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Towards Just and Equitable Coordination of Distributed Energy Resources

D.C. PREZIUSO*, J. GARBE, S. BENDER, S. BARROWS
Pacific Northwest National Laboratory
USA

SUMMARY

Increased adoption and coordination of distributed energy resources (DERs) promises to create cost savings, increased resilience, and flexibility in energy systems across the globe. Realizing the full realm of benefits of DERs involves more than their widespread adoption, though; it requires market structures and incentives that prompt end users to utilize their DERs in ways that are favorable for grid operations. This positions cost-reflective, consumer-centric, and local energy markets, such as transactive energy systems, as a valuable tool in the clean energy transition. As grid objectives continue to emerge and expand to include goals such as equity and justice, developing models and simulations of markets to address these topics is necessary. To support that need, this paper presents a framework of energy justice considerations that models and simulations can include when coordinating distributed energy resources. The framework provides 1) a flexible, foundation-level tool to support researchers in developing simulations that can account for dimensions of equity and justice; 2) a mechanism that can be used to create transparency into research processes and assumptions, communicate with a broad set of stakeholders, and incorporate stakeholder perspectives; and 3) a structure to inspire additional ways to account for dimensions in energy justice and equity in simulations of DER coordination systems.

KEYWORDS

Transactive energy; energy justice; framework; model; simulation

danielle.preziuso@pnnl.gov

INTRODUCTION

Increased adoption and coordination of distributed energy resources (DERs) promises to create cost savings, increased resilience, and flexibility in energy systems across the globe. These technologies are at the heart of the future electric grid, underpinning the success of smart cities and microgrids, beneficial electrification, increased integration of renewable energy technologies, and more. Realizing the full value of DERs involves more than their widespread adoption, though; it requires market structures and incentives that prompt end users to utilize their DERs in ways that are favorable for grid operations.

From transactive energy (TE) to peer-to-peer trading structures and community self-consumption mechanisms, local and consumer-centric energy markets have long been identified for their potential to derive value from DERs [1]. These types of energy markets often reflect dynamic grid needs, better aligning costs with time-dependent burdens that consumption creates for the grid when compared to traditional utility rates [2]. For example, cost-reflective pricing mechanisms that can provide volumetrically lower electricity rates rather than curtailing renewables can support households who do not have their own on-site generation. This positions consumer-centric and local energy markets as a valuable tool in the clean energy transition, with material research indicating capabilities in meeting traditional grid objectives (i.e., reliability, safety, and fair pricing) [3-5]. TE markets, in particular, tend to focus on grid reliability and efficient operations by balancing supply and demand of electricity through decentralized mechanisms, creating an emphasis on demand-side flexibility [6, 7]. With significant potential for buildings to provide flexibility as a grid asset [8], regulators and utilities must work to unlock and incentivize the building sector to leverage these resources in the energy transition.

Leveraging demand-side flexibility is not strictly a technical or engineering-focused challenge. As focus broadens from a clean energy transition to one that is also equitable and just [9], utilities and regulators are more frequently tasked with addressing non-traditional grid objectives; states continue to pass legislation requiring regulators to explicitly address dimensions of equity and justice [10]. As such, models and simulations that coordinate DERs must begin to explore the implications of such goals. It can take significant time for new electricity rate structures to be implemented (e.g., California's roll-out of time-of-use rates began with Assembly Bill 327 passed in 2013 [11], but the process of transferring residential customers across the three major investor-owned utilities in the state lasted through 2022 [12]). Given the lengthy process of rate structure changes, expanding the scope of research questions that DER coordination systems address will engage a larger set of stakeholders, supporting future deployments.

To that end, this paper highlights considerations for DER coordination models and simulations to provide a tangible method for implementing energy justice and equity considerations in future studies, using TE systems as an illustrative example. To so, we (1) review literature at the intersection of energy justice and key features of TE systems, (2) develop a framework for energy justice considerations that TE models and simulations can incorporate, and (3) visually depict the functional and structural changes that may occur in a TE model when the framework is applied.

LITERATURE REVIEW

Energy justice is a concept stemming from the climate and environmental justice movements. It is often defined through four key tenets: recognition, distributional, procedural, and restorative [13-16] (see Table 1). These tenets, and energy justice at-large, are used as conceptual frameworks to support research objectives and policy creation [17-19]. The combination of tenets offers a mechanism through which to evaluate where injustices occur, who is ignored in the energy system and its decision-making processes, if there is fair process, and opportunities to rectify legacies of harm. This provides a holistic view into the ways in which injustices can arise within energy systems. As such, the four tenets anchor both the literature review conducted herein and the proposed framework.

Table 1. Energy justice tenets and key themes of exploration.

Tenet	Key Questions of Exploration
Recognition	Whose perspectives, cultures, and societal values are embedded in the energy system?
Distributional	Who is burdened and who benefits from the energy system?
Procedural	Is there fair access to and impartial participation in decision-making processes?
Restorative	How can the energy system and its associated policies rectify legacies of harm?

Given the limited focus TE models have historically had on energy justice, this literature review presents a broad assessment of two key components on which TE markets, and other distributed coordination systems, depend—end-use flexibility and the technologies that can automate it. Flexibility capital, a concept first introduced by Powells and Fell [20], describes an individual's ability to alter patterns of behavior to support a given system [21-24]. Within the electric grid, this largely relates to shifting consumption to off-peak times of demand or shedding load during critical periods. Subpopulations across the country have varying degrees of flexibility capital in the energy system. For TE markets to avoid exacerbating injustices and work to rectify them instead, they must start to account for flexibility capital and the underlying causes of and connections to it. Given that TE systems rely on automated flexibility, access to smart technologies; sufficient knowledge to participate in dynamic markets through those technologies; and the privacy and security of data processed within and across technologies are also significant within the context of energy justice [25-28].

Recognition Justice

The lived experiences of diverse communities, how those views and perspectives are incorporated into market mechanisms, and the simulations that reflect them, are primary aspects of recognition justice to consider in TE models. TE markets largely depend upon technologies that enable participation and the ability and willingness to engage with the market. Historically, TE markets and models have focused on system architecture and controls [29]. The barriers for customer participation linked to technology adoption and household vulnerabilities (e.g., poverty, illness, energy insecurity) hold influence over energy behaviors, however, which have not been assessed to the same degree. The absence of inclusion can be analyzed as nonrecognition, a manifestation of recognition injustice [30].

Barriers to entry and participation can range from a lack of technologies within individual households to broader infrastructure needs that enable the market. For example, renters and low-income households may have insufficient capital or lack the agency to alter their living spaces to adopt or accommodate smart systems and technologies [25, 28, 31, 32]. Disadvantaged neighborhoods may face limited grid hosting capacity, making it more difficult to adopt DERs or electrify their homes [33]. Rural homes may also have limited infrastructure to connect to smart grids and broadband internet due to quality of supply in remote areas, presenting a potential barrier to entry when TE markets rely on such supplemental infrastructure [28]. Pilot programs for local and consumer-centric energy markets often skew in favor of highly educated and high-income participants, potentially excluding disadvantaged groups from the benefits of these programs [32, 34, 35]. Low-income and minority groups are less likely to be early adopters of enabling technologies, potentially limiting both their initial and long-term benefits from such incentives [36]. Hesitation to adopt smart systems due to privacy and security concerns may also exist among users [25].

Even if technologies and infrastructure are available to support participation, household vulnerabilities and dynamics may prevent the level of participation that many TE models currently anticipate or perpetuate existing and emerging household burdens. For example, low-income and rural households can experience vulnerabilities such as the "heat or eat" dilemma linked to their ability to pay energy bills and meet other household needs [22, 37, 38]. Low-income households also have a higher likelihood of living in inefficient housing [37] and a limited ability to change their daily schedules to accommodate shifts in energy consumption. These factors can all contribute to inflexibility [28].

Households with children and those with one adult also have a limited amount of flexibility due to fixed routines and a limited ability to coordinate energy activities with another person [22, 28, 39, 40]. If these households are incentivized to show flexibility in their consumption, they may end up sacrificing comfort and convenience to save money in ways that more affluent households may not [22]. Even burdens across individuals within a single home can arise. Societal gender dynamics that influence household responsibilities and behaviors often result in women taking on a larger share of domestic chores. These dynamics could disproportionately place the burden of exercising flexibility onto women in households that contain both men and women [21, 22, 41].

Similarly, in-home comfort may influence how and when the elderly, those with disabilities, and those with chronic illnesses or other medical conditions participate in TE markets. The elderly are more likely to spend time at home and may need to keep their houses at higher temperatures to be comfortable, particularly during colder months. Those with disabilities, chronic illnesses, or medical conditions may have medical equipment that cannot be turned off to conserve energy. These characteristics may limit these groups' ability to shift energy consumption outside of high demand, potentially restricting the economic benefit they derive and the additional costs they may accrue [22, 31, 42]. Energy and technology literacy can also affect users' ability to interact with smart systems and realize cost savings, particularly among the elderly [25, 28]. When smart technologies are not designed in an inclusive way, individuals with disabilities may face difficulties using them [28]. Recognizing these varied experiences within TE models not only reflects the diverse experiences of end users but also gives way to quantifying the benefits and burdens across the system.

Distributional Justice

Existing valuation methods to quantify impacts of TE market mechanisms [43] can support analyses of distributional justice. This process may look across communities identified through a recognition-justice lens to measure benefits and burdens accruing to subpopulations within a study's scope. With variable flexibility capital across subpopulations, TE systems that financially reward flexibility capital have the potential to subsidize wealthy households while overburdening vulnerable groups, such as the elderly, those with disabilities and medical conditions, and low-income households [20, 25, 28, 31, 32].

Current research on the realization of this concern is mixed [42, 44]. Some studies suggest that vulnerable groups have less capacity to be flexible [39, 42] while others indicate that vulnerable populations could have the same or higher levels of flexibility capital compared to their counterparts [45, 46]. Nuances in these results appear both across and within individual studies. One potential explanation for these diverging results is the rate, and its design, utilized within the studies. The same utility rate applied in different contexts can also generate different outcomes for the same segments of customers. For example, Yunusov and Torriti [46] found that a set of time-of-use tariffs benefitted low-income households when applied to Northeast England, whereas higher incomes households saw greater benefits when the same tariffs were applied to households in London. Community attributes and regional differences, such as differing peak consumption times, can alter how a set of rates impacts different areas, highlighting the significance of rate design on equitable outcomes [44, 46]. Most existing work analyzes critical peak pricing and time-of-use tariffs rather than cost-reflective or local energy markets, but the discrepancies that arise indicate that the price-forming mechanism in TE markets may influence who benefits and who is burdened by the system in different geographies.

Procedural Justice

Principles from procedural justice can help mitigate and minimize discrepancies in benefits and burdens in TE systems by ensuring a diverse and representative group of stakeholders inform the design and implementation of TE markets analyzed in research. This requires access to and uninhibited inclusion in decision-making processes related to deployment, which can include the models and simulations that test these concepts. Including vulnerable groups in pilot demonstrations and representative models ensures studies reflect outcomes for those segments of the population in addition to affluent communities who are more likely to participate [32]. In practice, establishing lines of communication to reach different segments of the population can support these efforts.

Customers in TE systems, and the agents in models that simulation them, should also have the opportunity to indicate the level of control they want to have over their consumption (e.g., centralized model vs. community-oriented governance models) [31]. For example, while operators typically favor systems that rely on automated technologies that can be remotely controlled by centralized mechanisms to achieve higher levels of participation [23], many customers are uneasy with significant external control and would prefer the ability to opt-out of those practices [21, 23, 28]. TE systems can accommodate these variable approaches to participation. Understanding the processes needed to do so can support community acceptance of deployment while maximizing participation. This could include consulting customers with disabilities and vulnerable populations while designing and implementing TE systems. The singular way many smart technologies are designed may make them inaccessible (e.g., because they lack inclusive features such as text that is read aloud or enlarged), requiring alternative or supportive technologies to participate [28].

Throughout TE operations, system operators can also transparently share information regarding the system, data use, and pricing mechanisms, so users have a clear understanding of their electricity market and the prices they pay [32]. Not only does this open communication have the benefit of limiting system inequities, but it also engages customers early in the decision-making process to boost future engagement [37], supporting access to key procedures in TE systems.

Restorative Justice

TE systems that seek to rectify historic and persistent injustices (e.g., disproportionate energy burdens, uneven quality of service) may hold potential to serve as a means for restorative justice. In TE models, this could be achieved through the price-forming mechanism or the simulation scenarios that are assessed. Of the justice tenets discussed, restorative justice has seen minimal consideration in the relevant literature, yet examples from other customer-centric markets and technology adoption can offer insights into how this might be achieved within TE systems. One way this has been considered is through the integration of a vulnerability index that accounts for existing disadvantages among users in the market structure [47]. Using the index as a weight within the market, the services provided by vulnerable houses can be prioritized. While Ghorbani-Renani et al. [47] applied this method in a peer-to-peer market, the concept may be extrapolated to TE price-forming mechanisms. For example, the TE market might take into account users' vulnerabilities and weight their bids to support those with less flexibility capital.

Restorative justice efforts can also take the form of supporting technology upgrades. Providing investments in weatherization and energy efficiency have been proposed as ways to improve housing quality for vulnerable populations [48]. Not only will these programs help reduce energy costs but increase in-home comfort and support more equitable health outcomes. This principle might be extrapolated to technologies that support flexible energy use, such as smart and automated control technologies within TE systems. Investments into these technologies can provide flexibility benefits through technological means to users who may not have the ability to derive flexibility capital through other means, such as manually shifting the time of their energy behaviors [23].

METHODS: FRAMEWORK DEVELOPMENT

Accounting for energy justice in DER coordination models requires additions to the standard considerations found in models and simulations. The proposed framework provides specifications to account for energy justice across each of the core tenets—procedural, distributional, recognition, and restorative—and their relevant body of literature. With a significant focus on the human dimension of the energy system within the field of energy justice, the framework focuses on defining customers and the assets to which they have access. Questions of energy justice can be explored by defining customer agents (i.e., the model representation of customers) and building asset agents in a way that accounts for varying demographics, vulnerabilities, illnesses, burdens, and limitations that historically overburdened communities face (Table 2). The framework also proposes potential specifications for a retail market to analyze market mechanisms that not only seek to maximize economic benefits or fairness within a DER coordination system but also seek to rectify legacies of harm.

The framework consists of direct model specifications to account for energy justice, the model component to which that adjustment should be made, and the literature indicating the reason for the modificiation. Note that some models and simulations may account for some of these specifications already but are still included to emphasize their role in this context and note potential modifications in the way the data points are used within analyses.

Table 2. EJ framework for transactive energy models.

	Model Component	Specification to Account for Energy Justice	Reasoning
Recognition	Customer agents	Define agent attributes (e.g., building asset adoption) that reflect the realities across diverse subpopulations	Low-income households are often unable to adopt new technologies that enable participation in TE markets. Other subpopulations may face similar hurdles [29, 30]. Reflecting their realities is necessary to understand outcomes for those individuals.
		Define agent attributes that accurately represent barriers to effective participation due to infrastructure across diverse subpopulations	Renters and low-income households may have insufficient capital or agency to upgrade their homes. Rural environments often lack supportive infrastructure (e.g., broadband internet) for TE systems [25, 28, 31, 32].
		Define agent attributes that incorporate existing household vulnerabilities (e.g., the ability to make monthly energy bills)	Energy insecurity (i.e., tradeoffs between meeting basic energy needs and other household needs) and other lived experiences are likely to affect household flexibility and who faces the burden of creating and/or implementing flexibility. This is particularly true for rural households, households with children and only one adult, low-income households, elderly households, and households wih disabilities or chronic illnesses [21, 22, 25, 28, 31, 37, 39-42].
Distributional	Customer agents	Use demographic characteristics to define agent attributes	With existing methods to quantify impacts to granular populations and known inequities across subpopulations, tracking relevant demographic traits enables analyses, which are necessary given the mixed results currently seen on value accrual in the literature [20, 25, 28, 31, 32, 43].
		Create agents that can accrue both monetary and non-monetary benefits and burdens	Incentivizing flexibility is more likely to encourage low-income households and those with chronic medical conditions and disabilities to sacrifice health and comfort

			compared to their counterparts [39, 42, 45, 46].
Procedural	Customer agents	Consult a diverse group of stakeholders to create agents and simulate outcomes for known vulnerable populations, their concerns and preferences	Consulting vulnerable populations boosts engagement with the system and can improve equitable outcomes [28, 32, 37].
		Create agents who can opt-out of participation based on preferences or accessibility	Some users may want to avoid participation out of a desire for control or a desire to protect their privacy and data [21, 23, 28].
Restorative	Customer agents	Model scenarios where customer agents acquire TE-enabling technologies through diverse means (e.g., access from restorative policies)	Weatherization and energy efficiency programs have long contributed to improvements in household energy consumption with real potential to expand these programs to flexible technologies [48].
	Market mechanism	Simulate market mechanisms that explicitly account for historic injustices and vulnerabilities and seek to rectify them	For market mechanisms to rectify historic injustices, direct consideration must be given to populations who have faced them [18, 47].

RESULTS: A JUST TRANSACTIVE ENERGY MODEL

To depict the differences between a standard DER coordination model to one constructed with the above framework, a class diagram defining customer agents and building asset agents, a complementary table explaining the attributes and operations in the class diagram, and a structural diagram of the retail market are presented below. Standard considerations are shown in black text, and additional considerations to address dimensions of equity and justice, derived from the above framework, are shown in green across the results. The standard components of the system are constructed as a loose representation of the TE system deployed in [49]. While TE systems can take many forms, the goal of this representation is to categorically reflect common structures, agents, and procedures to contrast against emerging energy justice components that may be implemented.

The class diagram (Figure 1), developed in the Unified Modeling Language, and variable definition table (Table 3) show the attributes and operations of the customer agent and the building assets they control. This includes the necessary technical and economic variables for enabling the market in addition to a series of characteristics stemming from the energy justice framework. The new attributes encompass demographic information, various burdens that households might face, and limitations that lived experiences may impose on a customer agent within a TE system. These attributes not only define the agents but broaden the parameters that a customer or building asset may consider in their operations. Including new parameters in existing operations requires an understanding of how those attributes affect both the operations and the outcomes. For example, note the *optOutOfMarket* operation in the customer agent. The operation itself is not new to TE models (i.e., many TE models and simulations account for some customers opting out), but with new attributes like *householdVulnerabilities*, *flexibilityCapital*, and *householdIllness*, the way in which that operation works may evolve. The new attributes and operations are not meant to be prescriptive or exhaustive, nor are they intended to supersede existing attributes and operations. They are simply indicative of the types of considerations the framework may elicit to account for equity and justice.

While the class diagram focused on customer agents and their assets, the structural diagram (Figure 2) depicts the typical components of a TE system and the types of information, data, and values that are exchanged between them. These value exchanges, at a high-level, are typically limited to load flexibility and price forecasts, bids, and clearing prices in the market, but for a TE system to account for dimensions of restorative justice, for example, more exchanges may occur. Figure 2 proposes the market could include a justice-focused weight. This might be an additional parameter applied to a customer's bid in the market, so it would be shared across the distribution system operator and customers through the retail market. This addition to the retail market does not change the functionality of the TE system but instead focuses on the values themselves and redestribution to rectify legacies of harm, essentially broadening the objective set for a TE system.

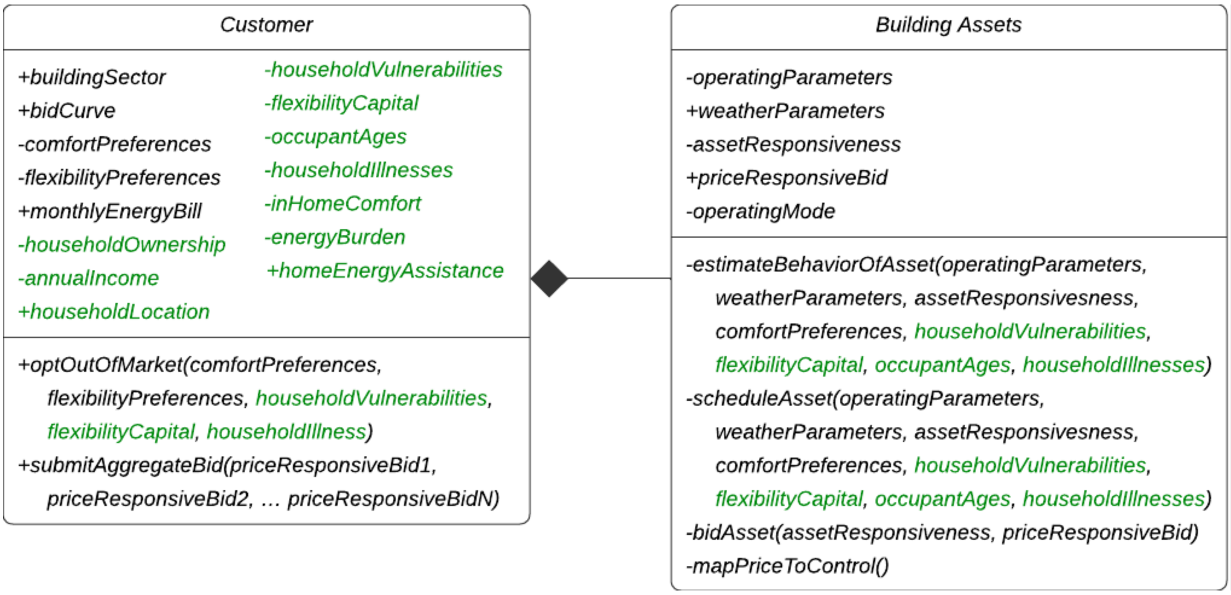

Figure 1. Class diagram of customer agent and building asset agents. Attributes are listed in the top half of each class, and the operations are listed on bottom half. Attributes of an agent are defining qualities while operations are the functions that the agent can perform.

Table 3. Definitions for each attribute and operation depicted in Figure 1.

Agent	**Attribute or Operation**	**Variable**	**Definition**
Customer	Attribute	buildingSector	Residential, commercial, or industrial customer
		bidCurve	Aggregate bid curve from home assets
		comfortPreferences	List of preferences related to in-home comfort that inform how the building assets operate
		flexibilityPreferences	List of preferences related to flexibility that inform how the building assets operate
		householdOwnership	Home ownership status (i.e., rent or own)
		annualIncome	Annual household income
		householdLocation	Physical household location
		householdVulnerabilities	List of household vulnerabilities
		flexibilityCapital	Constraints limiting flexibility that are not linked to preferences
		occupantAges	Ages of household occupants
		householdIllnesses	List of chronic household illnesses
		monthlyEnergyBill	Monthly energy bill
		inHomeComfort	Measure of in-home comfort (e.g., deviation in set-point from desired indoor temperature)

		energyBurden	Percent of income spent on energy services
		homeEnergyAssistance	Participant in an energy assistance, energy efficiency, or weatherization program
Customer	Operation	optOutofMarket()	Customer decision to opt of of TE market
		submitAggregateBid()	Submitting aggregate price-responsive bid into retail market through an automated technology (e.g., home energy management system)
BuildingAsset	Attribute	operatingParameters	Operating parameters, including constraints, that influence asset performance
		weatherParameters	Weather parameters that influence asset performance
		assetResponsiveness	Ability for technology to respond to market
		priceResponsiveBid	Price-responsive bid from asset
		operatingMode	Current operating mode of asset
	Operation	estimateBehaviorOfAsset()	Estimate the physical behavior of the asset
		scheduleAsset()	Prepare an operating plan for the asset
		bidAsset()	Prepare a price-quantity curve for the asset to participate in the retail market
		mapPriceToControl()	Map real-time price into control settings for the asset

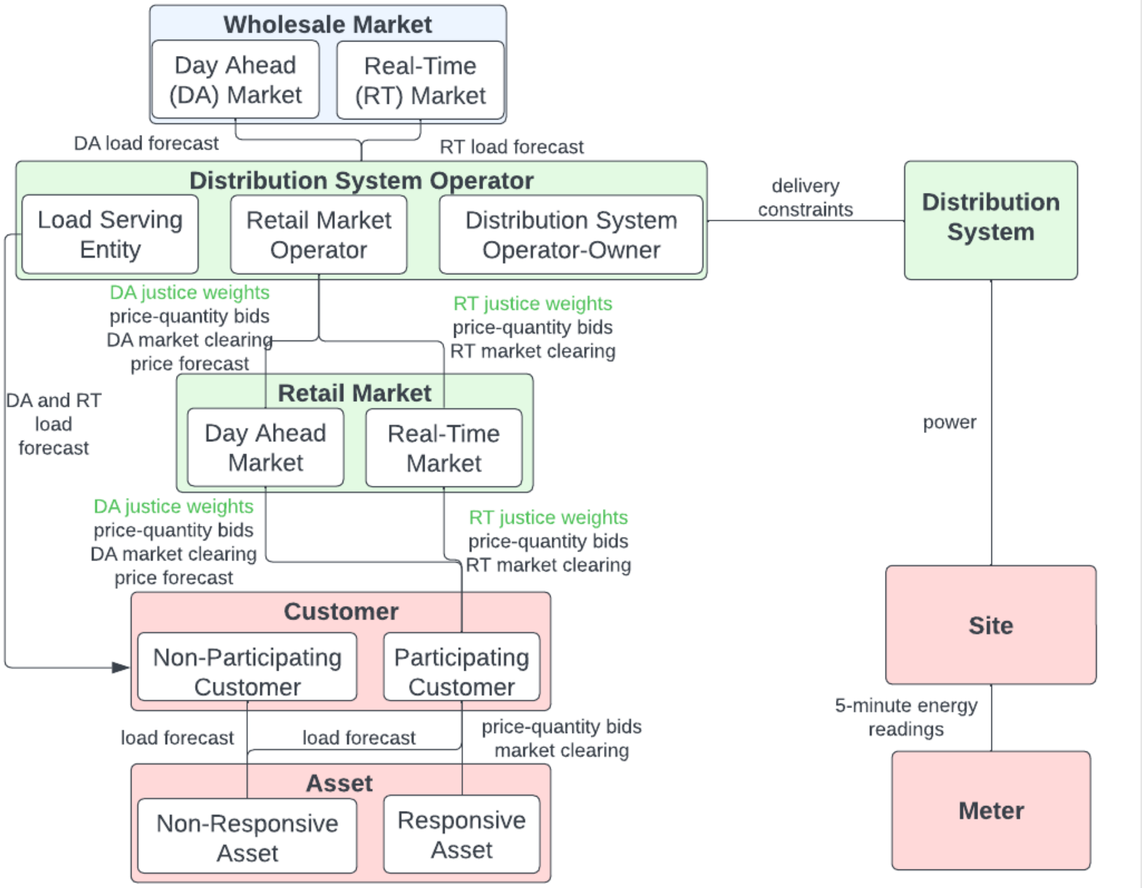

Figure 2. Structural diagram of key TE system components. For the representative TE market, both the wholesale and retail markets have day-ahead and real-time markets for which forecasts are necessary. Price-quantity bids and clearing prices are passed from the retail market to customers and distribution system operators. Justice-specific weights may be applied to bids to influence the resulting clearing price and/or whose bids are accepted. Adapted from [49].

DISCUSSION AND LIMITATIONS

The goal of the presented framework is to inspire a new set of considerations for DER coordination models and simulations using a representative TE system as an illustrative example. This framework is meant to expand the scope of objectives for DER coordination research to include energy justice and equity. It is not intended to prescribe or advocate for specific attributes or operations. For example, while the framework targets customer agents and their assets, the other agents shown in Figure 2 may also benefit from additional attributes and operations to promote energy justice in a TE system. If the distribution system operator computes justice-specific weights for the day-ahead market that are passed into the retail market, the operator may need additional information to inform those weights. Curating data to implement these attributes for customer agents and others could require new resources and innovative methods to approximate how those characteristics alter the behavior of customer assets and subsequent outcomes, if at all. This may increase the complexity of research projects and is not without potential barriers to execution. However, i is not necessary to implement all framework specifications at once. Implementing practical, relevant, and achievable components can expand the impact of TE research and prepare systems for deployment. This is particularly salient as utilities begin to explore new rate structures that better reflect costs of service, incorporate price signals that promote efficiency and flexibility, and reduce costs, particularly for low-income customers.

While the above framework focuses on the components of the model that might change, incorporating these factors also requires adjustments to the way in which models and simulations are built. The framework offers a mechanism through which to explore injustices, but any use of this framework for a specific location should begin with direct communication and inclusion of community members to first understand potential challenges, vulnerabilities, and lived experiences to reflect in the simulation and produce results relevant to their needs. Co-creating objectives for studies, appropriately scoping the system of interest, and computing granular results across stakeholder groups can support these efforts. While this can manifest in many ways, additional actions and considerations for energy justice can be identified across generic research stages: identifying model objectives, scoping the system of interest for the model, designing the valuation and analyses to assess how the model meets objectives, constructing the model and running simulations, conducting preliminary analyses defined by the valuation design, deploying the TE system in practice, and completing a post-deployment analysis to assess the degree to which objectives are met (Figure 3 and Figure 4) [43]. The specifications from the framework would be incorporated during the analysis design phase to ensure that the modeled system includes the data necessary to assess how the system fares, for example, with respect to vulnerable and disadvantaged communities. Again, these additions to the research steps are not prescriptive but a starting point for ways to research projects to evolve.

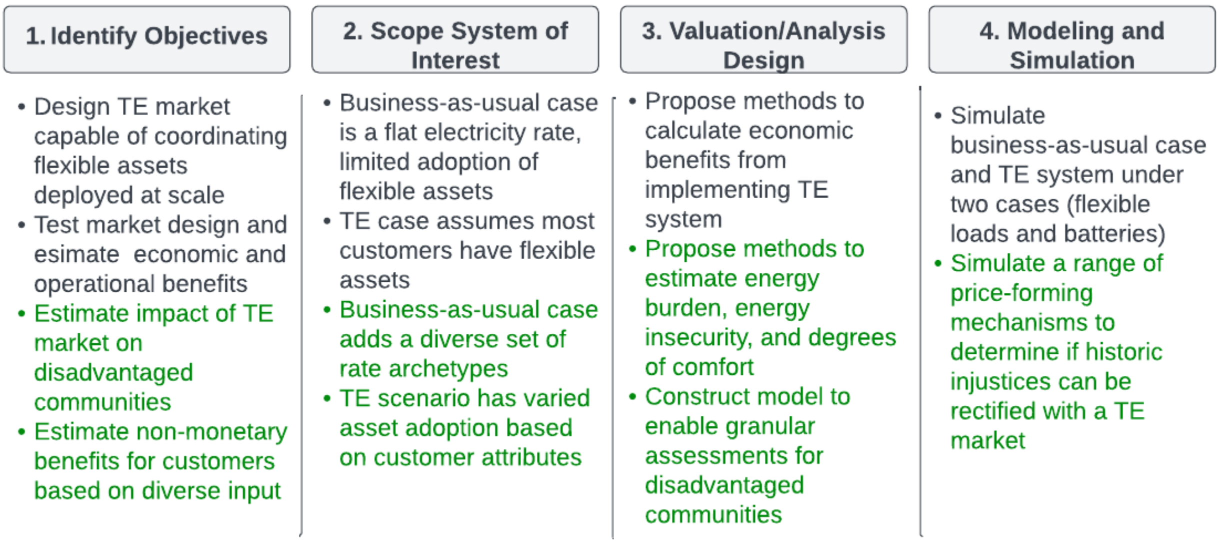

Figure 3. Energy justice considerations across generic research stages 1-4.

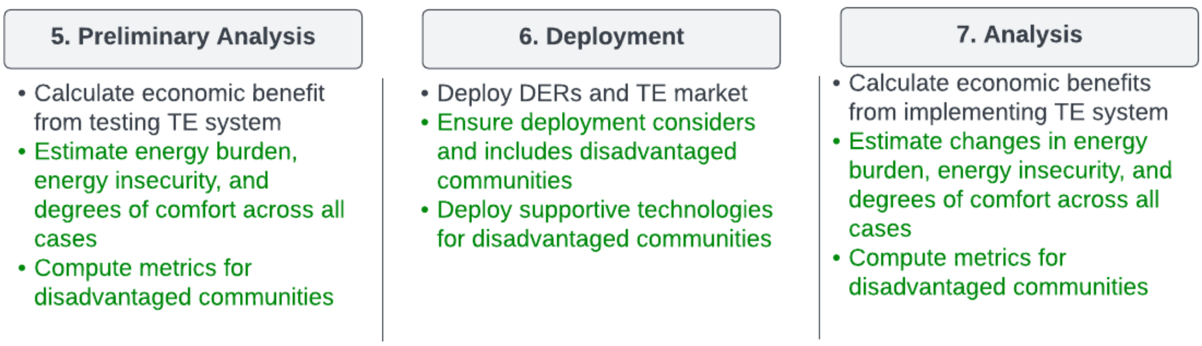

Figure 4 Energy justice considerations across generic research stages 5-7.

CONCLUSION

End users will continue to adopt DERs that can provide services to the grid, and electricity rates and retail markets will evolve to account for their technical capabilities. The full realm of benefits and burdens that these changes create across diverse subpopulations must be accounted for to ensure the distributed, decarbonized grid of the future is just. This requires consensus across a wide range of stakeholders, with regulator buy-in critical to creating this future. The presented framework proposes attributes for customer agents and their associated building asset agents in models for DER coordination systems through an illustrative TE example. Potential modifications to the price-forming mechanism in the retail market to support this outcome are also proposed, and ways to improve research processes to make these modifications possible are discussed.

Ultimately, the framework provides 1) a flexible, foundation-level tool to support researchers in developing simulations that can account for dimensions of equity and justice; 2) a mechanism that can be used to create transparency into research processes and assumptions, communicate with a broad set of stakeholders, and incorporate stakeholder perspectives; and 3) a structure to inspire additional ways to account for dimensions in energy justice and equity in simulations of DER coordination systems.

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