Securing Energy Equity with Multilayer Market Clearing

Qiwei Zhang, *Member, IEEE*, Fangxing Li, *Fellow, IEEE*

***Abstract*— Energy equity has been quickly gaining attention as policymakers seek to place "Clean Energy for ALL" at the center of the low-carbon energy transition. As a major driver of decarbonization, the power grid has started to build the groundwork for incorporating energy equity into grid modernization. However, existing research has mostly focused on energy equity from a social-science perspective, such as concept clarifications and tariff designs for residential customers. Little effort has been devoted to defining energy equity in wholesale markets and to reflecting energy equity in electricity price with technical models. To the best of our knowledge, this paper presents the first study attempting to understand and implement energy equity consideration within a physically constrained electricity market-clearing model. First, we identify and discuss several concerns regarding energy equity in the existing locational marginal pricing (LMP) model. Then, we propose a multilayer framework reflecting energy equity in LMPs. Finally, the proposed framework is elaborated via a modified PJM 5-bus system and demonstrated with the WECC 179-bus system.**

***Index Terms*— Energy equity, Energy justice, Electricity market, Locational marginal price (LMP), Economic dispatch**

NOMENCLATURE

Sets	
N_G	Set of generators
N_B	Set of buses
N_L	Set of lines
N_l^{cog}	Set of congested lines
N^F, N^M, N^T	Set of communities at each layer
Set^{need}, Set^{help}	Set of communities defined as need and help
Parameters:	
d_i	Electricity load
P^{min}, P^{max}	Lower and upper generation limits
C_i	Generation cost
L^{min}, L^{max}	Lower and upper line flow limits
$GSF_{l\text{-}i}$	Generation shift factors
D_i^F, D_i^M, D_i^T	Load of a community at high-, medium-, and low-burden layers
LMP^{cap}	Threshold of price adjustment
α, β, χ	Scale factor to tune the distribution of prices at high-, medium-, and low-burden layers
E_{ref}^F, E_{ref}^M, E_{ref}^T	Reference energy burden at each layer
E_i^F, E_i^M, E_i^T	Energy burden for a community at each layer
$\Delta\phi^{min}$, $\Delta\phi^{max}$	The maximum and minimum price adjustment
EC^T, EC^M	The equity credit factor for medium- and lower-burden layers.
Variables:	
P_i	Generation output
P_i^F, P_i^M, P_i^T	Generation outputs at high-, medium-, and low-burden layers
λ	Lagrangian multiplier for power balance
η^-, η^+	Lagrangian multipliers for power output constraints
μ^-, μ^+	Lagrangian multipliers for power flow constraints
LMP_i	Locational marginal price
LMP_i^F, LMP_i^M, LMP_i^T	Locational marginal price at each layer before price adjustment
LMP_i^{new}	Adjusted locational marginal price
$\Delta\phi^M$, $\Delta\phi^T$	Price adjustment at medium layer and lower layer
R^n, R^h	The ratio of burden deviation for any two entities in the need and help sets
J^n, J^h	The ratio of congestion value deviation for any two entities in the need and help sets

I. INTRODUCTION

A. Background

Human societies have been drifting into a future that is threatened by global warming and extreme weather, which involves ethical and moral considerations that are seldom mentioned in conventional technical models and analyses. Power systems are one of the most complex networks supporting human life and societal development. It is becoming increasingly clear that future power systems will encounter ethical conundrums that involve aspects of equity and morality, where existing schemes can no longer offer suitable answers.

The concept of energy equity has recently emerged to combine the consideration of ethics, morality, and philosophy with technical designs, such as electricity flows in power lines. This topic has garnered worldwide attention, and a range of efforts has already begun to lay the groundwork to achieve energy equity in practice. The U.S. Department of Energy (DOE) and national labs have started to deploy energy equity actions, such as [1], [2], and [3], to support the Justice40 initiative [4] released by the White House in 2022, which aims to deliver 40 percent of the overall investment in sustainable

The authors are with the Min H. Kao Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, TN 37996 USA (e-mail: fli6@utk.edu).

This article has been accepted for publication in IEEE Transactions on Energy Markets, Policy, and Regulation. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEMPR.2024.3377210

energy and climate change to underserved communities. In the same vein, the European Commission established an equitable platform for the energy sector to promote equity and inclusion in the energy sector in 2022 [5]. The challenge of energy equity has opened a new direction for the power system research community.

B. Literature Review

The definition of energy equity, along with its synonyms (e.g., energy justice), has been broadly discussed. Reference [6] establishes a systematical triumvirate of tenets to explain energy equity, which consists of distributional justice, procedural justice, and recognition justice. Reference [7] further adds restorative justice to the triumvirate tenets to reflect the repair of historical injustice. These four tenets have been widely used as a conceptual cornerstone in later research works. Reference [8] reframes the existing energy problem and discusses the concerns regarding energy equity in the existing energy system design. Reference [9] argues that restorative justice should be placed at the center of energy equity, instead of being treated as an individual step. Reference [10] targets recognition justice in energy justice and provides a detailed definition. Reference [11] branches from the existing tenets and presents an amended agenda with ten principles. Reference [12] provides an energy equity workbook to clarify the four tenets of energy equity with real-world examples.

Although the agenda and definitions for energy equity are rapidly evolving, at base, energy equity aims to deliver an energy system paradigm that fairly distributes the benefits and costs of energy service via an inclusive decision-making process. Many studies have analyzed and designed energy tariffs and energy policies to facilitate the implementation of energy equity in practice. Reference [13] identifies that the existing feed-in tariff design in Germany has favored certain communities, violating energy equity. Reference [14] analyzes the energy equity in distributing the cost of clean energy infrastructure. Reference [15] focuses on energy equity in current energy storage initiatives. Reference [16] comprehensively reviews energy equity in the existing electricity tariff design.

Traditionally, power system research has focused on reliability and economic operations, where energy equity is often overlooked. This oversight is further compounded by a lack of an interdisciplinary approach and insufficient emphasis on the social dimensions of power systems. However, the increasing awareness of just energy access has been shifting power system research to include a focus on justice and equity. This new direction aims to ensure that all population segments have access to reliable and affordable electricity services, moving beyond merely maximizing overall welfare. An equitable power grid is also key to addressing historical injustices, particularly for marginalized communities who have historically had limited access to reliable and affordable electricity. It's essential that the benefits and responsibilities within power grids are fairly distributed across all participants, thereby enhancing social cohesion. Therefore, a sustainable and resilient power grid in the future must be both technically efficient and socially equitable. Several pioneering works have begun to explore the implication of energy equity in power systems. Reference [17] emphasizes the importance of energy equity in power system resilience and delivers an enhanced power system resilience framework. Reference [18] develops social indexes to implement energy equity in a renewable siting problem in a power grid. Reference [19] explores the impact of inter-regional electricity flow on the transfer of energy equity-related issues between different areas. Reference [20] discusses the impact of transactive energy systems and power system infrastructures on energy equity. Existing challenges in this field include (1) defining energy equity within the context of power systems, (2) adopting an interdisciplinary approach, combining insights from power system engineering, economics, and equity, and (3) addressing the complexity of power system operations considering energy equity. This paper contributes to this evolving discussion by examining energy equity in the context of economic dispatch and pricing models. The specific contributions of this study are further detailed in the subsequent subsection.

C. Contributions

Our work explores and integrates energy equity within a physically constrained market-clearing model. An illustrative 3-bus example is developed to highlight potential concerns regarding energy equity in the existing pricing model. Built on this, an energy-equity-driven multilayer framework is proposed to embed the energy equity consideration into electricity market settlements. This framework accommodates community aggregators or load aggregators based on their energy burden. The LMPs resulting from the proposed framework aim to reflect a tradeoff between the considerations of energy equity, reliability, and cost minimization. Although energy equity has been widely discussed in terms of a policy concept, our work bridges this policy concept with technical models. To the best of our knowledge, our model is the first market-clearing model that embeds energy equity, reflecting energy equity in power market operations. Our analysis and framework are designed to aid stakeholders in understanding and implementing energy equity through mathematical formulations and examples. Furthermore, this effort also lays the groundwork for future energy equity studies in electricity markets.

D. Paper Organization

The rest of this paper is organized as follows. In Section II, the fundamentals of the electricity market and energy equity are reviewed and discussed. In Section III, the tenets of energy equity under LMP-based market settlements are illustrated and analyzed. In Section IV, the proposed energy-equity-driven multilayer market-clearing scheme is described. In Section V, the proposed energy-equity-driven multilayer framework with a modified PJM 5-bus system is illustrated, and the scheme is demonstrated on the WECC 179-bus system. Finally, conclusions and future studies are discussed in Section VI.

II. Energy Equity In the Electricity Market

An equitable power grid is an indiscriminate platform that all communities can participate in and benefit from. In this section, the electricity market-clearing model is briefly reviewed, and the concept of energy equity is clarified under the context of electricity market operations.

A. Fundamentals of Electricity Markets

The LMP scheme is dominant in settling electricity market transactions [21] [22]. The LMP is an indirect result of economic dispatch, which reflects the increased dispatch cost versus the marginal increase in load at a specific bus. Economic dispatch models often utilize a linearized power flow approach for LMP calculation, as detailed in equations (1)-(4) [22]-[24]. This paper also employs this linearized power flow method for LMP calculation for simplicity. While this linearization simplifies the application of Kirchhoff's laws, it is adequate for this paper to demonstrate the integration of energy equity considerations within the proposed framework [33].

$$\min \sum_{i}^{N_G} C_i P_i \tag{1}$$

$$\sum_i P_i - \sum_i d_i = 0 : \lambda \tag{2}$$

$$P^{\min}{}_i \le P_i \le P^{\max}{}_i, \forall i \in N_B : \eta^-, \eta^+ \tag{3}$$

$$L_l^{\min} \le \sum_{i=1}^{N_B} GSF_{l,i}(P_i - d_i) \le L_l^{\max} \forall l \in N_L : \mu^+, \mu^- \tag{4}$$

The formulation is shown in (5).

$$LMP_i = \lambda + \sum_{l}^{N_L} GSF_{l,i}(\mu^- - \mu^+), \forall i \in N_B \tag{5}$$

B. Energy Equity in Electricity Markets

Energy equity is often explained through four well-established tenets from a social science viewpoint: procedural equity, recognition equity, distributive equity, and restorative equity. Accordingly, we summarize these tenets and explore their implications within the context of electricity market. More detailed definitions and discussions on these tenets can be found in [30], [31], and [32].

Definition of Procedural Equity:

General: All communities should be able to sit at the decision-making table ensuring the process is inclusive and transparent, regardless of the results.

Electricity market: The market-clearing process should encourage the participation of all communities, regardless of the geographical location, amount of electricity consumption, etc. The needs of underserved communities are highly likely to be outvoiced by other communities. Thus, without a proper scheme, particular communities may lack sufficient attention from load aggregators or system operators. This oversight makes the behavior of these communities have no impact on the results of market clearing.

Definition of Recognition Equity:

General: Beyond merely allowing all communities to sit at the decision-making table, the divergent characteristics of all communities should be recognized.

Electricity market: The market-clearing process should fully recognize the characteristics of all communities, beyond simply allowing the participation of underserved communities. Each community may have unique characteristics, such as energy burden and load patterns, which should be recognized and reflected during market clearing.

Definition of Distributive Equity:

General: The decision-making results should evenly distribute benefits and burdens to all communities regardless of income, race, etc.

Electricity market: The market-clearing results should fairly distribute benefits and burdens to all communities. The cost minimization and reliability of grid operation should not be realized at the expense of particular communities, even if this consideration undermines overall social welfare. Under the existing market operation, particular communities may constantly be undermined to ensure the reliability of the whole grid at the minimum cost or to ensure the minimum cost of whole-grid operations, but distributive equity suggests that the benefits and burdens should be fairly distributed.

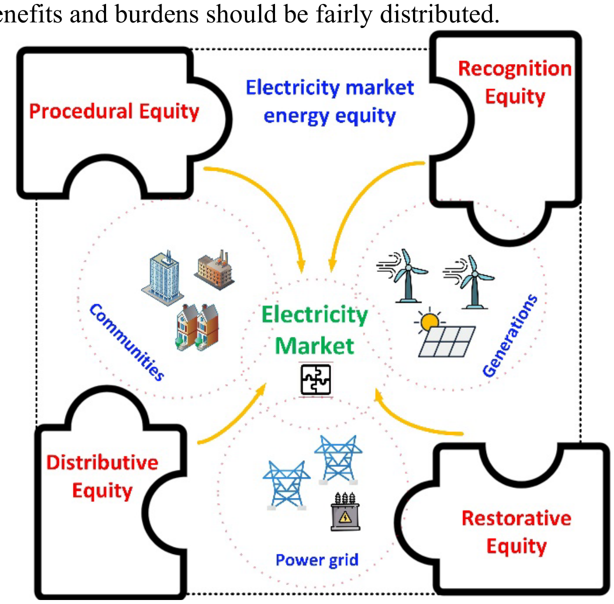

Fig. 1. Four tenets of an equitable future electricity market

Definition of Restorative Equity:

General: Restorative equity responds to the injustice that has occurred to the victim and aims to repair the harm that has been done to people/communities.

Electricity market: Market-clearing outcomes, such as high or low electricity prices, can disproportionately affect underserved communities. These outcomes are largely influenced by long-lasting factors, including geographical location and load patterns, which persistently bring advantages or disadvantages to specific communities. Current market-clearing mechanisms lack adequate compensation schemes to repair the disadvantages experienced by these underserved communities effectively.

In short, an equitable future power grid requires piecing together the four tenents for future electricity market operations, as shown in Fig. 1. The next section discusses potential concerns about the existing market-clearing scheme regarding energy equity, and Section IV proposes a multilayer market-clearing framework incorporating energy equity into market operations.

III. Equity Concern In LMP-Based Settlement: Disparities Between Communities

The LMP-based settlement scheme reflects the cost of electric energy at different locations and the reliability constraints of the electric grid. However, energy equity is not explicitly modeled in the existing scheme, which leads to a gap between the policy concept of energy equity and engineering practice. In this section, we discuss several potential equity concerns with a 3-bus example as follows.

A. Illustrative Examples

As shown in Fig. 2, two generators A and B are dispatched to satisfy the electric load for region/community A and region/community B, assuming community A is a high-income community and community B is a low-income community. Low-income communities (e.g., community B) have fewer electric appliances and tend to cut electric bills as much as possible. The high-income communities (e.g., community A) can afford more electric consumption for entertainment, in addition to essential electric consumption. The essential electric loads for both community A and community B are assumed to be 50 MW, while community A has consumed another 50 MW for entertainment. The LMP settles all the transactions at the marginal price of the next incremental load, and thus, Community A and Community B are both settled at $20, which is the cost of generator B. Although the payment provides sufficient incentive for generators to follow dispatch signals, the resulting settlement price treats divergent communities with the same prices.

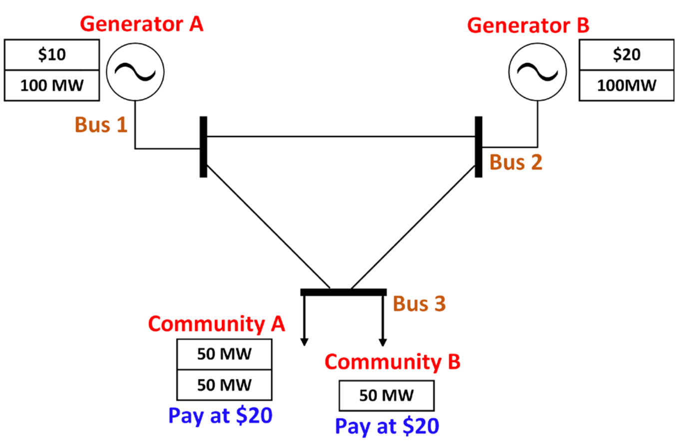

Fig. 2. Scenario 1

Fig. 3 shows a new scenario when the high-income community A is moved to the same bus with the low-cost generator A. The parameters are modified for the benefit of illustration. The transmission line between low-cost generator A and community B is congested as indicated with blue text. In this case, the high-income community A is settled at $10, which is the cost of cheap generator A. The low-income community is settled at $22.11, which is even higher than the cost of expensive generator B because of the congestion. Geographic locations offer advantages and disadvantages to different communities.

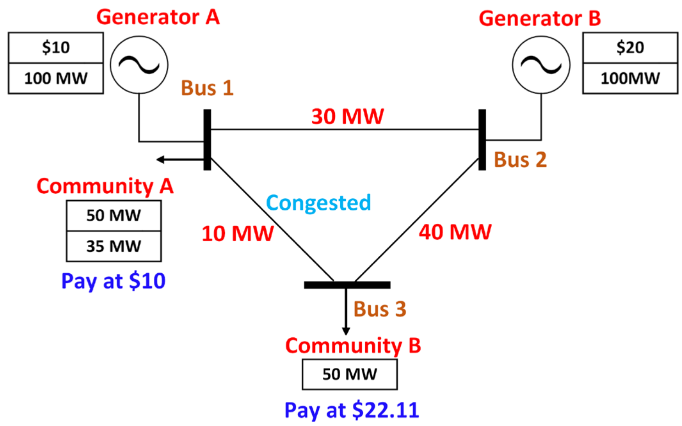

Fig. 3. Scenario 2

B. Energy Equity Concerns

The provided illustrative examples are specific scenarios, and it is possible to identify counter-scenarios within the same system that might support the current scheme. However, we only provide the above examples to discuss potential energy equity concerns in the existing LMP-based settlement.

(1) Under the existing settlement, all market participants on the same bus are settled at the same price. As in scenario 1, when both community A (high-income) and community B (low-income) consume only the essential electric load (50 MW), the marginal price is settled by the cheap generator A at $10. However, when community A consumes extra electricity for entertainment (50 MW), the expensive generator B ($20) is dispatched. The price for both community A and community B are settled at $20, even though community B remains limited to essential load consumptions. This observation illustrates a potential issue of **recognition inequity and procedural inequity** in the electricity market clearing process. Specifically, the market-clearing process prioritizes the needs of community A neglecting the economic disparities between community A and community B.

(2) The existing settlement may also exacerbate the geographical disadvantage of low-income communities. As shown in scenario 2, high-income community A is settled with a low price ($10) due to transmission congestion, even though community A consumes a large amount of electricity. In contrast, the low-income community B faces a higher price ($22.11) despite only consuming essential electricity. Therefore, this disparity will often place community B at a disadvantage because underserved communities have limited ability to relocate freely [28], and they are easily overlooked in the planning of power grid infrastructures [17]. This observation highlights a potential flaw in the distribution of benefits and burdens, suggesting a potential **distributive inequity** in the existing design. Similarly, the lack of measures to compensate

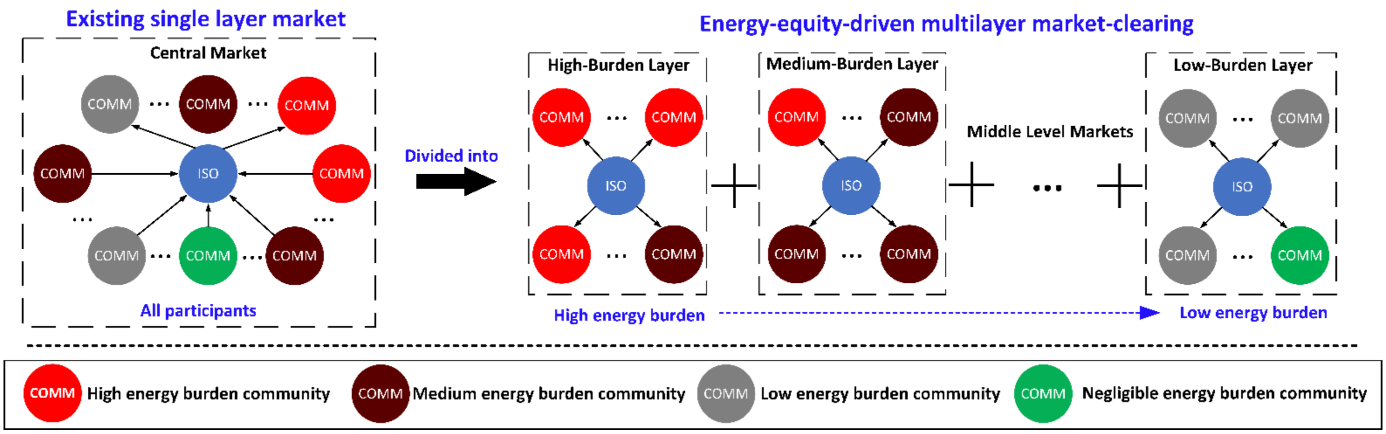

Fig. 4. Overall scheme of the energy-equity-driven multilayer market

historically underserved communities (such as community B) indicates a potential **restorative inequity** in the existing design.

IV. An Energy-equity-driven Multi-layer Market-clearing Framework

Previous sections examine the definition of energy equity and discuss potential energy inequity in the existing market-clearing process. This section presents a new energy-equity-driven multilayer market-clearing framework. Notably, utilities may simply apply different rates to different consumers to enhance energy equity, but this lacks justification on why a particular consumer should be charged at a higher rate, and how much higher. More importantly, this approach cannot tell how much each generator (producer) should contribute to enhance energy equity in the system, because electricity is pooled once produced and it is impossible to distinguish which producers contribute to the generation of each MWh consumed at a specific consumer. The proposed new multi-layer clearing model links producers and consumers together towards a rigorous approach to enhance society's energy equity. This further justifies the significance of the proposed method.

A. *Structure of the energy-equity-driven multi-layer market-clearing framework*

The proposed framework sequentially clears participants in different layers. This multilayered framework conceptually resembles a tax bracket system, where electricity prices are adjusted from the perspective of equity. Under this framework, underserved communities benefit from lower electricity prices, while more advantaged communities may incur higher charges. The framework is built on several foundational assumptions and key points, detailed as follows:

- The proposed framework divides the market participants according to their energy burden, which is defined as the ratio of energy expenditure to total household income [25]. There are many factors that may affect the value of energy burden, such as the local fuel price and the accessibility to energy-efficient homes, but low-income communities generally have a high energy burden value [29]. The proposed framework is also flexible to incorporate other indices that properly represent energy equity.
- Market participants are divided into three layers: the high-burden layer, the medium-burden layer, and the low-burden layer. This structure could be extended to include additional layers. The number of layers and the dividing criterion are based on the operators' preferences. To prevent disproportionate charges to the low-burden layer, it's recommended that the loads managed in both the high-burden and medium-burden layers are kept smaller relative to the load in the low-burden layer.
- In each layer of the proposed framework, there are two components: a market-clearing model and a price adjustment model. The market is cleared sequentially from the high-burden layer to low-burden layer, as shown in Fig. 4. This sequential process ensures a lower price in the high-burden and medium-burden layers, and a higher price in the low-burden layer. Within each layer, the price adjustment recalibrates prices for different participants based on their energy burdens or geographic advantages.
- The price adjustment does not affect generation cost recovery and revenue adequacy since it is designed to be revenue-neutral. **Nonetheless, the price adjustment will relatively decrease overall social welfare, which aligns with the principle of distributive equity that certain communities shouldn't bear excessive burdens in the pursuit of maximizing overall social welfare.** Further, the operators can adjust the threshold of different layers to control the price adjustment. The proposed energy-equity-driven multilayer framework provides a fundamental model for future power system energy equity works.
- Following the existing practices of independent system operators (ISOs), the economic dispatch and pricing are determined after the unit commitment decisions have been made (with fixed commitment decisions) [23]. Therefore, in the proposed framework, the outcomes of unit commitment directly influence the availability of units in the economic dispatch model, with this impact being implicitly integrated into the pricing results. Although a detailed exploration of an explicit unit commitment model is beyond the scope of this paper, examining unit commitment decisions through an equity lens presents valuable future research.

In the proposed framework, the market clearing at the high-burden layer aims to deliver the lowest possible electricity prices to communities with very high energy burdens, while the market clearing at the medium-burden layer provides affordable electricity prices to communities with relatively high energy burdens. The low-burden layer clears the rest of the participants together. The overall structure of the proposed framework is shown in Fig. 4, and each layer will be discussed in detail in the following subsections A.1 to A.3.

A.1 High-burden Layer

This high-burden layer is exclusive to underserved communities, whose energy burdens are high. These communities are assumed to barely afford the current electricity bill. The amount of load cleared in this market is assumed to be small. Generators with low marginal costs, such as nuclear and renewables, are generally cleared in the high-burden layer.

Market-clearing Model

The market-clearing model at this layer is the same as the existing single-layer model (1)-(4). The resulting energy price component in the LMP is low, and there is generally no congestion since the load amount is small.

Price Adjustment

Although low energy prices are ensured in this market, the prices at different communities are adjusted to reflect their energy burdens. The following equations (6)-(8) are considered to adjust the LMPs for each community. Equation (6) ensures that the sum of the payment before the adjustment equals the sum of the payment after the adjustment.

$$\sum_i LMP_i^{new} D_i^f = LMP_i^F \sum_i D_i^f, \forall i \in N^F \quad (6)$$

$$LMP_i^{new} \leq LMP^{cap}, \forall i \in N^F \quad (7)$$

$$LMP_i^{new} = LMP_i^F (\frac{E_i^F}{E_{ref}^F})^\alpha, \forall i \in N^F \quad (8)$$

Equation (7) sets up a cap on the adjusted price, guaranteeing that it remains within a certain limit determined by the market operators' preferences. In this high-burden layer, price adjustments are made according to the difference in energy burden across different communities. Implementing a price cap in this layer is essential to prevent overly large adjustments at the relatively low-burden communities at this layer because these communities still experience a significant energy burden. The actual value of the price cap considering energy burden can be empirically determined based on different markets' rules, similar to the current practice of price cap at various ISOs. Equation (8) adjusts the price based on the ratio of a community's energy burdens over the median energy burden at this layer. The higher the energy burden, the lower the electricity price. The marginal price from the dual variable is assigned at the reference burden, and the prices for all the communities are distributed around the marginal price based on a scale factor, *α*. The value of *α* is based on the operators' preference.

A.2 Medium-burden Layer

The medium-burden layer targets underserved communities whose energy burdens are relatively high. These communities are assumed to be only able to afford their essential electricity load but have difficulty covering electricity bills that would sustain a more comfortable lifestyle.

Market-clearing Model

The marginal prices in this market are expected to be higher than the marginal prices in the high-burden layer. The market-clearing model is similar to equations (1)-(4), but the transmission constraints are different. Equations (9) and (10) replace the original transmission constraint (4) considering the scheduled power flow in the high-burden layer. When sequential clearing is performed, the unused transmission capacity of the previous layer rolls over to the next layer.

$$L_l^{\min} - \sum_i GSF_{l,i}(P_i^F - D_i^F) \leq \sum_i GSF_{l,i}(P_i^M - D_i^M), \forall l \quad (9)$$

$$\sum_i GSF_{l,i}(P_i^M - D_i^M) \leq L_l^{\max} - \sum_i GSF_{l,i}(P_i^F - D_i^F), \forall l \quad (10)$$

Price Adjustment

After the LMPs are solved from the market-clearing model, the following pricing scheme (11)-(18) adjusts the congestion price component based on the value of the energy burden. Although all participants in the medium-burden layer have a relatively high energy burden by comparison to all market participants, the energy burden of some participants may be almost high enough to enter the high-burden layer, and the energy burden of some participants may be almost low enough to enter the low-burden layer. As discussed in Subsection III-B, congestion could bring price advantages/disadvantages to certain communities. Therefore, a scheme is needed to adjust and reflect the geographical and energy burden differences. The scheme in (11)-(18) decreases the price for disadvantaged communities with higher energy burdens, while it increases the price for advantaged communities with low energy burdens.

Participating communities in the medium-burden layer are divided into two sets: *help* set and *need* set (i.e., Set^{need}, Set^{help}) for each congested line. The *need* set contains those communities whose energy burden is higher than the average energy burden in the medium-burden layer, and the congestion price term is higher than the average price (i.e., price disadvantage due to congestion). As shown in (11) and (12), the *need* set Set^{need} is the intersection of Set_E^M and Set_D^M.

$$Set_E^M = \{i \mid E_i^M \geq E_{ref}^M, \forall i \in N^M\} \quad (11)$$

$$Set_D^M = \{i \mid GSF_{l,i}(\mu_l^- - \mu_l^+) \geq \sum_{i \in M} \frac{GSF_{l,i}(\mu^- - \mu^+)}{N^M}, \forall i \in N^M\} \quad (12)$$

Similarly, the *help* set contains those communities whose energy burden is lower than the average energy burden in the medium-burden layer, and the congestion price term is lower than the average price at the same time (i.e., price advantage due to congestion), which is a reverse of the *need* set in (11) and (12).

This article has been accepted for publication in IEEE Transactions on Energy Markets, Policy, and Regulation. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEMPR.2024.3377210

Equation (13) gives the objective function maximizing price adjustments. Equation (14) ensures that price adjustment does not increase the price at any of the communities in the *need* set. Equation (15) ensures that the total compensation to the *need* set equals the adjusted payment from the *help* set. Equations (16) and (17) adjust the congestion price at different communities accordingly. Equations (18)-(21) explain the formulation of parameters in (16) and (17). If communities in the *help* set receive the price advantage resulting from congestion, equation (17) collects the price advantage based on their energy burden and the amount of the price advantage. Equation (16) distributes the collected price advantage to communities in the *need* set based on their energy burden and price disadvantage. It is worth noting that if there is no congestion in the middle-burden market, the value of $J_{i,j}^{n}$ and $J_{i,j}^{h}$ are both set to 1. Equation (22) represents the upper and lower boundary of the price adjustment. Equation (23) shows the price at each community after the adjustment.

$$\text{Max} \sum_{i\in Set^{need}} \sum_{l} \left|\Delta\phi_{l,i}^{M}\right| \tag{13}$$

$$\sum_{l} \Delta\phi_{l,i}^{M} GSF_{l,i} \le 0, \forall i \in Set^{need}, \forall l \in N_{l}^{cog} \tag{14}$$

$$\sum_{i\in Set^{need}} \Delta\phi_{l,i}^{M} GSF_{l,i} D_{i}^{M} = \sum_{i\in Set^{help}} \Delta\phi_{l,i}^{M} GSF_{l,i} D_{i}^{M}, \ \forall l \in N_{l}^{cog} \tag{15}$$

$$\Delta\phi_{l,i}^{M} GSF_{l,i} = (R_{i,j}^{n} J_{i,j}^{n})^{\beta} \Delta\phi_{l,j}^{M} GSF_{l,j}, \forall (i,j) \in Set^{need}, \forall l \in N_{l}^{cog} \tag{16}$$

$$\Delta\phi_{l,i}^{M} GSF_{l,i} = (R_{i,j}^{h} J_{i,j}^{h})^{\beta} \Delta\phi_{l,j}^{M} GSF_{l,j}, \forall (i,j) \in Set^{help}, \forall l \in N_{l}^{cog} \tag{17}$$

$$R_{i,j}^{n} = \frac{(E_{i} - E_{ref}^{M})}{(E_{j} - E_{ref}^{M})}, \forall (i,j) \in Set^{need} \tag{18}$$

$$R_{i,j}^{h} = \frac{(E_{ref}^{M} - E_{j})}{(E_{ref}^{M} - E_{i})}, \forall (i,j) \in Set^{help} \tag{19}$$

$$J_{i,j}^{n} = \frac{(GSF_{l,i}(\mu_{l}^{-} - \mu_{l}^{+}) - \sum_{i} \frac{GSF_{l,i}(\mu_{l}^{-} - \mu_{l}^{+})}{N^{M}})}{(GSF_{l,j}(\mu_{l}^{-} - \mu_{l}^{+}) - \sum_{i} \frac{GSF_{l,i}(\mu_{l}^{-} - \mu_{l}^{+})}{N^{M}})}, \forall (i,j) \in Set^{need} \tag{20}$$

$$J_{i,j}^{h} = \frac{(\sum_{i\in N^{M}} \frac{GSF_{l,i}(\mu_{l}^{-} - \mu_{l}^{+})}{N^{M}} - GSF_{l,i}(\mu_{l}^{-} - \mu_{l}^{+}))}{(\sum_{j\in N^{M}} \frac{GSF_{l,j}(\mu_{l}^{-} - \mu_{l}^{+})}{N^{M}} - GSF_{l,j}(\mu_{l}^{-} - \mu_{l}^{+}))}, \forall (i,j) \in Set^{help} \tag{21}$$

$$\Delta\phi^{\min} \le \Delta\phi_{l,i}^{M} \le \Delta\phi^{\max} \tag{22}$$

$$LMP_{i}^{new} = LMP_{i}^{M} + \sum_{l} \Delta\phi_{l,i}^{M} GSF_{l,i}, \forall i \in N^{M} \tag{23}$$

A.3 Low-burden Layer

The low-burden layer is available to all other participants. In this layer, communities have very low energy burdens. These communities are assumed to be able to easily pay their current electricity bills.

Market-clearing Model

The modeling of the low-burden layer is similar to the medium-burden layer model. The transmission limits need to consider the scheduled power flow in the high-burden layer and medium-burden layer.

Price Adjustment

Some of the cheap units are cleared in the high-burden layer and medium-burden layer, and thus, the price in the low-burden layer is expected to be much higher than the price in the other markets. Further, generators participating in the high-burden layer and medium-burden layer have an opportunity cost since they would have been cleared in the low-burden layer for a higher price. The opportunity costs are compensated by the low-burden layer participants, as shown in (23)-(25). Equation (24) distributes the compensation based on energy burdens, and equation (25) ensures that opportunity costs are fully covered.

$$\frac{\Delta\phi_{i}^{T}}{\Delta\phi_{j}^{T}} = (\frac{E_{j}^{T}}{E_{i}^{T}})^{\chi} \tag{24}$$

$$\begin{aligned}\sum_{i} \Delta\phi_{i}^{T} \times D_{i}^{T} = & \sum_{i} P_{i}^{M} \times (LMP_{i} - LMP_{i}^{M}) \\ & + \sum_{i} P_{i}^{F} \times (LMP_{i} - LMP_{i}^{F})\end{aligned} \tag{25}$$

$$LMP_{i}^{new} = LMP_{i}^{T} + \Delta\phi_{i}^{T} \tag{26}$$

In this way, the incentive for generation stays the same, but the payment from the load is adjusted from the perspective of energy equity. Further, a concept of equity credit is introduced to motivate generators to prioritize participation in the high-burden layer and medium-burden layer. Based on equation (24), generators that participate in the high-burden layer and medium-burden layer are assigned equity credits.

$$\text{equity credit} = EC^{T} \times P^{T} + EC^{M} \times P^{M} \tag{27}$$

A list of owners with the most equity credits could be publicly released by ISOs to show their contribution to promoting energy equity. The equity credit in this paper is similar to a score system, which has no financial meaning, but future studies may investigate trade systems of equity credits. The opportunity cost of generators in the high-burden and medium-burden layers is compensated by the extra payment from the low-burden layer. Therefore, generator participation in the high/medium-burden layers is equivalent to participation in low-burden layer, and the equity credit provides sufficient motivation for the generators to prioritize participation in the high-burden layer and the medium-burden layer.

The implementation of the framework can be found in the following procedure table. Notably, in our design, the price adjustment for congestion is not implemented in the high-burden and low-burden layers. This is because the price adjustment at the low-burden layer is intended to increase prices to offset generators' opportunity costs incurred in the high-burden and medium-burden layers. The price adjustment for the low-burden layer only slightly adjusts the price based on the energy burden to further lower the price for very high-burden

This article has been accepted for publication in IEEE Transactions on Energy Markets, Policy, and Regulation. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEMPR.2024.3377210

communities. However, the price adjustment for congestion can be implemented in both the low-burden and high-burden layers similarly if the operator prefers.

Procedure	Multilayer market-clearing (market parameters, energy burdens)
Input	Market parameters and energy burdens
Output	Price for each participant
1	Determine the energy burden threshold at each layer
	High-burden layer
2	Solve model (1)-(4) for high-burden layer participants
3	Solve the price adjustment model (6)-(8)
4	Settle the transaction for high-burden layer participants.
	Medium-burden layer
5	Update the remaining transmission capacity with (9)-(10)
6	Solve model (1)-(4) for middle-burden layer participants
7	Solve the price adjustment model (11)-(23)
8	Settle the transaction for medium-burden level participants.
	Low-burden layer
9	Update the remaining transmission capacity with (9)-(10)
10	Solve model (1)-(4) for low-burden layer participants
11	Solve the price adjustment model (24)-(26)
12	Settle the transaction for high-burden layer participants.
13	**Return** the settlements for all participants

B. Reflecting Energy Equity

This subsection discusses how the proposed multilayer framework aligns with the principle of energy equity.

- *Procedural equity*

Communities at the same layer share similar characteristics, such as energy burdens, which offer a better participation environment. Since underserved communities and advantaged communities are cleared separately, underserved communities are better able to represent themselves, instead of being represented by others. Compared with the existing market structure, where all community loads are cleared together, the multilayer market-clearing structure intrinsically aligns with procedural equity.

- *Recognition equity*

The proposed price adjustment at each layer ensures that the energy burden of each community is recognized by the market-clearing process. Existing market clearing mostly recognizes the location and amount of the load. The proposed price adjustment tunes the price at each community based on their energy burden. Setting aside the outcome of the price adjustment, recognizing the energy burden at each community through the price adjustment is a design to acknowledge the recognition equity.

- *Distributive equity*

The overall energy-equity-driven multilayer market-clearing framework provides financial settlements where underserved communities have lower energy prices, and advantaged communities have higher prices. The benefits and burdens of the electricity market are more fairly distributed from the perspective of energy burdens acknowledging distributive equity.

- Restorative equity

The power grid infrastructure tends to remain unchanged for a certain amount of time, and thus, the price adjustment will help compensate historically underserved communities. The multilayer framework compensates historically underserved communities with low prices, which repairs some previous harm.

V. Case Study

A small test system (PJM 5-bus system) is presented in subsection V-A to illustrate the proposed energy-equity-driven multilayer framework in detail. A large test system (WECC 179-bus system) is presented in subsection V-B to demonstrate the performance of the proposed framework.

A. Illustrative example of the energy-equity-driven multilayer framework

The topology and parameters of the modified PJM 5-bus system are shown in Fig. 5. Each load is assumed to be a combination of three communities. The energy burden for each community is determined based on the real-world energy burden from selected counties in the U.S [26] for illustrative purposes, although not corresponding to the service territory in PJM . The details on the energy burden are listed in Appendix Table II.

A(1) Multilayer framework vs. existing single-layer framework

Fig. 6 shows a comparative analysis between the existing single-layer framework and the proposed energy-equity-driven multilayer framework. Under the single-layer framework, the LMP in all communities is $20. In contrast, under the multilayer framework, LMPs decrease as the energy burden of communities increases. Communities with higher energy burdens experience higher reductions in prices, while communities with lower energy burdens experience a small price increase This new framework segments the market into different layers and adjusts the price based on energy burden to better represent energy equity, as opposed to the existing scheme that treats all communities equally rather than equitably.

	High-burden layer	Medium-burden layer	Low-burden layer	Revenue under existing market clearing	Opportunity cost
Alta	$0	$0	$800	$800	$0
Park City	$90	$960	$0	$3000	$1950
Solitude	$0	$160	$5600	$6000	$240
Sundance	$0	$0	$0	$0	$0
Brighton	$0	$0	$5400	$5400	$0

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Table I. Opportunity cost and compensation at each layer

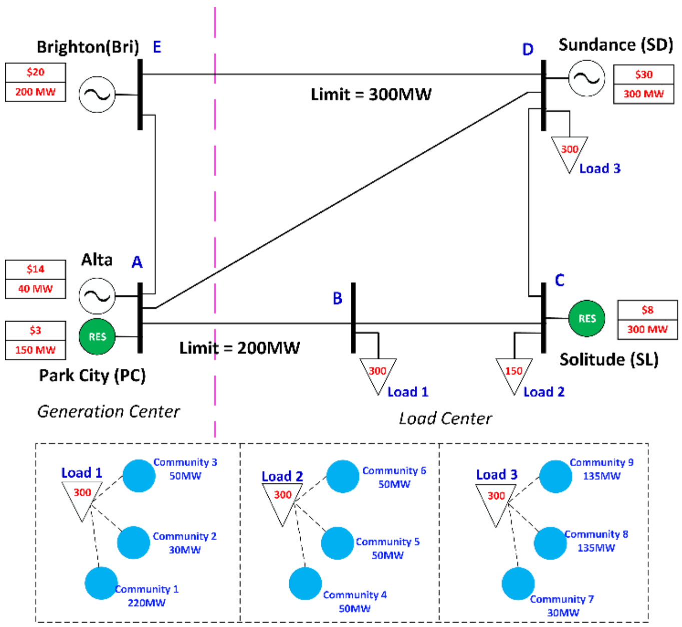

Fig. 5. Modified PJM 5-bus system as an illustrative example

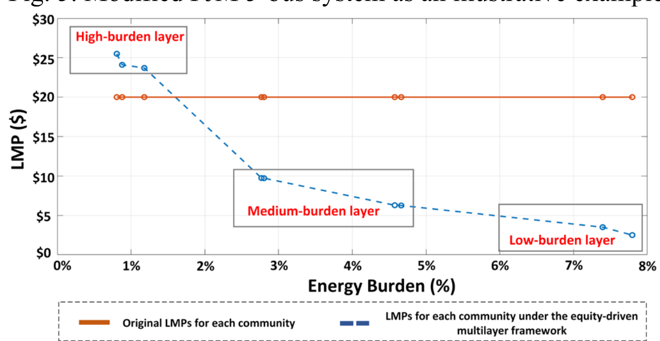

Fig. 6. LMP comparison for the modified PJM 5-bus system.

The opportunity costs incurred by units cleared in the high-burden and medium-burden layers are offset by the compensation derived from the low-burden layer. The price at the low-burden layer increases by a small amount since the amount of load that participates in the low-burden layer is much higher than the load that participates in the medium-burden layer and high-burden layer. The detailed values of the opportunity costs and compensation are shown in Table I.

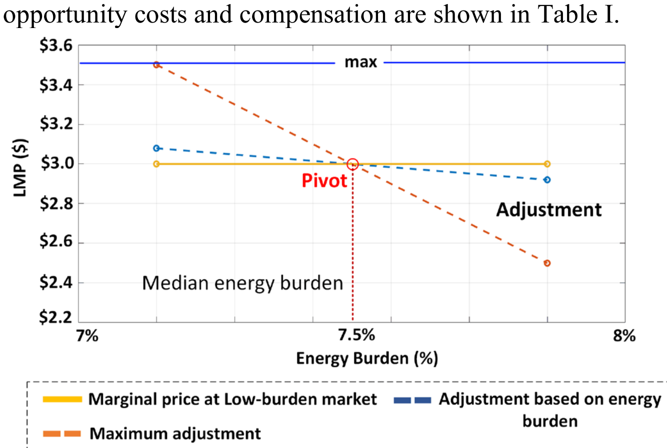

Fig. 7. Comparison of prices at low-burden layer

A(2) Details on Price adjustment

The marginal price at the high-burden layer is \$3, which is sufficiently small and affordable for underserved communities 2 and 7. Further, prices at communities 2 and 7 are adjusted based on their energy burden, as shown in the blue line in Fig. 7. Communities 2 and 7 are cleared at prices of \$3.08 and \$2.92, respectively. Although further adjustments are not recommended in the high-burden layer, the decision maker could tune the value of the weight α to adjust the price for different communities, as shown by the brown dashed line.

The marginal price at the medium-burden layer is \$8, which is higher than the high-burden layer (i.e., \$3). In the medium-burden layer, the median energy burden is 3.68%. Communities 3 and 4 fall below the median value and are thus categorized as the *help* set of the medium-burden layer. Communities 5 and 6 fall above the median value and are thus categorized as the *need* set of the medium-burden layer. Therefore, communities 3, 4, 5, and 6 are cleared at prices of \$9.74, \$9.71, \$6.30, and \$6.20, respectively. The price differences between the *help* set and the *need* set are small because the energy burden within the two sets is similar. The resulting price in the medium-burden layer is shown in Fig. 8. The pivot is located at the median energy burden. Similar to the high-burden layer, the decision maker could tune the value of the weight β to adjust the price for different communities, as shown by the brown dashed line in Fig. 8.

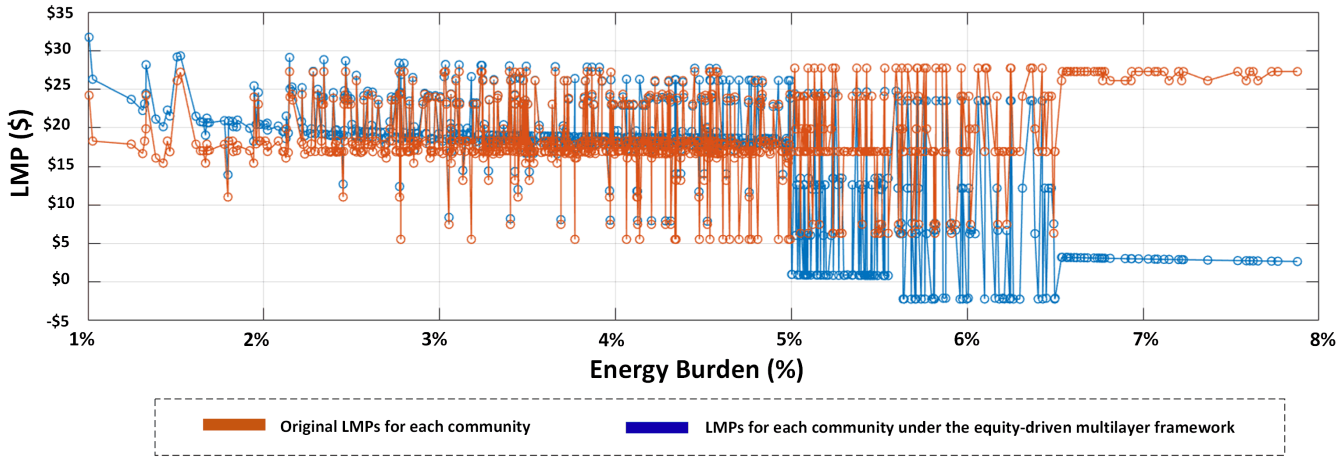

Fig. 10. LMP Comparison for the WECC 179-bus system.

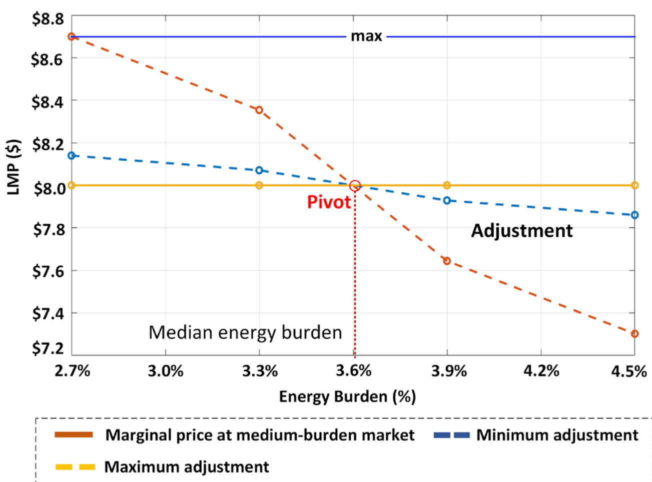

Fig. 8. Comparison of prices at low-burden layer

B. *Large-scale case study for the energy-equity-driven multilayer framework*

The large-scale case study is performed on a WECC 179-bus system based on the dataset from the CURENT Large-scale Testbed (LTB) with the one-line diagram shown in Fig. 9 [27] [34]. The system is assumed to consist of 870 communities, and the real-world energy burden in the WECC area is assigned to each community based on [26] for illustrative purposes.

The blue line in Fig. 10 shows the LMPs for each community under the existing single-layer framework. Notably, communities that have a very high energy burden are charged with high LMPs. For example, communities with an energy burden higher than 6.5% face high LMPs (i.e., $26.26) well above the average value (i.e., $18.70) across all communities. This observation implies that the existing framework may unfairly benefit certain low-burden communities at the expense of certain high-burden communities, leading to an uneven distribution of benefits and responsibilities. In contrast, the proposed framework clears different communities sequentially. The resulting LMPs in each community are shown in the brown line in Fig. 10. Compared to the existing framework, the proposed approach prioritizes underserved communities with more affordable prices. For example, in the proposed model, communities with an energy burden higher than 6.5% have an average settlement price of $3 (compared to $26.26), markedly lowering their energy expenses.

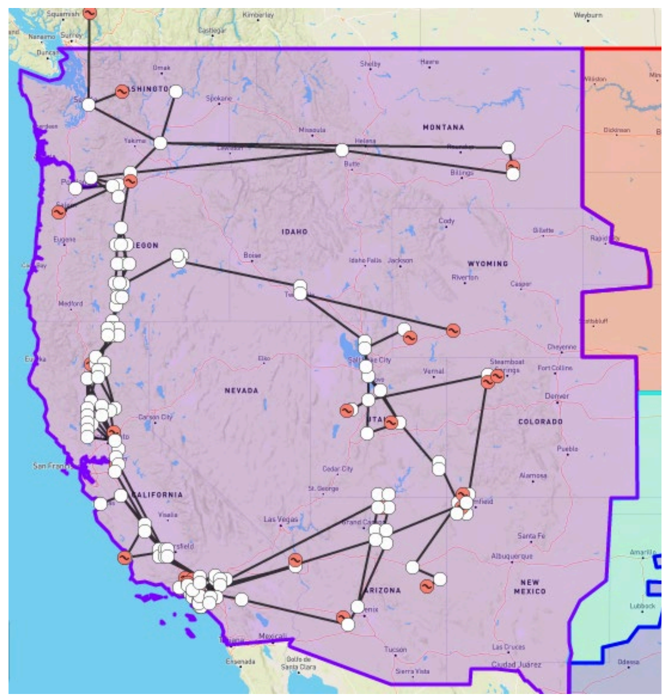

Fig. 9. WECC 179-bus system visualized in CURENT LTB.

It is worth noting that the proposed multilayer framework does not force the variation of price to align exactly with the energy burden. Thus, there may be instances where some communities with low energy burdens end up with lower prices than those with high energy burdens. As discussed in Subsection IV-A, the price adjustment model modifies the value of congestion components to adjust the price, which tends to correlate the value of the LMP with the energy burden. The proposed framework is designed to reflect the energy equity in the settlement, rather than compelling prices to change in proportion to energy burdens.

VI. Conclusion and Future Work

In summary, in this paper we have discussed the definitions and implications of energy equity in the electricity market-clearing model and provided an energy-equity-driven multilayer framework. First, we reviewed the tenets of energy equity from the social science perspective and discussed them under the scope of electricity market clearing. Second, we identified several concerns regarding energy equity in electricity market clearing and illustrated them with examples. Third, we proposed an energy-equity-driven multilayer framework to reflect energy equity in LMPs. The market-clearing results from the proposed framework acknowledge the energy burden of each community in addition to the considerations given to reliability and cost minimization. Finally, we elaborated the proposed framework with a case study of the PJM 5-bus system and a demonstration on the WECC 179-bus system.

The exploration of energy equity in power systems opens up several interesting research directions. We believe the following directions are particularly noteworthy (1) analyzing energy equity within the context of power grid decarbonization and clean electricity transition; (2) the impact of energy equity consideration on unit commitment decisions; (3) reflecting energy equity in both transmission-level and distribution-level operation models; and (4) proposing new energy equity indices considering power grid operational characteristics.

APPENDIX

Table II. Energy burden at each community (for illustrative purposes) in the PJM 5-bus system

	Energy burden	Real-world county	State
Community 1	0.81%	Summit County	UT
Community 2	0.88%	San Francisco County	CA
Community 3	2.80%	Davidson County	TN
Community 4	2.76%	Knox County	TN
Community 5	4.58%	Glades County	FL
Community 6	4.66%	Hancock County	TN
Community 7	7.39%	Wilcox County	AL
Community 8	7.80%	Buffalo County	SD
Community 9	1.18%	Somerset County	NJ

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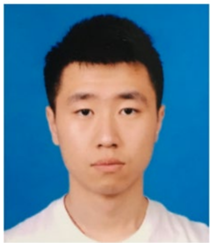
BIOGRAPHIES



Qiwei Zhang (Member, IEEE) is presently a Postdoctoral Researcher at Johns Hopkins University. Prior to this, he was a Research Scientist at the University of Tennessee, Knoxville (UTK), where he received his M.S. and Ph.D. degrees in electrical engineering in 2018 and 2022, respectively. His research interests include electricity market, power system cybersecurity, and renewable integration risk assessment.

Fangxing Li (Fellow, IEEE) is also known as Fran Li. He received the B.S.E.E. and M.S.E.E. degrees from Southeast University, Nanjing, China, in 1994 and 1997, respectively, and the Ph.D. degree from Virginia Tech, Blacksburg, VA, USA, in 2001. Currently, he is the John W. Fisher Professor in electrical engineering at the University of Tennessee, Knoxville, TN, USA. He has also been serving as the Director of CURENT since 2024. His research interests include electricity markets, renewable energy integration, demand response, distributed generation and microgrid, and power system computing. He served as the Chair of IEEE PES Power System Operation, Planning and Economics (PSOPE) Committee from 2020 to 2021. He has been serving as the Editor-In-Chief of *IEEE Open Access Journal of Power and Energy (OAJPE)* since 2020.

Dr. Li has received a number of awards and honors including R&D 100 Award in 2020, IEEE PES Technical Committee Prize Paper awards in 2019 and 2024, 5 best paper awards at international journals, and 7 best papers/posters at international conferences.