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Cutting through complexity: Coordinated demand response and future directions in global communication technologies

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ABSTRACT

The global electricity market is undergoing a transformative shift, envisioning a future resembling commodity trading platforms. Enabled by mature communication technologies, this evolution empowers energy consumers worldwide to actively engage in the energy market, negotiating arrangements for adjusting energy demand during grid stress and optimizing costs. In this era of technological advancements, this vision is materializing globally. Commercial and industrial entities are playing active roles in ancillary services markets, providing crucial grid support. Efforts are expanding to engage smaller users through third-party aggregators. However, many initiatives retain opt-in structures, limiting customer engagement. A promising solution is local energy markets, integrating modest flexibility reserves globally. This empowers small-scale users to choose services aligned with their preferences. This paper delves into the essential components facilitating the transition to globally applicable, aggregator-mediated demand-side management markets. Anchored in dynamic consumer engagement and nurtured by reciprocal information flows, this shift signals a fundamental reshaping of the global energy landscape. The paper introduces a universally adaptable demand response aggregation framework for energy enterprises to systematically devise consumer-centric programs. This framework serves as a foundational structure, fostering a strategic and flexible approach to meet evolving consumer preferences in demand response initiatives worldwide.

1. Introduction

The power industry is undergoing a substantial transformation driven by the global trend of renewable electrification, referred to as “RE-electrification”. This trend seeks to capitalize on the synergistic potential between the increasing electricity demand and non-dispatchable renewables. The synergistic potential involves the opportunity to balance energy needs with variable renewable sources, contributing to a more sustainable and resilient energy system. This coordination spans diverse end-use sectors, encompassing residential, commercial, industrial, agricultural, and transport domains (International Renewable Energy Agency (IRENA), 2019; Harsh and Das, 2022; Bardwell et al., 2023). The role of demand-side in transforming the functioning of electricity markets is anchored upon three foundational pillars, namely (COAG Energy Council, 2020; Mohseni et al., 2022; Mobtahej et al., 2022; Bashir et al., 2023): (i) the escalating integration of distributed, small-scale, geographically-dispersed energy resources such as renewable generation and storage technologies into the energy mix, (ii) the dynamic bidirectional exchange of electricity and information, facilitating end-consumers’ ability to contribute services that bolster grid operations, and (iii) the transformative redefinition of the relationship between electric utilities and customers, evolving utilities into service providers rather than mere commodity suppliers.

This dynamic landscape is underpinned by advancements in information and communications technologies, control systems, and computational methodologies that are revolutionizing electricity market mechanisms within the framework of the smart grid. Central to this evolution is the emergence of the "two-sided energy marketplace" concept, which heralds a paradigm shift from the traditional "load-following" model to a "supply-following" approach, aimed at achieving

Abbreviation: AMI, advanced metering infrastructure; ANSI, American National Standards Institute; API, application programming interface; CPN, customer premises network; DCU, data concentrator unit; DR, demand response; DRA, demand response aggregator; DSM, demand-side management; ETSI, European Telecommunications Standards Institute; HAN, home area network; HVAC, heating, ventilation, and air conditioning; IAN, industrial area network; ISO, independent system operator; IoT, Internet of Things; LAN, local area network; M2M, machine-to-machine; MQTT, message queuing telemetry transport; NAN, neighborhood area network; NIST, U.S. National Institute of Standards and Technology; Open ADR, Open Automated Demand Response; PLC, power line communication; TCP/IP, Transmission Control Protocol/Internet Protocol; WAN, wide area network.

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cost-effective flexibility solutions (Shezan, 2022; Mohamed et al., 2022). This model fosters direct interaction between energy suppliers and end-consumers, enabling the latter to actively propose the price at which they are willing to curtail their loads. This stands in contrast to conventional setups where responses are limited to independent system operator (ISO)-issued price signals. The ISO evaluates load reduction bids alongside bids from wholesale generators, ultimately clearing the market in alignment with the chosen settlement format – uniform price or sealed-bid first price. This difference highlights the shift towards a more responsive and customer-centric energy market, where consumers have the flexibility to participate in a way that aligns with their needs and financial considerations (Burger et al., 2016; Morey, nd; CGI Group Inc, 2016; Thang et al., 2022).

While double-sided auctions are prevalent in deregulated electricity markets, they are predominantly accessed by large-scale commercial and industrial entities capable of competing with generators. Yet, smaller end-users in residential, agricultural, and electric vehicle charging segments can also access the wholesale market through intermediaries such as demand response aggregators (DRAs) or demand response (DR) service providers. These intermediaries bundle the interruptible load of sector-specific customers with similar capabilities, achieving competitive capacity thresholds through economies of scale. This framework enhances transparency, in contrast to bilateral off-market programs between utilities and DRAs. By aggregating the loads of sector-specific customers with similar capabilities, economies of scale are achieved. This means that the aggregated DR can reach competitive capacity thresholds more effectively. As a result, the pricing and participation information in the market becomes more visible and accessible, leading to increased transparency. In contrast, bilateral off-market programs between utilities and DRAs may not provide the same level of transparency, as they may involve private negotiations and agreements that are less visible to the broader market (Harsh and Das, 2022; Rocky Mountain Institute, 2006; Equipment Energy Efficiency (E3), 2019; Australian Renewable Energy Agency (ARENA), 2020; International Energy Agency (IEA), 2003).

Despite these efforts, existing load aggregation programs have encountered challenges in engaging smaller customers and delivering value-added services. This can be attributed to the typical opt-in, mandatory participation structure wherein voluntarily enrolled customers lack the capacity to override aggregator-initiated DR events. The potential solution resides in the establishment of local flexibility markets at the lower retail level of double-sided electricity markets. Such a platform empowers end-users to express time-varying DR preferences and strategic behaviors, granting greater control over load reduction decisions based on wholesale price incentives. This approach also mitigates volume risk management costs associated with non-customer-centric designs (Guerrero et al., 2020; Tostado-Véliz et al., 2023; Fan, 2023; Tostado-Véliz et al., 2023).

This paper aims to underscore the economic potentials and synergies arising from the integration of wholesale and retail markets to enhance cost-effective flexibility procurement. It presents a systematic overview of crucial design components and trading mechanisms of two-sided energy markets, introducing a prototypical aggregator-mediated transactive energy market design. Additionally, the paper delves into a comparative exploration of pertinent communication technologies, protocols, standards, and control system requisites required for the successful implementation of coordinated, aggregator-mediated two-sided energy markets.

In this paper, the focus is on the economic potentials and synergies resulting from the integration of wholesale and retail markets for cost-effective flexibility procurement. While the concept of an aggregator-mediated transactive energy market design is not entirely new, novel elements, such as advanced DR mechanisms and real-time pricing structures, have been introduced to enhance its effectiveness and efficiency, distinguishing this approach from existing knowledge.

2. Aggregator-facilitated bilateral markets: enabling coordinated energy exchange

The paradigm of aggregator-mediated two-sided energy markets establishes a foundational framework for orchestrating a harmonious interplay between electricity generation and demand across the network, encompassing diverse entities and users. In stark contrast to the prevailing hierarchical structure characterizing established electricity markets, the two-sided model is based on a dynamic platform marked by bidirectional information and financial incentive signals, all underpinned by standardized market protocols (Guerrero et al., 2020). Illustrated in Fig. 1, this framework embodies a schematic representation of the archetypal aggregator-mediated, two-sided electricity market.

As depicted in Fig. 1, the elemental constituents underpinning aggregator-mediated two-sided energy markets encompass the following (Guerrero et al., 2020):

- Independent generators, distribution companies, third-party aggregators/retailers, end-consumers, and the ISO.
- The power grid, serving as the physical and technical nexus, navigating inherent constraints.
- Regulatory and financial frameworks governing the market dynamics.
- The intricate web of computational, control, and communication requisites that facilitate seamless interaction.

The trading arrangements intrinsic to the implementation of aggregator-mediated two-sided energy markets can be classified into three distinct categories, delineated by their varying degrees of automation: manual, semi-automated, and fully automated DR transaction frameworks.

In the manual architecture, responsive customers have complete discretion in determining their level of involvement in demand-side management (DSM) schemes. The semi-automated DR configuration introduces an automated layer into the equation, incorporating central control systems managing specific service delivery points and flexible loads within designated locations (Canmet Energy, 2011). This layered system supplements manual operational aspects.

Fully automated DR, the pinnacle of automation, entails a seamless orchestration of events. In such a scheme, a DR administrator transmits automated signals to intermediary retailers and end-consumers. This initiates connectivity to the entire ensemble of participating end-devices situated within a service location. This holistic integration is overseen by a centrally managed control system, effectively eliminating any manual intervention (Berkeley National Laboratory, 2012).

The intricate interplay of these trading arrangements forms the basis upon which the aggregator-mediated two-sided energy market landscape is situated, enabling optimal energy exchange in a digitally charged energy ecosystem.

Table 1 provides a comprehensive summary of the key differences between the conventional approach and the proposed two-way, aggregator-mediated demand side market. This comparative analysis is organized based on various attributes, offering insights into the contrasting features of the two approaches. The detailed breakdown in this table aims to enhance clarity and facilitate a better understanding of the innovations introduced in the proposed model for DR provision.

3. Facilitating smart grid technologies for aggregator-led dual-direction markets

3.1. Pivotal role of metering infrastructure

The realization of aggregator-triggered participation from end-consumers, aimed at reducing electrical consumption during predicted system-wide peak periods on a day-ahead decision-making basis, is

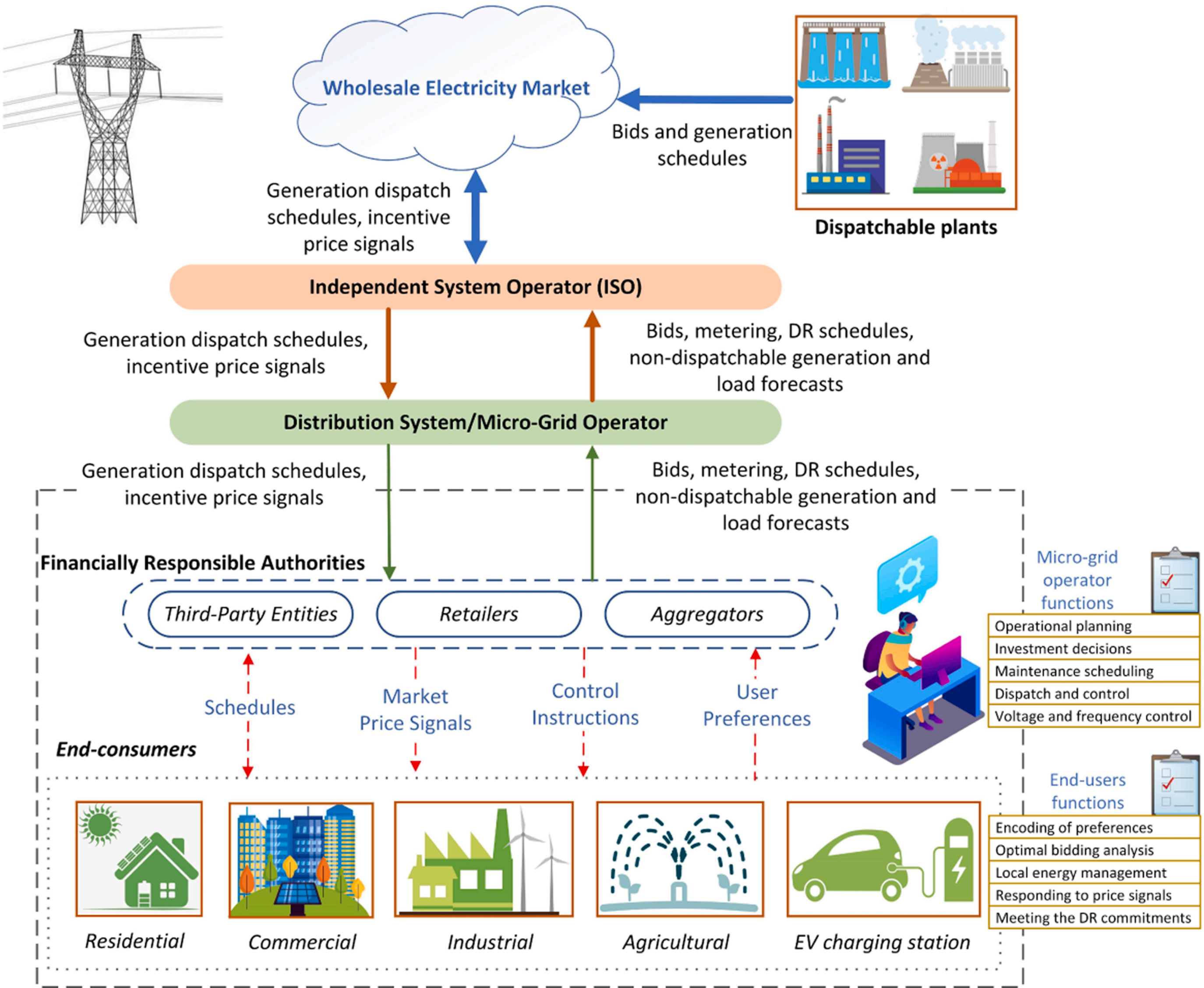

Fig. 1. Conceptual representation of an aggregator-mediated two-sided electricity market framework (adapted from Guerrero et al., 2020).

Table 1
Comparative analysis of conventional and proposed two-way, aggregator-mediated DR provision approaches.

Attribute	Conventional approach	Proposed approach (two-way, aggregator-mediated)
Market structure	Centralized, single-directional	Decentralized, bidirectional
Communication protocol	Point-to-point, limited information flow	Multi-agent, enhanced information exchange
Participant engagement	Passive consumers	Active engagement, demand response participation
Data handling and privacy	Centralized, limited privacy measures	Distributed, enhanced privacy protocols
Flexibility in demand response	Limited, predetermined schedules	Dynamic, real-time demand response
Decision-making mechanism	Centralized control	Distributed decision-making
Economic incentives	Fixed pricing models	Dynamic pricing, incentive mechanisms
Overall system efficiency	Standardized operations	Optimized resource utilization, efficiency
Scalability	Limited scalability	Scalable architecture, adaptive to growth

hinged upon the appropriate enabling technologies, contingent on the level of automation intrinsic to the trading arrangements. In particular, the integration of a double-sided competitive energy market complemented by a localized (retail) flexibility market within the distribution network, harmonized with the overarching utility-level wholesale market, demands the strategic deployment of select enabling smart grid technologies (Tostado-Véliz et al., 2023; Paterakis et al., 2017). These pivotal technologies encompass advanced metering infrastructure (AMI), control infrastructure, and communication infrastructure. The ensuing sub-sections delve into these technology categories, while offering insights into the requisite technologies for realizing the standard representative model (depicted in Fig. 1) within both manual and fully automated architectures. It is noteworthy that the semi-automated implementation necessitates the development of the underlying technologies and software capabilities intrinsic to both manual and fully automated configurations. In all scenarios, the role of the DR program administrator, often the distribution network operator, in collaboration with third-party aggregators, remains pivotal in communicating curtailment events to end-consumers for critical operating hours on the following day. The central point lies in the manner in which physical DR products are enacted in real-time (Berkeley National Laboratory, 2012).

As mentioned above, the cornerstone of a decentralized DR provision platform lies in the introduction of a localized (retail) flexibility market. Such an innovative market structure enables end-users to offer and trade their flexibility resources, such as modifying energy consumption patterns or providing DR services during peak periods. The key features of this market include transparent pricing mechanisms facilitated by advanced communication technologies and a user-friendly interface. This empowers consumers to make informed decisions aligned with their preferences and energy requirements. Additionally, the market fosters a dynamic ecosystem by integrating renewable energy sources and enhancing grid stability through strategic deployment of localized flexibility.

3.1.1. Essence of metering infrastructure

At the core of the double-sided energy market paradigm is the smart metering infrastructure, serving as the vital channel for two-way communication between meters and central systems. It stands as the main platform for accurate measurement and verification of the actual delivery of DR resources, alongside the ensuing financial settlements (Paterakis et al., 2017). While the conventional practice dispatches DR resources at an hourly resolution for the upcoming day, real-time metering and data presentation assume paramount importance to ensure the seamless execution of proposed DSM strategies. When demand-side flexibility resources become integral to a distribution network's resource portfolio, the designated DR program must translate to real-time adjustments. This necessitates providing the originally promised capacity even when making real-time adjustments. That is, the commitment to deliver the initially agreed-upon capacity remains unchanged despite any on-the-fly modifications or adaptations (Berkeley National Laboratory, 2012).

Of particular significance is the real-time performance monitoring enabled by the AMI – a consortium of smart meters, communication networks, and data management systems. During system-level DR dispatch, this monitoring empowers DRAs to validate the cumulative actual load reductions delivered across their extensive portfolios, ensuring alignment with corresponding day-ahead commitments. It also equips DRAs to address discrepancies through real-time DR markets, should any committed dispatch fail to materialize as expected (Berkeley National Laboratory, 2012). Notably, the optimal functioning of real-time balancing DR markets aligns with a pay-as-bid (discriminatory) settlement format, given the constraints imposed by very short gate closure times (Tostado-Véliz et al., 2023; Vlachos and Biskas, 2013). Furthermore, from the end-consumer perspective, particularly for larger load points responding with a degree of manual control, real-time data provisioning furnishes them with the means to verify their adherence to intended responses.

3.1.2. Command and control infrastructure

Central to large-scale, consumer-centric DR implementation is load control equipment, pivotal for remotely managing the energy supply to interruptible end-use devices such as heating, ventilation and air conditioning (HVAC) systems, and refrigeration systems, amongst others. This equipment, often integrated into the smart metering kit at customer service delivery points, assumes a paramount role. Automated delivery of processed DR mandates specific instructions relayed to smart energy management and control systems or in-unit controllers. These instructions initiate pre-defined curtailment actions aligned with cleared ordered pairs of price and DR supply quantity in the retail DSM market, informed by hourly-day-ahead considerations (Berkeley National Laboratory, 2012).

On a broader spectrum, tailored hour-specific demand reduction strategies, governed and directed by end-use participants, can be pre-programmed into site-wide energy management and control systems using open application programming interfaces (APIs). This feature empowers the formulation of automated trading strategies, thus dictating responses to aggregator-posted transactive DR incentive signals during the iterative market clearance process, thereby minimizing human intervention. Similarly, the interactions between DRAs, distribution network operators, and end-consumers, whether at the wholesale or retail level, can be fully automated through specifically programmed controllers, accommodating pre-defined sectoral elasticity of customer-supplied DR capacity – a paramount parameter impacting the DRAs' profit objectives (Neuhoff et al., 2016; Mansouri et al., 2023; Taheri et al., 2023).

End-use participants can exercise their preferences by choosing to opt in or out of specific demand-side management programs. They will receive information about the expected costs and benefits associated with their preferences during the enrollment process, ensuring that they can make informed decisions about their participation when signing up, rather than after the transactions take place (Neuhoff et al., 2016; Mansouri et al., 2023; Taheri et al., 2023).

3.1.3. Robust communications infrastructure

For technology-enabled DR deployments spanning small- to medium-scale landscapes, necessitating the efficient transfer of substantial data volumes, a low-latency, moderate-bandwidth communication pathway is indispensable. This pathway serves as the channel through which diverse deployment targets exchange signals and messages. Three distinct data communication domains can be considered for aggregator-mediated DR flexibility markets, namely: customer premises networks (CPNs), inclusive of home area networks (HANs) and industrial area networks (IANs); neighborhood area networks (NANs); and wide area networks (WANs). Importantly, the terms CPN and HAN are often utilized interchangeably within the literature, encompassing not only residential, but also commercial, industrial, agricultural, and electric vehicle charging segments (Paterakis et al., 2017). The interconnectedness of these domains is succinctly portrayed in Fig. 2, illustrating their interplay against the backdrop of the AMI network scope.

3.1.3.1. Home area network (HAN). A pivotal component of the HAN is the smart meter, aggregating sensor inputs from varied service delivery points while concurrently facilitating control commands to in-unit controllers. Communication technologies within the HAN domain span wired and wireless categories. Established wired options encompass power line communication (PLC), fiber optics, and Ethernet. However, the increasing deployment of wireless technologies in the HAN domain, driven by declining costs, is worth mentioning. Noteworthy wireless communication technologies include Zigbee Alliance, EnOcean Alliance, Z-wave, HomePlug, Bluetooth, Wi-Fi Alliance, Insteon, and cognitive radio (Meng et al., 2014; Mahmood et al., 2015; Kuzlu et al., 2014).

3.1.3.2. Neighborhood area network (NAN). The NAN domain encapsulates the critical last-mile communications between smart meters and DRAs, bridging the gap between CPN and WAN realms through data concentrator units (DCUs). These multi-interface (wired and wireless) units aggregate smart meter data within their territory, forming the channel between CPNs and the larger WAN domain. In this area, wired communication technologies such as PLC, Ethernet, and fiber optics find relevance, while wireless technologies such as WiMAX and cellular (3 G/4 G/LTE) operate within limited scope (Meng et al., 2014; Mahmood et al., 2015; Kuzlu et al., 2014).

3.1.3.3. Wide area network (WAN). The WAN takes center stage as the principal medium connecting NAN data concentrators, DRA control centers, distribution network control centers, and the ISO. Similar to HAN and NAN domains, the WAN divides into wired and wireless subdomains. Fiber optics, coaxial cable, and Ethernet serve as established wired technologies, while suitable wireless candidates include WiMAX, cellular, and satellite communications. Among the gamut of options, deploying a WAN over fiber optics cabling emerges as the most widely preferred choice to meet the stringent communication requisites of community energy systems, aligning optimal cost and reliability (Meng

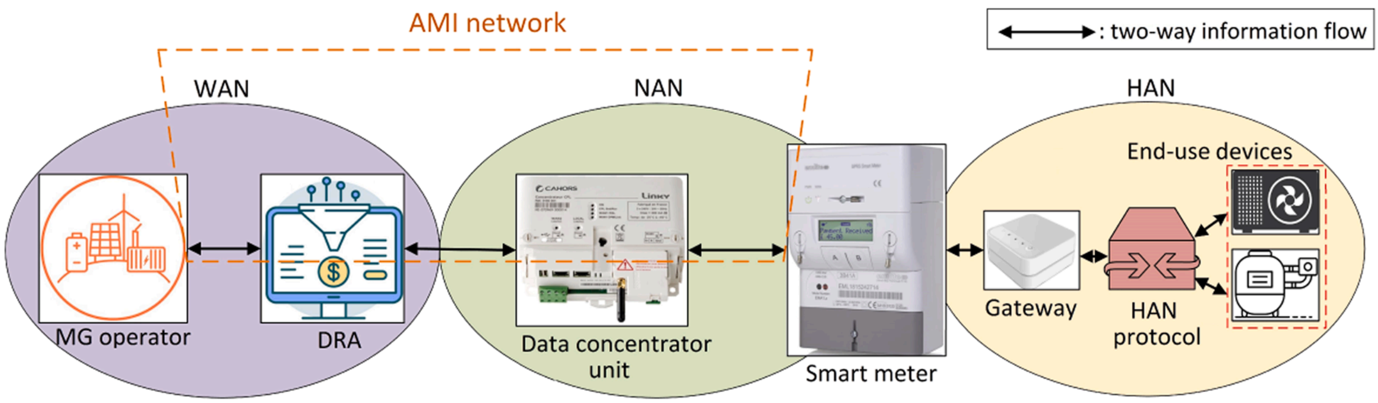

Fig. 2. Interconnectedness of communication paths in aggregator-mediated DR deployments.

et al., 2014; Mahmood et al., 2015; Kuzlu et al., 2014).

In describing the communication network within residential areas, a three-layered structure emerges, anchored by a network of gateways. Specifically, home gateways, DCU stations (neighborhood gateway nodes), and a master gateway station collectively form this architecture, creating a multi-tiered structure characterized by distinct gateways and communication pathways (Meng et al., 2014).

Fig. 3 offers a succinct summary of the data rate and coverage range requisites spanning three tiers of a smart grid, pivotal for implementing the standard representative aggregator-mediated two-sided market framework (Kuzlu et al., 2014).

The symbiotic interplay between these core technologies sets the stage for a robust and efficient aggregator-led dual-direction energy market, driving the optimization of electricity demand and supply within the evolving smart grid paradigm.

4. Communication protocols and standardization for demand response

4.1. Standardization initiatives

The pursuit of standardized communication protocols for DR initiatives has been a focal point of endeavors spearheaded by the Institute of Electrical and Electronics Engineers (IEEE). A host of significant standards development organizations, including the U.S. National Institute of Standards and Technology (NIST), the American National Standards Institute (ANSI), the International Organization for Standardization (ISO), and the European Telecommunications Standards Institute (ETSI), have joined forces to establish common frameworks. Illustrating the spectrum of notable communications standards across various domains within the DSM context, Fig. 4 encapsulates the vital efforts taken in this direction.

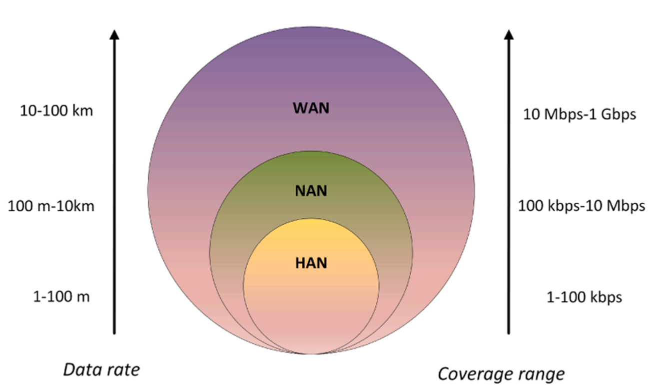

Fig. 3. Data rate and coverage range across three tiers of a smart grid.

Furthermore, the Demand Response Research Center at Lawrence Berkeley National Laboratory has conceived a communication specification designed to automate interactions underpinning the engagement of retail DR suppliers, third-party agents bundling individual DR products, and distribution system operators. This specification, named Open Automated Demand Response (OpenADR), features a non-proprietary interface. This interface empowers load-serving entities to transmit signals regarding wholesale prices and distribution network reliability states directly to aggregators and, consequently, to end-consumers. The 'Auto-DR' communication signals prompt responses from aggregator- and customer-owned energy management and control systems. These responses trigger pre-programmed DR strategies and interface with registered in-unit equipment controllers, thereby orchestrating a coordinated response. OpenADR not only supports interoperability among control equipment and DR flexibility markets but also establishes an accessible route for Internet-based communications (Canmet Energy, 2011; Berkeley National Laboratory, 2012; Paterakis et al., 2017).

Importantly, the real-time nature of OpenADR adequately accommodates real-time DR programs. In such programs, end-users are informed of events on the day they unfold. Improving the standard market framework, real-time DR trading stages can be integrated to maintain real-time delivery standards, especially for end-consumers who may face challenges in manually implementing complex load reduction strategies. Illustrated in Fig. 5, this timeline delineates the trajectory of day-ahead and real-time DR trade rounds. The day-ahead DR market's bid process ends at noon, shaping deliveries for a 24-hour-ahead timeline commencing from midnight. The real-time balancing DR market, on the other hand, comes into play to rectify imbalances emerging from day-ahead responsive load operations. These imbalances are rectified through real-time DR regulation, informed by updated forecasts encompassing load demand, wholesale prices, and meteorological conditions.

As an illustration of regional relevance, in a distinct context, an Australia-New Zealand joint communications standard, AS/NZS 4755.3.2 (Standards Australia, 2014), underscores the activation of demand-side flexibility resources. This standard, titled "Demand response capabilities and supporting technologies for electrical products," shapes a common framework for the region. Under this standard, various platforms have been developed to provide a demand flexibility hub on customer sites, channeling event signals to control systems that manage interruptible demand equipment. Such automated platforms not only facilitate DR event response scheduling but also empower asset optimization across diverse electricity markets.

It is noteworthy that non-compliance with contractual commitments in this context triggers financial penalties, highlighting the importance of cloud-based dynamic energy management. If a supplier or bidder fails to deliver as agreed, they are generally required to compensate for the unfulfilled commitments by paying the market price. These penalties

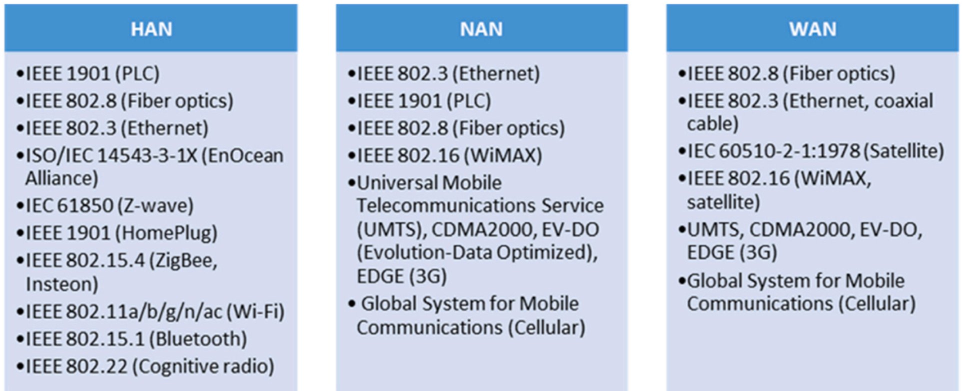

Fig. 4. Notable communications standards across different domains within the DSM provisioning context.

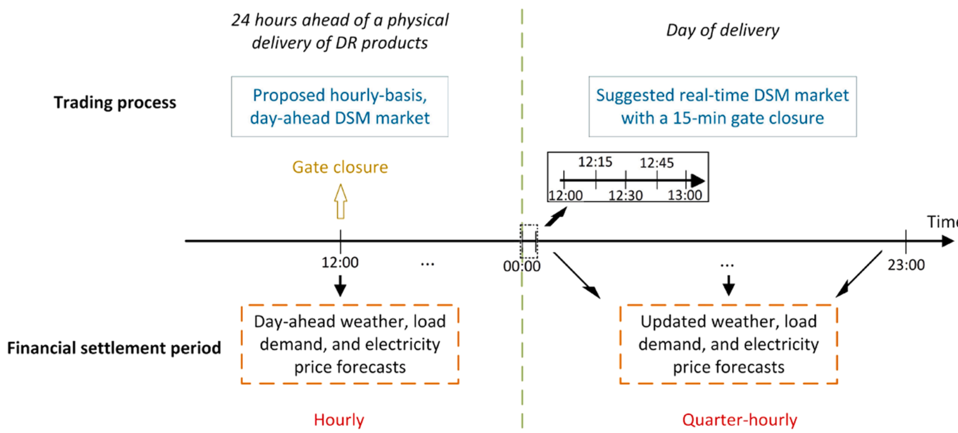

Fig. 5. Illustration of the trade timeline in the typical representative market, along with an additional regulating market addressing DR delivery imbalances over a quarter-hour settlement period.

serve as a mechanism to ensure accountability and incentivize adherence to contractual obligations within the DR framework. It is important to note that such penalties play a pivotal role in maintaining the integrity and effectiveness of the system. This management is aided by the message queuing telemetry transport (MQTT) protocol, ensuring seamless communication and effective performance (Standards Australia, 2014).

The MQTT's ability to efficiently transmit real-time data and commands between DR platforms and control systems guarantees that event signals are communicated seamlessly, enabling precise and timely responses to dynamic energy management requirements. This streamlined communication capability provided by MQTT facilitates not only the swift exchange of data but also real-time coordination between various elements of the DR system, ultimately contributing to the efficient and precise management of dynamic energy requirements, even in rapidly changing conditions (Standards Australia, 2014).

4.2. Integration with communication protocols

Commercial off-the-shelf microcontroller boards, such as Raspberry Pi, Arduino, Renesas, AVR, ARM, and Teensy, have emerged as central control systems or end-use-site-wide energy management and control systems. Their application, however, is constrained by inherent limitations in built-in RAM and flash resources, particularly when deployed as central control agents. The inherent limitations in built-in RAM and flash resources of microcontroller boards represent constraints in available memory for data storage and processing. These constraints can limit the ability to handle and execute complex control and management tasks. This underscores the significance of cloud-based dynamic energy management via the MQTT protocol. MQTT, a publish-and-subscribe messaging protocol operating atop the Transmission Control Protocol/Internet Protocol (TCP/IP), facilitates asynchronous communication between remote devices. It provides a streamlined interface for message exchange via networks such as the Internet, allowing devices and applications to publish and subscribe to topics managed by message brokers. With the ability to add pre-defined headers carrying metadata to enhance data traceability, MQTT supports machine-to-machine (M2M) and Internet of Things (IoT) communication concepts. It also aids data collection and processing through MQTT clients, driving the efficacy of industrial controllers with embedded micro-computing platforms.

It is worth noting that although MQTT facilitates asynchronous communication, it is consistent with real-time operations by enabling devices to exchange information without the need for continuous, synchronous updates. This means that MQTT allows devices to share data when relevant or as events occur, ensuring that critical information is delivered and processed in near-real-time, making it well-suited for applications that require timely responses to changing conditions or events.

Additionally, open IoT platforms such as ThingSpeak and NodeMCU facilitate data transfer, storage, analysis, and processing over the Internet or local area networks (LANs). A tailored distributed algorithm, executed in the cloud, drives data exchange between dedicated nodes and the cloud, enabling seamless information flow. This orchestrated data flow empowers the distribution system operator to relay wholesale market clearing prices and transacted bundled DR product volumes to DRAs. These DRAs then transmit corresponding retail market clearing prices and traded individual DR product volumes to respective end-users. The subsequent broadcasted data, reaching the site's energy management system through the HAN gateway, triggers the coordinated operation of consumers' appliances (Fernandez et al., 2018; Mobtahej et al., 2023; de Carvalho, 2020).

In tandem with the integration of open IoT platforms facilitating seamless data exchange, the intricacies of the localized (retail) flexibility market unveil a promising pathway for advancing DR provision. The orchestrated data flow, empowered by tailored distributed algorithms and executed in the cloud, represents a pivotal stride in enabling real-time communication between dedicated nodes and the cloud. This connectivity, coupled with the relay of wholesale market clearing prices and transacted bundled DR product volumes, establishes a dynamic framework. The subsequent transmission of retail market clearing prices and traded individual DR product volumes by DRAs to end-users further exemplifies the adaptability of the proposed model. Finally, broadcasted data, triggering coordinated operations of appliances in alignment with contractual performance requisites, envisions a future where this localized flexibility market becomes a cornerstone for optimizing energy consumption and enhancing grid reliability.

The integration of communication protocols and standards with cloud-based energy management systems bolsters the sophistication, reliability, and equity of responsive load procurement frameworks, culminating in the optimization of DR strategies within the evolving energy landscape.

5. Conclusions and policy implications

The electricity industry stands poised for a monumental transformation, transitioning toward the paradigm of the 'grid of grids.' This paradigm envisions a dynamic shift from a singular, centralized network to an interconnected tapestry of smaller networks, capable of harmonious collaboration or autonomous operation. This evolution necessitates the introduction of novel market entities to harness the potential of demand-side flexibility resources – a cornerstone of the balanced interplay between generation and demand. In this landscape, third-party DRAs have emerged as pivotal orchestrators, consolidating consumption changes from diverse customers to offer flexibility, capacity, and ancillary services to system operators. The integration of DRAs within electricity markets, and the cohesive interlinking of wholesale and retail markets, calls for an evolution in the existing deregulated market structure. This evolution involves transitioning towards a two-sided design framework, empowering end-consumers to actively opt-in to DR events.

The advantages inherent to a double-sided electricity market, where both demand and supply actively engage in scheduling and dispatch processes, are far-reaching. Such a framework holds the potential to:

- Mitigate the scale at which enrollment in DR programs becomes economically viable, fostering heightened visibility of dispatchable demand-side flexibility resources. This, in turn, amplifies market competitiveness and liquidity, driving down market-clearing prices.
- Elevate the precision of short-term forecasts and long-term predictions of market-driven wholesale and retail electricity prices, as well as load demand profiles. This precision extends to maximizing the penetration of distributed energy generation behind-the-meter and deferring energy infrastructure investments.
- Promote fairness by reflecting the nuanced value of load reduction and accommodating the sectoral elasticity of DR supply. This equitable approach garners increased market share, carrying crucial financial ramifications for utilities and aggregators. Additionally, it charts a course towards realizing the optimal deployment of DR resources for the greater social good.

The shift towards aggregator-mediated, two-sided energy markets carries significant policy implications for governments, regulatory bodies, and energy market operators. To capitalize on the potential benefits of this transition, policymakers must adopt a forward-thinking approach that fosters innovation, competition, and consumer empowerment. Regulations need to be adapted to encourage the participation of third-party aggregators, ensuring that they can seamlessly interact with the existing market structure. Open standards and communication protocols, as exemplified by initiatives, such as OpenADR, play a pivotal role in promoting interoperability and transparency. Policy frameworks should also incentivize the deployment of advanced metering infrastructure and smart control systems, which are the cornerstones of enabling end-consumer engagement and efficient DR schemes. Moreover, associated governing agencies should consider mechanisms that promote information dissemination and education among consumers, facilitating their understanding of DR programs and benefits. By creating an environment conducive to collaboration, technological advancement, and informed decision-making, policymakers can drive the successful integration of aggregator-mediated two-sided energy markets into the broader energy landscape, contributing to more resilient and sustainable energy systems.

In embracing this transformative journey, it is imperative to acknowledge the complexities and interdependencies across communication protocols, market mechanisms, and technological infrastructures. As the energy landscape continues to evolve, future work must delve into refining the integration of demand-side flexibility and the orchestration of real-time DR strategies within a dynamic, multi-layered energy ecosystem. By further elucidating the interplay between communication technologies, market architectures, and behavioral dynamics, the path to sustainable, efficient, and resilient energy systems becomes clearer.

CRediT authorship contribution statement

Soheil Mohseni: Conceptualization, Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Methodology. **Alan C. Brent**: Conceptualization, Formal analysis, Investigation, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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