

Market models and optimization techniques to support the decision-making on demand response for prosumers

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ABSTRACT

Demand Response (DR) programs are essential for easing end-user demand on the power system, adding benefits across the power sector by reducing peak demand and power flow congestion. With the modernization of power grids, DR programs ensure the integration of Distributed Energy Resources (DER) in a controlled manner through Advanced Metering Infrastructure (AMI), which enables communication between grid operators, prosumers and consumers. However, the diversity of DR programs, the spread of DERs, the advent of prosumers, and the several types of power trading among system entities make network and market operation more complex. In this context, optimization methods have been widely applied in distribution grids and market operation, assisting in the decision-making of DER management, prosumer's and consumers' welfare, and DR program applications. This work will address the main market models comprising DR programs to assess opportunities in prosumers' decision-making with the help of optimization tools. Thus, different optimization techniques are introduced that have been addressed in the literature aiming at the application of market models, taking into account the prosumer framework. As a whole, this review paper aims to present the main perspectives of energy market models with demand-side management actions considering the prosumer design.

1. Introduction

The electricity sector is undergoing modernization, characterized by technological evolution, based on the philosophy of the 3'Ds: generation system decentralization, digitization through smart devices, and decarbonization through the use of renewable sources. These modernization's aim at environmental preservation and socioeconomic development [1]. In addition, technological enhancement in the electric system through intelligent systems such as Advanced Metering Infrastructure (AMI) architecture, network communications, and smart meters cybersecurity, is fundamental for the configuration of smart grids, ensuring the integration of Distributed Energy Resource (DER) into power grids in a reliable manner [2–5]. DERs are described by Distributed Generation (DG) systems, Battery Energy Storage Systems (BESSs), Electric Vehicles (EVs), and Demand Response (DR) structures.

Massive deployment of DERs in electrical grids has caused the modification in energy markets [6], impacting the power systems restructuring, demanding resources that provide flexibility, reliability, environmental sustainability, and energy security. These factors increase the operational complexity of electrical networks [7,8], enabling

end-users to play an active role in the network. For instance, EVs users, in addition to significantly increasing the peak load on the grid, can also supply energy and services through Vehicle-to-Grid (V2G) technology [9].

In this way, users can adapt their energy demand based on: (i) electricity tariff hourly prices or (ii) incentives provided by the system operator to improve the efficiency and power grids reliability [10]. Such consumer decision-making, regarding demand flexibility given a configuration in electricity supply, characterizes the application of DR programs [11].

The electricity supply can have a bidirectional energy transaction, which occurs as a result of users who own DG and supply surplus energy to the distribution system [12]. This process characterizes the figure of prosumers [13]. Besides, many of these prosumers have smart meters, making it possible to interact with grid, Independent System Operator (ISO) and energy market operators by managing consumption, generation, and energy storage [13,14]. Smart meters are a fundamental part of the AMI and are being widely deployed in different parts of the world, ensuring the bidirectional flow of data between users and power system utilities [15].

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To deal with this modernization in the power sector, Virtual Power Plants (VPPs) can be a tool to assist in grid management, given the presence of DERs and the dissemination of DR programs in consumers and prosumers aggregators [16]. In addition, VPP can enable free and competitive energy trading between prosumers and operators, and between prosumers and consumers through Peer-to-Peer (P2P) model [17]. In the P2P trading, all network points interact in a common purpose of managing the resources available for the production, commercialization and distribution of a good or service [18,19]. According to Sousa et al. [14], in P2P models, peers can trade electricity directly with each other or through an entity that manages trading activities between a community and the rest of the system. Additionally, hybrid derivations combine these two models.

In this context, the integration of DERs in the grid requires monitoring and managing tools to coordinate several topologies, Business Models (BMs), and energy market trading to allow computational models to assist in the decision-making of prosumers in the power sector. A widely used decision-maker to address the prosumer problem is optimization techniques. Thus, the grid and market operator can use optimization to (i) find the equilibrium point of the power market, especially in complex structures, as in the case of P2P models [20,21]; (ii) perform optimal load scheduling, shifting demand or supply according to market prices [22–25]; and (iii) optimize bilateral energy transactions between prosumers, either in trading and/or energy sharing, making better use of DG systems and BESSs [26–28].

This paper discusses the DERs interventions in smart grids according to prosumers frameworks based on Virtual Net Metering (VNM) infrastructures used to manage DR programs. Also, this study highlights the role of market models, market aggregators and prosumers BMs in identifying the relationship of these entities with the main optimization techniques applied in studies of prosumers and DR.

Thus the main contributions of this paper are:

- Provide a market design for integrating prosumers and DR programs;
- Discuss the BM, power grid, and market models for prosumers and participating in DR programs, highlighting the VNM frameworks;
- Briefly address the main optimization techniques that have been used for decision-making in the energy market from the perspective of prosumers;
- Provide a future outlook of barriers and opportunities based on four levels: prosumers, aggregation and community, ISO and market regulation.

Note that in this work the term ISO, which means the Independent System Operator, is used interchangeably to represent both Distribution System Operator (DSO) and Transmission System Operator (TSO).

This review paper is organized as follows: Section 2 presents a brief comparison analysis of review papers that address the topic DR. Section 3 presents the main characteristics of DR programs applied to prosumers. Section 4 discusses the impacts of prosumers on the energy market, presenting methods of grid energy metering infrastructure and prosumers BMs with a focus on DR programs. Section 5 presents optimization techniques used in the literature for decision-making in the actions of market and grid operators applied to prosumers participating in DR. Section 6 presents a set of opportunities and recommendations for further development within this topic. Finally, Section 7 gathers the main conclusions of this work.

2. Literature review comparison

The future outlook and opportunities for prosumers are related to the decentralized operation of electrical networks with Information and Communication Technology (ICT) and have been widely discussed in the literature. On this subject, DR programs can play a stimulating role in managing the energy resources of these prosumers. In this sense, some review works address interactions between prosumers and the DR. Thus,

Espe et al. [29] discuss the evolution and future directions of prosumer communities in smart grids through a systematic review. In addition, Gough et al. [30] present a state-of-the-art review on prosumer flexibility, pointing out the DR programs as an opportunity for prosumers. Hussain et al. [31] presented a review of several DR techniques with a specific view on pricing signals, optimization, appliance scheduling used and their benefits. The authors also prepared a comprehensive comparison considering the multiple criteria of the smart grid paradigm.

In Guo et al. [32], a road-map on interactions between smart grid agents and integrated energy systems of data center is provided to aid prosumers' operations. To investigate prosumer operations in decentralized energy models, Wang et al. [33] identifies optimization models as the most commonly used method in the literature to model the prosumers' operations.

In Jordehi [10] the DR, optimization problems are also discussed. The author points out some directions for future research based on prosumers technologies, objective functions and DR programs types. Patnam and Pindoriya [21] present an overview of mathematical models and DR optimization algorithms from a prosumer perspective. The authors detailed the modelling procedure for DR implementation at the home, community, and network levels.

As many DR projects for prosumers are being discussed in the literature and being implemented, some review papers are building their ideas through prosumers BM. Zia et al. [34] discuss local energy market, DR, P2P market, and propose an architecture for energy transactions based on the Brooklyn microgrid project. Di Silvestre et al. [35] highlight renewable energy community transactions, market and regulation in an Italian electricity system perspective. On the other hand, Moura et al. [36] presents several prosumer aggregations BM and reviews the aggregation policies, potential market and market regulation according to countries' experiences.

As seen, the works that have contextualized optimization and DR thus far are based on the mathematical formulation and application of optimization algorithms in DR programs from a prosumers perspective. On the other hand, some papers discuss the interaction between prosumers BM, market models, and energy transactions. Nonetheless, gaps in the review studies that synthesize the use aspects of DR programs utilization in the prosumers context with the approach of optimization techniques focused on energy market problems are identified. In that regard, this paper briefly presents the main optimization techniques that have been applied in the context of DR, prosumers and the energy market. To elucidate the prospects of optimization models that can add value to the prosumers BM and in the existing market models to analyze and inquire about possible decisions in the face of obstacles.

Considering the research gaps highlighted in the literature mentioned above, this study executed a comparison to other existing studies accounted for the perspectives concerning: optimization techniques, management of network technologies to assist the prosumers' interests, ISO, aggregators and community energy markets, market regulations and project BM. Table 1 briefly highlights the comparison of this study with the related literature. To contribute to this approach and fill these gaps in the literature, as shown in Table 1

3. Demand response

Historically, the concept of DR was first disseminated in the US in the 1970s, with the implementation of demand-side management [37]. DR consists of actions that are implemented by utilities, aggregators, or the grid operator to change the power consumption profile [38]. Changing the consumption profiles aims to ensure the reliability of the energy supply, especially in times of high demand [39]. Demand-side management encompasses the concepts of Energy Efficiency (EE) and DR. [40,41]. However, this study will only focus on DR programs.

The application of DR comprises a set of measures that influence the energy market, either through pricing or incentives [42]. This resource can be integrated into prosumers management, bringing numerous

Table 1
Comparison between literature reviews on the participation of prosumers in demand response.

Authors	Optimization Techniques	Market Model	ISO	Market Regulation	Project BM
[10]	✓	-	-	-	-
[21]	✓	✓	✓	✓	-
[29]	-	✓	-	✓	✓
[30]	-	✓	-	-	✓
[31]	✓	✓	-	-	-
[32]	-	✓	✓	-	-
[33]	✓	✓	-	✓	-
[34]	-	✓	✓	✓	✓
[35]	-	-	✓	✓	✓
[36]	✓	-	✓	✓	-
Proposed	✓	✓	✓	✓	✓

benefits, such as (i) the decrease in generation costs since there is a change in the demand profile by reducing consumption at peak hours [43]; (ii) greater energy efficiency providing more flexibility and reliability to the power system; and (iii) optimization of generation resources, and consequently, reducing Greenhouse Gases (GHG) emissions since it is estimated that there will be a decrease in the dispatch of thermal plants [44,45].

3.1. Demand response programs

The DR mechanism took shape with the smart meters as enablers of bidirectional communication between the utilities and end-users [46]. This technology presents real-time information on consumption and energy balance, enabling the management and control of loads and generation, where consumers can follow their demand profile and even

energy prices throughout the day, helping in daily consumption planning [24,39]. Thus, the use of DR along with smart meters provides: the optimization of consumption and EE as well as the establishment of new tariff modalities causing the diffusion of DR programs [45,47].

A DR program encourages users to monitor their energy consumption in real time. Through consumption data, users can manage energy use according to their interests. On the other hand, the market operator aims to create a synergy between the concerns related to the grid operation and consumers. In this way, the market operator uses the DR program mechanisms to optimize the energy resources, achieve reliability, grid EE, and reduce the costs of system services [48].

To meet these proposals, the programs can be divided into Price-based Program (PBP) and Incentive-based Program (IBP) [49], as shown in Fig. 1. The PBP comprises the time-of-use [50], real-time price [51] and critical peak pricing [52], while the IBP is composed of the ancillary services market [53], emergency programs [54], direct load control [55], interruptible contracts [56], demand bidding [57] and capacity market [56].

The PBP aims to change the consumption profile, changing the shape of the standard demand curve as a function of the hourly price throughout the day [58]. On the other hand, IBP is characterized by promoting financial incentives to end-users by reducing consumption in critical moments of system operation, such as high demand and load flow congestion [59].

3.2. Demand response analysis for prosumers

Technical advances in operating a smart grid make it possible for users to exchange power with the grid during peak/off-peak hours. This concept of bidirectional energy flow characterizes prosumers, who can consume and generate energy to meet their energy needs, and to supply the grid. The DR resources of prosumers are characterized by the use of DERs, such as DG systems, BESS, V2G, and heat pumps. Thus, in the context of the prosumer, the concept of DR is characterized by the use of DERs to minimize the cost of energy through optimal management, using energy from the grid only at times when the tariff is lower. Meanwhile, consumers who are connected only to the electricity grid are

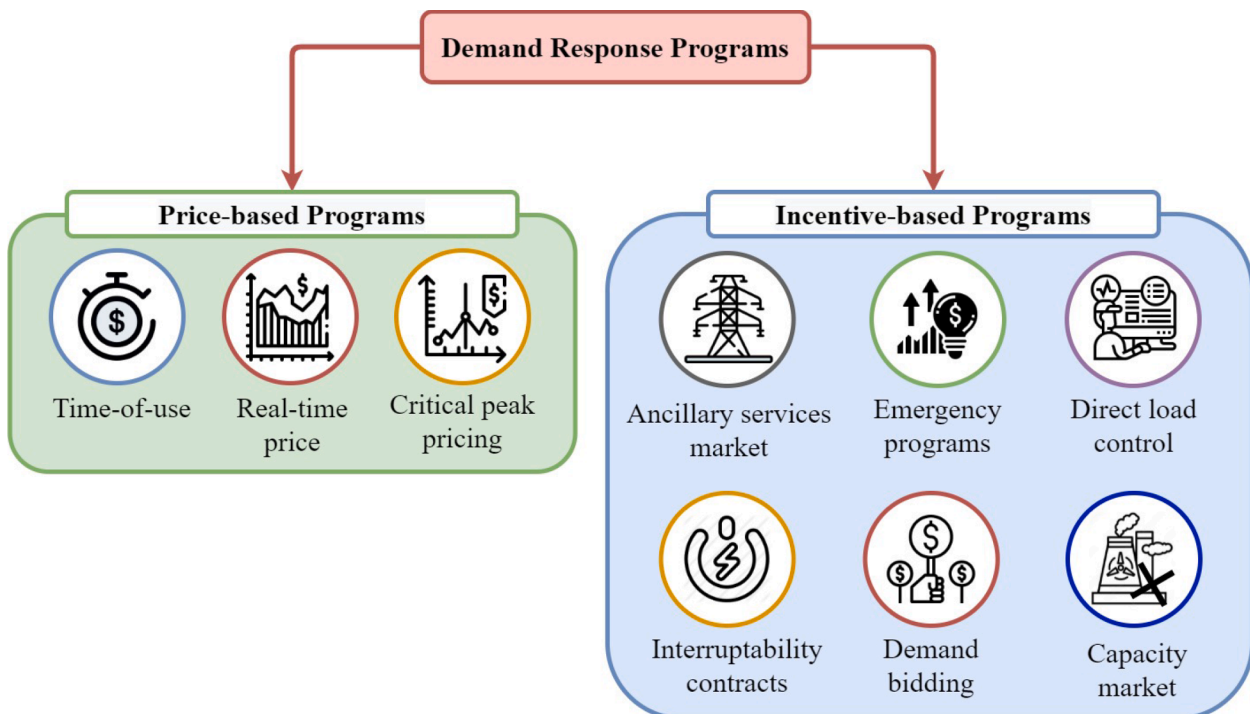


Fig. 1. Types of demand response programs.

subject to the dynamic prices of the retail market, whose DR action is in the management of self-consumption [60,61].

Prosumers in the context of using DR can adopt measures that reduce the system peak demand. Marangoni et al. [40] suggests adding alternative sources to the grid, such as renewable sources (solar and wind), to meet the daily consumption of the consumer while the surplus energy can be injected into the utility's grid. However, renewable sources have considerable volatility and uncertainties, making the energy market difficult.

To address the unpredictability of renewable resources, the real-time market makes use of dispatchable sources such as biodiesel/diesel. These generators operate as a backup, working in parallel with the grid to meet the consumer's demand at peak hours and/or demand increase. These actions should be coupled with rational energy use management providing flexibility, reliability and energy security to the local grid.

According to Ali et al. [62], prosumers adopting PBP can present benefits such as peak consumption and load shifting, optimizing the electric grid operation. The energy price is a control variable that affects prosumers' energy consumption profiles through load rescheduling during peak and off-peak hours. Thus, the use of optimization algorithms in DR programs can have as one of the objectives the maximization of prosumer social welfare and the minimization of operating costs.

In Cioara et al. [63], it is estimated that distribution system operators by including retailers and aggregators, joined IBP make the prosumer play a significant role in the operation of the power grid. Prosumers can model their energy demand to meet various grid-level objectives and obtain financial benefits in return. The ISO will send a regulatory signal to each prosumer specifying a request to modify consumption for a limited period and, as a reward for decreasing consumption will receive financial incentives.

Thus, from the prosumers' point of view, by joining the IBP, this will be able more actively to participate in the energy market can bid the amount of energy and yet to reduce or increase their demand with the operator/aggregator by accepting or not accepting the offered bids. Those prosumers, generally, make use of optimization programs to define the ideal load curve to meet the agreed consumption profiles with ISO whether optimizing or load shifting in time some [63,64].

The expansion of DR programs is a trend for prosumers and a key factor in reducing overall consumption and improving system energy efficiency, managing peak demand from industrial, commercial, and residential sectors. Grid users will be increasingly active in the energy market, being able to control consumption in real-time either through smart meters installed in consumer units or through aggregators in a VPP [49]. Therefore, through smart devices and optimization algorithms, prosumers can make effective decisions about their energy management. Such a decision must consider operational constraints and energy balance, reducing the peak load at specific periods. In turn, these arrangements can lead to a decrease in electricity generation prices, thereby reducing system operating costs [65].

4. Energy market

This section discusses consumers' impacts on the DR energy market. Several market models comprising DR programs are addressed, with the aim of investigating opportunities in prosumers' decision-making with the help of optimization tools. In addition, this section presents the prosumers frameworks in the integrated energy market, as well as their BMs concerning DR.

4.1. Demand response in market models

The large-scale application of DR causes changes in demand, postponing the dispatch of expensive generating units [66]. This effect contributes to ancillary services, such as (i) aid in the control of operational power reserve and energy balance; (ii) energy reserve; and (iii)

network frequency control, among others [53,67]. DR is also used for emergency services [68], shifting the system load during peak periods [69]. In addition, the DR can bring benefits to the energy and reserve market.

In this way, it is possible to level the consumption load curve according to supply, providing significant benefits for both the operator and the end-users [48]. On the one hand, PBPs sensitize end-users through tariff variation, which is reflected in local, retail or wholesale market transactions. On the other hand, IBPs use incentives as a tool to provide services to the network and reduce the market price. Fig. 2 shows the DR basic model in the energy market.

For the wholesale market, generation agents bid price-quantities for the existing energy supply. In simple markets, the one-sided pool is applied, in which the bids offered form the aggregate supply curve. In this model, demand is estimated by the ISO and then used to perform the dispatch [70]. On the other hand, in complex markets, the two-sided pool can be applied, in which the ISO dispatches are based on a demand curve created from the price-quantity bids offered by market buyers, such as distributors and large-scale consumers [70]. This is the case for several markets, such as PJM [71], MISO [72], ISO New England [73], ERCOT [74], Ontario [75] and Nord Pool [76].

In other words, the two-sided pool uses the projection of hourly demand from end-users to estimate the energy dispatch and settle the market clearing price. In this scope, the IBP application can be treated as an offer in the wholesale markets, being another technology to provide services, such as time shift of expensive generating units, capacity resource in auctions, and provision of ancillary services [53,67].

In the retail market case, consumers can negotiate conditions, terms, and prices of electricity directly with power providers, such as retailers and generation agents [77]. Thus, the market operator determines the market clearing price. This price is charged to entities participating in the market, such as large-scale consumers, aggregators and community markets.

The market operator usually calculates the market clearing price per hour. In this way, the price reflects the average cost of generation and transmission, demand curve profile, and dispatched plants profile [78]. This market price is the basis for tariffs charged to residential and small-scale customers by retail suppliers. Thus, in the retail market, PBPs are the most used, aiming to model the tariffs charged to consumers to sensitize the end-users to the price.

Recently, several prosumers frameworks and BMs have encouraged participation in DR programs in wholesale and retail markets. This factor improves the potential DER market, contributing to ancillary services in the electrical system and reducing the market equilibrium point [79]. Table 2 presents the DR programs in several regions that have incentive programs to offer flexibility from DERs to provide ancillary services to the network.

Each region has different policies for implementing DR programs as show in Table 2. Regions with a developing energy market make DR available to large consumers to avoid network contingency problems, as is the case in Africa and South America. In markets where DR programs are already established, the objective is to improve the energy quality and safety of the electrical system, acting as a mechanism for ancillary services and ensuring consumers' elasticity, making it increasingly participatory in market operations. As in the USA as of August 2021, the Federal Energy Regulatory Commission has been allowing DER aggregators to compete in all organized regional wholesale electricity market [86].

The proposal of most developed countries is to make the offer of flexibility of consumers and prosumers a reserve of capacity to assist in the transition of the energy matrix. In other words, for countries to be able to reduce the share of polluting sources for renewable sources, it is necessary to build a reserve of capacity guaranteeing reliability in the energy supply [95]. Another major interest in DR programs for the use of ancillary services is to encourage increased use of storage systems, user flexible loads, load aggregators, virtual power plants and other

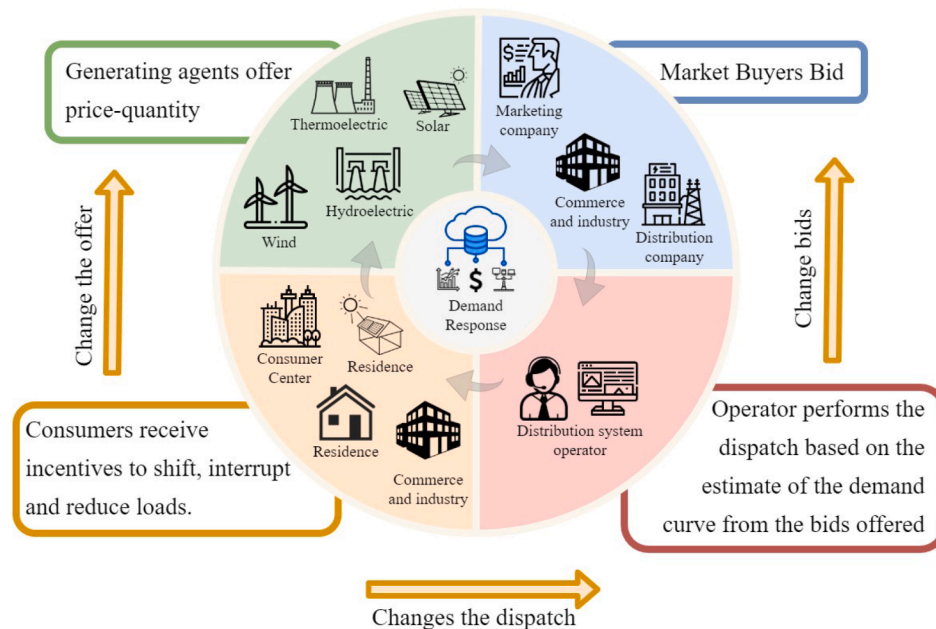


Fig. 2. Demand response basic configuration in the energy market.

resources, as some USA regions are proposing [96]. In addition, most developed energy markets use ICT to provide information and automatic control of market agents, such as Hong Kong and some regions of the USA [85].

In general, the contribution of prosumers in the energy market is associated with the metering system, which records the import and export energy from the grid. Thus, depending on the measurement infrastructure used, different DR programs can be offered.

4.2. Prosumers frameworks

There are different frameworks to manage the electricity being consumed and produced by end-users, located upstream of the meter in the electrical system [97]. These frameworks characterize VPPs, which are aggregators of industries, businesses, or residences. These aggregators can have demand management, community market, or energy resource program. Thus, VPPs are controlling entities with a real-time interface for wholesale markets and the grid [16]. The basic configuration of a VPP with consumer management is discussed in [98–104].

Virtual power plants have an Energy Management System (EMS) responsible for managing and controlling the load flow [105], transferring decentralized energy in a P2P model. Thus, electricity monitoring is performed by VNM [36]. VNM can be used to regulate energy transactions, allowing the sharing of generation credits, in which different entities enjoy the same energy production [106–108]. Also, with the VNM data, the energy trading in a VPP, using P2P, may occur via blockchain, which has become quite popular [63,109,110].

Fig. 3 presents different VNM frameworks in terms of involved entities and power transfer configuration. According to [36], there are four types of frameworks capable of describing the virtual measurement models in a VPP. The single entity has only one agent capable of virtually transferring energy between its facilities. In other words, an owner who has several consumer units, and at least one of them has DG. In periods of surplus generation, it is possible to give this excess production to his other properties.

The third party metering model consists of energy transfer between two different parties. A prosumer can transfer its energy surplus to other consumers through an energy trade contract established at a point in the network, managed by a service provider [111]. This model is also known as P2P energy trade [36]. On the other hand, the shared generation

framework corresponds to a group of entities that share the generation system and, therefore, the energy production is distributed among them. In this case, the generation system can be a collective property or developed by a third party [112]. It highlights that in the third party model, there is a contract between a prosumer who wants to transfer the surplus energy and a consumer who pays to receive this surplus. Already in the shared generation model, an energy community is created that produces energy and distributes it among the consumers involved in an egalitarian manner, as in a condominium.

Finally, the aggregation framework concerns multiple parts aggregated into a grid. These aggregated producers trade their generation output to an entity, which is the aggregator. The aggregator is a central entity that is able to act as a market broker or redistribute energy surplus to several consumers, constituting a VPP or a retail aggregating platform [36,108,113]. In other words, the aggregator can buy energy in the retail or wholesale market, and trade it to its aggregated parts. In addition, the aggregator may sell surplus energy from its aggregated parts to other consumers in the distribution network.

Each VNM framework may cause different effects on DR programs. The single entity model does not change the DR baseline for each end-user of the network, since only surplus credit is transferred between consumer units, reducing their operating costs without interfering with net consumption [114]. On the other hand, the third party model also does not interfere with the DR baseline for each consumer unit. However, in this model, there are P2P trading that can bring more benefits to consumers than participating in DR programs. In this way, market regulators need to carefully study or examine the price of offering load flexibility to make DR programs interesting for consumers who have bilateral contracts [115].

Through shared generation and energy aggregation models, end-users can participate in DR programs in markets where regulation allows only large consumers to offer load flexibility, as small consumers can combine groups and aggregation to reach the minimum necessary to participate in the program. In these frameworks, the net sum of consumption offered by the energy community or by the aggregator is considered in the DR program [116]. However, estimating the typical consumption curve of these groups is complex, leading to baseline manipulation [117]. In addition, the energy community and the aggregator may contract energy in the retail market or carry out P2P trading with third parties, causing a disinterest in interactions with the

Table 2
Demand response programs for ancillary services.

Region	Market models	DR Programs	Description
Africa South Africa	Wholesale	Interruptible contracts	Large customers receive a tariff for self-generated or reduced energy based on the incentives available in each region [80].
Asia Bangladesh	Retail	Time-of-use	Regulatory entity started campaigns through electronic and print mass media to urge end-users to reduce electricity at peak times [81].
Hong Kong	Retail	Emergency programs, Direct load control	Automatic DR project in which some commercial and industrial customers' loads will be automatically reduced by ISO during emergency conditions [82].
Japan	Retail	Direct load control	Kyocera, IBM Japan and Tokyu Community started a project of Automatic Management System DR, sending requests to consumers when the system is under stress conditions [83].
Singapore	Retail and Wholesale	Interruptible contracts	Customers can temporarily provide needed reduction by shutting down non-critical equipment or even using on-site backup generators for short periods [84].
South Korea	Wholesale	Emergency programs, Demand bidding	Korea recently launched a dedicated DR program for small resources and allowing fixed payments to an economic DR participant proportional to activated capacity [85].
Europe Belgium	Wholesale	Capacity markets	Capacity remuneration mechanism to ensure the security of supply during decommissioning of nuclear capacity [86].
UK	Wholesale	Time-of-use, Real-time price, Interruptible contracts, Ancillary services markets	UK is the country with the greatest potential for DR in Europe, using programs with similarities to those used in the USA [87].
North America California	Retail	Direct load control, Interruptible contracts, Demand bidding, critical peak pricing, Capacity market, Real-time pricing	Commercial and residential customers can control aggregated load during peak periods. For larger customers, the ISO offers a range of DR programs [88].
Florida	Wholesale	Direct load control, Interruptible contracts, Real-time price, Time-of-use, Capacity markets	Florida has several DR programs that can be offered to all types of consumers [89].
New York	Retail	Demand bidding, Ancillary services market, Real-time price, Interruptible contracts	Six different DR programs are offered for clients of all scales [90].
Ontario	Retail	Real-time price	

Table 2 (continued)

Region	Market models	DR Programs	Description
Texas	Wholesale	Critical peak pricing, Real-time price, Time-of-use, Emergency programs, Direct load control, Capacity market, Interruptible contracts	The aggregator pre-notifies your facility to provide the necessary load shedding to guarantee the ISO request in terms of total load shedding in critical periods [91]. ERCOT allows end-users to bid on the market or reduce energy usage by responding to wholesale prices [92].
Oceania Australia	Wholesale	Demand bidding	From October 2021, large industrial and aggregated customers of a similarly large size can participate in the DR market [86].
New Zealand	Wholesale	Critical peak pricing	Request commercial buildings to reduce the power drawn from the grid [93].
South America Brazil	Wholesale	Time-of-use	Brazilian Electricity Regulatory Agency has motivated price-based DR programs. Additionally, pilot projects are being developed to expand the DR market to ancillary services [94].

regulated energy market. Thus, the DR baseline, the price and incentive of DR programs need to be measured to stimulate the participation of the load flexibility offer without harming and benefiting market agents and the ISO.

4.3. Prosumers business models considering demand response programs

Prosumers BMs constitute a diversified set of energy policies and market regulation that the energy system can face regarding VNM frameworks, the use of VPP and the implementation of an energy trading interface, such as the blockchain. Table 3 presents the BM of the projects intending to insert prosumers into networks that include DR programs. It is beyond of the scope of this study to classify the BMs. Interested readers on the BMs classification for prosumers are referred to [118].

According to [126], there are at least 51 market regulation projects or software proposals for negotiations between prosumers and consumers in the energy market. However, only a few projects clearly describe the proposed configuration of DR programs in their BMs. Some of these projects were closed due to lack of funding, such as Yeloha!, in the United States [36,110]. The projects currently in force are Smart Microgrids in Ceará, Brooklyn Microgrid, Piclo, Vandebrom, Sonnen Group, LichtBlick through the Swarm Energy platform, Electron through the Artemis platform, and Powerpeers. On the other hand, Centrica plc is a pilot project in development.

In particular, the Artemis project is a partnership project between governments, which is developing an energy flexibility platform, carried out by Electron and Gridwiz, and Imperial College London, and has been applied in the energy aggregator in South Korea since September 2020 [110,125].

Most BMs involve P2P negotiations, with and without energy aggregators. In addition, there is a trend in energy transaction frameworks that make use of blockchain in VPPs. The entry of blockchain technology into VPPs promotes energy sharing at the local level and the

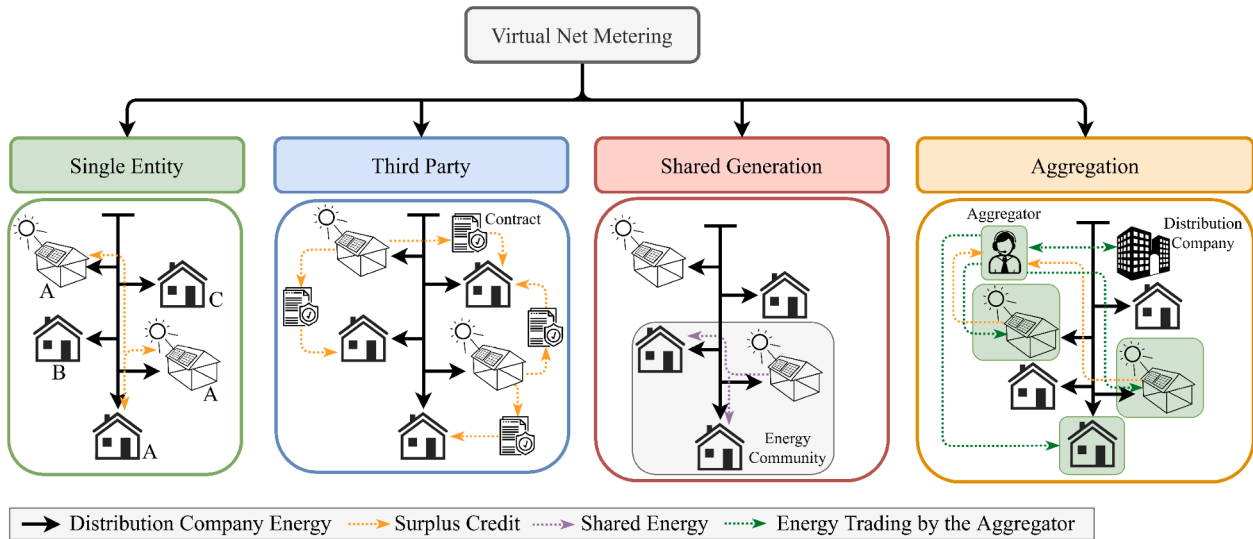


Fig. 3. Virtual Net Metering frameworks.

Table 3
Demand response participation in the prosumers business model.

Project	Country	VNM	VPP	Blockchain	Demand Response
Yeloha! [110,119,120]	USA	Third Party	-	-	DR is offered in the wholesale market at the same price as power generation.
Brooklyn Microgrid [119]	USA	Third Party	-	✓	Using price as a proxy, the ISO manages energy use, load balancing, and DR at negotiated rates.
Centrica plc [121]	UK	Third Party	✓	✓	Customers are allowed to offer flexibility in the auxiliary frequency response services market, or participate in capacity markets.
Smart Microgrids in Ceará [122]	Brasil	Shared Generation	-	-	The microgrid can offer flexibility to the grid, operating autonomously for 1-h and exporting energy to the grid. However, Brazil does not have regulations for the flexibility market so far.
Piclo [110,119,123]	UK	Aggregation	✓	-	Distribution network operators make offers for demand flexibility during peak periods.
Vandebrom [110,119]	Netherlands	Aggregation	✓	✓	Provide automatic frequency restoration backup through DR management.
SonnenCommunity [110, 119,124]	Germany	Aggregation	✓	✓	Monitors the supply and demand balance, allowing the storage system to be managed according to the DR.
LichtBlick (Swarm Energy) [110,119]	Germany	Aggregation	✓	-	Offers ancillary services to increase network flexibility.
Electron (Artemis) [110, 119,125]	South Korea	Aggregation	-	✓	Allows prosumers to change DR in real-time.
Powerpeers [36,126]	Netherlands	Aggregation	-	-	Allows the operator to send demand reduction incentives and manage the storage system for prosumers.

microgrid operation level. Additionally, blockchain can be implemented privately, publicly, or federally [127].

Concerning the proposal of the DR programs, the projects aim to contribute to network flexibility and reduce demand during peak periods, either through platforms that aid communication between the distribution system operator and the electricity users or through load management and BESS stimulated by hourly prices. On the other hand, some projects target proposals to improve ancillary services through the management of energy reserve capacity and frequency restoration, such as Vandebrom and Lichtblick [119].

5. Optimization

This section reviews the literature on how optimization techniques have been applied in the energy market context with prosumer participation in DR programs.

5.1. Optimization techniques

In recent years, DR programs and optimization techniques have been applied for better use of energy resources. In this sense, optimization methods can help the system operators provide flexibility to maintain the security of power systems and optimize the grid utilities. DR

programs can be a competitive alternative to other power sources, thereby enhancing competition and liquidity in energy markets. Optimization techniques are based on mathematical programming or heuristic models. In addition, it is also possible to find optimal solutions via game theory. Analyzed optimization models involve the following groups: applied technique, objective function, type of grid, prosumer device, and market design. These factors interfere with the decision variables of each prosumer. Therefore, in this subsection, some optimization techniques are presented that can help the prosumer in decision-making about which is the best energy market model according to their own profile.

5.1.1. Linear programming

One of the optimization techniques adopted to solve optimization problems that encompass Renewable Energy Resources (RES), DR programs, prosumers and energy markets is Linear Programming (LP). In Muqet et al. [128], the authors proposed a storage system scheduling with Photovoltaic (PV) system and grid using LP for the reduction of monthly consumption cost. The authors analyzed five different energy management scenarios to find the optimal operation of the system. The author considered the energy source uncertainties, as well as the cost associated with the initial investment storage system.

Abrishambaf et al. [129] proposed a model of a community grid with

one central management unit. The community manager can control consumption and resources generation by establishing contracts with its members. The authors employed LP through the implementation of the decision trees to demonstrate the impact of using DR and DER in the consumers and prosumers and to minimize Operation Costs (OC). The study's results validate the use of DR programs and pay incentives to reduce their consumption compared to purchasing energy from the market. However, in several periods, the community manager purchased energy from the energy market, because load demand was greater than the local energy resources, proving that proposal can be an improvement.

In Avau et al. [130] LP is used to develop a model decision-making for residential prosumers, that minimizes the cost of electricity. The model analyzes the impact of distribution tariff structures on DER scheduling based on wholesale electricity prices and introduces a distribution tariff metric (relative flexibility value), that allows comparing the energy costs under different distribution tariff structures to the energy-optimal benchmark. However, the authors do not analyze DR programs insertion in the optimization model developed, and only consider the advantages of applying DR programs for prosumers and the energy market.

5.1.2. Mixed integer linear programming

Depending on their decision variables, binary and integer variables may be used through Mixed Integer Linear Programming (MILP), for instance. The application of MILP, in problems considering prosumers and DR, started in 2012 with Mariethoz et al. [131] to minimize the consumers' energy deviation to the energy balance estimated by the aggregator. It explores the flexibility of loads and generators, integrated into a predictive dispatch scheme negotiated with nodal prices. Although the focus is on minimizing fluctuation, a small economic analysis could have been presented.

Muqet et al. [22] proposed an EMS for a microgrid to reduce its OC and increase its self-consumption of renewables DG. It applies MILP along with a PBP to minimize energy cost, considering battery life degradation and different sizes of PV generation. On the other hand, Marangoni et al. [40], in addition to PV and DGs, applied the biogas generation to minimize costs and support decision-making. However, the authors did not consider storage devices that could help in economic analyses.

Many works apply MILP to find the lowest OC, as is the case of [26] and [132]. Chen et al. [26] developed a new Prediction Integrated Strategy Optimization (PISO) model to solve the optimization problem in the Continuous Double Auction (CDA) market. The authors use neural networks in Extreme Learning Machine (EML) to formulate market forecasts. These forecasts come as constraints, along with the bid, DG, BESS, and operation safety constraints, in the optimization but do not inform whether the load and wind generation data come from historical or dummy data. In [132] an energy box is proposed as a viable communication solution between consumer and aggregator, in addition to carrying out the EMS. The authors report only the exchange of data between the prosumer and aggregator. However, there are already platforms that operate with blockchain contracts, as is the Artemis platform case. Another gap is that the authors did not consider the micro-Combined Heat and Power (CHP) system slope curve, which can be a problem for the aggregator depending on the granularity of the market operation.

Yang et al. [133] developed a study that aims to determine the DR program for the Regional Multi-Energy Prosumers (RMEP) under electricity usage time and gas tariffs and analyzes bidirectional energy flows between prosumers and the main network. Its objectives are an optimal operation strategy for RMEP connected to the grid considering the time-of-use and price, the ideal quantities of electricity and gas supply for prosumer, and the exchange of energy with the grid, and the quantitative impacts of the price of electricity/heating/cooling usage time. However, this article has a gap, that despite having been proposed,

the ideal amounts of electricity and gas supply for energy prosumers and energy exchange with the grid were not discussed.

Optimization techniques can also be applied together to find the best solution, such as [134], which uses MILP and LP for two-step optimization. The first step is to apply MILP to minimize the equivalent annual cost to meet demand. In the second stage, it employs LP to maximize the revenue obtained by absorbing the surplus from renewable generation. The authors show that the willingness and ability of prosumers to participate, the frequency of request to participate in DR programs, the amount of electricity absorbed, and the aggregator price signal will be the prosumers limitations who jointly apply DR programs and heating systems.

5.1.3. Dynamic programming

Dynamic Programming (DP) is an optimization approach that transforms a complex problem into a sequence of simpler problems. Alahaivala et al. [135] has been used DP to investigate the potential benefit of a residential micro-CHP system as a power sink, considering its effect on both the prosumer and the power system. However, the authors do not assess how prosumers can increase the system price elasticity or even encourage the emergence of new electricity tariffs to unleash demand-side flexibility, which can be exploited in the wholesale market.

In Sun et al. [136], DP is applied to perform the unit commitment problem for storage, in a residential microgrid. Although the authors carried out DERs asset management in a DR market, residential microgrid have no impact on the elasticity price in the retail energy market due to their small capability.

5.1.4. Bilevel programming

A special kind of optimization is bilevel programming, where one problem is embedded within another. In particular, the energy market uses this optimization to respect the interests of market and system entities, as well as end-users. In this sense, Riaz et al. [137] performed a bilevel optimization to minimize Generation Cost (GC) in the upper-level problem and maximize the prosumers' aggregate self-consumption in the lower-level problem. The authors developed an efficient mechanism for DR aggregation through the DERs penetration level. However, it is unclear how prosumers can trade energy and how this may modify electricity price elasticity in the wholesale market.

5.1.5. Stochastic programming

In addition, optimization can include intrinsic uncertainties of the technologies involved in the problem and uncertainties, regarding environmental and seasonal characteristics. To address these uncertainties, Stochastic Optimization Programming (SP), Robust Optimization Programming (RO) and Chance-Constrained Programming (CCP) may be implemented. In particular, papers that address uncertainties aim to incorporate the volatility of energy market prices in the decision-making of prosumers.

Das and Basu [138] performed SP, applying tent chaos mapping to generate load, weather, Wind Turbine (WT) and PV output uncertainty scenarios. The authors assessed the risk of microgrid participation in the competitive energy market by using Conditional Value at Risk (CVaR) criteria. Although the DR programs encourage the microgrid to be capable of compensating energy imbalances in the real-time market, the compensation may provoke changes in the market-clearing prices, which was not considered in the problem formulation.

5.1.6. Robust optimization

The WT output and aggregated load uncertainties are also implemented in [139]. The authors have been used RO for the optimal cost of scheduled energy and reserve from grid and prosumer resources. Although the paper investigates the prosumers' leeway to submit battery energy content as a bid parameter, the import/export cost between the prosumer and aggregator was not considered. This factor may change

the flexibility capability offering from the DR aggregators to the DR market. In this sense, Park et al. [140] proposed a method to aid aggregators in creating incentives for prosumers to offer their flexibilities. Then, the aggregator can decide whether to participate in the DR flexibility market or the day-ahead energy market. However, this work does not consider the day-ahead margin assurance payment on the flexibility market, which is a strategy already adopted in many markets, such as MISO and NYISO [141].

5.1.7. Chance-constrained programming

The CCP is implemented in [142] to fairly consider the reserve cost induced by renewable generation uncertainties. The authors propose a novel P2P joint energy and reserve market. However, the main limitation of this decentralized market is that the feasible operating under any usage of the reserve is not guaranteed. In this sense, the authors point out that a workable approach is to reschedule the power flows in a real-time market, which is a challenge due to the high computational effort needed.

5.1.8. Evolutionary algorithms

Heuristic optimization methods have also been used for research encompassing DR programs, prosumers, and the energy market. Genetic Algorithm (GA) is a robust technique applied to complex problems with a large number of decision variables [143]. Arun et al. [144], proposed an intelligent residential EMS, for prosumers aiming at optimal sizing of RES and BESS to minimize the Total Cost (TC) through a GA. EMS was an effective use of RES by optimally controlling the BESS operation and properly scheduling the loads. In this work, the optimization only was applied in the sizing of devices capacity.

Neves et al. [145] compared DR optimizations in the presence of local RES generation for isolated hybrid microgrids, considering different agents as the grid manager and the end-users. To model the DR from the grid manager point of view, a GA was used to take full profit of centralized renewable generation, while the modelling of the prosumer side was performed using a LP algorithm to earn gains in the local PV generation and off-peak tariff. Nevertheless, the benefits for the electricity system were found to be slightly higher when the optimization is performed from regarding the grid manager. Also, the authors do not consider using the battery in the analyzed systems.

In Faia et al. [146], Particle Swarm Optimization (PSO) is implemented to propose DR optimization considering the optimal battery schedule in a residential house PV generation. A PSO approach was implemented to solve the optimization problem, and the results were compared with a deterministic model (MILP with CPLEX solver). The main goal was to minimize the OC, considering that the user has storage units and is also enabled to do DR in specific loads. Despite this, the authors did not consider reduction and shifting capabilities in the problem formulation.

5.1.9. Game theory

Game theory is a decision-making technique that takes into account strategic interactions between rational decision makers in the mathematical formulation. In this way, Liu et al. [147] conducted a Stackelberg game for energy sharing management. The authors propose interactions between the microgrid operator and prosumers to maximize their profits. However, this paper considers prosumers only as consumers with rooftop PV systems, and strategies with DR incentive-based systems were not discussed. In his future work, Liu et al. [148] performed a coalitional game for energy sharing management of CHP and PV prosumers. Nevertheless, the authors discussed only DR price-based strategies and the interaction between prosumers, microgrid operators, and the market operator was not addressed.

To consider the interests of different decision-makers, Tang et al. [149] developed interaction strategies between a grid and buildings using the Stackelberg game based on their identified Nash equilibrium. In addition, the author addressed the effects of building demand

baseline uncertainty. However, the paper does not indicate how the dynamic price can interfere in prosumers trading or even in the real-time market or the day-ahead market. On the other hand, Zhang et al. [79] propose a dynamic price based on a P2P trading model that includes local energy suppliers and a community coordinator as market participants. However, the authors do not point to the effect of the proposed model on DR in the real-time market or the day-ahead market.

In [150], the authors implemented a tool to aid the multi-energy trading based on Nash-type non-cooperative game formulation. The authors determine a fair pricing P2P trading between residential and commercial prosumers. Although the paper considers demand-side management, the effect of IBP is not discussed. In [151], Nash bargaining theory is performed to monetize prosumers flexibility, taking into account synergies between the aggregator and the DR provides. Even so, the authors consider only the day-ahead market, and the aggregator is not allowed to trade energy in the intraday market.

5.2. Optimization techniques summary

In Section 5.1 the main optimization techniques that have been applied in DR program studies in the prosumer and energy market context are presented. A summary of the main characteristics of the reviewed references in this study is presented in Tables 4 and 5. The main characteristics addressed for comparison consider: (i) the optimization technique, (ii) objective function, (iii) grid system, (iv) energy source prosumer device, (v) energy market model, (vi) market participation level, and (vii) DR program type.

The papers presented in this section point out that there is a balance in the authors' proposals in relation to VNM frameworks. Fig. 4 classified each paper in Tables 4 and 5 according to the VNM frameworks and the optimization method.

Optimization techniques that consider uncertainty tend to address complex trending models with more variables involved, such as third parties, shared generation and aggregation frameworks. In addition, game theory techniques can also be a useful tool in these three complex VNM frameworks, as they consider the interactions of different players in the market. To investigate VNM trends in the energy market, Fig. 5 presents the Sankey diagram involving the 27 papers reviewed in Tables 4 and 5.

The Sankey diagram shows the market model and DR program trends at each VNM framework. As the single entity aims at the economic return of prosumers, it is natural to see a trend in this framework toward PBP operating in the energy market. In addition, approximately 74% of the papers studied address DR programs for the energy-only market. In contrast, the aggregation topology can often be used to provide services to the system operator through IBP.

5.3. Benefits of optimization in decision making

The development of tools capable of combining DR programs, energy markets and optimization techniques is essential to assist prosumers in decision-making. Thus, the prosumer is able to verify what is the best time to consume or inject energy into the grid, whether it is necessary to adjust the consumption baseline concerning the contracted DR program, among other measures that help achieve the desired goal [133]. For example, the authors in [153] developed a tool for the prosumer to certify whether there is the feasibility of participating in DR programs based on their consumption.

Environmental preservation is a factor that also influences the combination of DR programs and prosumers. For example, mitigating GHG emissions through reduction of peak demand decreases the number of emissions and incentivizes higher penetration of RES intermittently in electric power systems [130,154]. Furthermore, as many studies are from countries where heating systems are needed, some studies focus on the application of CHP, as discussed in [155], [135] and [133].

Another point is that prosumers can use BESS, helping to store

Table 4
Optimization studies on prosumers participating in DR programs (Part 1).

Technique	Objective	Grid	Prosumer Device	Market	Participation	DR program	Authors
LP	Min OC	Microgrid	PV + BESS	Reserve	Retail	PBP	[128]
LP	Min OC	Real Microgrid	PV + WT	Energy	Local	PBP	[129]
LP	Min OC	Real Microgrid	PV + BESS+ PV + HP	Energy	Wholesale	PBP	[130]
MILP	Min Profit (PFT)	Market System	BESS + EV	Energy + Reserve	Wholesale	IBP	[131]
MILP	Min OC	Real Microgrid	PV + BESS + DGS	Energy	Local	PBP	[22]
MILP	Min OC	Domestic System	PV + DGS + Biogas	Energy	Local	PBP	[40]
MILP	Min OC	Real Microgrid	WT + BESS	Energy	Retail	PBP	[26]
MILP	Min OC	Domestic System	PV + BESS + EV + WT + micro-CHP	Energy	Retail	IBP	[132]
MILP	Min OC + Max PFT	Microgrid with Energy District	PV + GGS + EV	Energy	Local	PBP + IBP	[133]
MILP	Min OC	Domestic System	PV + WT + BESS	Energy + Reserve	Local	PBP	[144]
MILP + LP	Min Costs + Max Exceeds	Market System	PV + BESS + micro-CHP	Energy + Reserve	Wholesale	IBP	[134]
DP	Min OC	Domestic System	micro-CHP	Energy	Wholesale	PBP	[135]
DP + LP	Min OC	Domestic System	PV + BESS	Energy	Retail	PBP	[136]

Table 5
Optimization studies on prosumers participating in DR programs (Part 2).

Technique	Objective	Grid	Prosumer Device	Market	Participation	DR program	Authors
Bilevel Programming	Min GC + Max SC	59-buses IEEE System	PV + BESS	Reserve	Wholesale + Retail	PBP + IBP	[137]
SP	Max PFT + Min CVaR	Microgrid	PV + WT + GT + BESS	Energy	Retail	IBP	[138]
RO	Min OC	Microgrid	PV + WT + BESS	Energy + Reserve	Wholesale	IBP	[139]
RO	Min D	Market System	WT + BESS+ EV	Energy	Wholesale	IBP	[140]
CCP	Min OC	9-buses IEEE System	WT	Energy + Reserve	Local	IBP	[142]
GA	Min OC	Domestic System	PV + WT + BESS	Energy	Local	PBP	[152]
GA + LP	Min GC+ Max PV	Market System	PV	Energy	Local	PBP	[145]
PSO	Min OC	Domestic System	PV + BESS	Energy	Local	IBP	[146]
Stackelberg game	Max PFT	Real Microgrid	PV	Energy	Local	IBP	[147]
Coalitional game	Min OC	Microgrid	PV + CHP	Energy	Wholesale	IBP	[148]
Stackelberg game	Max PFT + Min FL	Real Microgrid	PV + WT + Nuclear	Energy	Local	IBP	[149]
Non-cooperative game	Max PFT	Microgrid	PV	Energy	Local + Wholesale	IBP	[79]
Non-cooperative nash game	Min OC	Energy District	PV + BESS + EV+CHP	Energy	Local	PBP	[150]
Nash bargaining game	Max PFT + Max SW + Min OC	Market System	WT + OGG	Energy	Wholesale	PBP	[151]

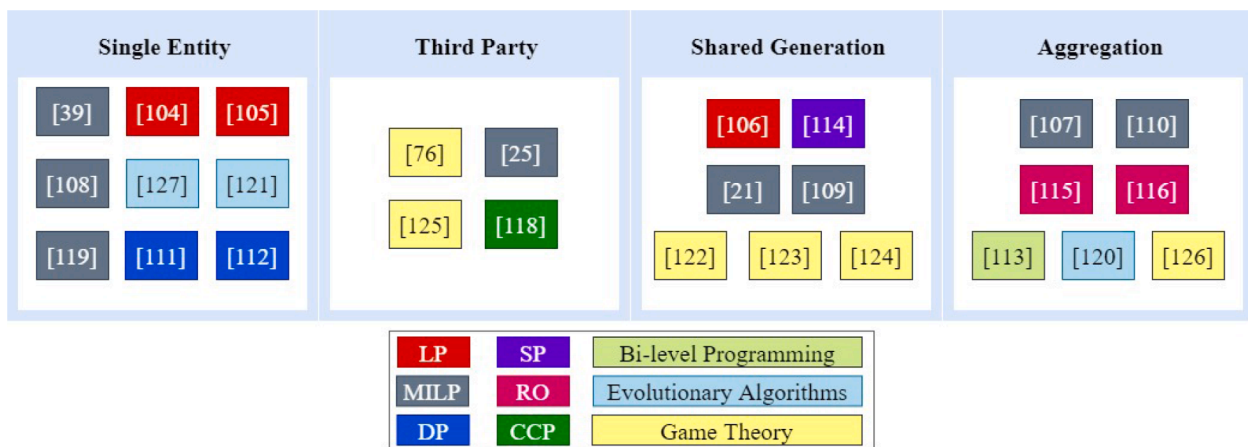


Fig. 4. Optimization papers classified according to the virtual net metering framework.

electricity at times when the price is low to sell at higher prices. However, this requires an investment in storage devices, which are expensive. Several studies, such as [40], [136], [156], [137], [139], [144], [130] and [154], have been studying the impact of BESSs on

prosumer-targeted DR program.

Overall, the studies conducted between 2018 and 2021 were directed at the energy market analysis aimed at maximizing profits as well as minimizing costs. These studies involved a series of actions, such as

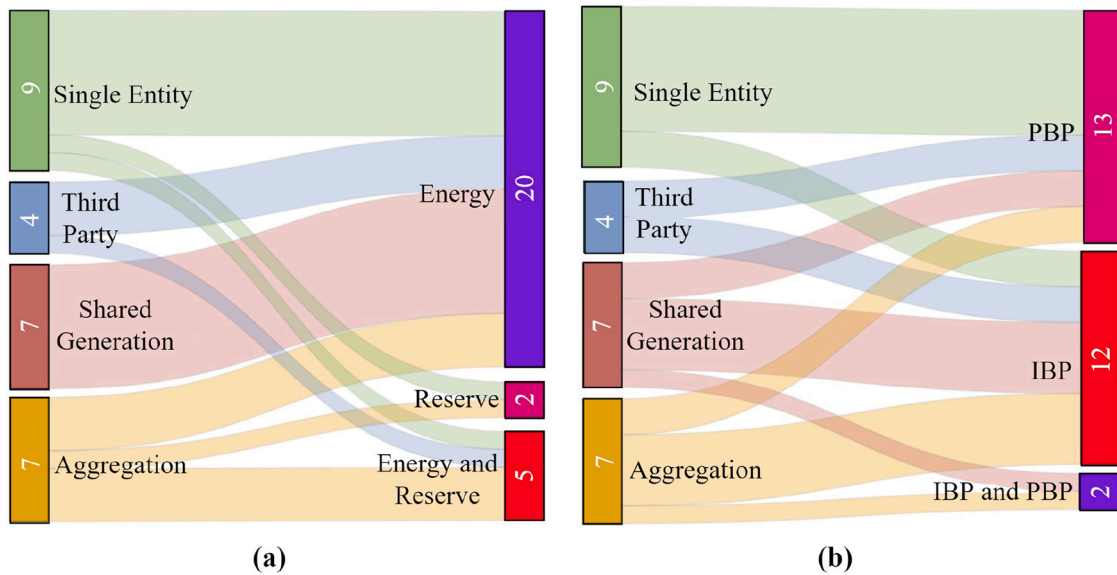


Fig. 5. Sankey diagram based on number of paper reviewed: (a) market model; (b) demand response program.

problem identification, scenario and available resources analysis, and options cost-benefit evaluations. Thus, the use of optimization techniques was essential in the decision-making process to achieve the desired results.

6. Future outlook: barriers and opportunities

Based on the works under consideration in this study, a large number of pilot projects and consolidated prosumers projects that have DR guidelines in their BMs clearly show the potential value of prosumers in emerging DR, pointing to the trend toward decentralized aggregation markets or P2P trading. In contrast, the real long-term value has yet to be proven, especially as most initiatives have trialed the technology in

small-scale projects that are still in an early development stage. With the new technological options in power systems, such as blockchain, the possibilities of implementing local and retail markets mechanisms increase, making the consumers' objectives such as profit, and self-consumption, social welfare, more attractive [109].

To discuss future outlooks and trends of DR programs applied to prosumers, this section is divided into two guidelines. First, the main barriers that must be overcome by decision-makers in the energy market are discussed. Then, the opportunities and recommendations on the topic identified by the authors are exposed. Fig. 6 points to future fields of relevant research, opportunities, and the possible barriers associated with different electricity market players.

In addition, Fig. 6 illustrates the main parameters considered for

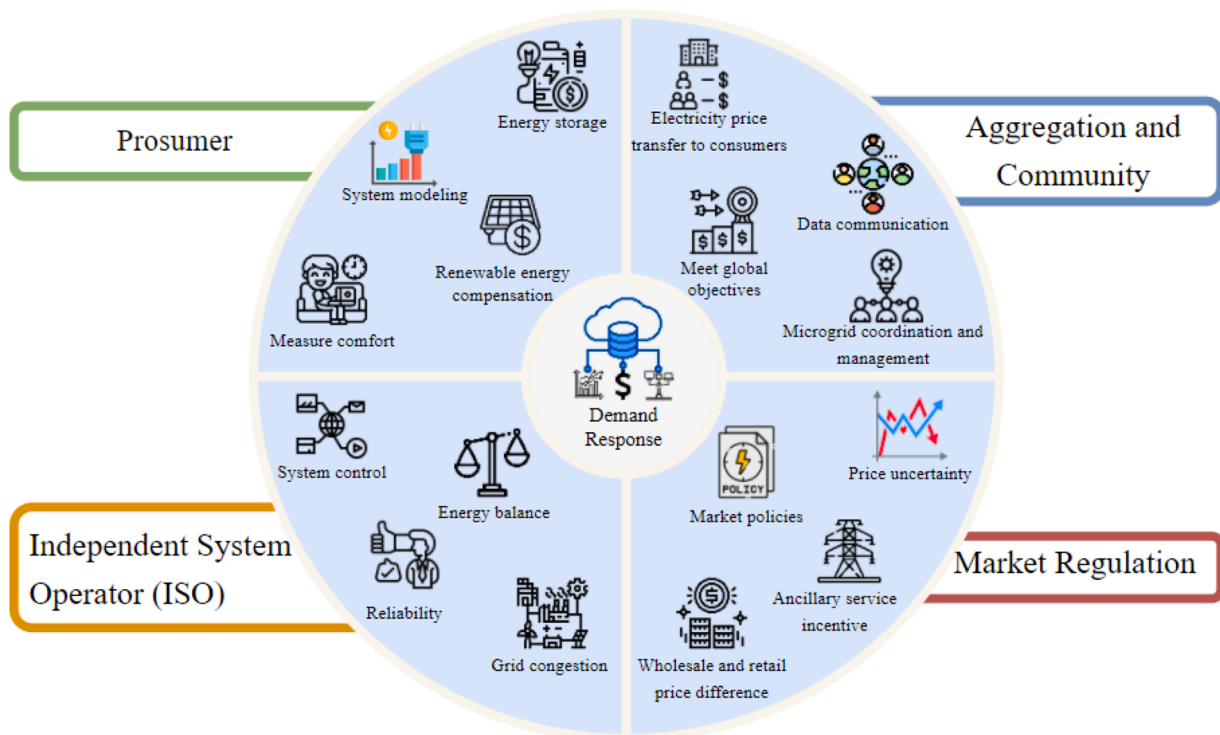


Fig. 6. Overview of barriers and opportunities of stakeholders in the electricity market.

barriers and opportunities analysis, concerning four levels: (i) Prosumers, (ii) Aggregation and Community, (iii) ISO and (iv) Market Regulation. Following, these parameters are discussed, providing an overview about DR programs, optimization techniques and their implementation at four levels researched.

6.1. Barriers and conflict of interest

Studies of markets and DR programs that adhere to optimization techniques to aid in decision-making are usually focused on cost-benefit analysis, considering the inherent uncertainties and risks. In general, prosumers, aggregators and community markets objectives functions concern maximizing profit, social welfare and self-consumption, while ISO carries about optimal dispatch and maximization of grid flexibility to postpone investments in generation, transmission and distribution systems. In addition, prosumers and ISO must operate according to the market regulations controlled by the market operator.

In this way, to highlight and identify the barriers caused by conflicts of interest, this section will discuss the main barriers according to the parameters pointed out in Fig. 6.

- **Prosumer:** The use of BESS to make the DG output more flexible and dispatchable can help prosumers optimize economic and social aspects. However, this technology has a high investment cost, which is one of its main drawbacks. Besides, BESS presents computational complexities due to nonlinear features in its operation, which consequently strongly impacts its reduced life cycle. Other factors that may bring problems to modeling prosumers' systems are EMS and systematic DER modeling. In relation to the optimization techniques, these factors rely on massive real-time measurements, which may not always be available or require extra technological investment. Regarding the electricity market stakeholders, when load and generation data are missing or wrong, it may be reflected in mistakes in the energy balance, DR market and market clearing-price. In addition, the prosumer EMS is generally responsive to the renewable energy compensation price, however in some cases this price does not have the necessary stimulus for the prosumer to participate in DR programs.
- **Aggregation and Community:** Concerning obstacles, we can mention: (i) meeting global objectives such as energy cost, peak power and minimizing grid power losses; (ii) cohesively managing and coordinating the microgrids that are interconnected to pass on information about electricity prices and the applicability of DR programs; and (iii) maintaining interaction between the aggregator and users by means that enable data communication in real-time and with data encryption to ensure privacy.
- **Market Regulation:** In the context of market regulation, a few issues need to be improved, such as public policies, renewable source incentives and financial incentives. In this way, DR programs can contribute more effectively to the electricity market. The main barriers in this scope are: (i) use of DR in ancillary services, e.g., primary regulation is generally mandatory and not remunerated; (ii) lack of guidelines regarding net metering and feed-in tariffs may discourage the adoption of DR programs; and (iii) discrepancy between wholesale and retail energy prices. In addition, the data update time of the market operator may be less than the ISO operating interval in some markets. This factor must be considered in the optimization methods, as some generating units do not have a fast response time to market price variations.
- **ISO:** The barriers concerning the ISO and integration of DR programs, as well as the use of optimization techniques are related to (i) mass digitization of electric grids applying the real-time supervisory system and large-scale system control; (ii) the integration of RES together with DR, which increases the complexity of the operation problem. Simultaneous operation of RES, DR, V2G and other resources in the distribution grid can lead to bidirectional power flow,

which is a challenge in the distribution grid operation; (iii) reliability guidelines, contingencies, electrical losses in power transmission, which requires continuous investments and improvements of the generation, transmission and distribution systems; and (iv) balancing between generation and demand.

Optimization tools play an essential role in consolidating DR programs as a viable BM for prosumers. In addition, the optimization of these resources allows the management of network technologies to assist prosumers' interests, ISO, aggregators and community energy markets, and market regulations. Optimization techniques and DR programs can be used in the decision-making process of ISO, market agents, and prosumers, and to develop indicators for regulating the electricity market. However, these optimization problems require high performance and efficiency, both in processing consumption data and receiving hourly energy tariff data. Such factors require an expensive investment in ICT architectures. In other words, the more accurate the mathematical modeling is to reality, the greater the computational time and effort. This factor makes the use of some computational techniques applied in the system operation and management of DERs in real-time unfeasible.

There are few pilot or ongoing applications that use optimization for pricing and resource management. This limitation occurs because, despite the challenges of computational processing, optimization problems are not usually modular and easily expandable for the entry of new resources and new network topologies. As a result, this tool to aid in decision-making is more applied in models for studies in a controlled and regulated environment. Another limitation of the current optimization tools is the lack of holistic constraints that consider the cultural profile of the population's energy consumption, extraordinary local events and empirical knowledge of distribution network agents.

6.2. Opportunities and recommendations

To summarize the fields that can be explored in the literature, to add value to prosumers BMs in energy market models, the authors point out the following study opportunities and recommendations concerning the four levels highlighted in Fig. 6.

- **Prosumer:** Through the papers considered throughout this review, the consumer's potential to produce electricity and participate in the market as a prosumer was verified. However, it is necessary to improve DR concepts and optimization in light of barriers by listing some possible opportunities (i) use BESS and DR programs to optimize the consumption baseline, facing the uncertainties of RES; (ii) develop intelligent technologies for real-time monitoring for the implementation of Home Energy Management Systems (HEMS) that optimize the generation and distribution of energy throughout the day; and (iii) improve mathematical models of existent electrical appliances to improve management and maximize the utility function and minimize operating costs.
- **Aggregation and Community:** It was noted that current studies present grid operation with well-defined aggregators and some of these studies show that aggregators have already taken the first steps toward coordination with the community energy market. However, there is a need to (i) develop business and asset management models through the use of DR programs and optimization; (ii) perform the technical and economic feasibility analysis of migrating from the utility's power grid to participate in community electricity markets or through microgrids or VPP managed by aggregators; and (iii) develop hardware and software for the implementation of sophisticated algorithms that better integrate DR and optimization.
- **Market Regulation:** From the point of view of market regulation, it is perceived that it is necessary to foster studies that identify the relationship between the DR programs, prosumers optimization models, and market regulation highlighting points such as (i) the use

of DR as ancillary services; (ii) the analysis of the impact of DR in encouraging price regulation among those involved in the energy market, aiming at satisfaction for generating and consuming. In addition, to analyze the legalization of the sale of surplus energy from prosumers at a price compatible with the electricity market; (iii) the use of DR resources to control or shift the load in the face of variable electricity prices, through studies and measures that seek a balance between DR actions and wholesale market prices; and (iv) the development of public policies that strike a point of balance between the various markets to improve DR programs and pricing schemes.

- **ISO:** From the ISO point of view the opportunities identified are the following: (i) integration of DR programs and new optimization techniques for real-time grid operation (ii) use of DR for better utilization of DG, minimizing reverse power flow and improving the profile and local grid voltage levels to mitigate reliability and contingency problems, (iii) application of DR to postpone investments in generation, transmission and distribution systems; and (iv) development of mathematical models to aggregate the use of DR, the uncertainty related to RES to minimize losses and operating costs.

Market models and prosumers BMs infer the mathematical problem that can be performed in the optimization. The well-defined mathematical formulation can assist the construction of pilot projects and market modeling studies, as well as the evaluation of opportunities for aggregating agents. Each region's market model may have a different BM applied to the prosumer, ensuring that the DR brings benefits to its market regulation. Additionally, in places where the market is open for small-scale users, there is an incentive for end-users to participate in DR programs.

7. Conclusion and future work

7.1. Conclusion

Demand response is an essential tool for both grid operators and end-users, especially with the spread of DERs and the investment in the digitization of the power sector. These factors allow for greater flexibility of loads, generation management, and energy negotiations between prosumers and grid operators in different grid frameworks. In addition, the digitization of the distribution grid promotes end-user engagement with DR programs, as it allows grid operators to send incentives and present the tariff price in real-time to customers.

In this way, DR programs in consumers and prosumers energy production are reflected in the energy market, generating impacts on the energy balance, interconnected network planning, system reserve capacity, and ancillary services. However, the advent of these technologies makes the system more complex, with the need for decision-making studies of market price management and incentives that guide the DR programs. Thus, the application of optimization techniques for studies of prosumers who participate in some DR programs is a trend.

Optimization is a tool that can incorporate power system parameter constraints, energy market regulatory conditions, and prosumers frameworks. In addition, optimization models can represent diverse interests of prosumers, communities and aggregators in the objective function. Also, can help market regulators and ISO objectives to find the optimal operating point of the system.

From this literature review, one can conclude that considering the use of optimization techniques in the context of existing market models and DR programs may offer certain benefits. However, the interaction between DR and other system components can ensure improvements as follows: (i) to assist in ancillary services, such as frequency and voltage profile control, (ii) to postpone certain costly investments in network infrastructure; (iii) to integrate DER such as PV, BESS, WT to minimize losses and operating costs; and (iv) DR to bring a significant effect on cost savings and improved efficiency in energy systems. This change has

also meant that consumers are becoming more active in the energy system. Transforming these consumers from passive agents to prosumers which was one of the main approaches of this study to verify market models and optimization techniques to support the decision-making on DR for the prosumer. However, the success of the applicability of DR programs in the relation between prosumers and the energy market is linked to the integration of electric systems management chains, such as regulation, planning, and expansion in a way to reveal its full potential.

7.2. Future work

This work presents barriers and opportunities for DR programs applied to prosumers and the interests of aggregators, ISOs and energy market regulation policies. In this sense, possibilities are pointed out that can be explored in future works. For future research, the following is highlighted:

- There is a need for technical-economic analysis to support the pricing of the contribution of prosumers in the energy market to encourage prosumers to offer their energy production as a service for the ISO.
- The data collected from the AMI need to be transmitted quickly and securely since the exchange of information and energy measurements are essential for the control and management of the DERs and the relations between prosumers and system and market operators.

In this sense, ICT needs to be implemented and improved to provide real and reliable data to be combined with optimization techniques, aiding energy market clearing price estimation and assisting DSO decision-making. Furthermore, there is a lack of mathematical models of DERs that represent their operational limitations, such as equipment degradation. These models can better represent optimization problems to help the system operator and market operators in decision-making. Furthermore, more realistic mathematical models can contribute to the development of BMs and new market regulations that reflect the interests of prosumers.

CRedit authorship contribution statement

W.N. Silva: Conceptualization, Writing – original draft. **L.F. Henrique:** Writing – original draft, Visualization. **A.F.P. da C. Silva:** Investigation, Writing – original draft. **B.H. Dias:** Writing – review & editing, Supervision. **T.A. Soares:** Writing – review & editing, Supervision.

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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