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Equitable Access to Residential (EQUATOR) EV Charging

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16. Abstract The EQUATOR project will quantify access to charging infrastructure in New York City (NYC) and optimize access-aware investments in utility-operated charging infrastructure. First, access to charging infrastructure will be quantified in terms of its availability, affordability, quality-of-service, and environmental metrics by means of data-driven analyses of static and dynamic spatio-temporal transportation and power grid data (e.g. on a zip code and hourly basis). Second, these metrics will be used to allocate utility's investments in electric vehicle (EV) charging under budget constraints to reduce access disparity across zip codes.		
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Equitable Access to Residential (EQUATOR) EV Charging

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Executive Summary

The transportation sector is the largest source of greenhouse gas emissions in the United States with emissions from light-duty vehicles constituting its major share. Electrified transportation, therefore, is one of the critical aspects of the global trend towards decarbonization. Access to electric vehicles (EV) charging infrastructure shares a symbiotic relationship with EV adoption, and subsequently with the global decarbonization efforts, as outlined in the 2021 United Nations Climate Change Conference (COP26) declarations, and the local environmental conservation initiatives, e.g. the New York State Climate Leadership and Community Protection Act. Thus, the problem of access to and affordability of public EV charging infrastructure is critical for all stakeholders in EV roll-out and adoption, including investor-owned charging companies, electric power utilities, consumers, and regulators.

However, accessibility of the EV charging infrastructure is redundant if it is not affordable. Affordability of the charging infrastructure is a function of the policies used to promote EV adoption, e.g., the EV charging tariff. The business modalities of charging tariffs, therefore, have a profound impact on the equitable transition to electrified transportation. Since lower-income communities are more likely to use public charging infrastructure, the currently employed justice-incognizant public EV charging tariffs disproportionately affect low-income households, disadvantaged communities, and communities of color, exacerbating the already present racial, financial, and cumulative social disparities in EV adoption. Thus, it is imperative to design business models that ensure that the costs and benefits of EV adoption and public charging infrastructure are equitably distributed in the society. Since utility-owned public charging infrastructure is critical to ensure equitable access to adoption of EVs and charging infrastructure in the society, we focus on the design of volumetric public EV charging tariff in this report.

Our results, based on the developed metrics of accessibility and affordability of EV charging infrastructure, and evaluated using statistical and machine learning methods, demonstrate that population density is not correlated with the density of EV chargers, hindering New York's EV adoption and decarbonization goals. On the contrary, the distribution of EV charging stations is heavily skewed against low–income, Black–identifying, and disinvested neighborhoods in NYC, however, positively correlated to presence of highways in a zip code. Based on these techniques and datasets, we develop a Graphical User Interface (GUI)-based web dashboard that visualizes the injustices in the access to EV charging infrastructure.

To alleviate the disparities in the existing EV charging infrastructure and ensure an equitable future roll-out, we develop an energy justice-based decision support tool for designing public EV charging tariffs from the perspective of electric power utilities. The designed framework ensures economic efficiency of the tariff while simultaneously guaranteeing an equitable distribution of environmental and public health costs of electrified transportation infrastructure. We use Pareto optimality for multi-objective design

criteria in the proposed tool to incorporate preferences of the policymakers, and show that economic efficiency can be achieved without sacrificing equity in the society.

In this project, we use NYC EV charging station network, electrical power grid, and demographic and highway data for our analyses. The methods and algorithms developed in this project, however, are generalizable, and can be implemented on a city- state- or national level to measure the accessibility, affordability, and equitability of the EV charging infrastructure.

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1. Introduction

The transportation sector is the largest source of greenhouse gas emissions in the United States (29% of the total GHG emissions in 2019 [1]), with emissions from light-duty vehicles constituting its major share. For example, the light-duty vehicles in New York City (NYC) emit 80% of the city's total transportation emissions [2]. Electrified transportation is one of the critical aspects of the global trend towards decarbonization. With light-duty electric vehicle (EV) prices rapidly declining to as low as $18,875 [3] (after United States (US) federal tax credits and state rebates [4]) and their ranges expanding to 400 miles [5], it is anticipated that access to charging infrastructure will become the most prominent adoption barrier for EVs [5A]. The significance of the availability and affordability of charging infrastructure for adopting and continuing EVs in subsequent purchases is difficult to understate [5B]. From a planning perspective, insufficient EV charging infrastructure manifests itself in suppressed EV demand, discouraging private sector investments in EV charging. Thus, public investments and policy incentives are required for seeding EV charging infrastructure market [2]. Similarly, from the consumers' perspective, the availability of public EV charging is an important factor in decisions for EV purchases in the US [6]. For instance, a 2017 online survey of US EV owners found that public charging and access to fast charging were viewed as top criteria when buying an EV [7]. In line with [7], the survey in [8] determines that a "*lack of charging facilities in my area*" was the third-ranked reason for not purchasing an EV and a "*lack of quick charging stations*" the fourth. Thus, access to EV charging infrastructure shares a symbiotic relationship with EV adoption, and subsequently with the global decarbonization efforts, as outlined in the 2021 United Nations Climate Change Conference (COP26) declarations [9], and the local environmental conservation initiatives, e.g. the New York State Climate Leadership and Community Protection Act [10]. The European Union's Alternative Fuels Infrastructure directive underscores this relationship by recommending at least one public EV charger for every ten EVs on the road [11]. The problem of access to and affordability of public EV charging infrastructure, therefore, is critical for all stakeholders in EV roll-out and adoption, including investor-owned charging companies, electric power utilities, consumers, and regulators.

To alleviate the accessibility and affordability barriers in charging infrastructure and spur investments in EV adoption, the US government's 2021 Bipartisan Infrastructure Law includes an ambitious $7.5 billion plan for installing 500,000 EV charging stations across the US by 2030 [12], [13]. Similarly, many states in the US have embarked on programs for deploying public EV charging infrastructure. For example, Con Edison, an electric power utility in NYC, will install the first 100 curbside EV charging ports in 2021, under the New York Reforming the Energy Vision (NYREV) program [14]. Moreover, the New York City Department of Transportation (NYC DOT) plans to create a network of 1,000 curbside EV charging stations in NYC by 2025, and increase them to 10,000 by 2030. For reference, currently there are only 80 curbside EV chargers in NYC [15]. Similarly, NYC DOT aims at equipping 20% of all spaces in municipal public parking lots with EV chargers by 2025, and increase it to 40% by 2030 [16]. Kansas City, Missouri, plans to install 30 to 60 EV chargers under its Right-Of-Way project [17] in 2021. Other curbside EV charging station projects are underway in California, Washington, New Jersey, and Ohio [18], [19]. However, these deployments are limited in size, do not close the constantly growing charging-capacity gap [20], and are not equitably designed in terms of their accessibility, affordability, and environmental and public health impacts.

Accessibility is measured in terms of the geospatial distribution of the EV charging infrastructure in a particular region. The geospatial distribution includes the location and capacity of EV charging stations, and its correlation to the existing EV penetration levels along with the socio-demographic features of the population inhabiting the area under consideration. Therefore, accessibility is defined not only in terms of the capacity of EV charging infrastructure to meet the EV charging demand, but also in terms of the ease for socio-demographically diverse communities to access this infrastructure. Thus, a numerical analysis of the EV charging demand and the available EV charging infrastructure capacity should be complemented with the identification and quantification of such socio-demographic features that enable or restrict the access to EV charging infrastructure in a particular region.

Moreover, accessibility of the charging infrastructure is redundant if it is not affordable. Affordability of the charging infrastructure is a function of the policies used to promote EV adoption, e.g., the EV charging tariff [21]. In practice, two business models for EV charging tariffs are available in the US. The first model caters to the private EV chargers, mostly deployed at home. Many electric power utilities in the US, including Con Edison in New York [22], Southern California Edison in California [23], and Ameren in Illinois [24], use this model to offer special commercial fixed and Time-of-Use (TOU) tariffs for EV charging at home, as established for example, in the New York State Senate Bill S3929 [25] and Minnesota Statutes 216B.1614 [26]. The second business model is developed for the public EV charging infrastructure, either owned by the electric power utility or by private charging companies. This business model constitutes multiple tariff structures including a time-based rate ($/min), session-based tariff (fixed price per session session), energy usage-based tariff ($/kWh), and monthly/annual subscription tariff [27 – 29]. However, Muratori *et al*. [30] show that most public EV charging tariffs in the US have a TOU energy usage-based structure. This is due to the relatively inelastic and less flexible charging demand at the public charging stations, where the customers are less responsive to extremely time-granular charging tariffs [31].

The business modalities of charging tariffs have a profound impact on the equitable transition to electrified transportation. For instance, owing to the high capital and installation costs of charging equipment at home, lower-income communities are more likely to use public charging infrastructure [32,33]. However, public charging can be 2 – 4 times more expensive than home charging [34], offsetting the low running cost and fuel economy of EVs [35], disproportionately affecting low-income households, disadvantaged communities, and communities of color [21], and exacerbating the already present racial, financial, and cumulative social disparities in EV adoption [36]. Since the charging tariff directly affects the equitable access to EVs, policymakers should ensure the incorporation of equity in their transport electrification efforts to reconcile decarbonization policy with environmental justice [37]. Thus, it is imperative to design business models that ensure that the costs and benefits of EV adoption and public charging infrastructure are equitably distributed in the society. Since utility-owned public charging infrastructure is critical to ensure equitable access to adoption of EVs and charging infrastructure in the society, we focus on the design of volumetric public EV charging tariff in the rest of this report. The choice of volumetric tariff is in line with the current real-life practice [38] and the recommendations in [31] for nascent EV charging markets.

The design of tariff for the utility-owned public charging infrastructure is not only a techno-economic problem, but social and political acceptability of the tariff also plays an important role in its adoption [31]. Therefore, the design practice of public EV charging tariff is generally governed by the three core principles pertaining to the cost recovery of the power utility, operational profitability of the charging infrastructure, and equity concerns for participating and non-participating EV customers [39]. Cost recovery and profitability guarantee that the energy and network costs of the power utility associated with the charging infrastructure are recovered along with a reasonable rate of return on the capital investment. Equity for non-participating owners ensures that the designed tariff should not result in undue cost-shift to customers who do not use the charging infrastructure [39]. Similarly, equity for participating customers establishes a cost-causation based 'fair' appropriation of costs to different customers [31]. These principles underline the importance of equitable distribution of costs and benefits of EVs and charging infrastructure in the design of the charging tariff. However, existing charging tariff design practices are marred by a misleading dichotomy of economic efficiency versus equity, resulting in economically inefficient and socially inequitable tariffs [21], [35]. Therefore, it is critical to formulate a modeling framework for designing EV charging tariffs that not only considers efficiency by ensuring techno-economic feasibility but also recognizes and ameliorates social inequities in the existing charging infrastructure and tariff business models.

2. Literature Review

Current literature addresses some aspects of equitable transition towards electrified transportation and disparities in access to EV charging infrastructure across race and income. For instance, Cheyne *et al.* conclude that disadvantaged and minority communities are disproportionately affected by environmental and transportation injustice [40]. Hardman et al. extend these results by showing that the current EV charging infrastructure is not equitably dispersed, and EV incentives do not support low–income buyers.

This skews the EV buying power towards predominantly white, male, high-income, and educated households [21]. Similarly, lack of access to EV charging infrastructure near multi-unit housing units (mostly inhabited by low-income communities) is a key barrier in EV adoption [32]. A census block group–level analysis in California shows that Black– and Hispanic–majority neighborhoods have lower access to public EV charging infrastructure [41]. Brockway et al. investigate the effects of grid limits on the growth and adoption of Distributed Energy Resources (DERs) in the service territories of California's Pacific Gas and Electric (PG&E) and Southern California Edison (SCE). Results demonstrate that a high correlation exists between race and grid limits in these regions, such that in Black–identifying and disadvantaged communities, hosting capacity [42] for DERs drastically decreases [36], hindering EV adoption in these neighborhoods.

Similarly, the design of charging tariffs for successful grid integration of EVs [38], economically feasible operation of public charging stations [45], value of EVs as flexible loads and demand response resources [46], and peer-to-peer (P2P) trading [47] has been widely discussed in literature. For example, Jeon *et al.* [46] analyze the economic value of EV demand response programs using three charging price scenarios, including a TOU-based tariff, EV aggregator controlled smart charging, and vehicle-to-grid (V2G) control capability. The results demonstrate that the maximum reduction in the operating cost is dependent on the penetration levels of EVs in the system, and not on the structure of the charging tariff. A dynamic pricing mechanism for EV aggregators developed in [48] identifies real-time charging price model as an effective policy for leveraging demand response potential while guaranteeing a stable grid operation. Similarly, an operational framework based on dynamic charging tariff [38] is proposed in [49] to optimize P2P trading between an EV aggregator and a privately-owned charging company equipped with solar generation. In line with [48], [49], a load-shift-incentivizing electricity tariff proposed in [50] accounts for flexible EV charging in an agent-based electricity market. Authors conclude that the revenues and expenditures of charging managers are optimized using the designed tariff structure, however, based on the characteristics of the wholesale market, the potential for undesired avalanche effect can be significant. Moreover, the authors in [51] compare the impact of multiple EV charging tariff structures on the load profile of the grid and conclude that twice-a-day charging combined with real-time pricing is the most cost-efficient EV charging strategy for catering to early morning and day-time valleys in the load profile. An online two-stage charging scheduling algorithm is presented in [52] that integrates the real-time information of charging stations with the historical EV demand to minimize the charging cost and charging time. The effect of electricity tariff on the residential load profile and coordinated charging of EVs is discussed in [53,54].

From the accessibility perspective of EV charging infrastructure, the existing literature caters to the socio-demographic and census block group–based analysis of equitable distribution of EV charging infrastructure, it mainly focuses on qualitative discussions [21] or data-driven analysis of isolated socio-economic factors [36], [32], [41]. To the best of authors' knowledge, a systematic analysis of correlations between socio-demographic features and their mutual effect on the access and affordability of EV charging infrastructure is missing. Moreover, the analyses in this report are presented with a zip code–level granularity, which is aptly suited for an urban justice setting.

Moreover, from the affordability perspective of EV charging infrastructure, while the existing literature delves in depth into the economic value of demand response programs incorporating EVs [46], real-time pricing strategies for EV charging [48,50 - 52,38], P2P and V2G energy trading [46,48], and impact of EVs on residential electricity tariff and load [53,54], an evident research gap exists in the design of equity-centric public EV TOU charging tariffs from the perspective of the power utility. The choice of the TOU structure for public EV charging is motivated by the gamified survey and hedonic regression analysis presented in [47]. Authors in [47] and [55] show that the correlation between willingness to pay for EV charging and the time-of the-day are not significantly correlated, and EV charging customers respond ideally to the TOU tariff structures. Moreover, while real-time pricing in liberalized EV charging markets have benefits for customers, these pricing mechanisms introduce a plethora of data privacy issues pertaining to trackability and position of vehicles and targeted advertisements, the cost of which might override the benefits of dynamic pricing [56]. Hence, owing to the equity implications of the EV charging tariff in the society, it is imperative that equity- and justice – centric frameworks are developed for the design of EV charging tariffs, especially from the perspective of the power utility.

In this report, we design metrics to quantify the accessibility and affordability of EV charging infrastructure on a zip code-level, and analyze them using the socio-demographic and transportation features of NYC. Furthermore, we develop an energy justice-based decision support tool to design equitable EV charging tariffs from the perspective of the power utility. Although we use NYC EV charging station network, electrical power grid, and demographic and highway data for our analyses, the methods and algorithms developed in this project, however, are generalized, and can be implemented on a city- state- or national level to measure the accessibility, affordability, and equitability of the EV charging infrastructure.

3. Methods

This section details the methodologies used to define metrics, quantify accessibility and affordability of EV charging infrastructure, and develop an energy justice-based decision-support tool for EV charging tariffs.

3.1 Accessibility of EV charging infrastructure

To quantify the accessibility of EV charging stations, we develop a hypothesis that the distribution of EV charging stations is closely related to the inter-dependent socio-demographic features of population. We further hypothesize that features of the local transportation landscape may also be related to the distribution of EV charging stations. For instance, owing to a high influx of traffic, zip codes with high concentrations of major roadways may be more desirable locations for charging stations. Hence, the identification and quantification of such features is of paramount importance. We consider socio-demographic features like population size, median household income, poverty rate, and racial makeup of population, and transportation features like presence of highways and number of highways in each zip code. These features serve as markers to the current imbalances in the accessibility and affordability levels of EV charging stations in the society [57]. In this report, we do not seek to furnish causal claims, however, identify correlations that exist in data so that targeted policy interventions can be designed to facilitate an equitable roll-out of EV charging infrastructure.

Fig. 1. Map showing the five constituent boroughs of NYC, along with the commercial and non-commercial traffic routes (highways).

We perform correlation analyses to identify features in the demographic and highway datasets that impact the distribution of EV charging stations in NYC. To this end, we define the following two target features:

- A binary variable representing the presence of at least one EV charging station in a particular zip code
- The total number of EV charging stations in each zip code

Moreover, we test the aforementioned initial hypotheses by defining two groups in our dataset, such that all zip codes with at least one EV charging station constitute one group whereas the remaining zip codes constitute the other group. Across the five boroughs of NYC, shown in Fig. 1, there are 180 zip codes with accompanying demographic data from the ACS [58]. 100 of these zip codes have at least one EV charging station and 80 have no EV charging stations. Hence, group 1 in our dataset comprises 100 data points, whereas group 2 contains 80 data points. Owing to a normal distribution of EV charging station data and an almost equal sample size of the two data groups, we use t-test as a hypothesis testing tool to compare the average values of the two groups [59]. Our null hypothesis assumes that means of the two data groups are equal, i.e., there are no statistical differences between the two groups. The null hypothesis implies that the socio-demographic features do not affect the presence of EV charging stations in zip codes, rendering the two groups statistically identical. We use both p-value and t-value to assess the likelihood to reject the null-hypothesis. In this case, we use the p-value ≤ 0.05 as statistically significant [60], indicating a strong evidence against the null hypothesis. On the contrary, for significance level (α) = 0.05, t-value is significant if $|t| \geq 1.96$. While correlations can be identified between individual demographic features and distribution of EV charging stations in NYC, the inter-dependency of these features cannot be ruled out. For example, the median household income of a particular zip code may or may not be related to the racial makeup of its population. Therefore, we analyze the dependency between socio-demographic features using conditional analysis. The number of EV charging stations in each zip code is analyzed as a function of the percentage of population identifying as white or non–white, conditioned on a threshold income. We choose this threshold as the annual median income of NYC for 2015–2019, which is estimated to be \$64,000 [58].

To account for the environmental and public health impacts of EV charging infrastructure, we develop metrics pertaining to the environmental and public health benefits of installing EV charging stations. These metrics are based on generator emissions that serve the load, including the EV load, in NYC. We consider five pollutants – carbon dioxide (CO_2), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), methane (CH_4), and particulate matter ($PM_{2.5}$) – because they are emitted by fossil-fuel fired power plants, and have significant environmental and public health impacts [61]. Another reason to include these pollutants in the proposed metrics is the availability of their emission rates, and their incorporation in the existing damage modeling tools. We define the environmental impact of EV charging stations in terms of the abated social cost of the global pollutant CO_2, whereas the public health impact is defined using the locational marginal social costs (public health costs) of local pollutants - SO_2, NO_x, CH_4, and $PM_{2.5}$ [62]. Notably, the social cost of carbon is a global parameter, however, the social costs of local pollutants vary drastically with the location at which these pollutants are emitted [62].

3.2 Multi-Objective optimization problem for incentives and investments in EV charging infrastructure

To develop a decision-support tool for equitable roll-out of EV charging infrastructure and tariff, we develop a multi-objective optimization problem for designing such electricity tariff (residential EV charging tariff) in the system that not only expedites the adoption of EVs but also incentivizes the investments in EV charging infrastructure. We employ a holistic energy justice approach to develop a justice-cognizant tariff-design procedure by adapting the energy justice framework presented by Sovacool *et al* [63,64]. Based on these frameworks, we define the following seven considerations for the proposed justice-cognizant tariff-design framework.

- Availability of energy
    - Availability of EV charging infrastructure for EV loads
- Affordability of energy
    - Affordability of EV charging infrastructure for EV loads
- Environmental degradation due to the designed tariff
- Public health impacts of the tariff
- Inter-generational equitable distribution of costs and benefits
- Intra-generational equitable distribution of costs and benefits
- Economic welfare in the system

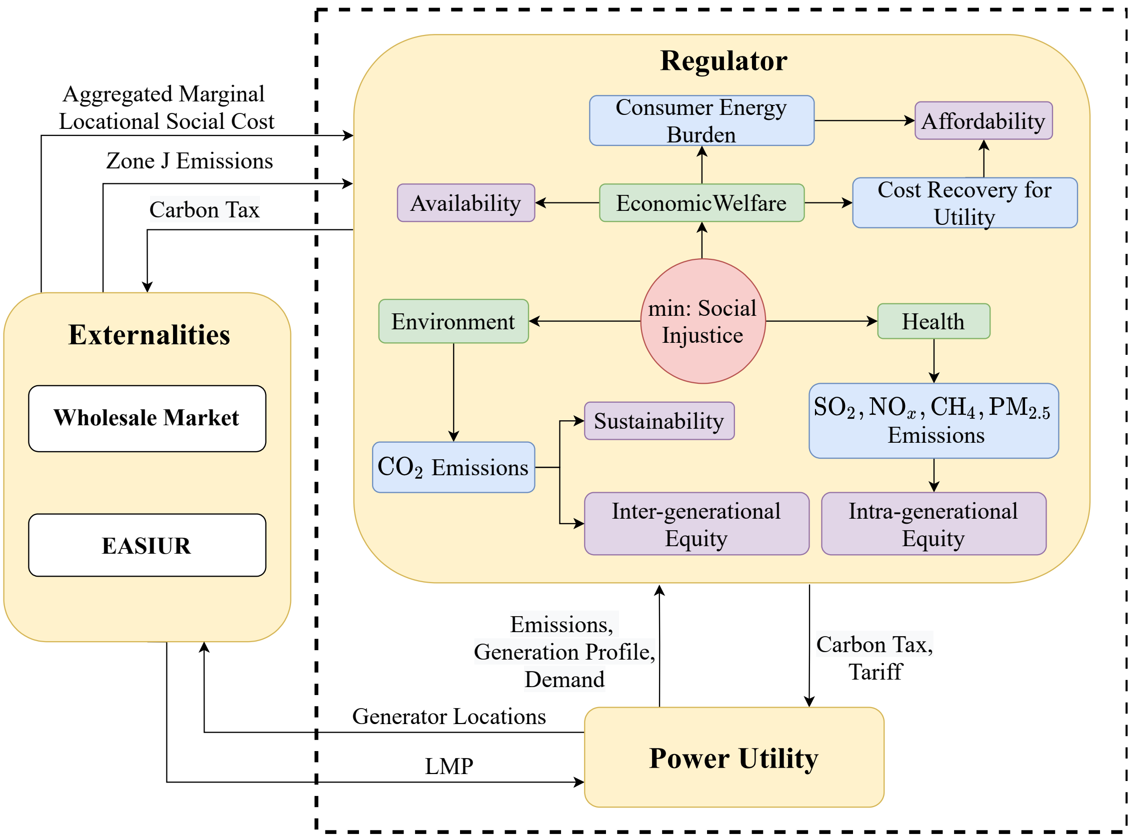

Fig. 2 A schematic diagram showing the SLSF game between the regulator and the power utility (shown in dashed box). Red color displays the multi-objective function of the regulator, with its individual components shown in green. Blue color shows the constraints while purple depicts the justice considerations.

Since there are multiple stakeholders that play a part in the design of electricity tariff, including the public utility commission (also known as system regulator), electric power utilities, and consumers [65], we model this problem as a Stackelberg game, where the regulator is a leader and the power utility along with the consumers is modeled as a single follower. Hence, we develop a Single Leader Single Follower (SLSF) Stackelberg game to determine the justice-cognizant tariff in the system.

From the viewpoint of the regulator, we model availability and affordability of energy using power balance and energy burden [66] constraints, respectively. Power balance ensures that all system load can be supplied at all times, whereas the energy burden constraint guarantees that a household does not paymore than a fixed percentage of their income for energy procurement. Availability of EV charging infrastructure is also modeled using the power balance constraint such that sufficient generation is present at each bus of the system to cater for the EV load at that bus. Affordability of EV charging infrastructure is modeled such that a median household does not pay more than a specific percentage of their mean annual income for charging EVs.

Environmental sustainability of the energy produced in response to the demand (created as a function of designed tariff) is evaluated using CO_2 emissions. In addition, we use a locational marginal social cost of local pollutants from EASIUR [62] to model the public health considerations of the designed tariff. Similarly, inter-generational equity is defined in terms of minimizing the impact of global warming potential of CO_2 here-and-now to reduce the impact of current energy production passed on to the future generations. Public health impacts, as described above, are also used as a proxy for modeling intra-generational equity such that the health costs of energy production are equitably distributed in the system. Finally, economic welfare is formulated using the utility functions and costs of consumers, and revenue and operational/capital costs of the power utility.

Hence, the multi-objective function of the regulator encompasses the following justice considerations:

- Economic welfare,
- Public health
- Environmental sustainability

Similarly, availability and affordability along with revenue adequacy considerations are modeled as constraints in the regulator's problem. The designed energy justice framework is shown in Fig. 2, and is implemented on the New York Independent System Operator (NYISO) – Manhattan power network, shown in Fig. 3.

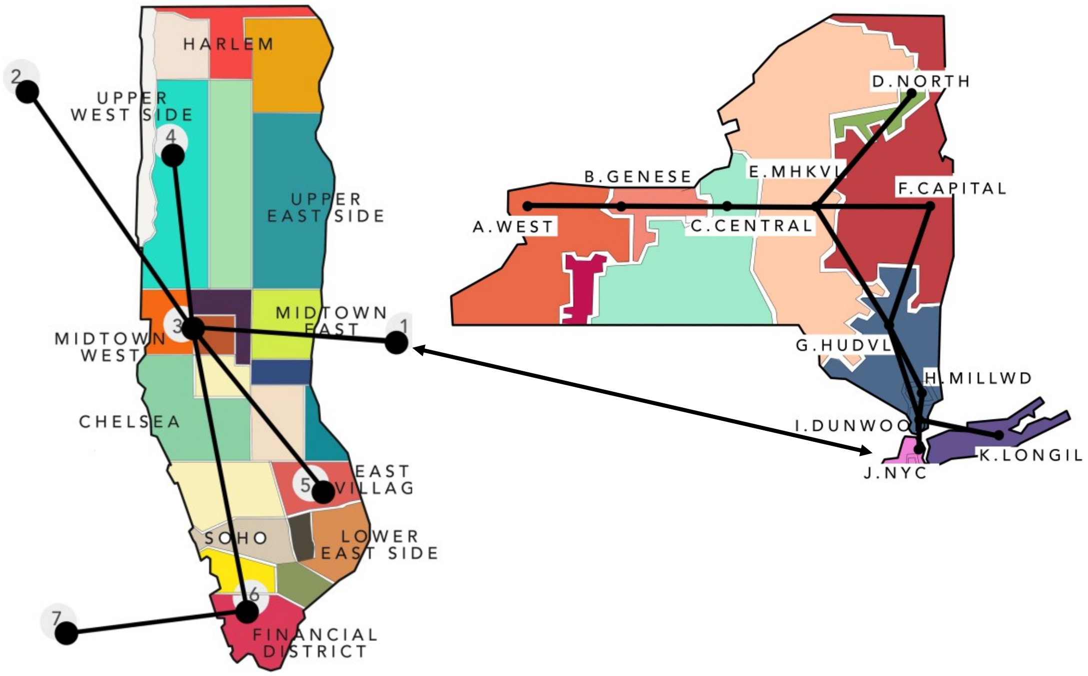

Fig. 3. A diagram of the 11-zone NYISO transmission system connected to the 7-bus Manhattan distribution system. The T&D interconnection is shown between NYC and bus # 1.

3.3 Multi-Objective Optimization Problem for Public EV Charging Tariff

We use the aforementioned energy justice framework to design an optimal and equitable EV charging tariff. The new problem formulation incorporates the seven energy justice considerations as described above, but considers only the EV load in the system instead of the total system load. We note that the EV load constitutes only a fraction of the total system load, the data for which is acquired using the publicly available EV Registration Map dataset from the New York State Energy & Research Development Authority (NYSERDA), and EV charging station load from independently-owned charging companies, e.g., ChargePoint. This approach is motivated by the fact that EV charging tariff should be designed such that the economic, environmental, and public health effects of EV load can be independently accessed and ameliorated using EV charging tariff, and siting and sizing decisions of future roll-out of EV charging infrastructure. The key differences in the energy justice-based EV charging tariff model as compared to the energy justice-based electricity tariff model are as follows:

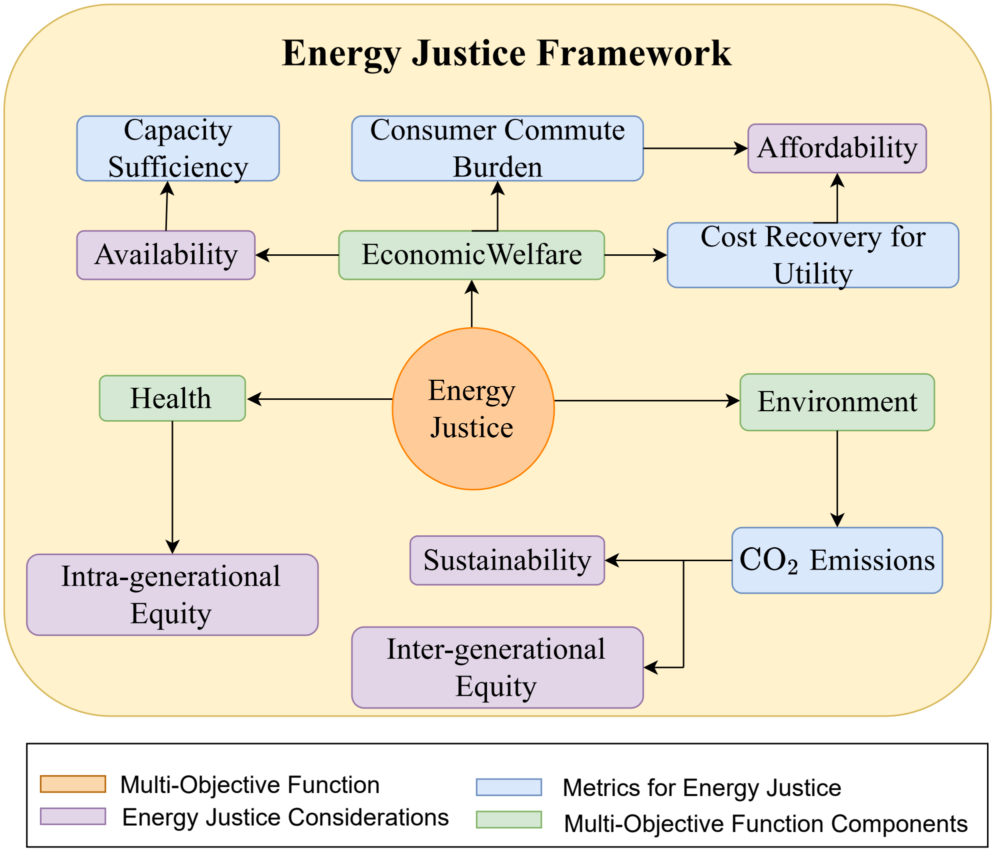

Fig. 4 A schematic representation of the energy justice framework designed for electric power utility to optimize equitable public EV charging tariff.

- The availability constraint of the EV charging infrastructure is modeled by ensuring sufficiency of charging capacity for the forecasted EV demand at each bus. Since the existing distribution of EV charging stations and their associated capacities are neither uniform across different buses, nor are correlated with the EV load, we introduce a slack variable to compensate for the difference, if any, between the forecasted EV load and charging capacity at each bus. The slack variable sites new EV chargers at buses where the capacity is less than the forecasted load.
- We define commute burden as a constraint which limits the daily expense of the median household for EV charging at each bus to be less than a pre-defined percentage of the daily mean household income at that bus.
- Revenue adequacy for the EV charging project of the power utility is defined as the ability of the utility to recover the capital cost of rolling-out EV charging infrastructure along with a pre-negotiated rate of return, and its operating cost from the EV charging revenue. Since, the problem only designs EV charging tariff and considers only the EV load, only the capital investment and operational costs of EV charging infrastructure are considered in this model, as compared to the total grid capital and operational cost in the model developed in Quarter 2.

- The minimum and maximum tariff limits are designed such that the minimum EV charging tariff is set as the energy tariff in the system. The choice of this minimum tariff is motivated by the current EV charging tariff design practice, which accounts for rents and opportunity cost of land used for EV charging infrastructure, especially in urban centers. Therefore, it is natural that the EV charging tariff cannot be less than the energy tariff in the system.
- The global and local emissions produced by the generators to cater for the system load are accounted in the same way as described in the energy justice framework for electricity tariff. However, since we only optimize the EV charging tariff in the proposed model, we only consider the percentage of total emissions which were produced to cater for EV charging load, and not the total system load.

The proposed problem structure, developed from the perspective of an electric power utility is shown in Fig. 4.

3.4 Solution Technique

We leverage Karush-Kuhn-Tucker (KKT) conditions to convert the designed bilevel SLSF game into a single-level equivalent [67]. This single-level equivalent contains multi-objective optimization problem (the regulator's problem) and the complementarity slackness conditions (in the KKT conditions of the power utility), resulting in a Multi-Objective Problem with Equilibrium Constraints (MOPEC) [68]. Owing to the multi-objective nature of this problem and the existence of complementarity constraints (which do not satisfy the standard constraint qualifications for non-linear problems (NLP)), off-the-shelf NLP solvers cannot be used in this case [69]. Hence, we propose a two-step integrated solution methodology to solve this MOPEC. This methodology, shown in Fig. 4, is summarized as follows:

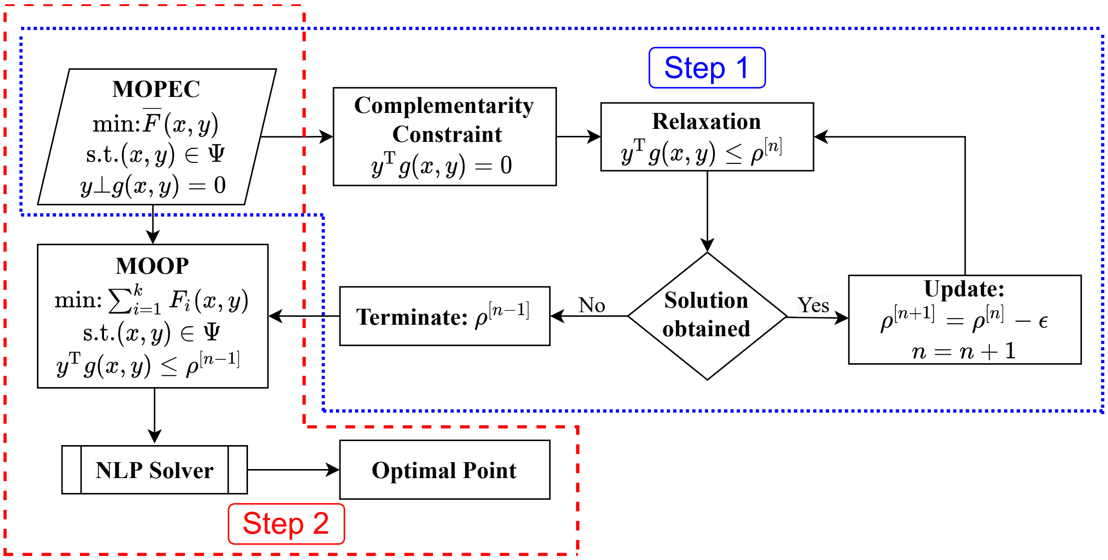

Fig. 5. Flowchart for the integrated MOPEC solution technique. Step 1 (dotted blue box) is the Scholtes's relaxation technique for complementarity constraints, and Step 2 (dashed red box) is the objective sum method for MOOP.

- Scholtes's relaxation technique for complementarity constraints (Step 1): To make the problem amenable to be solved using off-the-shelf NLP solvers, we employ Scholtes's relaxation technique iteratively to treat the complementarity constraints in the formulated MOPEC [70]. The relaxed MOPEC does not contain strict complementarity slackness conditions and results in a generic non-linear multi-objective problem.
- Objective Sum Method for Multi-Objective Problems (Step 2): For the multi-objective problem attained in Step 1, we use the objective sum method for the multi-objective function [71]. This method additively weighs each component of the multi-objective function, hence making it amenable for available NLP solvers. The choice of individual weights for the components of the multi-objective function depends on the articulation of preferences by the decision-maker (in this case, the regulator) [72].

Scholtes's relaxation technique guarantees the convergence of to the strongest attainable stationary point (C-stationary point) [69], whereas the objective sum method provides sufficient conditions for Pareto optimality [71]. Hence, at the culmination of the proposed integrated solution methodology, we obtain a set of Pareto optimal points, referred to as the Pareto frontier.

4. Data and Results

To determine the socio-demographic and transportation factors affecting the distribution of EV charging stations in NYC, we use the publicly available Alternative Fuel Station Locator dataset from Alternative Fuel Data Centre at the US Department of Energy [73]. This dataset provides a current accounting of the types and locations of all alternative fuel stations in NYC. For this analysis, we include only electric charging stations and exclude those providing other alternative fuels, like biodiesel, compressed natural gas (CNG), or liquefied natural gas (LNG). Each data point in the EV charging station dataset corresponds to one station, irrespective of the number of EV service equipment ports (charging outlets) and the type of connectors. The data comprises charging stations operated by major EV charging companies in the US, including Blink, ChargePoint, Electrify America, EVgo, FLO, Greenlots, OpConnect, Tesla, SemaConnect, and Webasto, however, does not include residential EV charging locations. Similarly, we obtain the demographic data of NYC from the American Community Survey (ACS) [74]. We use ACS 1– year estimates data profiles for 2019, which includes features of median household income, poverty rate, and population percentage of different racial groups by zip code. Using the NYS Streets data from the New York State (NYS) GIS Offices, we obtain the routes and spatial information of major roadways, which include interstates, interstate connections, state touring routes and connectors, state 900 routes, US highways, and US highway business routes and connectors [75], in NYC. The transportation information is then mapped to individual zip codes of NYC, shown in Fig. 1, using the zip code boundaries dataset from the Department of Information Technology & Telecommunications [76]. The socio-demographic and transportation data used in this project is available in [77].

The installed capacity of EV charging stations in each zip code of Manhattan is obtained using the “Electric Vehicle Station Locator” from NYSERDA [78]. Each zip code is matched with a bus number, as defined in Fig. 3, and the aggregated installed EV capacity at each bus is determined, see Table 1.

Table 1: Installed EV charging capacity at each bus of the Manhattan power network

Bus No.	Installed EV Charging Capacity (kW)
3	2112.8
4	3321.4
5	5047.4
6	1822.4
Total	12304

Similarly, the energy usage at EV charging stations on different buses of the Manhattan power network is calculated using the data available through *EValuateNY* tool developed by Atlas Public Policy and NYSERDA [79]. The quarterly energy usage at each bus is tabulated in Table 2.

Table 2: Energy usage at charging stations located at each bus of the Manhattan power network

Bus No.	Average Energy (kWh)	Median Energy (kWh)	Energy (kWh)
3	2578	2463	5494
4	2766	2905	10879
5	7863	8213	25713
6	863	924	2524
Total	14070	14505	44610

Since the data provided by *EvaluateNY* does not take into account all the public charging stations, and residential charging equipment, we therefore, use the NYSERDA's 'Electric Vehicle Registration Map' [80] to calculate the total number of registered EVs in each zip code of the Manhattan power network. These metrics are then used to calculate the EV charging load at each bus of the system, shown in Table 3, using the battery capacities of individual EV models registered in each zip code, the data for which is available in [81].

Table 3: Total EV charging load at each bus of the Manhattan power network

Bus No.	Total Min. EV load (kWh)	Total Max. EV load (kWh)
3	50376.4	73365.2
4	55558.7	84504.5
5	71815.6	106335.2
6	22683	31617.1
Total	200433.7	295822

Using data from [74], we show the population density in each zip code of NYC in Fig. 6. We note that the population density in NYC is neither uniform across zip codes nor across the five boroughs. Using Figs. 1 and 6, we observe that Brooklyn has the highest population density (shown in yellow in Fig. 6) whereas average population density is very low in Staten Island and Manhattan. Similarly, using the EV charging station data in [73], we show the distribution of EV charging stations in NYC on a zip code level, in Fig. 7. We note that the distribution of EV charging stations in heavily non-uniform among different boroughs such that the maximum number of charging stations are concentrated in Manhattan, whereas Bronx, Queens, and Brooklyn have little to no charging stations in most of the zip codes.

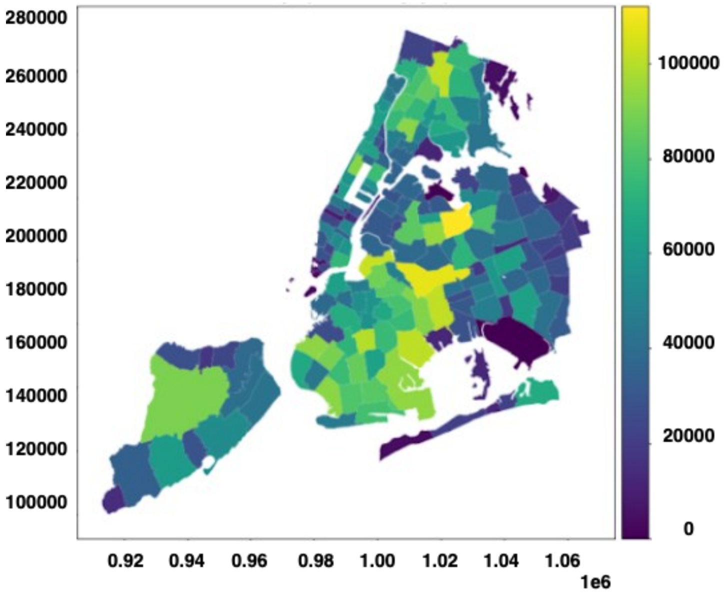

Fig. 6. Heat map depicting the zip code-level population density in NYC, based on data in [74].

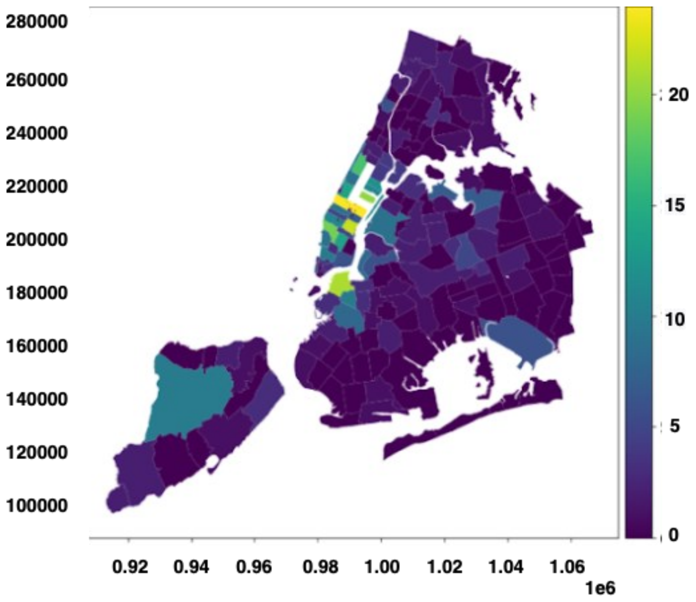

Fig. 7. Zip code-level distribution of EV charging stations in NYC, based on data in [73].

As an initial hypothesis, we compare the trends in population density in zip codes and boroughs to the associated distribution of EV charging stations. Comparing Figs. 6 and 3, we note that there exists a huge disparity between the distribution of EV charging stations and population density in NYC. While geographical areas (multiple contiguous zip codes) in Brooklyn have some of the highest population densities, the same areas have very few EV charging stations. Similarly, most of the EV charging stations are concentrated in Manhattan, where population density is one of the lowest. This indicates that population density is not a good indicator for the distribution of EV charging stations, underscoring inaccessibility of residential EV charging infrastructure as an acute barrier to EV adoption. Thus, further analysis of sociodemographic data is required to capture features that determine the presence and accessibility of EV charging stations. Therefore, we analyze the demographic characteristics that correlate with the development and allocation of EV charging stations in NYC.

The correlation coefficients obtained from the data analysis are shown in Table 4. The coefficients are measured between the demographic/transportation features and the target features of whether an EV charging station is present and the number of EV charging stations in a zip code. Median household income and percentage of White–identifying population in a zip code show the highest positive correlation with the presence of at least one EV charging station and the number of stations present in that zip code. Hence, higher the median income of a given zip code, the higher the probability that at least one EV charging station will be present in that zip code. Similarly, a higher median income also implies a higher number of EV charging stations in a zip code. The same pattern holds when we compare the relationship between the percentage of White–identifying population in each zip code and the two aforementioned target features. We also observe a weak positive correlation of 0.32 between the presence of highways in a zip code and the number of EV charging stations present in that zip code. Hence, although the percentage of White–identifying population is a good indicator for predicting the distribution of EV charging stations across zip codes in NYC, certain regions in Staten Island and Brooklyn do not follow this correlation. However, median household income explains the distribution of EV charging stations throughout NYC.

Table 4: Correlation coefficients between the demographic/transportation features and the target features of whether an EV charging station is present and the number of EV charging stations in a zip code.

Demographic Feature	Station Present	No. of Stations
Median household income	0.45	0.58
White-identifying population (%)	0.43	0.43
Highway present	0.32	0.23
Asian-identifying population (%)	0.24	0.16
Highway count	0.2	0.07
Poverty rate	0.2	0.01
Hispanic-identifying population (%)	0.18	-0.06
Black-identifying population (%)	-0.02	-0.14

Based on the two data groups defined in the Section 4, we perform a two-sample t-test between these two populations for different demographic and transportation features to determine (dis)similarities between the two groups. Table 5 shows the results of this analysis along with the mean and median values of the features for each group. The mean values for median household income and percentage of White–identifying population for zip codes with at least one charging station are significantly higher than for zip codes without any charging station. Meanwhile, the mean value for percentage of Black–identifying population is significantly lower in zip codes with at least one charging station versus those without any. Based on the results of two-sample t-test, reported in Table 5, we observe that median household income, percentage of White–identifying population, percentage of Black–identifying population, and presence of highways in zip codes offer significant *t*-values and *p*-values. Hence, using the *p*-values, we can reject the null hypothesis for these features, concluding that the means of the two groups of zip codes are not equal, indicating that there are significant statistical differences between the two groups. Similarly, the same features have significant *t*-values, indicating that the two groups of zip codes are dissimilar from one another.

Our analysis concludes that presence of highways is the most significant feature that distinguishes the two data groups, followed by median household income, and percentages of White– and Black-identifying population. The results complement the trends observed in correlation analysis, and offer critical insights into demographic features that determine the distribution of EV charging stations across NYC.

Table 5: Results of hypothesis testing between the group of zip codes with and without EV charging stations.

Demographic Feature	*t*-stat	*p*-value
Median household income	4.02	.000087
Poverty rate	-1.21	.23
White-identifying population (%)	3.36	.00094
Black-identifying population (%)	-3.37	.00094
Hispanic-identifying population (%)	-0.93	.35
Asian-identifying population (%)	0.87	.39
Highway count	-0.83	.41
Highway present	5.15	.00000056

Moreover, for the Manhattan power network, shown in Fig. 3, the fixed-rate equitable EV charging tariffs are shown below:

Table 6: Fixed volumetric tariff for public EV charging stations.

Commute Burden	Charging Tariff [$/MWh]
6%	Infeasible
7%	
8%	41.68
9%	45.23
10%	

We see that with a volumetric rate, it is not possible for the power utility to recover its capital cost along with a pre-determined rate of return (12% in this case) while ensuring a commute burden $\leq 7\%$. However, for commute burden $\geq 8\%$, the utility can recover its cost, and generate the requisite profits. EV charging tariff increases as the commute burden increases, however, stays constant for commute burden $\geq 10\%$. This is the optimal value where equity can be achieved in the charging ecosystem without sacrificing economic efficiency. For a TOU charging tariff (TOU defined in accordance with the standard and current practice at Con Edison), we obtain the following results:

Table 7: TOU tariff for public EV charging stations.

Commute Burden	Charging Tariff [$/MWh]	
	Peak Tariff	Off-Peak Tariff
6%	Infeasible	
7%	55.35	16.8
8%	59.26	16.8
9%	63.75	16.8
10%	65.82	16.8

We note that the infeasible range reduces when a TOU charging tariff is implemented in the system. The utility can recover its capital and operational costs for commute burden $\geq 7\%$, in contrast with 8% in the fixed tariff case. The peak charging tariff increases with the increase in commute burden, while the off-peak tariff remains constant. This provides an efficient price signal to consumers to charge their EVs during off-peak times, while minimizing the impact of commute burden on marginalized communities. We underscore that these tariffs, in correlation with the median household incomes [57], can be used to determine optimal investments in EV charging infrastructure. Such investments can be budget constrain investments for consumers, efficient EV incentive roll-out for utilities, or the installation of future public EV charging infrastructure.

5. Discussion

This section details the outputs, outcomes, and impacts of the project in terms of outreach, technical contributions, and their impact in the transportation sector.

5.1 Outputs

5.1.1. Publication

We have compiled the results of our analysis on equitable distribution of EV charging infrastructure in the following peer-reviewed publication, which is currently under review:

- H. Khan, S. Price, C. Avraam, Y. Dvorkin, "Inequitable access to EV charging infrastructure", 2022. [Online]. Available: https://arxiv.org/pdf/2111.05437.pdf

5.1.2. Webinars

We conducted the following two webinars to disseminate the results of this research, and involve stakeholders in the design of our policy questions and frameworks:

- **Webinar on June 17, 2021:** Listening Session: Analysis of Socio-economic Factors in the Distribution of Electric Vehicle Charging Stations in New York City. (No. of registered attendees = 41)
- **Webinar on November 17, 2021**: Listening Session: Building a Decision Support Tool for Optimal & Equitable Distribution of EV Charging Stations in NYC. We had about 30-40 people in attendance, including NYC officials (DOT and Mayor's Office), and representative from the private sector (Con Edison, Quanta Technologies and Charge Point) and national laboratories (PNNL, NREL, LLNL)

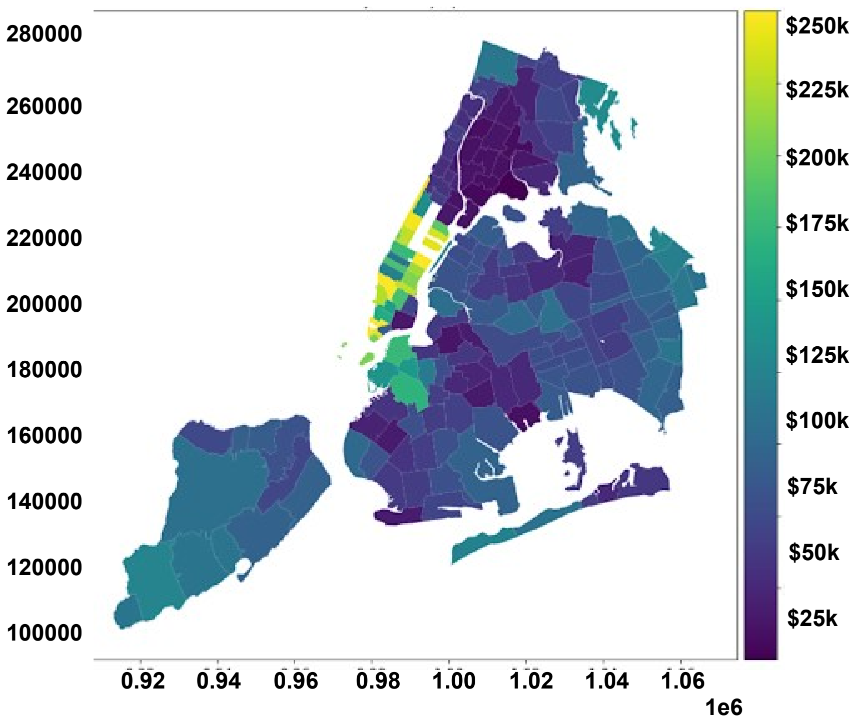

Fig. 8. Distribution of household income in NYC by zip code, based on data in [74].

5.1.3 Documentation

- Report on the application of the proposed metrics to NYC Open data, Available at [83].
- Webinar Recording, Available at: https://www.youtube.com/watch?v=MFlW2ObkGfU

5.1.4 Datasets

The generated datasets include zip code-level socio-demographic dataset, EV charging station dataset, and transportation dataset. The socio-demographic dataset includes features for racial breakdown of population, mean household income, and poverty rate in NYC on a zip code basis. Similarly, EV charging station dataset comprises of location, type (L1, L2, Fast), and charging company features, whereas the transportation dataset includes the number of highways in each zip code of NYC. Further details about datasets can be found in [82], [84].

5.1.5. Optimization Framework

The developed multi-objective energy justice-based electricity tariff design framework is available in [57].

5.1.6. Dashboard for visualizing injustices in the EV charging infrastructure

The project resulted in a Graphical User Interface (GUI) that visualizes injustices in the access to EV charging infrastructure. The developed GUI has a zip code-level granularity and provides detailed insights into the conditional correlations between the density/number of EV charging stations and the socio-demographic features of the population in a particular zip code. The zip code-level results of household income and percentage of White-identifying population in NYC, based on the developed GUI, are shown in Figs. 8 and 9.

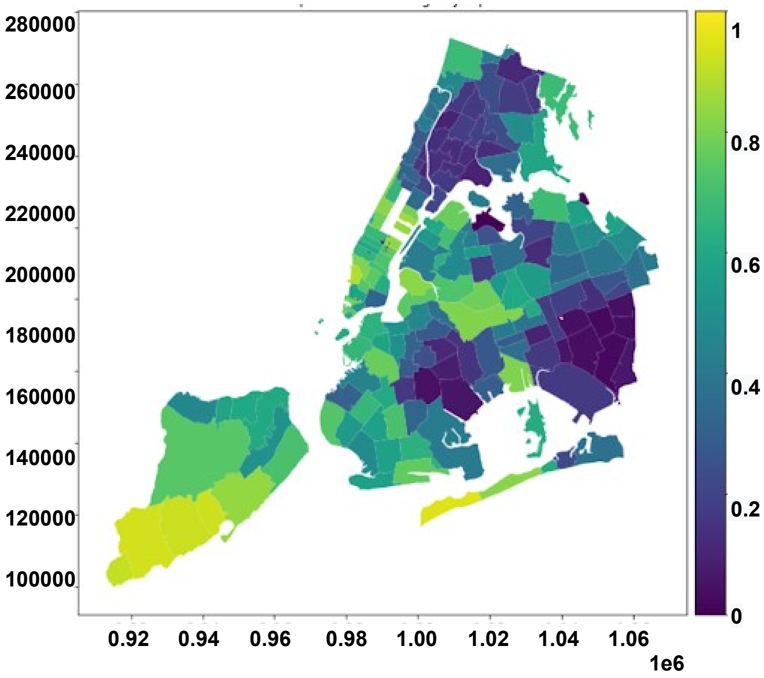

Fig. 9. Percentage of White-identifying population in NYC by zip code, based on data in [74].

The developed dashboard can be accessed at [85] to determine and visually represent the accessibility of EV charging infrastructure. The analysis in this report is carried out for NYC, however, the dashboard has the capability to analyze the EV charging infrastructure in any area (county, city, or country) on a zip code level, owing to the availability of data in format furnished in [84] for that particular area.

5.2. Outcomes

The following outcomes were achieved as a result of the conducted research and analyses under the EQUATOR project.

5.2.1. Size and Diversity of Audience

- The conducted webinars were attended from a myriad of diverse professionals including those in academia, industry, public policy, electric power utilities, and city government. The areas of interest of the attendees comprised transportation design and policy, engineering, operations research, electrified transportation, and power systems.
- Each webinar was attended by approximately 40 attendees.
- The pre-prints of peer-reviewed publications available on open-source platforms like ArXiv [57, 82] and ResearchGate have been accessed by more than 200 times by researchers, scientists, and industry professionals from North America, Europe, Asia, and Africa.

5.2.2. Industry Collaborations and Partnerships

The project engaged Consolidated Edison and Charge Point as external industry partners.

- Con Edison was represented by John Catuogno, Director of Commodity Forecasting, and Ivan Kimball, Director of Electricity Supply.
- Charge Point was represented by Dedrick Roper, Director, Public-Private Partnerships, and Marissa Galizia, Director Product Portfolio Management.

These individuals were engaged as non-paid advisors to the project, and contributed by providing technical advisory from the utility and private sector's perspective to a better understanding of the real-life bottlenecks for wide-spread adoption of EVs.

5.3. Impacts

5.3.1. Development of Metrics

The project resulted in a data driven analysis about the intersection of transportation/demographical data and EV charging infrastructure. The results contribute to a better understanding of the social implications of policies devised in the electric transportation sector, and open avenues for designing such interventions that alleviate social inequities in this domain.

The proposed metrics for availability and affordability of EV charging stations, associated environmental degradation and public health impacts, and their application to the zip code level demographical data of NYC adds to the body of literature about electrified transportation, EVs, EV charging infrastructure, equitable infrastructure development, environmental justice, public health, and justice considerations in transportation and energy sector. The developed metrics and their evaluation on real-life data contributes to a better understanding of intersectionality and tradeoff between energy economics, environmental sustainability, and public health. The quantification of this tradeoff is instrumental in equitable distribution of costs and benefits associated with EV charging infrastructure in the society.

5.3.2. Energy justice-based decision support tool for EV charging tariffs

The designed metrics are incorporated into an energy justice-based framework for designing optimal and equitable EV charging tariff. The proposed framework operationalizes equity and justice as design goals in the decision-making framework for regulators and power utilities and adds to the knowledge of incorporating equity in analytical and optimization frameworks. These metrics and results can be easily used to design holistic frameworks that ensure a just allocation of energy and transportation resources in the society, along with an equitable distribution of costs and benefits of these resources.

5.3.3. Development of solution methodology for solving MOPECs

The proposed integrated solution methodology for the justice-cognizant tariff-design framework adds to the mathematical and algorithmic literature on solution of MOPECs.

5.3.4. Equitable policy recommendations for EV charging infrastructure

The designed decision-support tool provides policy recommendations to ensure equitable distribution of costs and benefits of electrified transportation, EV adoption, and EV charging infrastructure via EV charging tariff. The proposed approach is novel in terms of its emphasis on equity while designing tecno-economic policies for energy and transportation infrastructure.

5.3.5. Public health impact

We incorporated the impact of transportation and energy emissions on public health into our analysis using dedicated tools like EASIUR [62]. The adoption of the proposed decision-support tools by public utilities and city governments while designing the roll-out of public EV charging infrastructure and associated policies would result in the reduction of disproportionate public health costs of transportation and energy infrastructure borne by the marginalized communities and communities of color. The equitable distribution of public health impacts would not only ameliorate the current injustices in the transportation and energy sector but would also contribute to the quality of life in the aforementioned communities.

5.3.6. Reduction in emissions

The proposed decision-support explicitly reduces the impact of local and global emissions in the system. A redirected focus from economic efficiency to equity and justice allows for such financial policies and technical outcomes that prioritize inter- and intra-generational equity at par with economic efficiency, paving way for decarbonization and just transitions in the transportation and energy sectors.

6. Conclusion

Electrified transportation is one of the critical aspects of the global trend towards decarbonization. While major global, federal, and state-level efforts are underway to facilitate the transition to EVs, existing injustices in the transportation and energy sectors call for an equitable uptake. Equity, however, cannot be holistically operationalized as a design goal in the transition to EVs unless the disproportionate public health and environmental effects of emissions are not incorporated in the techno-economic design of EV adoption and infrastructure deployment policies.

In this project we developed metrics to identify injustices in the existing EV charging infrastructure, especially in NYC. The metrics, based on statistical and machine learning techniques, are incorporated in the development of an equity-centric decision-support tool for designing public EV charging tariffs. The developed framework incorporates energy justice considerations and ensures that the economic, environmental, and public health impacts of electrified transportation are equitably distributed in the society. Moreover, we also developed a GUI-based dashboard that visualizes injustices in the access to EV charging infrastructure.

The proposed GUI-based dashboard and energy justice-based decision support tool will be instrumental in visualizing, quantifying, and ameliorating injustices in EV adoption, and enabling equitable accessibility and affordability of EV charging infrastructure. These tools can be used by local, city, state, or federal governments, electric power utilities, privately-owned charging companies, elected officials, and community and advocacy groups to ensure equitable transition to electrified transportation infrastructure.

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Appendix