costs between them. While existing studies show costs ranging from $20,000 - $150,000, we find costs range anywhere between $122,000 and $440,000. This data is critical for new investment in the U.S. to construct a national charging network of DC Fast charging corridors. We find that a significant proportion of the full project costs are taken up by on site "make-ready infrastructure" costs that vary greatly due to site-specific factors and design choices. DCFC installations should be considered civil construction projects with significant electrical infrastructure planning and installation that requires the cooperation of many local stakeholders. We find that costs can be greatly reduced by working with local electrical utilities early in the design and site selection stages when possible. Our study finds that some cost shift towards utility side costs can greatly reduce overall construction costs for sites along highways. We also find that grid-connected DCFC design are substantially cheaper than off-grid solar powered DCFC with onsite storage.

1. Introduction

Electrification of transportation is generally considered a major pathway to shift the current fossil-fuel dominant surface transportation system towards a more energy efficient and less polluting future. In the context of light duty vehicles, this means adopting plug-in electric vehicles (PEVs) which include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) that are considered more energy efficient and less polluting than most internal combustion engine vehicles (ICEVs). Some studies indicate that most of the global light-duty vehicles fleet should be BEVs by 2050 to meet climate mitigation goals (IEA, 2021). For these reasons and more, many governments, including the State of California have supported the adoption of BEVs through various incentive mechanisms (Hardman et al., 2018; Wolinetz and Axsen, 2017).

The success of large scale BEV adoption is partly reliant on the development of recharging infrastructure. There are different modes and levels of charging for these BEVs including slower AC chargers known as Level 1 and 2, which provide power ranging from 1 to 20 kW. DC Fast Chargers are the fastest option for BEV charging and have very high-power demands on the grid. They have an AC/DC converter outside the vehicle to deliver DC power directly (DCFC) to the BEV battery typically at 50 kW or greater. These chargers are considerably more expensive than level 2. Usually, level 2 and DC Fast Chargers can communicate with the BEV, and charging can be controlled allowing the charging station (or electric vehicle supply equipment, EVSE) to optimize the charging process based on available software and information. The charge time depends on the state of charge in the battery, and other physical constraints such as ability of the battery to accept higher charge rate, the charging cable used and the charging station or EVSE. Due to

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Abbreviations: DCFC, DC Fast Charger; BEV, Battery Electric Vehicle; CPUC, California Public Utilities Commission.

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inconsistencies in definitions of charging infrastructure across reports and studies within the topic area, we provide a comprehensive set of definitions for terms used in this paper in Table 1 (Hardman et al., 2018; DOE, 2014; Idaho National Laboratory, 2015; Francfortb, 2017; Transport Research Board, 2013).

This study focuses on DC Fast Charging infrastructure, specifically on corridor charging stations. We were tasked by the California Department of Transportation (Caltrans) to study the construction and launch of 54 different DC Fast Charger installation projects in 36 different locations. These sites were selected under the "30–30" project along priority highways, such as Interstate 5, State Route 99, and U.S. Highway 101. The objective of the "30–30" project was to "fill the gaps within California's DC Fast Corridor Network along key routes of the State Highway System where sufficient commercial zero-emissions vehicle (ZEV) fueling opportunities do not currently exist". Uniquely, these sites are at remote or underserved locations that other commercial networks likely did not consider to be economically viable in their business model but were found to be necessary to support long distance travel using BEVs (Robinson, 2020).

The U.S. Department of Energy's (DOEs) 'EV project' identified that DCFCs are more effective when located close to inter-metro major transportation corridors (DOE, 2014). However, such optimal corridor charging locations across major transportation corridors sometimes lie in rural areas. Fast chargers enable using BEVs on journeys above their single-charge range that would have been impractical using standard chargers. Studies have found that customers strongly prefer BEVs with longer range and higher battery capacities. Charging time and overall driving range are usually identified as the strongest barriers to BEV adoption in customer surveys. As the battery size of electric vehicles grows (and their driving range with it), demand for charging at DC Fast Charging stations located in long distance corridors outside metropolitan areas is expected to grow substantially (Ji et al., 2019; Francfort et al., 2017; Hardman et al., 2018; Schultz and Rode, 2022).

While most drivers will charge from residential EVSE, there is considerable need for non-residential charging stations in workplace and public settings. Like any other infrastructure investment, understanding the costs is an important starting point to making policy decisions such as (1) choosing which investments to make, (2) who should pay and (3) how to balance risk and reward for stakeholders while aiming to achieve climate mitigation goals. After all infrastructure investments are known to have long lead times and BEV charging is a good example for needing critical mass for widespread BEV adoption in time to achieve long term climate goals (Hogan, 2009).

It is generally understood that DC Fast Charging (DCFC) infrastructure entails very high costs for construction. However, for a variety of reasons, the cost of DCFC infrastructure is not readily available to the public. Whenever such costs are known, such information is guarded as proprietary information with charging network companies. Furthermore, the available examples for DCFCs construction cost studies are limited to attain a generalized understanding of the cost factors. General attempts at modelling the costs of DCFC do not go beyond including the cost of the EVSE unit and some estimate of labor and material costs for total construction. This is an oversimplification. Reputable qualitative studies indicate that DCFCs will require significant upgrades to the electrical distribution grid infrastructure along with the high costs of on-site wiring (Baker et al., 2019) and civil construction support for BEV parking spots (Clean Cities US DOE, 2012). These costs are referred to as "make-ready infrastructure" by industry stakeholders. The cost factors that mostly contribute to final costs can help determine whether economies of scale influence the cost per charger and if choice of technology/ site design changes the final costs. These questions and their answers can help planers and policymakers optimize the rollout of a national DCFC network across the United States and achieve the most output from limited resources.

One of the first planned attempts to understand the costs of EVSE installations in the United States was called the "EV Project". Initially it started as a project proposed by the Electric Transportation Engineering Corporation (ETEC, a subsidiary of ECOtality Inc.) to spend funding made available by the American Recovery and Reinvestment Act's (ARRA) on EVSE stations in 10 cities across the United States. The EV Project had a budget of $229.6 million with funds equally contributed by federal funds and ETEC partners. The U.S. Department of Energy (DOE) was tasked with capturing lessons learnt from the initial projects. The EV Project from 2009 to 2013 deployed more than 12,500 Level 2 charging stations and 110 dual connector DCFCs at publicly accessible locations. While ECOtality filed for bankruptcy in 2013, some of the initial EVSE investments survives in the Blink electric vehicle charging network. The DCFCs selected for these projects had a capacity of 60 kW and sites were in metropolitan areas. The EV Project's initial data identified that cost of installing a DCFC ranged between $8,500 and $50,820. However, the total cost of installations included only the costs paid to the electrical contractors to install Blink DCFCs. The contractor's costs typically would have included permit costs, engineering drawings (usually required), contractor's installation and administration labor, subcontracted construction labor or equipment (e.g., concrete, asphalt, trenching, boring, etc.), and materials other than the DCFC itself, which was provided by The EV Project. Installation costs did not include the cost of any AC Level 2 EVSE units that may have been simultaneously installed at the same site (Idaho National Laboratory, 2015). Later studies by the DOE that were informed by the EV Project attempted to model the full costs of DCFC installation by agglomerating together many chargers into a given site as a "charger complex". This study included the costs of additional components. However, in this design, some make-ready infrastructure capacities were shared amongst several DCFCs preventing all the chargers from achieving maximum capacity if chargers were used in unison. The new installation costs ranged from $ 385,500 - $392,000 for the installation of 6 DCFCs with a rated 50 kW charger capacity. However, the total combined electrical service capacity of the 6 chargers together was 160 kW. (Francfort et al., 2017).

The study by Rocky Mountain Institute (Nelder and Rogers, 2019) obtained cost information from interviews with various charging networks. Information was obtained under non-disclosure agreements with the assurance that the data would be anonymized and aggregated. A whitepaper by Nicholas (2019) cites the previous RMI study as a primary source of information. RMI estimated a cost range of about $ 20,000–$150,000 per 50 kW DCFC station. The CALeVIP (2021) cost data are

Table 1
Some Charging infrastructure nomenclature and definitions.

Word	Definition
Charger	The above-ground appliance or the EVSE[1] unit that delivers electricity to charge the BEV[2]
Connector	A charger may have one or more connectors. It is the physical socket that connects to the BEV
Charging Station/ Electric Vehicle Charging Station	Synonymous to "gas station", a charging station is a physical address where one or more chargers are available for use. They can be public, private, or shared private
Make-ready infrastructure	All necessary on-site electrical infrastructure in between the utility connection and chargers, including all conduit, electrical service panels and concrete work
EV ARC	Photovoltaic (PV) power supply on a motorized sun tracking, structure. Includes PV panels, batteries, wireless communications, emergency panel, lighting, and transformers.
EVSE	Electric Vehicle Supply Equipment (EVSE) is the above ground electric Vehicle charging station hardware, including, but not limited to, Level 1, Level 2, and DC Fast Chargers.

[1] Electric Vehicle Supply Equipment (EVSE) is the above ground electric Vehicle charging station hardware, including, but not limited to, Level 1, Level 2, and DC Fast Charge.
[2] Battery Electric vehicles.

Table 2
Summary of the final cost information of installing DC Fast Chargers from available literature and studies funded by public and private agencies. Notice the vast range of cost information and the way this information was presented, such as the number of chargers and what is included in final costs.

Study	Conducted by	Cost Range	Other remarks
California Energy Commissions CALeVIP Cost Data	California Energy Commission (2021)	$75,841 – 118,131 total project cost per DC fast charger	Further inquiry revealed that CALeVIP cost data may not reflect the full costs of DC fast charging station construction.
Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas	Nicholas M. (2019), ICCT	$ 45,506–65,984 (50 kW – 350 kW) one charger per site	$ 17,692–25,694 per charger // 6x (50 kW – 350 kW) per site
Reducing EV Charging Infrastructure Costs	RMI (2019)	$ 20,000–150,000 (50 kW – 350 kW)	
Costs Associated with Non-Residential Electric Vehicle Supply Equipment	DOE EV Everywhere (2015)	$ 31,000–61,000 single port	($ 10 K – 40 K EVSE unit cost + 21 K average installation cost
Electrification of Transportation Strategic Roadmap (Conducted for the Hawaii Public Utilities Commission)	EThree (2018)	$128,094	
Considerations for Corridor and Community DC Fast Charging Complex System Design	Idaho National Labs (2017)	$64,250–65,333 ($ 385,500–392,000 for 6x50 kW units)	
What were the Cost Drivers for the Direct Current Fast Charging Installations? The EV Project	Idaho National Labs (2015)	$8,500 – 50,820 (for 60 kW chargers and includes only contractor's costs)	

self-reported by site applicants who wish to obtain a rebate from the California Energy Commission (CEC). Their data indicated a $75,841 – $118,131 total project cost per DC fast charger (California Energy Commission, 2022).

A summary of the available studies conducted by government organizations and non-profit organizations that have researched and modelled the costs of installing DC Fast Chargers is provided in Table 2, which includes a summary of the costs.

Comparing the information in these cost studies was challenging for many reasons. The first being, different studies used DC Fast Chargers with different charging speeds as the baseline for study. For example, the EV project used 60 kW charging speeds, whereas Idaho National Labs (2017) study used a charger complex design that has 6 of 50 kW chargers that ultimately had a ceiling capacity of 160 kW for the charger complex. RMI's (2019) study used 3 different charging speeds, 50 kW, 150 kW and 350 kW DCFCs as the baseline. The second is that some studies did not include all the cost segments in the final cost calculations. For example, the EV Project included only contractor's installation costs and did not include EVSE costs or the cost of new service connection from utilities. The third reason is the apparent lack of openness to share information. Studies that opted to gather cost information from interviews explicitly mention in their reports that sources interviewed "were hesitant to share full-cost data or to share information at the component level" (Nelder and Rogers, 2019) because doing so could reduce their competitive advantage in an industry that is only in the early stages of market maturity. While the California Electric Vehicle Infrastructure Project (CALeVIP) database has the most realistic cost information, our interviews with the program administrators suggests that the cost data indicated may not reflect the full construction costs for the same reasons. It is a program funded by the California Energy Commission and other co-funding partners to the tune of $203 million where selected DCFC projects are given rebates for a fraction of the project costs. Since each individual application for funding has an upper limit, the applicants are under no obligation to share the full costs of DCFC installation projects after the upper limit for obtaining rebate funding is met (Francfort et al., 2017; Idaho National Laboratory, 2015; DOE, 2014; Meng et al., 2019).

2. Materials and methods:

The data used for this project is unique. We had access to full cost data from the Caltrans ZEV "30–30" project. Caltrans had asked our help for data collection and reporting, and since it was a publicly funded project, all costs are publicly disclosed.

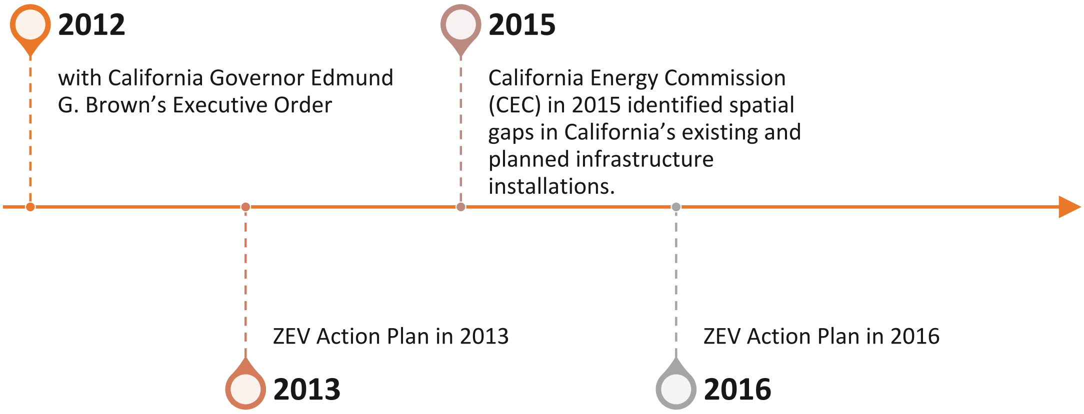

Fig. 1. Project timeline history (Brown, 2012).

Fig. 2. Map identifying possible Caltrans sites for DCFC installation based on CEC study (Robinson, 2020).

2.1. *History of the Caltrans "30–30" project*

The California Governor's ZEV Action plan of 2013 put into actionable goals the need for BEV infrastructure in public places. The ZEV Action plan released in 2016, further homed in on the ZEV 30–30 project that specifically directed the State to install public DC Fast Chargers at a minimum of 30 locations (Fig. 1) (Governor's Interagency Working Group on Zero-Emmission Vehicles, 2016). The project was originally proposed to be completed in 2018 with a budget of $25.3 million. However, due to legal obstacles, the project implementation was delayed till early 2020. Since the project was originally planned in 2016, the DC Fast chargers in the original plan had an output up to 50 kW capacity. This charger capacity was considered very high at the time. By 2020 the maximum capacities of DCFCs had expanded beyond 50 kW to 150 kW and more. However, when the project was finally implemented in 2020, the scoping and original design did not change to reflect the changes in the market DCFC technology from 2016 to 2020.

Fig. 2 is a map from the Caltrans project memorandum. The site selection process was informed by a consultation report published by the California Energy Commission (CEC) in 2015 that identified spatial gaps in California's existing and planned infrastructure installations (Robinson, 2020) and a study that identified potentially high demand and high congestion rest areas in the future (Behdad et al., 2020; Lee, 2016). The chosen 36 sites for DCFC installation were distributed between 27 highway Safety Roadside Rest Areas (SRRAs), 5 Maintenance Stations, 2 District Offices, and 2 Park and Ride Lots along priority transportation corridors, including Interstate 5, State Route 99, and U.S. Highway 101 in the State of California. (Robinson, 2020).

2.2. *What is a Safety Roadside Rest Area (SRRA)?*

According to Caltrans:

> "Caltrans provides Safety Roadside Rest Areas as a part of the State Highway System pursuant to Streets and Highways Code, Sections 218–226.5. Safety Roadside Rest Areas provide opportunities for travelers to safely stop, stretch, take a nap, use the restroom, get

> water, check maps, place telephone calls, switch drivers, check vehicles and loads, and exercise pets. Rest areas reduce drowsy and distracted driving and provide a safe and convenient alternative to unsafe parking along the roadside."[1]

SRRAs are an important feature of the nation's highway system, and they are used every day by travelers using the highway system. Some rest areas along busier highways have two separate rest areas in tandem next to each other on opposite sides of the highway to service traffic traveling in opposite directions. Out of the 27 SRRAs selected for this project, 22 were such a location that had a twin rest stop next to each other. That is, 11 locations with twin rest stops that were servicing traffic traveling in opposite directions. Because such twin rest areas had their own dedicated facilities, such rest stops were considered unique sites, even though they were alongside the freeway on opposite sites. For example, Boron Westbound (WB) SRRA and Boron Eastbound (EB) SRRA (Fig. 3) were located on opposite sides of the freeway but were considered as two unique rest stops.

2.3. *Interviews and data collection*

We initially interviewed Caltrans engineers and project managers who were tasked with the DCFC construction. A sample interview question matrix can be found in appendices 1 and 2. Then, project cost data were collected from contractors' bid documents and utility interconnection bills. In addition, we analyzed information from detailed civil/ electric design plans to further understand the costs information obtained from winning bid documents. We also interviewed engineers from private charging networks to understand their project design and implementation process.

Fig. 3. Map of Boron Rest areas servicing westbound and eastbound traffic (From Google Maps used under fair use).

3. Analysis

3.1. *Planning and early states of project implementation*

Caltrans would initially create a working unit with a project manager and a project engineer (also referred as the design engineer) for a given Caltrans district. The project manager is responsible for scoping, scheduling, and costing for the project and the project engineer is responsible for the design and technical guidance of the project.

We spoke to project managers and design engineers to understand the early stages of the project implementation process. At this point, they considered 3 main issues. (1) purchasing EVSE unit(s), (2) getting adequate power supply for the BEV parking spot (EVSE unit) and (3) designing and construction of necessary on-site make-ready infrastructure. This early design and planning stage is important for understanding cost variables in the project.

Purchase of the EVSE unit was done through the Department of General Services which administers all California State contracts with suppliers. Then design engineers survey the proposed construction site to understand initial conditions. At this level they estimate the existing capacity of the electrical supply connection and assess the necessary civil and electrical work to make the EVSE units operational. From our interviews, we identified that design engineers must finalize the engineering design for the site, which has a detailed project plan for building civil/ electrical construction for all sites. This plan includes a detailed site plan, with detailed parking spots, their layout, and existing and modified electrical works plan. They also included other plans such as tamper protection designs for EVSE.

A significant piece of the initial stages is about getting power to the remote locations and then getting power from the utility drop site to the designated BEV parking spot(s) (Fig. 4). From our interviews we understood that there are two ways to obtain a utility connection. Either (1) the existing electrical connection and panel can be modified to handle the higher electricity load required by the DCFC or (2) opt for a completely new service connection. Caltrans opted for a new utility connection in almost every location. The observation of project engineers was that previous electrical loads were very small that they were only adequate for lighting and other needs in rest areas. This decision makes a significant cost difference in these remote sites compared to most urban sites selected by other private networks.

In most locations, utilities needed to upgrade their infrastructure with new electrical cabinets and brand-new panels on site. In addition, new infrastructure must be built to supply adequate power to a new location. Fig. 5 includes two maps, the first is the modified electrical design to accommodate the EVSE unit and the second is a google satellite map of the rest area for greater clarity. As seen in Fig. 5, there is a considerable distance between the utility service drop site to the BEV parking spot which needs to be connected by PVC (Polyvinyl chloride) insulated copper conduit wire that is buried under 30'' in this design. The conduit sizes, insulation requirements and undergrounding and safety requirements are guided by the National Fire Protection Association standards or NFPA 70, National Electrical Code (NEC) and Caltrans safety requirements.

The site shown in Fig. 5 is a good case study to analyze cost factors involved because we were able to obtain electrical and civil design plans for the site upgrades and map them to real cost information. Fig. 5 represents the Willows Northbound rest area (SRRA) alongside highway 5 in California.

3.1.1. *Case study 1: Willows Safety Roadside rest area (SRRA) vs Maxwell SRRA*

We will also use this example to compare the costs between two twin SRRAs along Highway 5, Willows SRRAs and Maxwell SRRAs in case study 1. The two locations had cost variations because of different design decisions at the planning stages. The previous example of Willows Northbound and Southbound SRRAs opted for two different utility

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[1] Caltrans (2022), "Safety Roadside Rest Areas" https://dot.ca.gov/programs/design/lap-landscape-architecture-and-community-livability/lap-liv-h-safety-roadside-rest-areas.

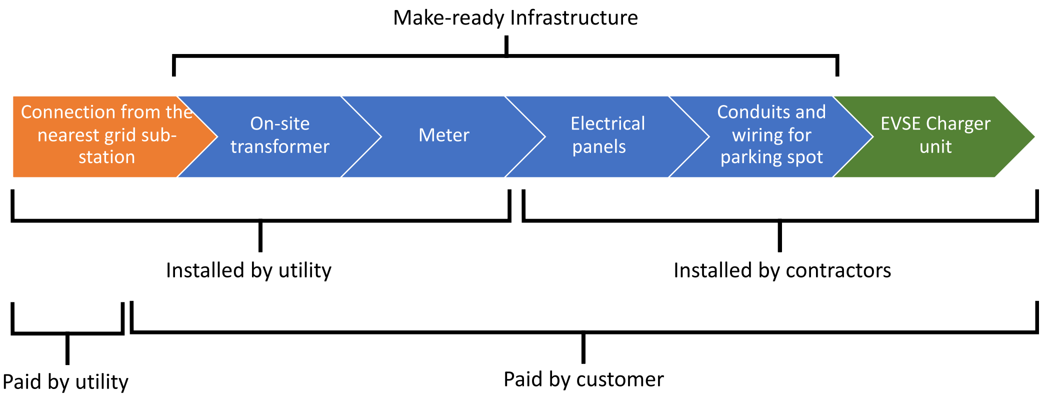

Fig. 4. Summary of infrastructure required for a working DCFC and who is involved with what. The blue indicates the make-ready infrastructure, the green indicates the above ground EVSE unit and orange indicates all utility infrastructure leading to the work site.

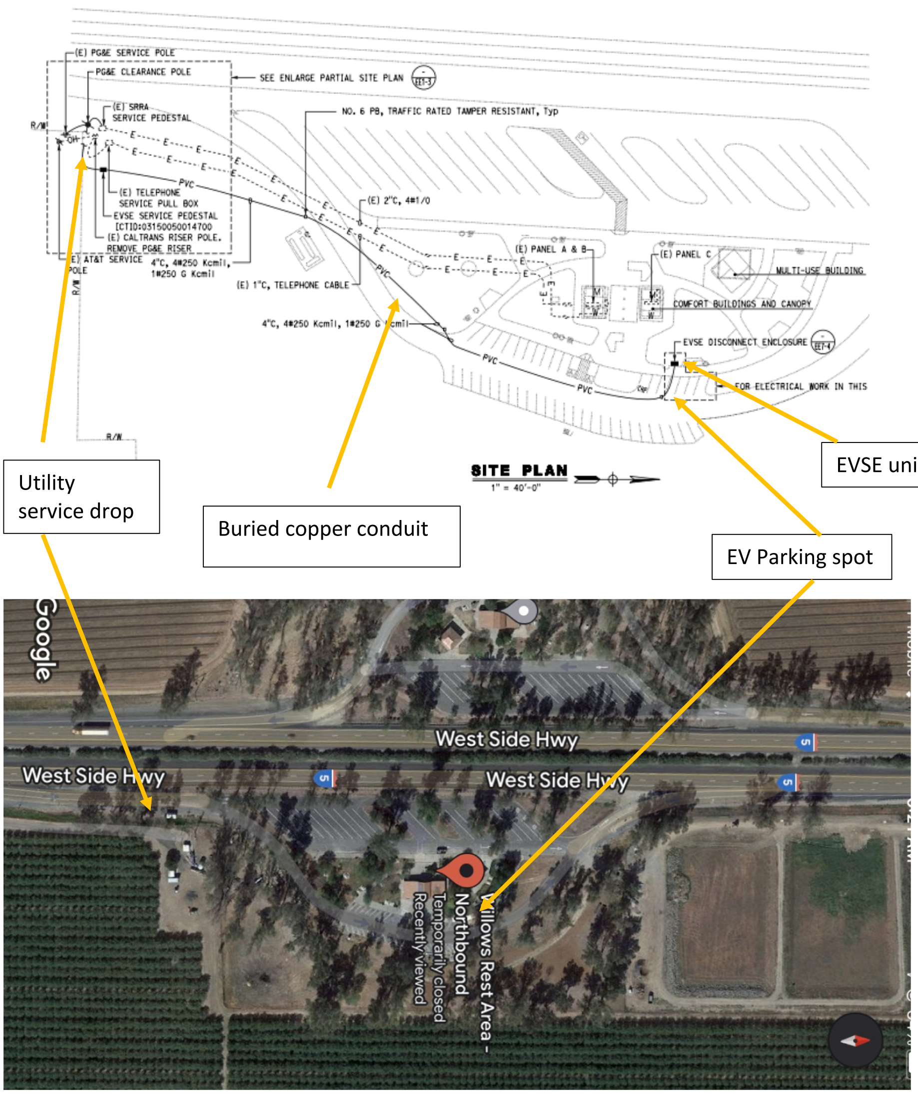

Fig. 5. Brief overview of the on-site make-ready infrastructure in a rest area (from Caltrans).

connections, thereby receiving two different utility interconnection bills as indicated by the utility fee column in Table 3.

Maxwell Northbound and Southbound SRRAs are similar rest stops along Highway 5 that have a very different construction cost than Willows SRRAs. In many ways the rest areas are very similar and are located only 25 miles apart. But the different design implications have led to

Table 3
Project costs of Willows Safety Roadside Rest Area (SRRA) vs Maxwell SRRA. The conduit and conductor costs are a sub-cost of the make ready infrastructure costs. They are indicated in parathesis not to be confused as a new cost element.

Description	Utility fee ($)	Make-ready infra. Cost	Conduit & Conductor (Sitework) costs	EVSE
Willows Safety Roadside Rest Area (Northbound)	$14,918.30	$321,300	($123,951)	$26,000.00
Willows Safety Roadside Rest Area (Southbound)	$22,673.09			$26,000.00
Maxwell Safety Roadside Rest Area (Northbound)	$24,211.72	$878,900	($516,983)	$26,000.00
Maxwell Safety Roadside Rest Area (Southbound)				$26,000.00

almost $540,000 differences in costs as seen in Table 3.

A systematic cost comparison between the above locations is necessary to understand the significant cost differences. They both have “twin” rest areas servicing northbound and southbound traffic on opposite sides of the Highway 5. Willows SRRAs have two different utility service connections for the two sites, whereas Maxwell only received one service connection to the Southbound SRRA. Everything else about the 2 locations (or 4 SRRAs) is the same. They have the same contractor, relatively similar geography, and the same equipment. However, the make-ready infrastructure cost is more than twice in Maxwell compared to Willows.

A further examination of engineering drawings and the engineer’s cost calculations explains this cost difference is from extending a special conduit from the Maxwell SRRA (Southbound) to the Maxwell SRRA (Northbound) under the freeway for electricity connection. The material and labor cost for “Conduit & Conductor (Sitework)” for Willows and Maxwell were a significant portion of the make-ready costs. For Willows it was about 38 % of the make-ready costs whereas, it was about 58 % for Maxwell as seen in Table 3. Such additional costs included cost of directional drilling under the highway to connect the conduit from one side of the highway, the cost of standard copper wire insulated by PVC conduits and additional trenching costs. The design engineer said they arrived at this design after initial negotiations with the local electric utility with the best available information to them at the time.

3.2. Make-ready cost components

We were able to analyze the make-ready infrastructure costs from the construction related winning bid documents for Caltrans. They included the costs of setting up the site, trenching for conduits, laying concrete pads and construction of switchboards and transformer vault. Different local construction groups had won the contract from Caltrans at different locations across the State. Some groups had only one project undertaken by them, such as the Moon Lim Lee Safety Roadside rest stop. Therefore, the make-ready costs of that site can be directly ascertained from the winning bid document. Some contracts were awarded for multiple sites; therefore the winning bid documents had lumped together cost for the multiple sites. In such locations, we were only able to identify an average cost for make ready infrastructure. We were able to find a few unique winning bid documents that encompass different cost segments. Fig. 6 is a summary of those costs of what constitutes the construction costs per DC Fast Charger.

We compiled all the cost items in winning bid documents into six categories: electrical, labor, site preparation, traffic management, irrigation facilities and other costs. The electrical and labor costs included conduit trenching, boring costs, and costs of other wires and conduits. Site preparation costs included all other non-electrical civil construction costs such as charging station foundation, barrier post costs, concrete costs, and cost to backfill trenched areas and restore rest stop surfaces, sidewalks, and pavements as before. This also included the cost of making EV parking spots ADA accessible as seen in Fig. 7. All state funded designs need to have minimum ADA accessibility to be compliant

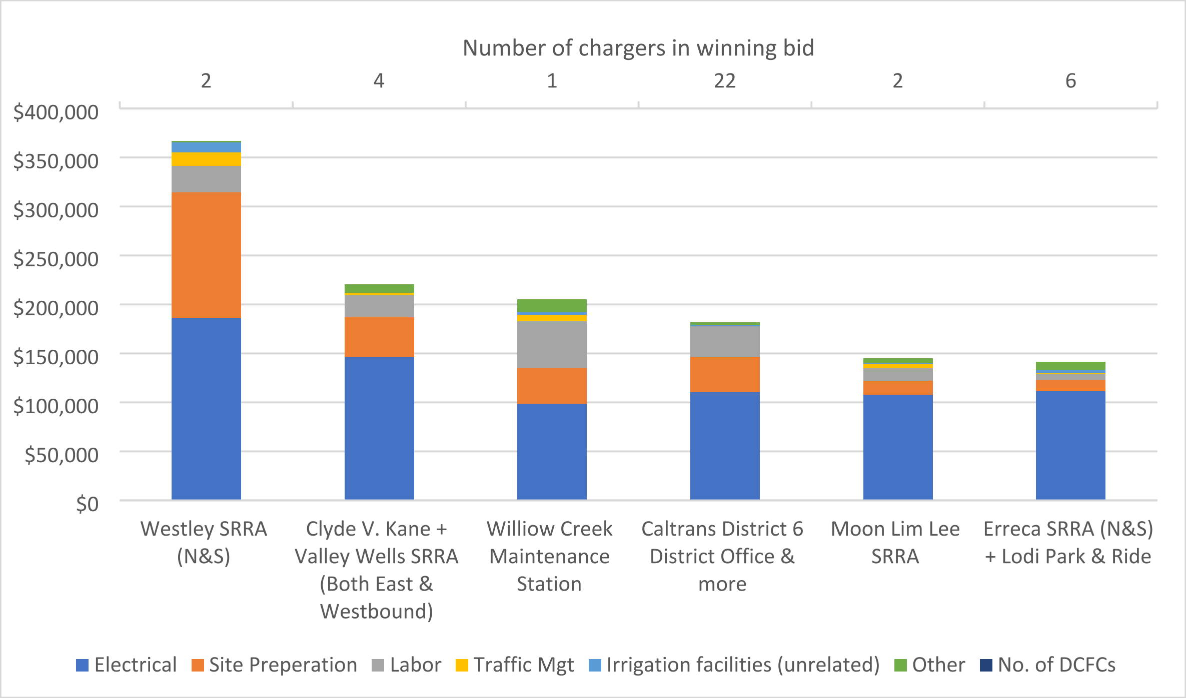

Fig. 6. Per DCFC cost breakdown of make-ready costs.

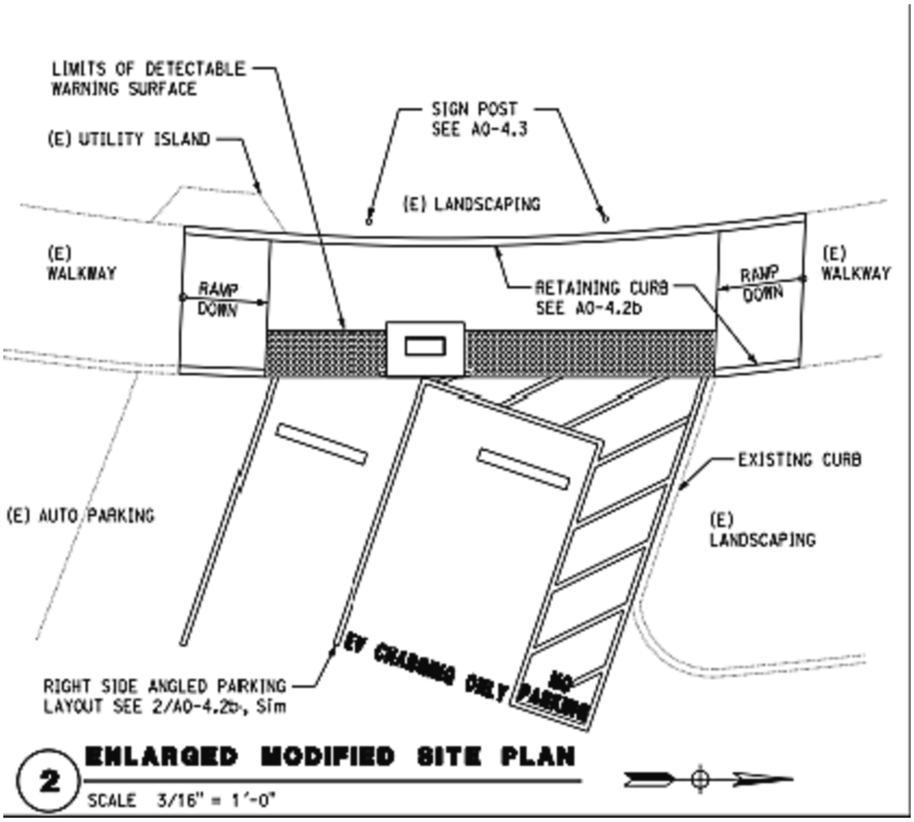

Fig. 7. ADA accessible EV parking spot (from Caltrans).

with the Americans with Disabilities (ADA) Act of 1990. Traffic management costs are incurred during construction phase in managing traffic around the construction site. Costs of irrigation facilities maintenance are a Caltrans specific cost.

3.3. *Utility interconnection costs*

Fig. 8 is used to summarize the utility costs passed onto Caltrans at different sites. For our analysis, the costs were allocated per DCFC and

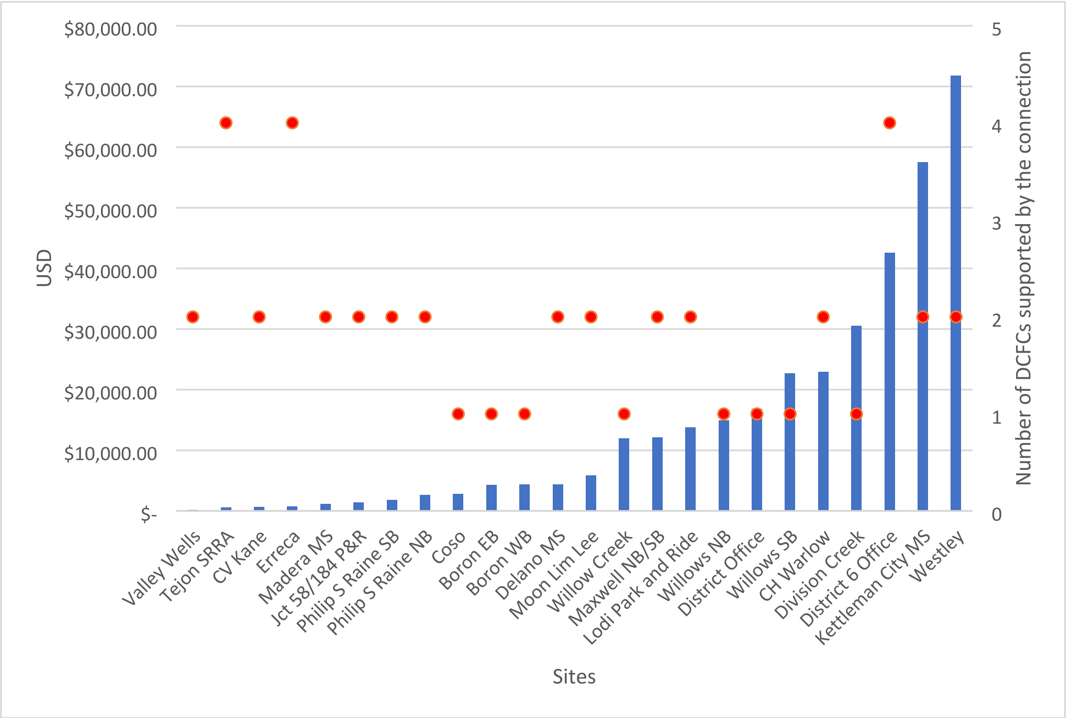

Fig. 8. Cost of utility service connection per DCFC passed onto the customer.

some sites such as Maxwell had only one utility connection for Northbound and southbound rest areas, whereas sites such as Willows rest areas had two different utility interconnections for each rest stop servicing northbound (NB) and southbound (SB) traffic as seen in Fig. 8. Maintenance Stations are indicated as MS. To better understand the costs, Fig. 8 includes the number of DCFC stations supported by each utility connection in the vertical axis to the right.

Utilities will determine the necessary upgrades to their network based on two factors to upgrade their costs. They look at other neighbors in the vicinity of the site and plan their infrastructure based on how much upgrades they anticipate in the future. If your charging station site is the only anticipated customer, then the utility network upgrades are done solely for your benefit and as such, much of the distribution line extension costs will be passed onto the customer. It is the responsibility of the utility customer (i.e., Caltrans) to provide on-site space for necessary substations and transformers on customer's premises. Fig. 8 indicates how much utility cost expenses were passed on and billed to Caltrans at different sites.

A major learning experience from almost all our interviewees was how project engineers have underestimated the timelines and costs of working with major utilities. Given the remoteness of most of the sites, power utilities needed to expand the energy supply capacity of the local distribution grid and plan to procure other electrical equipment such as transformers and other utility side make-ready infrastructure. Almost all interviewees suggested a 4 to 6-month precautionary lead-time to begin working with electric utilities.

3.4. *Alternative Solar off-grid DCFC installation design*

Out of the 36 sites, Caltrans had opted to try an experimental off-grid Solar arc DCFC design in 3 remote sites where the electrical grid-extensions would have been very expensive. Here the EVSE charger directly connects to four solar tracking stations with attached storage. The solar photovoltaics (PVs) are called solar EV ARC (trademark) in the Caltrans bid documents because they have some sun tracking features. The design of this charging station is straightforward. Four solar stations with attached battery storage would feed a single DC Fast Charger unit on the site located almost next to the solar units. As seen in the engineering drawing Fig. 9 and Fig. 10, the EVSE unit is connected by underground conduits to the four solar and battery stations located almost next to each other. This design does helps bring down on-site make ready costs and incurs almost no electrical utility costs. While the solar PV units and attached storage units add extra costs to the design, they avoid the need to have expensive on-site conduits bringing power from the grid to the EVSE units.

3.4.1. *Case study 2: Shandon Safety Roadside Rest Area (solar)*

Shandon SRRA is located alongside route 46 in Caltrans district 5. The engineers chose the unique solar powered DC Fast charger design for this location. Table 4 includes a breakdown of all the costs incurred for the 50 kW DC Fast Charger installed (Table 4).

3.5. *Main cost components of the off-grid EV charging system*

This unique design of DC Fast Charger complex supported by on-site solar and extended storage capacity does not require a dedicated utility service connection. The cost breakdown for installing the DC Fast Charger in SRRA is shown Table 4. The shaded items contain the costs of the Solar EV ARC system and the direct costs of the charging system whereas the other items in Table 4 incorporates the labor costs as well as compliance and site preparation costs incurred from the project.

The total cost for this project is indicated above as $857,560 per DC Fast Charging unit with solar and storage capabilities. We present this case study with a stand-alone solar PV to understand the likely costs of such an alternative design. This type of design is best suited for highly remote sites with low usage. Until we have a better understanding of the charger usage pattern with the dynamics of the Solar PV and battery storage systems, the authors do not aim to comment on its performance. Considering the high costs of this off-grid design, other parts of the world have opted to supply power to remote EVSE stations with diesel or

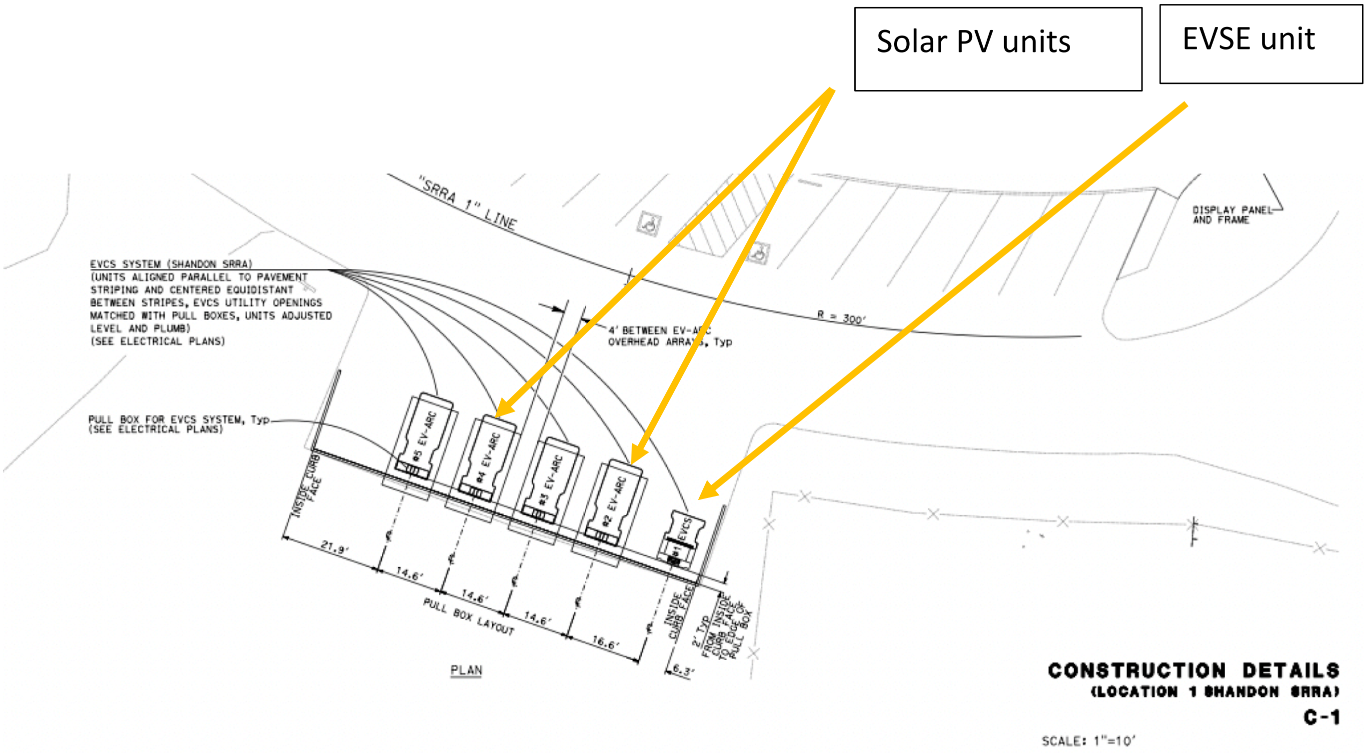

Fig. 9. Site design for on-site solar EV ARC + attached storage design of DCFC (from Caltrans).

Fig. 10. Shandon Rest Area (Images from Google under fair use).

Table 4
Cost breakdown of the Shandon safety roadside rest area charging system with necessary components that enable the operation of the off grid DCFC charging station.

Item	Unit Price
4 EV ARC (Sun-tracking PV array with battery storage)	($420,545)
DC Fast Charging Station	($51,150)
Additional Battery Storage	($60,132)
5-year monitoring and maintenance plan	($31,221)
Taxes, training, and testing	($51,150)
Other	($13,588)
Total of EVSE system	$627,786
Electrical Trenching and Backfill	$24,000
Site Specific other costs	$66,873
Contractor's other costs averaged for this site	$138,900
Total	$857,559

vegetable oil-based generators (Schmidt, 2018).

3.6. Cost of installing DCFC of higher powers

What lessons can we take from this project to charging stations with higher powers? We can simulate the costs of installing a DCFC with a higher power by comparing the full project costs of installing a DC fast charging station at a rest area that opted to build four 50 kW DCFCsin one site. This is a close approximation to constructing a 200 kW DCFC in each site.

El Tejon SRRA (Fig. 11) cost of installing one 50 kW was roughly $208,355. So, we can estimate the cost of a 200 kW DCFC around $833,420 per DCFC. This is also in line with the judgement from our interviews.

3.7. Economy of scale in DCFC installation in one location

In the case of Tesla Superchargers, the tendency was for multiple DCFCs (40–80) to be installed in one location. This is also true of other private charging networks. From our analysis, we find some indication of economy of scale in the installation of DCFC. Fig. 12 is the outcome of our findings. When 2 or more DCFCs were installed in on location sharing on site “make-ready infrastructure”, they can save some costs. However, this is not as significant because more DCFCs will require more utility supply capacity and upgrade to other onsite make-ready infrastructure. Furthermore, out dataset is not large enough to conclusively identify any potential benefits from economy of scale.

There is some evidence to suggest that Tesla is minimizing construction and installation costs by prefabricating make-ready infrastructure in a shared pre-cast concrete foundation with multiple EVSE units. According to unverified reports, these prefabricated units are then transported to the final location of interest and installed (Lambert, 2022; Herger, 2022). This strategy can help reduce construction costs and timelines. However, the authors are unable to verify this claim independently.

3.8. Project execution

While the design phase of the project started in 2019, implementation of the construction projects began only in 2020 and were impacted by the Covid-19 crisis. The California Governor's stay at home orders were issued on March 15, 2020. That some impact on the projects. The Covid-19 impacts ranged from implementation delays as contractors tested positive for Covid-19, delays in getting supplies to some cost overruns as the prices of primary construction materials such as concrete increased in the State of California (Mentz, 2020). All the projects were

Fig. 11. El Tejon SRRA has 4 DCFC on one side of the highway (from Plugshare used under fair use).

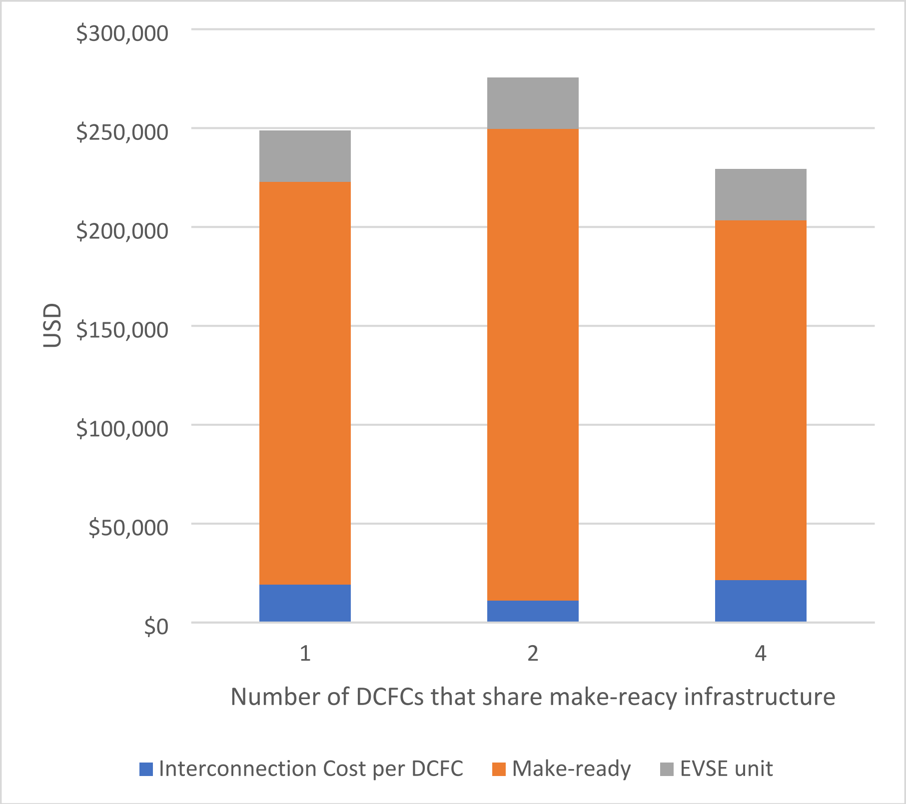

Fig. 12. Average construction and installations costs per DC Fast Charger at sites that had shared make-ready infrastructure between multiple DCFCs.

completed by March of 2022.

4. Discussion

Based on our study we find that the installation of corridor DC Fast chargers requires more effort and funding than cost information available in the literature review. There are added challenges for corridor DCFC installations along major transportation corridors. Regular DCFC installation requires significant onsite make-ready infrastructure for the operation of chargers at maximum rated power following National Electrical Code and NFPA guidelines. The infrastructure must undergo substantial planning and administrative processing, and requires engineering designs, architectural designs, planning for labor mobilization, planning for safety, and coordinating with local stakeholders such as electrical utilities and local suppliers for the successful construction and launch of DCFCs.

While existing studies indicate that DCFC construction and installation costs ranging from $20,000 to $150,000, the project we analyzed had total costs ranging anywhere between $122,000 and $440,000 for grid connected corridor DCFCs. For off-grid systems, the costs were found to be even higher. We believe that this is due to the following reasons:

1. The nature of the sites selected have additional stresses that drive costs higher. On the one hand It is difficult to mobilize labor and materials for a construction project in a remote site such as a Caltrans safety rest area. On the other hand, it was necessary to take adequate precautions to manage the traffic and safety during construction in a location that usually has a daily high foot traffic.
2. Most DCFC construction projects in an urban dense location would benefit from existing local infrastructure already invested by cities and local utilities. Although we take this for granted, such shared infrastructure creates a complimentary eco-system that brings down costs for construction in an urban setting. The selected remote sites did not have this advantage of complimentary infrastructure.
3. The co-location of DCFC stations on both sides of a freeway adds significant costs and challenges especially if the local electrical grid infrastructure is only accessible from one side of the freeway. Significant challenges were faced in extending make-ready electrical infrastructure from one side of the freeway to the other side to make sure that the DCFCs in both sides of such “twin” rest areas have adequate power supply to support BEV charging at maximum rated speeds.

4.1. *What can be done to bring down costs?*

Based on our findings, we suggest that design engineers and contractors in the future can reduce costs by adopting some flexibility with the on-site architectural and engineering design plans. A flexible design that allows BEV parking spots to be moved closer to the utility drop site can save on costs such as pavement repairs, buried copper conduits, trenching and borings costs. It is also a prudent choice to receive a dedicated utility service connection for every corridor charging station site wherever possible.

Given the nature of corridor charging sites, always select sites to install DCFC in locations where adequate distribution grid capacity and infrastructure is available from both sides of the freeway. When it is necessary to lay conduit under the freeway, it is cheaper for the utility to do it before the meter at a higher voltage than at a lower voltage for the contractor. At low voltage, the electrical design needs more conducting materials to compensate for higher resistance leading to additional boring, trenching, and ultimately higher costs. We recommend closely working with local utilities to obtain separate service connections for corridor charging sites when possible. Planning corridor DCFC installations should be an ongoing process before and during the construction phase. Some advanced planning before the construction phase can save significant resources. Moreover, as the DCFC technologies are improving rapidly, it helps for planners to be up-to date about new EVSE designs, speeds, and technologies.

We also observe that most civil construction groups have limited experience with installation of DCFCs. A step in the right direction was made by the California Assembly Bill 841 and CA Public Utilities Code 740.20 that requires the presence of at least one electrician who hold an Electric Vehicle Infrastructure Training Program (EVITP) certification on site for DCFC installations from September 2021 onwards to be eligible for CALeVIP rebates in California.[2] Certification and training programs should be expanded to train electricians and new programs should be dedicated for civil engineers and civil contractors who want to work in installation of DCFCs. The insights of trained electricians and civil construction partners in DCFC installations can help reduce missteps, bring down costs in construction, and help expedite the construction process.

4.2. *Regulatory guidance and oversight over electric utilities*

Based on the sites we analyzed, it costs the customer between $100 and $71,700 per site to bring adequate power to the charging stations from the local grid. We do not have enough information to calculate how utilities determine the cost of utility fees for a new connection and upgrades. But some factors that influence this are (1) existing feeder capacity, (2) distribution grid infrastructure availability in the vicinity, and (3) projected future demand from neighboring customers of the site. A study from Western Australia have suggested that capacity of existing electricity network should be considered in the overall planning and site selection process as well as in determining the optimal speed (in kW) of chargers for a chosen location. For example, they determine that higher power chargers such as 350 kW charger should be built in urban locations with sufficient capacity of electricity network to avoid very high utility interconnection and installation costs (Bräunl et al., 2020).

Not all costs of grid upgrades are passed onto the customers. Some costs are rate-based, and that amount is determined by a complex web of rules that are enforced by the CPUC. A new resolution issued by the CPUC in October 2021 is an attempt at clarifying such rules on how to recover line extension costs and utility side make-ready costs for BEV chargers. These rules will come into force in California from 2022 for the general rate case (GRC) of that year and will be monitored by the CPUC on a rolling basis. Before this CPUC resolution, only customers participating in dedicated utility programs were allowed to fully rate base their utility side make-ready costs. Progressive action will help alleviate uncertainties about utility side costs and help make a better business case for DCFC installations. Further research is necessary to understand and compare the regulatory action of other States and their respective public utility commissions.

4.3. *Infrastructure Investment and Jobs Act of 2021–2022*

In 2021, the U.S. Federal Government passed into law a comprehensive funding package to upend America’s infrastructure. Amongst other things, this bill aims to build a nationwide network of 500,000 BEV chargers across the United States. We believe there are many insights from our study to help the planning and infrastructure investment of $7.5 Billion for this effort.[3]

According to our calculations, the necessary investment for a national robust and reliable network of 500,000 DCFCs requires much higher funding than what is allocated from the federal government. However, the federal bill does not seem to specify if all the 500,000 chargers are to be DCFCs. Our calculation for a network of 500,000 DCFCs across rural America can be as expensive as $74 Billion.

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[2] CALeVIP (2021), “How do I comply with the Electric Vehicle Infrastructure Training Program (EVITP) certified electrician requirement?” https://calevip.org/faq/how-do-i-comply-electric-vehicle-infrastructure-training-program-evitp-certified-electrician-0.

[3] The White House (2021), “Fact Sheet: The Bipartisan Infrastructure Deal” https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.

Therefore, we observe the need to fill this gap in funding from other sources. Ratepayers funding for utility side make-ready costs can help alleviate some cost burden.

5. Conclusions

This study focuses on publicly available corridor DCFC construction in locations that belong to the California Department of Transportation. All the 54 DC Fast Charger installations in 36 different locations we analyzed are now operational and accessible along priority highways such as Interstate 5, State Route 99, and U.S. Highway 101. Installing DCFCs in transportation corridors will always be a challenging task for the reasons mentioned before. Strategies mentioned above in site selection and advanced planning can bring down costs. But because the United States highway network go through a diverse terrain with very diverse physical features and sometimes sparsely populated regions, there will be the need to invest in public charging infrastructure in very isolated and costly locations to fill the gaps in the charging network. These sites will incur higher than average costs and private networks will have limited incentives to build infrastructure in such locations.

A key objective of the Caltrans "30–30" project was to identify the learning experiences and sharing that information publicly. We think such publicly funded infrastructure projects can help advance our understanding of the challenges and costs of installing corridor DCFCs. In this study, we want to emphasize the need to analyze more corridor DCFC case studies in the future to advance our understanding of them. Such information needs to capture the full costs of installations such as utility costs, make-ready infrastructure costs and EVSE costs. While we think private partners should also be incentivized by public funding, we have limited information of construction costs that can be independently verified where private changing networks are concerned.

We think that a broader analysis of the business case for public DCFCs is necessary to understand the different revenue streams for investments. The business case for DCFCs can be very different based on location, charging speeds and ownership structure. We have identified in our study that DCFC installations capable of higher charging speeds incur higher costs and DCFC installations in transportation corridors will incur above average costs. Further research into public charging behavior at different prices and at different locations might shed light on how to optimize much needed public funds to locations and sites where public funding is most necessary.

CRediT authorship contribution statement

Tisura Gamage: Methodology, Validation, Formal analysis, Investigation, Visualization, Data curation, Writing – original draft. **Gil Tal:** Resources, Supervision, Project administration, Funding acquisition. **Alan T. Jenn:** Supervision, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix 1:. Sample interview question

1. What are the main cost segments/ components that you identified during the project design stages for the DCFC complexes?
2. In the design phase, did you consider the ability for further capacity improvements in the future as technologies change and charging speeds improve? (Upgradability) If so, what extra costs did you incur? (Costs of electrical equipment, extra conduits and extra Structural support (Concrete pads etc.)
3. What safety features did you incorporate and what are their costs? (I.e., overcurrent protection, extra grounding, insulation, customer safety features)
4. What are the typical components for labor costs?
   a. Trenching for conduit?
   b. Laying concrete pads
   c. Constructing transformer vault?
   d. Other constructions
5. What are the main material costs identified? (Other than the equipment)
   a. Conduits?
   b. Cable?
   c. Concrete?
6. Other than the DCFC unit, what other electrical devices and equipment are required? What are their costs? Capacities?
   a. Transformer?
   b. Meter?
   c. Overcurrent protection?
   d. Other?
      i. Credit card reader?
      ii. Network and data related equipment?
7. Did you consider capacity for potential onsite energy storage and/ or power generation systems that may be added in the future? (i.e., Additional cable, conduits laid?)
8. Do you foresee significant cost differences between the different DCFC sites? Is there a difference between urban and rural DCFC complexes?
9. Are there different site/ complex designs that meet the requirements of the scope of the project? Do they have cost differences?
10. Why were these sites considered and chosen?

  a. Close to a transportation corridor? (Highway)
  b. Close to the energy grid?
  c. Do they cost less/ more?
11. Who owns the host site of the DCFC complex? Do you have to pay rent or fees for site ownership?
12. Did you require new electrical service to be added to the host site for the DCFC complex? If so, did utility charge extra fees to extend the service from the grid to the host/ expand capacity/ install new equipment?
13. How many charging ports per DCFC? Does that impact on the final cost? How was the number of chargers per site decided?
14. Does a typical DCFC contain all of the following units? Did you have to install them separately?
  a. AC/DC Conversion
  b. charger-to-vehicle communication
  c. Power delivery
15. How did you determine the size and capacity of the DCFC and the other equipment such as the transformer and power conduits? What are the costs?
16. How do you incorporate uncertainties in technology into the design?
17. Is the site co-located with something else?
18. Did you have to incur any other licensing/ regulatory/ insurance costs?
19. Who bears the costs of maintenance and repairs?

Appendix 2:. Evaluate Zero-Emission Vehicle Charging Stations at Caltrans facilities

Objectives: Research Direct Current Fast Charging (DCFC) installation cost, challenges, and opportunities for process improvements for future installations.

Interview Questionnaire matrix: Response from X.

Main Topic	Sub-topic	Responses
Main Cost segments	Equipment Costs	
	Material Costs	
	Labor Costs	
	Soft Costs	
	Other	
Equipment Costs	DC Fast charger	
	Transformer?	
	Meter?	
	Overcurrent protection	
Other material Costs	Conduits?	
	Cable?	
	Concrete?	
Labor Costs	Types of work?	
Upgradability? (Costs)	Charging speed improvement	
	Capacity (no. of ports)	
	Technology	
Safety features (Costs)	Equipment	
	Customer	
Onsite energy storage/ generation? (If any)	Solar	
	Storage	
Alternate designs and Costs		
Site selection	Location advantage?	
	Costs?	
	Site Ownership?	
Soft costs	New service connection	
	Credit card reader	
	Network connection	
	Licensing/ regulatory fees	
Number of ports	Current	
	Future?	
Technical specification	Charging capacity/ speed	
	Temperature effects?	
Technology Uncertainty		
Site costs	Co-location	
	Site ownership	
Other		

References

Baker, E., Cruickshank, C., Jenni, K. E., Davis, S., 2019. *Comparing in-person and online modes of expert elicitation.* Retrieved 11 15, 2021, from https://scholarworks.umass.edu/mie_faculty_pubs/620.

Behdad, K., Ogden, J., Sheldon, A.F., Cordano, L., 2020. Utilizing Highway Rest Areas for Electric Vehicle Charging: Economics and Impacts on Renewable Energy Penetration in California. National Center for Sustainable Transportation.

Brown, E. J., 2012. *Office of Governor Edmund J. Brown Jr.* Retrieved from EXECUTIVE ORDER B-16-2012: https://www.ca.gov/archive/gov39/2012/03/23/news17472/index.html.

California Energy Commission, 2022. *California Electric Vehicle Infrastructure Project (CALeVIP) Cost Data.* (California Energy Commission) Retrieved May 1, 2022, from https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/california-electric-vehicle.

Clean Cities US DOE, 2012. Siting and Design Guidelines for Electric Vehicle Supply Equipment. U.S. Department of Energy.

DOE, 2014. *A guide to the lessons learned from the clean cities community Electric Vehicle Readiness Projets*.

Francfort, J., Salisbury, S., Smart, J., Garetson, T., Karner, D., 2017. Considerations for Corridor and Community DC Fast Charging Complex System Design. Idaho National Laboratory.

Francfortb, E., 2017. Analysing the usage and evidencing the importance of fast chargers for the adoption of battery electric vehicles. Energy Policy 108.

Governor's Interagency Working Group on Zero-Emmission Vehicles, 2016. 2016 ZEV Action Plan. Office of Governor Edmund G, Brown Jr.

Hardman, S., Jenn, A., Tal, G., et al., 2018. A review of consumer preferences of and interactions with electric vehicle charging infrastructure. Transport Research Part D.

Hogan, W. W., 2009. Electricity Market Structure and Infrastructure. In *Acting in Time on Energy Policy*.

Idaho National Laboratory. (2015). *What Can be Learned From The EV Project to Inform Others Who May be Interested in a Similar Study?*.

IEA, 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency.

Ji, W., Nicholas, M., Tal, G., 2019. Electric Vehicle Fast Charger Planning for Metropolitan Planning Organizations: Adapting to Changing Markets and Vehicle Technology. TRB.

Lee, R., 2016. *Transportation Electrification.* Retrieved from California Public Utilities Commission: https://www.cpuc.ca.gov/-/media/cpuc-website/files/legacyfiles/1/11288-1-ppd-lee-.pdf.

Meng, J., Way, R., Verdolini, E., Anderson, L.D., 2019. Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition.

Mentz, Z., 2020. *First-quarter 2020 agg revenue up at U.S. Concrete*. Retrieved from Pit&Quarry: https://www.pitandquarry.com/first-quarter-2020-agg-revenue-up-at-u-s-concrete/.

Nelder, C., Rogers, E., 2019. Reducing EV Charging Infrastructure Costs. Rocky Mountain Institute.

Nicholas, M., 2019. *Estimating electric vehicle charging infrastructure costs across major U.S. metropolitian areas.* The International Council on Clean Transportation (ICCT).

Robinson, K., 2020. *Caltrans ZEV "30-30" Implementation.* Retrieved from Caltrans: https://catc.ca.gov/-/media/ctc-media/documents/tab-49-4-20-presentation-a11y.pdf.

Schultz, F., Rode, J., 2022. Public charging infrastructure and electric vehicles in Norway. Energy Policy.

Transport Research Board, 2013. Overcoming Barriers to Electric-Vehicle Deployment. National Research Council.

Wolinetz, M., Axsen, J., 2017. How policy can build the plug-in electric vehicle market: insights from the REspondent-based Preference And Constraints (REPAC) model. Technol. Forecast. Soc. Change 238–250.