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Advancing Energy Equity Considerations in Distribution Systems Planning

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***Abstract*—Current distribution system planning (DSP) processes do not explicitly account for energy equity considerations, such as who is most affected by power system burdens, where those burdens are concentrated, and what investments can be made to improve baseline conditions. This paper proposes an iterative framework for advancing energy equity as an objective of the DSP process, showing how measurement strategies, or metrics (informed by conceptual foundations of energy justice), can be applied to benchmark equity performance at various stages. This methodology is applied for equity-aware distributed energy resource (DER) hosting capacity analysis and outage analysis to provide critical insights on infrastructure upgrade decisions compared to a business-as-usual (BAU) case. The analysis is performed on a taxonomy feeder representing the West Coast urban/semi-urban system with augmentation of electric vehicles (EVs) and rooftop solar photovoltaic (PV) generators. The study considers disadvantaged community (DAC) and non-disadvantaged community (NDAC) load regions to enable equity-aware simulations. The results demonstrate how equity-aware planning could reveal the limitations of the traditional DSP process as DAC regions are found to have lower DER hosting capacity and higher outage vulnerability. Overall, this work provides insights on the need to incorporate energy equity as an integral part of the DSP process.**

Keywords*— energy justice, energy equity, distribution systems planning, hosting capacity, DER adoption

I. INTRODUCTION

The power distribution system is a crucial part of the electric grid responsible for delivering power to customers. Conventionally, the fundamental objective of distribution system planning (DSP) has been to deliver power to its end-users reliably, safely, and cost-effectively. To that end, the planning process includes various steps such as the system base case assessment and the growth projection of load and distributed energy resources (DERs), usually performed with historical data inputs [1]. Energy equity, though not historically considered a component of DSP, has significant relevance in guiding the future planning process. Energy equity is defined as the fair distribution of benefits and burdens of energy production, distribution, and consumption. This concept can be applied as a lens to understand how distribution system benefits and burdens are distributed across different customer groups, allowing for targeted infrastructure investment decision-making that results in the equitable allocation of new technology solutions. However, there is little guidance on how system planners should begin to incorporate the many facets of energy equity in the DSP process. As such, modeling and analysis methods that include energy equity parameters in traditional power grid models need to be developed [2] to enable equitable energy systems that can support the socio-economic development of communities at large [3].

For example, a study on the Texas freeze blackout in February 2021 showed that areas with a larger minority population were more than four times as likely to suffer a blackout than areas with a predominantly white population [4]. A study on the Puerto Rico blackout event caused by Hurricane Maria in 2017 found that socially vulnerable and politically marginal communities waited longer for power restoration crew assignments than communities with greater urban density and in proximity to essential service providers [5]. Both the Texas and Puerto Rico examples highlight how power system burdens are spread disproportionately across populations, leading to increased disaster vulnerability for DAC groups.

Recently, few distribution utilities have begun to include targets of providing equitable services to their customers [6]. Recent advancements in technology and equity-centered policy guidance are encouraging utilities to deliver clean, resilient, and equitable power in addition to meeting the traditional objectives of reliable, safe, and affordable power delivery [6]. However, the methods and processes to include equity considerations have not been sufficiently explored [7]. This paper proposes an equity-aware analysis—the first of its kind, to the awareness of the authors—wherein system and infrastructure disadvantages are disaggregated to assess disparities across individual customers or customer groups. The objective of this paper is to show that equity-aware DSP is possible and provide an overview of how metrics and equity inputs can be incorporated in the traditional DSP steps—from the base case assessment, to forecasting and hosting capacity analyses, to scenario planning, and investment decision-making—to yield equitable outcomes for society.

The key contributions of the paper are: (1) A framework for equity inclusion in the DSP process; and (2) an equity-aware DER hosting capacity methodology that provides key insights on system infrastructure upgrades to enable equitable DER access for both disadvantaged community (DAC) and non-disadvantaged community (NDAC) regions. The DER access analysis includes photovoltaic (PV) hosting analysis and electric vehicle (EV) adoption analysis. An equity-aware outage analysis methodology is also proposed, which provides instruction for ranking outages and developing restoration strategies for DAC and NDAC regions to ensure equitable restoration. The remainder of the paper is organized as follows.

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Section II introduces the basic concepts of energy equity and justice. Section III discusses the proposed equity-aware DSP process. Finally, the case study and results and conclusion are discussed in Sections IV and V, respectively.

II. ENERGY EQUITY: BACKGROUND

Energy justice and equity attempts to address the disproportionate technical, social, and economic impacts of energy infrastructure and operations across society, those of which have been historically borne upon underfunded, underrepresented, and marginalized communities. Conceptually, energy justice is comprised of four pillars: recognition justice, distributive justice, procedural justice, and restorative justice. The first helps identify "who" is disproportionately impacted by energy system burdens in society; the second considers "where" these burdens are most concentrated; the third evaluates "how" to make decision-making processes accessible and inclusive to disproportionately impacted groups; and the fourth informs "what" can be done to mitigate historical energy injustices in the transition to a just energy system [8]. Informed by these four tenets, energy equity refers to the fair distribution of both energy burdens and benefits across society [8].

The challenges with incorporating energy equity into the distribution system—that is, investing in equitable outcomes through DSP—are many. For one, it is difficult to translate policy to practice. Although more and more state and federal energy policies make endeavors to raise energy equity concerns, how energy equity is defined, measured, and achieved can vary—and the level of authority given to regulators to translate this policy into guidance for utilities can be unclear. Nevertheless, a number of states have implemented legislative actions that elevate the procedural and distributive justice elements of equity in grid planning processes, including the power distribution side. For example, 2021 policies in Oregon [9] and Illinois [10] direct regulators to increase transparency in DSP, particularly as it relates to cost-saving mechanisms and customer options, and utilities to outline distribution grid investments that benefit low-income and disproportionately impacted communities.

However, planning for and investing in equitable outcomes requires ways to "measure" equity—or metrics—with a two-fold purpose: they must inform both the current level of equity (or lack thereof) within a distribution scale relevant for analysis, but also the relative efficacy of targeted investments to improve this baseline level of equity. In other words, metrics are needed to determine who is most disproportionately impacted by distribution system burdens and how, where those burdens are concentrated, and whether investments to mitigate those burdens actually work. It is, therefore, helpful to think of metrics as they relate to the four energy justice dimensions: recognition (who?), distributive (where?), procedural (how?), and restorative (what?).

There are several metrics that already exist within the literature and in practice that relate energy equity and energy justice concepts, as demonstrated in Table I. Metrics can be used before, during, and after the equity-aware DSP process to benchmark the level of equity in each of these phases.

Table I. Equity Metrics and Examples

Equity Metrics	**Examples**
Energy burden and affordability	Electricity bill/household income
Energy access	Distribution of DERs (percent of local electricity generation mix from clean energy sources, energy storage deployed, EV adoption)
Environmental burden	Percent change in emissions (greenhouse gases, fine particulate matter, and other pollutants)
Electricity reliability and resiliency	Distribution of savings/costs, reliability indicators like (SAIDI, SAIFI CAIDI), hours to access critical services/income (social burden), restoration efficiency (time to recovery, cost of recovery)
SAIDI- System Average Interruption Duration Index; *SAIFI*- System Average Interruption Frequency Index; *CAIDI*- Customer Average Interruption Duration Index	

III. METHODOLOGY FOR EQUITY-AWARE DSP

The DSP process involves several sequential steps that take projections and arrive at a spatio-temporal map for the infrastructure upgrades needed in their system. This process, traditionally, does not account for energy equity or energy justice explicitly. Methods to include energy equity in the DSP process are presented below.

A. Generic DSP Framework with Equity Considerations

A conceptual framework for energy equity inclusion in the DSP process is shown in Fig. 1. The energy equity considerations are translated to relevant planning parameters (like access to DERs) in the DSP simulations. For instance, in the base case assessment, equity considerations are incorporated as recognition justice elements by identifying the DAC regions and assessing their current level of distribution system benefits and burdens. For the load/BTM (behind-the-meter)-DER forecast step, energy assistance programs for DACs (such as solar PV rebates, improved efficiency lighting, etc.) are considered as equity indicators that could alter the load and residential DER growth projections. The DERs in this step could include rooftop solar, EVs, smart thermostats, and more. For the utility-DER investment and locational distribution steps, equitable energy access and energy security constraints could alter the optimal distribution of utility-level DERs.

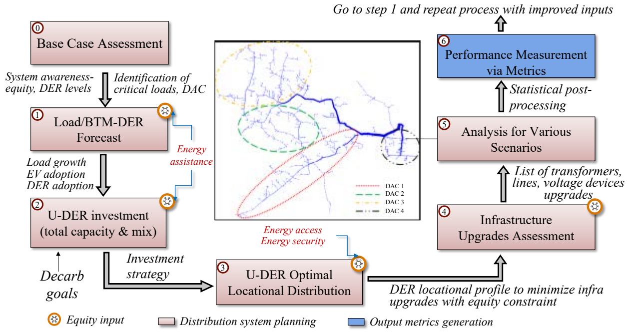

Fig. 1 Overview of equity-aware DSP process

Consequently, the infrastructure upgrade process must also be equitable to ensure equitable DER access. In the final step, system performance is measured by equity metrics (see Table I) generated via numerous scenario simulations.

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It is noteworthy that the socioeconomic condition of the households and their geographic locations (and other DAC indicators) are key determining factors for the equity-aware DSP process, such as identifying DAC regions, load and DER growth projections, access to DERs, etc. However, this data is not readily available for analysis due to privacy concerns, among other reasons. Therefore, in this work, we rely on the following two assumptions to identify DAC and NDAC regions in the distribution feeder - (a) Spatially disadvantaged: customers located far from the substation are naturally disadvantaged in terms of worse voltage profiles and reduced resiliency. (b) Socioeconomically disadvantaged: lower income households are assumed to correspond to lower demand (load) and infrastructure inadequacies such as aged transformers [11].

The criterion of classifying a part of the feeder into DAC/ NDAC may vary from community to community and these assumptions may need to be validated and revised with real-world data or specific tools [12]. Further, in this work, load growth data is derived from the US Energy Information Administration (EIA) [13]; the rooftop solar PV adoption data is derived from the National Renewable Energy Laboratory's (NREL) tool, dGen [14]; and the EV adoption projections are derived from industry sales forecasts [15]. Two subproblems are addressed to demonstrate the method for modeling equity considerations in the DSP process: (1) equity-aware DER hosting analysis and (2) equity-aware outage analysis.

B. Equity-Aware DER Hosting Capacity Analysis

The DERs considered for this subproblem are rooftop solar PVs and EVs. The proposed method for equity-aware DER hosting capacity analysis is performed separately for PV and EV as follows:

STEP 1: Identify the DAC and NDAC parts of the feeder.
STEP 2: Determine the load growth rates for the DAC and NDAC regions.
STEP 3: Determine the base case DER penetration level for DAC and NDAC regions.
STEP 4: Populate DAC and NDAC regions with increased DER penetration and solve powerflow for stressed feeder conditions (i.e., daytime for PV when most over-voltage violations occur and evening for EVs when transformers and lines operate close to thermal limits).
STEP 5: Collect a list of network operational violations (i.e., voltage violating ANSI limits (0.95-1.05 pu) [16], transformer and line conductors violating their thermal ratings).
STEP 6: Increase DER penetration and repeat from STEP 4.
STEP 7: Gather the spatiotemporal list of all the violations for all penetration levels. Post-process the violation list to get insights into the hosting capacity of DAC and NDAC regions.

C. Equity-Aware Outage Analysis

A utility or distribution operator aims to understand the system reliability for the entire system, although that may not be equitable across individual parts of the system. We propose a method that proactively and intentionally accounts for equity considerations at the DAC and NDAC regions identified and tagged on the feeder. The outage analysis is performed to determine the impact of each line and transformer outage on the number of customers and the total load lost. The analysis is performed through a tool (based on NetworkX module in python) that translates the tagged distribution network model into a tagged graph where the nodes and links are flagged with identifiers: DAC and NDAC correspondingly.

For each link element (that includes lines, transformers, regulators) that is out of service (outage), the total load lost, amount of DAC load lost, amount of NDAC load lost, total number of customers without power, and total number of DAC and NDAC customers without power are recorded. The DAC and NDAC information/data is utilized to rank the outages unlike the business-as-usual (BAU) case (not considering equity) where only the total load lost and the total number of customers without power are considered. The analysis will provide insights to the utility or the planner to develop a list of critical contingencies equitably. This analysis can help improve the reliability/resilience of the system by adopting appropriate strategies towards either building redundancy to the critical contingencies or strengthening those assets (lines, transformers, regulators, etc.) to limit their failure probabilities. The distribution system's reliability/resilience is an important goal that is considered in the DSP process. The proposed method can aid in identifying the critical contingencies for both DAC and NDAC regions.

This process allows us to observe the hosting capacity and outage analysis for DAC and NDAC regions individually. Zooming down to this micro-level, rather than viewing the system holistically, allows for targeted equity investments. The equity-aware DSP process considers other subproblems in an iterative manner with varying inputs for equity and other DSP goals. This process offers insights into tradeoffs between various inputs, costs and performance to inform investment strategies.

IV. RESULTS AND DISCUSSION

A. Test System Description and DAC identification

The distribution feeder model considered is based on a taxonomy feeder model developed in reference [17]. Since there is significant DER and EV growth in the West Coast region of the USA, a taxonomy feeder for that region is selected (as shown in Fig. 2). Characteristics for this feeder are described in Table II. The feeder is augmented with rooftop solar PV generation and EV load at the residential load locations. Two DACs are identified as shown in Fig. 2 (i.e., DAC 1 (spatially disadvantaged) and DAC 2 (socioeconomically disadvantaged)). The DAC 2 region is assumed to have lower-income households since it has lower loads compared to the other sections of the feeder.

Table II. Taxonomy Feeder Description

Component	Characteristic
Residential Customers	380
DAC Customers	160
NDAC Customers	220
Large Commercial Loads	12
Total Load	5.3 MW
Total Laterals	11
Total Service Transformers	50

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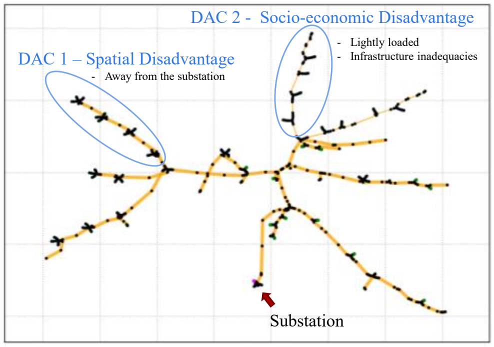

Fig. 2 Taxonomy feeder with DAC and NDAC regions identified

B. Equity-Aware DER hosting (PV and EV hosting)

i. Equity-Aware PV Hosting

A graphical visualization of the PV hosting analysis is shown in Fig. 3, where each of the subfigures show the voltage violation locations with 80%, 100%, 120% and 140% PV penetration levels, respectively. The red dots (see Fig. 3) denote the location of voltage violations. It can be observed that the spatially disadvantaged DAC 1 region experiences the greatest number of voltage violations as solar PV penetration increases, making it a less suitable candidate for hosting solar PV. On the other hand, the south-east region of the feeder remains violation free even at 140% PV penetration, lending locational favorability to solar PV deployment in a BAU case. In contrast, in an equity-aware case, a utility might consider the option of upgrading infrastructure in DAC regions to increase its hosting capacity (via installation of voltage regulators, for example). Thus, an equity-aware hosting analysis provides additional insights that inform a utility's decisions on the needed solutions to ensure equitable DER access for DAC regions.

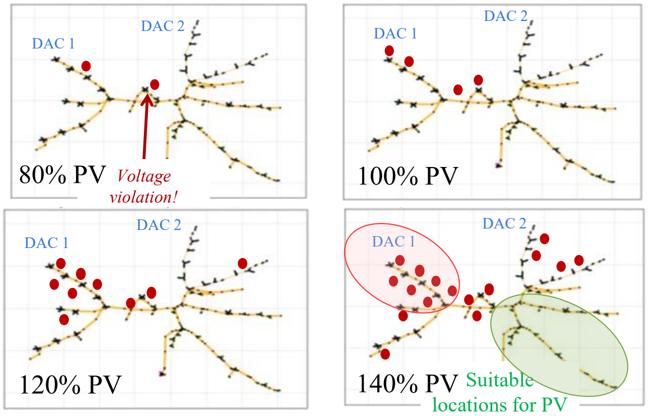

Fig. 3 Equity-Aware PV hosting capacity analysis for DAC and NDAC regions

ii. Equity-Aware EV adoption analysis

A multi-year EV adoption analysis is conducted to assess system readiness of the feeder. Base year (2022) EV adoption level is assumed to be 25% and 5% for NDAC and DAC regions (in percent of load, respectively). For subsequent years, DAC region growth is assumed to be 20% of the growth in NDAC regions. Similarly, a load growth profile is considered where DAC regions are assumed to have a lower load growth rate. Power flow analysis for each year provides thermal violations of transformer and conductors as shown in Fig. 4. Due to lower adoption rates of EVs in the DAC regions, the BAU analysis suggests no upgrades are needed in these regions, ultimately making them less suitable for EV hosting. If energy equity policies and programs enabled similar EV and load growth in DAC and NDAC regions (equity case), then there would be a need for infrastructure upgrades in both regions (upgrades are shown in Table III). In the BAU case, if there are additional incentives to promote EV adoption, the system will be insufficient. But, if an equity-aware DSP was employed, the system would be ready to enhance the EV adoption as the transformers and lines in the DAC would also be upgraded. The upgrades in NDAC regions remain the same for the BAU and the equity-aware cases.

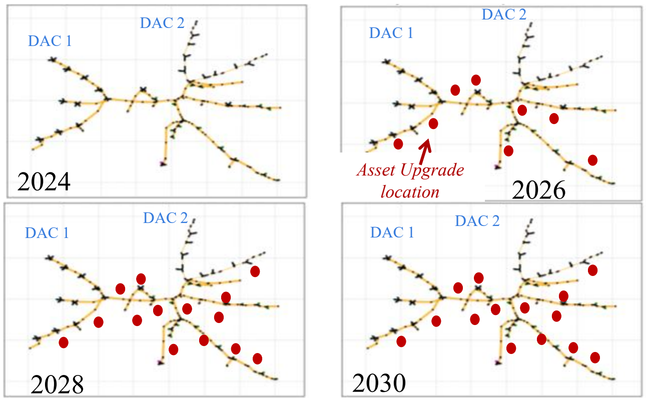

Fig. 4 EV hosting capacity analysis- BAU case

TABLE III. TRANSFORMER AND LINE UPGRADES FOR BAU AND EQUITY-AWARE CASES

Year	Transformer Upgrades			Line Upgrades		
	NDAC	DAC-BAU	DAC-Equity	NDAC	DAC-BAU	DAC-Equity
2022	0	0	0	0	0	0
2024	0	0	0	0	0	0
2026	8	0	1	2	0	0
2028	23	0	3	6	0	2
2030	30	0	4	8	0	3

C. Equity-aware Outage Analysis

To evaluate the reliability of the network, utilities often perform outage analyses. To that end, an exhaustive analysis is presented here to capture the effect of line outages on the test feeder. For the BAU case, the outages are ranked based on the largest number of customers affected. This corresponds to 28 cases of line outages where the number of customers experiencing outages at any given time ranges between 24 to 76 customers. Fig. 5 below shows a heatmap of unserved customers where shaded customers are the ones that remain in service. The analysis captures cases where the net load unserved varies from 1-2.5 MW. A similar analysis could be done by ranking outages based on total load lost. However, it is observed that ranking using these metrics doesn't necessarily capture the cases where DAC customers may be unserved.

To capture the cases that affect the DAC and the NDAC customers, a case is presented where the outage cases are ranked based on the number of DAC customers unserved. Fig.6 shows the results of the analysis with 47 line-outages based on highest number of DAC customers affected. This case serves to capture

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the disparity that could be missed if a simple outage-based ranking was used like the BAU case. By looking at cases which may adversely affect DAC communities utilities could design equitable operation and planning activities.

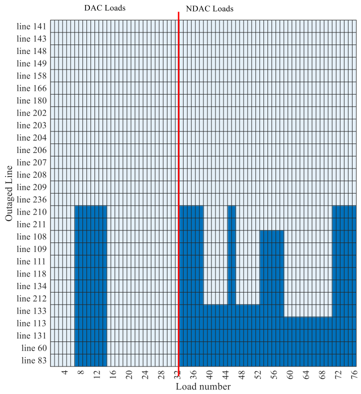

Fig. 5 BAU case – Ranking based on total customers unserved

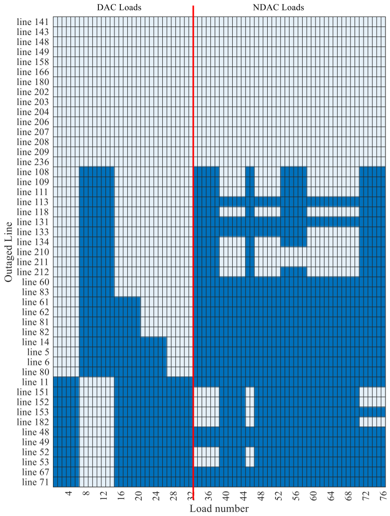

Fig. 6 Equity-Aware outage analysis – Ranking based on most DAC customers unserved

If network upgrades were conducted based on the BAU studies to improve reliability, it is apparent that the upgrades wouldn't necessarily improve service for DAC customers. Thus, it is important to consider both variations of this analysis and utilize a mixed approach when considering system upgrades to improve reliability equitably.

V. CONCLUSION

It is important to proactively model the equity considerations in power DSP and operations. The first step to achieve energy equity and energy justice is to recognize and acknowledge the existence of parts of the community that are disadvantaged and in need of assistance. When this is done, incorporating the DAC explicitly in the planning and operational analysis will help to visualize and validate some of the baseline inequity in the system. This research effort proposed a generic framework to include justice and equity consideration in the DSP process. Further, methodologies for two specific subproblems of equity-aware DER hosting capacity and equity-aware outage analysis are presented. The results on a taxonomy feeder revealed that if DACs are not explicitly identified and considered in DSP process, the utility actions on infrastructure upgrades may not be equitable. The next steps in developing an equitable DSP process are to work with real-world data and validate our assumptions and findings with utilities, communities, and other key stakeholders. Real-world data may show different dispersion of DAC communities, medically vulnerable populations and may add constraints associated with utility processes that could influence and provide interesting findings.

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