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Literature review. Pricing rule alternatives for the European day-ahead market

1. Introduction

The day-ahead market occupies a central position within liberalized electricity markets, establishing reference prices for wholesale electricity on an hourly basis for the subsequent day. These reference prices play a crucial role in coordinating all other segments of the electricity market, including over-the-counter (OTC) transactions. Consequently, the prices determined in the day-ahead market exert a significant influence on the profitability of electricity producers and subsequently affect consumer prices, thus affecting the profitability of retail suppliers.

From the end of 2021 throughout the year of 2022, the electricity sector has witnessed a significant rise in consumer prices, attracting considerable attention from both political and media spheres. The escalation of consumer prices in 2022 prompted concerns, which were echoed in notable political speeches, such as that of EU Commission President Ursula von der Leyen, as well as widespread coverage in newspapers. The underlying cause of these high consumer prices was primarily attributed to soaring wholesale prices (Fig. 1), placing the focus on the pricing rule implemented in the wholesale market.

This pricing rule was then often referred to as merit order and simplified as the most expensive generation technology used determines the prices for all producers. In 2022 this meant the enormously increased natural gas prices triggered high wholesale electricity prices for all producers. This, combined with the argument that only 20% of the electricity in the European union is generated from natural gas, (see Fig. 2) was seen as a proof of the inefficiency of the working of this market.

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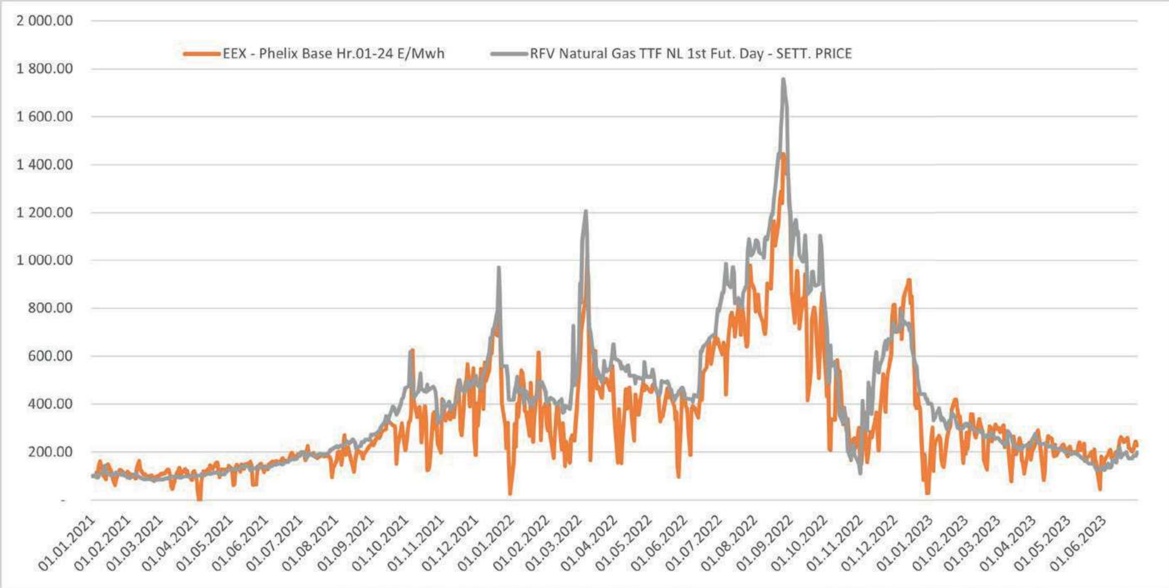

Figure 1. Development of electricity wholesale prices and natural gas prices from 2021 to 2023

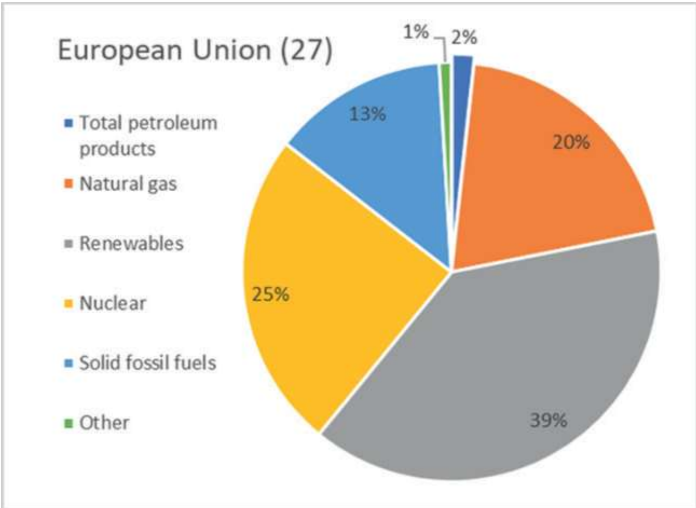

Figure 2. Electricity generation mix for European Union in 2021

Source: Eurostat

Figure 1 illustrates the EEX-Phelix-Base 01-24 in €/MWh, representing the daily average of wholesale electricity prices for the Austria/Germany zone, as well as the Refinitiv Natural Gas Title Transfer Facility Netherlands First Futures Month in €/MWh serving as a reference for the Gas Price. The figure show cases the evolution of these two indices, which have been normalized to a starting value of 100 in January 2021. The depicted time frame spans from 2021 to April 2023. One can see the enormous rise in both prices for 2022.

Throughout post-liberalization history, a recurring trend emerges: whenever there is a surge in electricity prices, the focus inevitably turns to the pricing rule of the day ahead market.

Notable examples include the summer of 2000 in California, when wholesale electricity prices skyrocketed by nearly 500% compared to previous years. This alarming situation sparked intensive discussions of pricing rules within the main electricity markets, as in P.L. Joskow and E. Kahn (2002) and E. Kahn et al. (2001). Similar scenarios unfolded in Germany, as discussed by V. Grimm et al. (2008) and J. Haucap (2013), as well as in Britain, as discussed by C.D. Wolfram (1999) and N. Fabra et al. (2002).

Furthermore, alongside political concerns regarding the pricing rule's effect on market inefficiencies, academia has extensively explored another critical issue known as the "missing money problem." This refers to the observation that after the liberalization, wholesale electricity prices have been too low to cover the total costs of the electricity producers. The conclusion once again was the wholesale electricity market is working inefficiently, and diminishes incentives for investment, which hinders the investment in renewables as well as possibly leading to future problems concerning the security of supply.

In order to increase the investment in renewable energy generation, schemes for direct governmental support have been introduced. These schemes increased the profitability of renewables but, depending on their structure, reduced the profitability of the other generation technologies (e.g., all baseload technology in Germany, J. Haucap (2013)). To counteract the missing money problem and the increasing share of renewable generation, balancing or capacity markets were introduced to the "energy-only" markets. The structure of a balancing market differs depending on the country, but the principle is largely the same: producers are financially rewarded for providing potentially used capacity. The construction of a balancing market is also an argument for the inefficiency of the working of the wholesale electricity market.

A different perspective emerges when examining the relation between installed capacity and peak demand. It has become apparent that even before the liberalization of electricity markets, many countries had overcapacity, wherein the installed capacity exceeded the peak demand, for example, see S. Moret et al. (2020). This phenomenon has only intensified since market liberalization (Fig. 3). In such circumstances, it is efficient for wholesale prices to not cover total costs, since investment in new capacity shouldn't be profitable. This hampers progress towards achieving climate goals. The introduction of a balancing market, on the other hand, made it profitable even to invest in overcapacity that might never be dispatched.

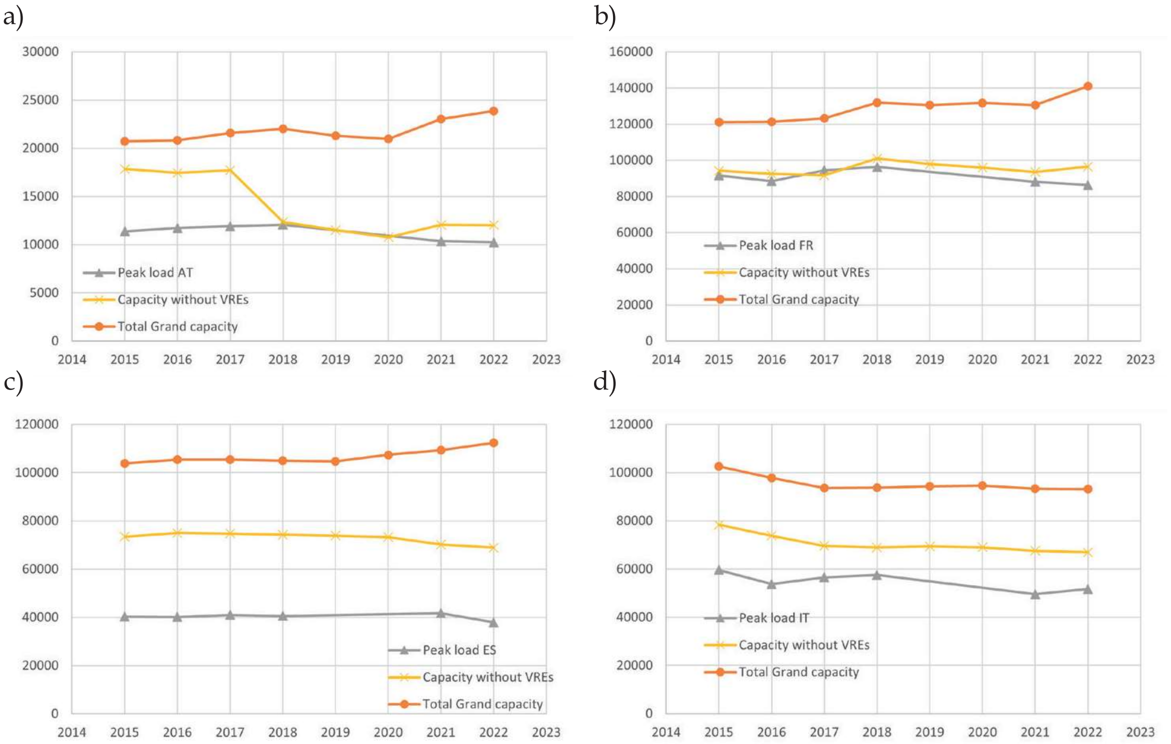

Figure 3. Development of peak load and Installed Capacity: a) peak load, installed capacity and installed capacity without variable renewables in MWh for Austria from 2014 to 2022; b) peak load, installed capacity and installed capacity without variable renewables in MWh for France from 2014 to 2022; c) peak load, installed capacity and installed capacity without variable renewables in MWh for Spain from 2014 to 2023; d) peak load, installed capacity and installed capacity without variable renewables in MWh for Italy from 2014 to 2022

Figure 3 is constructed from ENTSOE data for yearly peak load averaged on the hour and net generating capacity installed in the country. We can see that the orange line, depicting the total installed capacity, overshoots the peak load, depicted in grey, for the time period from 2015 to 2022. This shows the amount of overcapacity present in European countries. Through the balancing market, the costs of this highly inflated market are priced to the consumers.

Furthermore, despite the prevalence of overcapacity, there have been several instances where systems came close to experiencing blackouts or brownouts. The main contributor to this problem is the variable nature of renewable generation. When comparing the installed capacity to peak demand, it is clear that there is costly overcapacity in the system. However, when we exclude renewable sources from the equation (represented by the yellow lines in Figure 3, particularly in cases where a significant share of nuclear power plants, such as in France, is currently maintained, we can observe that peak demand reaches the capacity limits.

The intricate nature of the electricity wholesale market, compounded by constant political intervention, complicates the assessment of its working. These interventions often erode investment incentives (apart from renewables) and always increase (political) risks. While the translation of wholesale prices to consumer/retail prices falls outside the scope of this paper, the findings of the Austrian Bundeswettbewerbsbehörde in their investigations published in July of 2023 are worth noting: they indicate that there is limited competition within the retail supplier market. Consequently, rising wholesale prices tend to translate into rising consumer prices, while decreases in wholesale prices only gradually translate to lower prices for end consumers.

In light of these complexities and their far-reaching implications, a comprehensive analysis of pricing rules in the day-ahead market becomes imperative. This paper aims to contribute to the understanding of the market's efficiency, laying the groundwork for informed discussions on potential improvements and policy interventions. By doing so, we aspire to promote a more sustainable and economically viable electricity market that supports the transition to renewable energy sources while ensuring reliable and affordable electricity for consumers.

Considering the complexities and challenges faced by the electricity market, this paper aims to provide a comprehensive review of the academic literature concerning different pricing rules for the day-ahead market. The primary research questions that motivate this literature review are as follows:

1. What criteria are used to evaluate pricing rules for the day-ahead market in variousstudies and how can they help to improve the current discussion?
2. What alternative pricing rules exist for the day-ahead market, and how do they perform according to the identified criteria for evaluation?

By conducting a thorough review of the academic literature, this paper intends to contribute to the understanding of the implementations of pricing rules in the day-ahead market. Rather than focusing solely on short-run prices, this analysis considers broader perspectives such as investment incentives, security of supply, market structure, and the unique characteristics of electricity as a commodity.

This literature review aims to identify the criteria used to evaluate pricing rules and their performance in the context of the European electricity market. By examining the strengths and weaknesses of different pricing rule alternatives, valuable insights can be gained regarding their suitability for addressing the challenges faced by the market.

It is worth noting that this paper does not delve into broader structural changes or macroeconomic events but specifically concentrates on the analysis of pricing rules in the day-ahead auction. By narrowing the scope in this way, we can provide a focused and in-depth examination of the subject matter.

The rest of this paper is organized as follows. Section 2 provides an overview of the electricity market, including its liberalization, market structure, and its most important market, the day-ahead market. This section finishes by introducing the criteria for evaluating pricing rules.

Section 3 delves into the currently implemented uniform pricing rule (UP) and explores its main competitor, the discriminatory pricing rule (DP), along with the Vickrey–Clarke–Groves pricing rule (VCG), which has garnered academic interest. A comparative analysis of these pricing rules sheds light on their advantages and limitations.

Lastly, Section 4 presents a synthesis of the prominent conclusions drawn from the reviewed literature. It summarizes the key insights and findings regarding the evaluation of pricing rules for the day-ahead market, providing a comprehensive understanding of the subject matter.

In conclusion, this paper aims to contribute to the ongoing discussion and debate surrounding the reform of pricing rules in the European electricity market's day-ahead auction. By critically analyzing the academic literature and examining different pricing rule alternatives, this research strives to enhance our understanding of the factors that should be considered when designing efficient and effective pricing mechanisms.

2. The European day-ahead market

2.1. Liberalization of the European electricity market

The electricity market encompasses four primary components: generation, transmission, distribution, and consumption.

Electricity generation is a complex and dynamic process that involves a multitude of technologies, inputs, and operational considerations. Each technology presents its own set of advantages, limitations, and environmental implications. Operational limits, such as temperature thresholds and load balancing, are crucial to prevent damage to the equipment and to ensure the stability of the power grid. Additionally, the supply of electricity is subject to uncertainties arising from weather conditions, seasonal variations, and the need to effectively match the unpredictable patterns of consumer demand.

Transmission, as a critical component of the electricity system, involves the long-distance transfer of power. However, it faces inherent limitations dictated by fundamental physical laws, most notably Kirchhoff's Laws, which impose restrictions on the capacity of transmission lines. These limitations arise from factors such as line losses, voltage drop, and thermal constraints, necessitating careful management and planning of the transmission infrastructure.

Distribution encompasses the local transfer of electricity over shorter distances, typically from distribution substations to end consumers. This stage of the electricity supply chain involves transforming the high voltage electricity from transmission lines into lower voltages suitable for consumption by households, businesses, and other entities. Effective coordination and synchronization between transmission and distribution networks are crucial to ensure the efficient and reliable delivery of electricity to end-users. Even though they have a major influence on the efficient working on the liberalized market as well as the implementation of the optimal pricing rule, we will basically exclude them from the scope of this paper.

The inelastic nature of electricity demand, where consumers' electricity consumption remains relatively unchanged despite price fluctuations, has significant implications for market clearing. This lack of responsiveness to price changes, attributed in part to prevalent consumer contracts that insulate consumers from short-term price variations, can lead to imbalances between the supplied and demanded quantities at a given price level. However, the introduction of smart meters and their increasing rollout holds promise for addressing this problem. Smart meters provide real-time information on electricity use and pricing, enabling more dynamic pricing structures and empowering consumers to make informed decisions about their energy consumption.

In the past, the electricity market was operated by vertically integrated monopolies, as depicted in Figure 4. These monopolies controlled all aspects of the market, and prices were set by pricing committees based on costs and a stable return.

Figure 4. Monopolistic electricity market before liberalization

As a result of liberalization, a fundamental reorganization took place, leading to the dismantling of long-standing monopolies and the introduction of competition in both the retail supply and the generation of the electricity (Fig. 5). The motivations driving this liberalization, as highlighted by F.P. Sioshansi (2006), were multifaceted and encompassed objectives such as eliminating inefficiencies, addressing regulatory complexities, overcoming inadequate investment in infrastructure, and facilitating decentralized decision making. The overarching goal was to establish a regulated, non-discriminatory, and transparent electricity market accessible to all participants, as emphasized by N. van Bracht et al. (2019). This restructured and liberalized electricity market aims to foster competition, promote efficiency, and enhance overall market dynamics for the benefit of consumers and the industry as a whole.

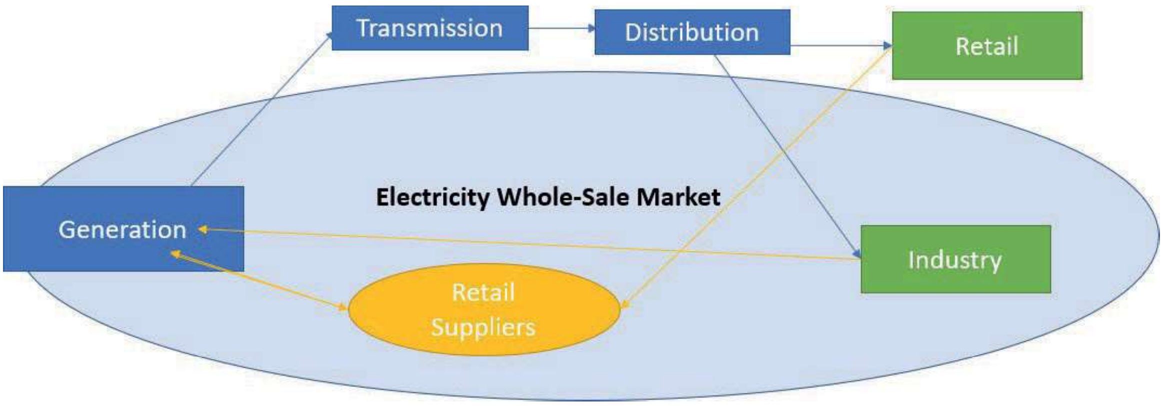

Figure 5. The Liberalized Electricity Market

The wholesale market stood as the cornerstone of the newly established electricity market, facilitating competitive generation and supply. It was believed that fostering competition between multiple producers would lead to a more effective reduction of wholesale prices compared to price regulation in a non-competitive market. However, this competitive market structure presented challenges in terms of ensuring fair and transparent electricity pricing.

In addition, the transmission and distribution of electricity were excluded from competition due to the potential negative effects that could arise from an unregulated approach. Consequently, investment in transmission networks remain highly regulated, ensuring the reliability and stability of the grid, while investment in generation capacity is now open to participation from various market players. This differentiation in competition has helped strike a balance between promoting efficiency and maintaining the necessary control and oversight of critical infrastructure components.

To address the challenges experienced in regions such as Italy and California, where blackouts and capacity-related problems emerged, ancillary markets were established. While transmission and distribution remained under regulated frameworks, ancillary markets played a crucial role in managing the challenges associated with supply–demand imbalances and congestion. Through their establishment, liberalized electricity systems aim to enhance the resilience, responsiveness, and overall reliability of the grid, drawing lessons from past experiences to build a more robust energy infrastructure.

Several papers, such as T. Jamasb and M. Pollitt (2005), have investigated the effectiveness of the liberalization at achieving the advocated goals. It was found that the level of competition is still relatively low in all liberalized segments, including generation and retail supply. This can be attributed to the inherent characteristics of the electricity market, such as the presence of economies of scale, oligopolistic ownership, entry barriers, inelastic and volatile demand, and strategic bidding. These factors make the market susceptible to market power abuse, leading to distorted prices and inefficient outcomes. Therefore, the design of pricing rules and auction mechanisms becomes crucial in promoting competition, mitigating market power, and achieving efficient market outcomes.

The level of competition is especially low in the retail supplier segment, which also explains why rising prices rapidly translate into consumer prices but lowering prices do not. For instance, the Bundeswettbewerbsbehörde in Austria has published a graphic illustrating the Herfindhal–Hirschman Index (HHI) for different regions, highlighting the considerable market concentration (Fig. 6).

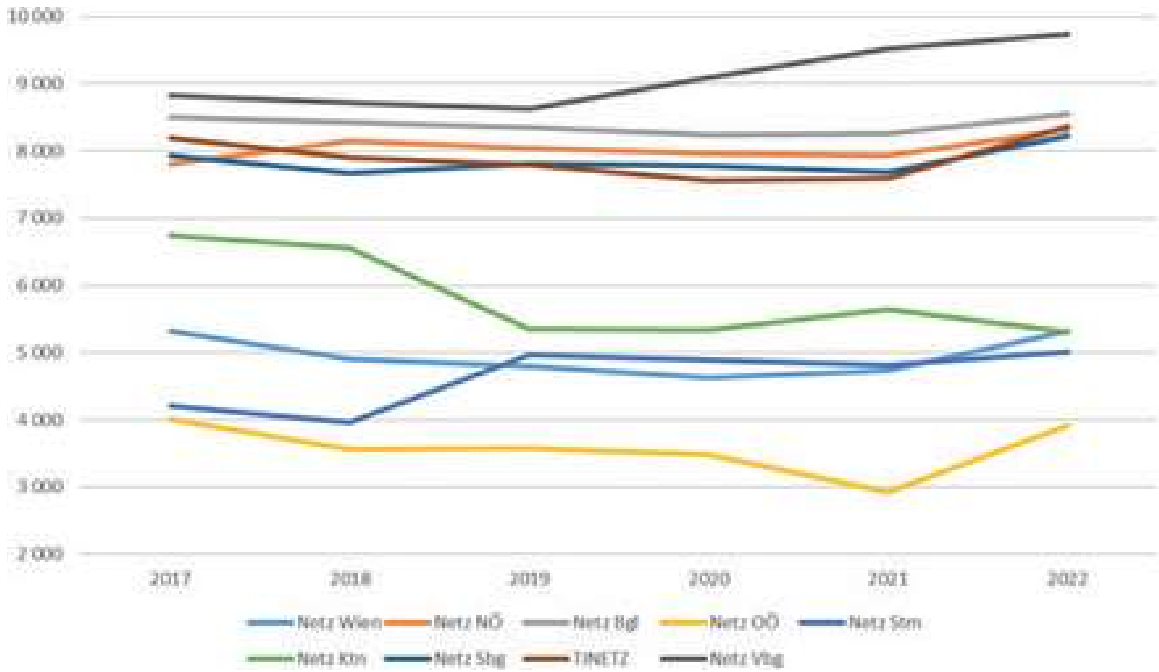

Figure 6. Development of HHI of the retail supply for Austria's nine regions

Similar findings have been observed in other European countries as well.

Furthermore, the transition from state ownership to private ownership of electricity generating companies has not occurred as extensively as expected.

This is evident in the ownership structure graphic (Fig. 7) of electricity generating companies in Austria, where dark green boxes represent entities that are 100% state owned. It is apparent that the state continues to play a significant role in electricity generation. It is worth noting that Austria is not an isolated case, as this pattern is also observed in other countries across Europe. This example was chosen due to the recent publication of the E-Control investigation.

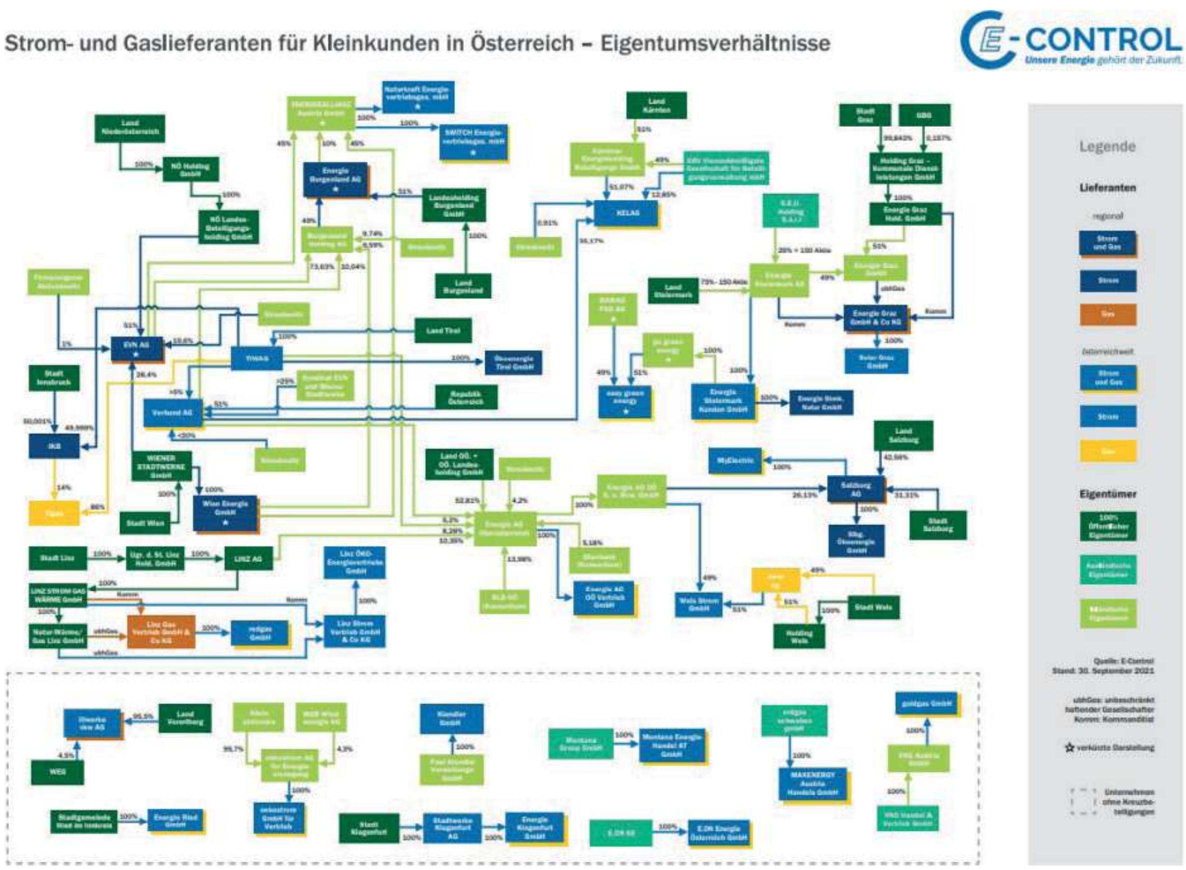

Figure 7. Ownership structure of electricity generating companies in Austria

2.2. The wholesale electricity market

The wholesale market for electricity comprises spot markets, which include the day-ahead and intraday markets, as well as long-term markets, which include futures, forwards, and options.

Among the spot markets, the day-ahead market holds significant importance, as already mentioned. Operated through power exchanges, it serves as the central market for electricity. Participants in the day-ahead market optimize their portfolios by submitting bids for the following day. This allows, for example, producers to efficiently manage their electricity supply in response to anticipated demand. The day-ahead market's influence, due to arbitrage, extends beyond the spot markets and affects the pricing in all other markets, including OTC trades.

Bidding rules govern the day-ahead market auctions: market participants submit bids specifying the quantity of electricity (in megawatt-hours) and the price (in euros per megawatthour) for each hour of the following day, while adhering to price floors and caps set by the rules of the market. To accommodate the increasing complexity of the generation of electricity, including the inclusion of renewable energy sources, the introduction of complex bids and block bids have become essential. Complex bids allow participants to express more sophisticated pricing strategies, while block bids enable the submission of bids for consecutive hours or even an entire day. Additionally, step-wise bid functions provide participants with the flexibility of specifying different prices and quantities for various price levels, or "steps." This can allow more nuanced price differentiation and better reflect the cost structures or market strategies of the different producers. However, it is important to recognize that an increased number of steps as well as all other bid amendments can also raise the risk of strategic bidding, where participants manipulate their bids across different price levels to influence market outcomes and maximize their own profits. Effective monitoring and regulation are crucial for mitigating the potential for strategic behavior and ensure a fair and competitive market environment.

Clearing rules determine the outcome of the day-ahead market auctions. Aggregate supply and demand curves are formed based on the submitted bids, representing the quantities of electricity supplied and demanded at different price levels. The market clearing price (MCP) is determined by the intersection of these curves, indicating the price at which the supply and demand of electricity are balanced. Individual market participants are then allocated quantities of electricity based on the clearing price and their submitted bids.

To provide a visual representation of the market clearing process, Figure 8 shows the aggregate supply and demand curves for a hypothetical hour in the day-ahead market. The supply curve depicts the relation between the quantities of electricity supplied and the corresponding prices, starting with lower quantities for low prices and gradually increasing as prices rise. On the other hand, the demand curve depicts the quantities of electricity demanded at different price levels, exhibiting a relation that is inverse to that of the supply curve. The MCP is determined by the point of intersection between these curves, indicating the price at which the supply and demand of electricity are in balance. The MCP plays a crucial role in influencing the prices that participants either receive or pay for the electricity they trade in the market, reflecting the equilibrium between the quantity supplied and the quantity demanded.

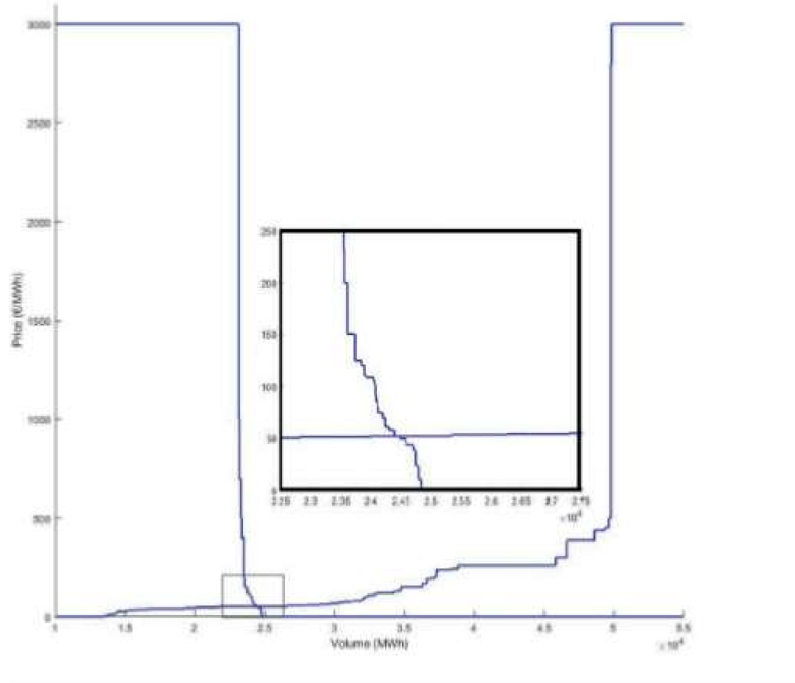

Figure 8. Clearing rule in DAM

Source: Soloviova et al. (2021)

2.3. Criteria for evaluating pricing rules

After the MCP is determined, the pricing rule decides what prices the winning bidders pay and receive as well as what happens with differences between the two sums. The evaluation of pricing rules in the day-ahead market encompasses multiple perspectives, including efficiency-theoretic ones and the political point of view.

From an efficiency-theoretic perspective rooted in economic theory and mechanism design, a pricing rule should aim for **productive efficiency**, which maximizes the efficiency of the current generation portfolio. In electricity markets, productive efficiency is synonymous with an efficient dispatch, where generators are dispatched in order of the lowest marginal cost. To achieve this, it is crucial that the producers' bids reflect their costs, a concept known as **truthful bidding**. If the pricing rule encourages truthful bidding as a dominant strategy, an efficient dispatch is guaranteed. Moreover, promoting truthful bidding simplifies the process of deciding on a bid, enhancing efficiency and fostering participation from smaller bidders (Lange et al. 2022).

On the other hand, the political perspective focuses on what is perceived as beneficial for consumers and aligns with political agendas. This perspective often prioritizes **low average prices** to ensure affordability for consumers and supports sustainability goals, particularly by incentivizing investment in renewable energy sources. However, it is important to strike a balance, as excessive profits for producers can generate high political costs due to public perceptions of unfairness. Therefore, discussions surrounding pricing rules often emphasize the need to ensure reasonable profits for producers while preventing excessive profits that might generate public backlash. This consideration shapes the evaluation of pricing rules and influences discussions surrounding incentives for investment and the fairness of the market.

In evaluating pricing rules, the **consumer surplus** is often included as a metric. Consumer surplus measures the difference between the willingness to pay for a unit of electricity and the charged price. Maximizing consumer surplus entails setting prices equal to the marginal costs for each unit of electricity. However, this approach may not cover the producers' fixed and total costs, affecting their profitability and incentives for long-term investment. The profitability and price stability of producers play a critical role in shaping their incentives for investment, which, in turn, shape the future generation portfolio. Negative profits can deter investment in generation capacity, which may be efficient in the case of overcapacity but problematic under normal capacity conditions. Positive investment incentives are currently politically motivated by the pursuit of climate goals.

Another important criterion for evaluating pricing rules is their effect on preventing **predatory, entry-deterring, and collusive behavior**. These behaviors interact with the aforementioned metrics in various ways, with truthful bidding being a key consideration. Truthful bidding becomes achievable when market power is minimal, as it influences the asymmetry of profits between producers of different sizes and the costs associated with market entry. Collusion directly affects short-run efficiency by driving prices above the level achievable under perfect competition, while entry-deterring behavior reduces competition and leads to long-run inefficiency. Predatory behavior can take different forms, such as supply reduction. Therefore, an ideal pricing rule should foster a level playing field, discouraging collusion and predatory pricing, while promoting fair competition and encouraging market entry.

Simplicity of pricing rules is also valued, as this ensures rational behavior by bidders and facilitates the correct interpretation of the results of the market.

In summary, the evaluation of pricing rules in the day-ahead market involves balancing the efficiency theoretic and political perspectives. It encompasses criteria such as productive efficiency, consumer surplus, investment incentives, prevention of anti-competitive behavior, simplicity, and market fairness. Striking the right balance is crucial to develop pricing rules that achieve both political objectives and market efficiency while ensuring fair outcomes for all stakeholders.

3. Literature review

The objective of this literature review is to analyze and characterize pricing rules in electricity day-ahead markets. By examining the academic literature, we aim to gain insights into the various approaches and assumptions adopted in studying pricing rules in these markets. This review seeks to provide a comprehensive understanding of the structure of the supply, the characteristics of the demand, information certainty, and other important factors that influence the performance of a pricing rule. Through this analysis, we aim to shed light on the effectiveness and limitations of different pricing rule frameworks and contribute to a broader understanding of the dynamics of an electricity day-ahead market. The literature can be categorized into four main approaches: analytical, theoretical, empirical analysis, and simulation studies. This review aims to provide an overview of the different approaches and their assumptions.

Analytical papers

Analytical papers form the majority of the literature an overview of of the reviewed analytical papers is given in Table 1. Analytical papers are characterized by precise assumptions and mathematical derivations of their results. These papers primarily focus on the supply structure, characteristics of the demand, and information certainty. While assumptions regarding the supply structure are essential for analytical modeling, it is worth noting that the assumption of an asymmetric oligopoly, which closely reflects the reality (Grimm et al. 2008; Vasin 2014), is relatively scarce in these papers due to its complexity. However, alternative assumptions regarding the structure of the market are sometimes considered to explore different scenarios and assess the potential impacts on outcomes. For instance, alternative models may model perfect collusion through a monopolistic market setup.

Regarding demand assumptions, a certain demand is often assumed for markets with "shortlived" bids, such as hourly segments of the day-ahead market, due to the high persistence of demand (Fabra et al. 2002, 2011). Additionally, assuming inelastic demand in the short run is reasonable since the retail consumption share is unable to respond to price changes, which are likely to affect the day-ahead market (see 2.1). However, an assumption of more elastic demand is also plausible in the long run, considering the deployment of smart meters and the adaption of behavior or contracts.

Another crucial assumption relates to the degree of certainty of the information that suppliers have regarding their cost structures and those of their competitors. This assumption plays a significant role in analytical modeling and influences the strategic decision-making of market participants.

Analytical papers typically analyze the day-ahead market as a one-shot auction using game theory to determine equilibria. However, a significant limitation arises from the repetitive nature of day-ahead auctions and the potential for strategic learning. To address this limitation, more recent studies have employed evolutionary game theoretic models to capture strategic learning, albeit at the expense of formulating a longer and more rigorous set of assumptions.

Simulation papers

Simulations have gained prominence in the literature due to their ability to capture the dynamics of repetitive and competitive markets, which analytical models may struggle to represent effectively. Simulation studies often adopt a Q-learning agent-based approach, enabling producers to learn and adapt their bidding strategies based on past experiences (Sugianto, Liao 2014). This approach facilitates the exploration of the effects of repeated trading in auction markets and provides valuable insights into market behavior and outcomes.

Table 1

Overview of the analytical studies

Author	Year	Approach	DP	UP	VCG	Supply	Symmetric	Demand certainty	Elastic	Cost certainty
Zhao et al.	2023	analytical, empirical	x	x		oligopoly	y	y	n	y
Willems, Yu	2022	analytical	x	x		oligopoly	y	n	y	y
Lange et al.	2022	analytical	x	x	x	oligopoly	y/n	y	n	n
Cheng et al.	2022	analytical	x	x		oligopoly	y	n	y	y
Sessa et al.	2017	analytical, empirical	x		x	oligopoly	n	y	y/n	y
Holmberg, Wolak	2015	analytical	x	x		duopoly	y	n	n	n
Ausubel et al.	2014	analytical	x	x		oligopoly	y	y	both	n

Table 1 cont.

Author	Year	Approach	DP	UP	VCG	Supply	Symmetric	Demand certainty	Elastic	Cost certainty
Vasin	2014	analytical	x	x	x	oligopoly	n	y	n	n
Fabra et al.	2011	analytical	x	x		duopoly	y	y/n	n	y
Holmberg	2009	analytical		x		oligopoly	y	n	n	y
Dechenaux, Kovenock	2007	analytical	x	x		oligopoly	y	y	n	y
Fabra	2003	analytical	x	x		duopoly	y	y	y	y
Fabra et al.	2002	analytical	x		x	duopoly	y	y	n	y
Federico et al.	2003	analytical	x	x		monopoly, perfect competition	y/n	y	n	y
Klemperer, Mayer	1989	analytical	x	x		oligopoly	y	n	n	y

Theoretical papers

Theoretical papers in this domain serve as summaries of results derived from other academic papers, enriched by concluding remarks. They are particularly prevalent during periods of intensive discussion regarding auction rules and market prices.

Empirical papers

Empirical studies in this area are relatively scarce due to the inherent complexity of isolating the effects of pricing rules within the broader dynamics of the electricity day-ahead market. These studies face challenges in disentangling the specific effects of pricing rules from those of other market factors and external influences.

In summary, the reviewed academic literature on pricing rules in electricity day-ahead markets encompasses analytical, theoretical, simulation, and empirical studies. Analytical papers, while often requiring assumptions on the supply structure, rarely employ the assumption of an asymmetric oligopoly, due to its complexity. Simulation studies have emerged to capture the repetitive nature of day-ahead auctions and facilitate strategic learning. Theoretical papers provide synthesized insights from the existing literature, while empirical studies face challenges in isolating the effects of a pricing rule. Table 2 provides an overview of the analyzed papers, categorized by their approach.

Table 2

Overview of the discussed literature

Author	Year	Approach	Author	Year	Approach
Zhao et al.	2023	analytical, empirical	Dechenaux, Kovenock	2007	analytical
Willems	2022	analytical	Hailu, Thoyer	2007	simulation
Lange et al.	2022	analytical	Fabra	2003	analytical
Cheng et al.	2022	analytical	Fabra et al.	2002	analytical
Heim, Götz	2021	empirical	Federico, Rahman	2003	analytical
Viehmann et al.	2021	simulation	Evans, Green	2003	empirical
Ocker et al.	2018	empirical	Newbery	2003	theoretical
Ocker et al.	2018	analytical, empirical	Rassenti et al.	2003	experimental
Aliabadi et al.	2017	simulation	Engelmann, Grimm	2009	experimental
Sessa et al.	2017	analytial, empirical	Klemperer	2002	theoretical
Holmberg, Wolak	2015	analytical	Joskow, Kahn	2002	empirical, simulation
Ausubel et al.	2014	analytical	Bower	2002	empirical
Sugianto, Liao	2014	simulation	Kahn et al.	2001	theoretical
Vasin	2014	analytical	Wolak, Patrick	2001	theoretical
Haucap	2013	theoretical, empirical	Kagel, Levin	2001	experimental

Table 2 cont.

Author	Year	Approach	Author	Year	Approach
Fabra et al.	2011	analytical	Bower, Bunn	2001	simulation
Azadeh et al.	2010	simulation	Harbord, McCoy	2000	theoretical
Holmberg	2009	analytical	Hudson	2000	simulation
Grimm et al.	2008	theoretical	Wolfram	1999	theoretical
Tierney et al.	2008	theoretical	Fehr von der, Harbord	1998	theoretical
Cramton, Stoft	2007	theoretical	Tenorio	1997	theoretical
Ockenfels	2007	theoretical	Klemperer, Mayer	1989	analytical

Search strategy. The search strategy employed to identify the academic literature to be reviewed was designed to ensure a comprehensive and systematic approach. The initial step involved conducting a keyword search using the terms "merit order" and "pricing rule" in the Scopus database. These keywords were selected to target relevant studies that specifically address the determination of pricing rules in electricity day-ahead markets. The search was limited to the academic literature to ensure the inclusion of rigorous and scholarly works. The identified papers underwent further screening and selection based on their relevance to the research topic and the criteria outlined for the literature review. This search strategy aimed at encompassing a broad range of studies while maintaining a focus on high-quality research in the field of electricity day-ahead market pricing rules.

The next section is organized as follows. Firstly, we will delve into an analysis of the two prevailing pricing rules commonly employed and studied in multi-unit auctions, namely, UP and DP.

We will begin with the examination of the uniform pricing rule, considering it the status quo, and explore its operational characteristics based on the findings from the reviewed academic literature. First we will cover the key features that can be derived from studying the pricing rule independently, without specific assumptions. Subsequently, we will present the characteristics of the uniform pricing rule as concluded by analytical papers, employing different sets of assumptions. Furthermore, we will shed light on the insights obtained from empirical and simulation analyses.

Subsequently, we will follow the same approach for the discriminatory pricing rule. We will examine its workings and characteristics by considering the theoretical, analytical, empirical, and simulation results. This comprehensive evaluation will allow a direct comparison between the two pricing rules.

Lastly, we will focus on the investigation of the Vickrey auction pricing rule. Although research specific to this pricing rule in the electricity market, particularly the day-ahead market, is relatively scarce, we will include an examination of its general operation. Additionally, we will provide a direct comparison of the Vickrey rule with the other pricing rules. By incorporating these analyses, we aim at offering a comprehensive understanding of the characteristics and implications of each pricing rule in the context of electricity day-ahead markets.

3.1. Alternatives for a pricing rule

3.1.1. Uniform pricing

UP, the predominant pricing rule implemented in European day-ahead markets, operates by ensuring that all winners in the auction receive the MCP, regardless of their bids. Under this pricing rule, all winning buyers value the commodity at or above the price, while all winning sellers value it below the price. This mechanism guarantees that no participant is left with the feeling of "overpaying" or "underpaid" since all participants receive the same price.

However, recent events have highlighted the high political cost associated with UP, making it difficult to justify bidders with very different cost structures receiving an identical price. Despite this challenge, UP continues to be widely used due to its other advantages, which are worth considering.

One of the key advantages of UP is its transparency and straightforward price discovery mechanism. This pricing rule provides clear and unambiguous information about the market price, enabling market participants to easily assess the value of the commodity based on the MCP. Furthermore, UP supports efficient coordination, particularly for OTC contracts. By relying on the UP rule's reference prices as a consistent benchmark, participants can enhance coordination and reduce complexities in contract negotiations. The simplicity of UP is another notable advantage. The absence of complex pricing mechanisms or differentiated payments based on individual bids reduces barriers to entry, encourages market participation, and fosters competition.

Overall, UP's transparency, facilitation of price discovery, coordination advantages for OTC contracts, and simplicity contribute to efficient market operations and reduced transaction costs. These benefits have led to its widespread adoption in most European day-ahead markets, making it the pricing rule of choice for market organizers and participants. However, it's important to acknowledge the challenges associated with justifying UP in situations where bidders have significantly different cost structures. In order words, the UP rule is equipped with high political costs.

Analytical studies have provided valuable insights into the implications of UP in electricity day-ahead markets. The following points summarize the key findings of these studies.

Perfect competition

Under conditions of perfect competition, analytical studies have shown that UP enables truthful bidding and therefore an efficient dispatch. Studies by G. Federico and D. Rahman (2003) and B. Willems and Y. Yu (2022) have demonstrated that UP in a perfectly competitive setting establishes truthful bidding and leads to an efficient dispatch. It ensures that production is allocated to producers with the lowest costs, promoting efficiency and maximizing social welfare (Cramton, Stoft 2007).

Imperfect Competition

In scenarios of imperfect competition, the following characteristics of UP have been identified:

- Vulnerability to collusion. Uniform pricing has been found to be susceptible to collusion. P.D. Klemperer (2002) and other studies have highlighted the potential for collusive behavior among market participants. Under the UP rule, the bids for marginal units have an influence on the payments for inframarginal units. This creates incentives for punishing deviating producers (Fabra 2003) and signaling between producers (Klemperer, Meyer 1989).
- Supply reduction and bid shading. Analytical studies, including A. Ockenfels (2007), L.M. Ausubel et al. (2014) and J.H. Kagel and D. Levin (2001), have shown that UP can lead to a reduction of the supply and bid shading in imperfectly competitive markets. Generators strategically withholding bids or shading their bids can manipulate the market and increase the MCP, resulting in inefficient dispatch, reduced productive efficiency, and higher consumer prices. With a high degree of market power, a reduction in the supply and bid shading can be exploited through one dominant supplier.
- Factors Influencing Collusive Behavior. Studies by V. Grimm et al. (2008) suggest that uncertain demand and supply, as well as asymmetric characteristics of the producers, can decrease the likelihood of collusive behavior under UP. Greater transparency in market operations, as emphasized by A.E. Kahn et al. (2001), can act as a deterrent to collusion and promote competitive outcomes.
- P. Cramton and S. Stoft (2007) show that UP with an increasing number of competitors converges quickly to complete efficiency.

Monopoly

In a monopolistic setting, UP exhibits the following characteristics.

Monopolistic Pricing. Uniform pricing can be seen as a form of third-degree price discrimination in a monopolistic environment. Analytical studies, such as G. Federico and D. Rahman (2003), have shown that UP allows the monopolist to increase monopolistic profit and capture consumer surplus. Each demand realization can be treated as a separate market, enabling the monopolist to adjust prices accordingly.

Empirical results

Empirical studies have provided evidence of collusive behavior and its impact on creating price spikes. For the UK electricity generation market, P.D. Klemperer (2002), N.H. von der Fehr and D. Harbord (1998), C.D. Wolfram (1999) and F.A. Wolak and R.H. Patrick (2001) highlight instances of collusive behavior leading to price spikes. P.L. Joskow and E. Kahn (2002) found abusive capacity withholding in their analysis of the California market in 2000 when comparing it to an adapted perfect competition base case. Moreover, F. Ocker et al. (2018) demonstrates collusive behavior triggered by the regular repetition and the small and stable set of suppliers in the German balance market operating under UP. Similar conclusions were reached by S. Heim and G. Götz (2021).

Simulation results

Simulations also provide insights into the tendency for strategic bidding under UP. J. Viehmann et al. (2021) present an agent-based simulation demonstrating that UP motivates strategic bidding, particularly through rising prices of second bids. Additionally, A. Hailu and S. Thoyer (2010) and L. Sugianto and K. Liao (2014) confirm the sensitivity of the UP rule to asymmetries of the generators. L. Sugianto and K. Liao (2014) observe a jump in average prices and total dispatch costs, while A. Hailu and S. Thoyer (2010) note bid shading among high levels of competition and large capacity bidders.

Impact of renewable generators

Analytical and empirical studies have highlighted the "merit-order effect" of renewable generators under UP. J. Haucap (2013) analyzes the German market, where prioritized renewable dispatch is implemented within the UP day-ahead market. This implementation shifts the aggregate supply curve to the right, resulting in a decrease in the MCP within the UP setting. As a consequence, revenues for generators are diminished, and the dispatched hours for non-renewable generators decrease, further affecting their ability to recover total costs. Therefore, UP may require higher price spikes to stimulate future investment in new generating capacity.

3.1.2. Discriminatory pricing

A superficial understanding of electricity auctions might suggest that if not all bidders receive the MCP but instead their bid, the overall price paid would decrease. This alternative to the UP rule is commonly referred to as the discriminatory pricing rule (DP) or the pay-as-bid (PAB) rule. The DP establishes for every hour and every producer or bidder a price, thereby eliminating a general reference price.

In March 2001, the British regulatory authority Ofgem initiated a transition from UP to DP in England and Wales. This transition was motivated by the expected reduction in wholesale prices of electricity and the belief that DP is less susceptible to strategic manipulation by large traders. Similarly, before its collapse, the California Power Exchange commissioned a report by leading auction theorists to explore the feasibility of switching to a DP format for the exchange's day-ahead market. This move was prompted by the increasing occurrence of price spikes during both on- and off-peak periods.

Implementing DP in double-sided blind auctions requires certain adaptations, such as specifying how prices are paid to selected suppliers and by selected demands. In the UK, an open auction was implemented to address this, as stated in P. Cramton and S. Stoft (2007). However, it can still be implemented as a non-synchronous auction with reduced transaction costs.

Analytical studies

Analytical studies indicate that even under perfect competition, generators (except for those that only produce when full demand is reached) include a markup in their bids, leading to reduced productive efficiency, consumer surplus, and social welfare (Federico, Rahman 2003; Grimm et al. 2008).

From a game-theoretic perspective, the PAB auction design triggers a "guessing the MCP" game, where participants bid the estimated MCP. Consequently, truthful bidding is not a dominant strategy according to V. Grimm et al. (2008). The absence of truthful bidding results in inefficient dispatch and reduced production efficiency. This "guessing the MCP" game becomes particularly burdensome for small generators. As day-ahead auctions are repeated, participants' estimations of the MCP converge, leaving little room for error. The cost of accurately predicting the MCP increases, discouraging bidders with limited information from participating. As a result, dominant producers can exploit their informational advantage. The costs of estimation are further boosted by the increasing share of renewable energy and their intermittent character. Non-truthful bidding reduces transparency and makes it hard for regulators to identify market power (Kahn et al. 2001).

B. Willems and Y. Yu (2022) analyze the markup not as a result of market power but the need to recoup total costs. In the long run, the revenue of base-load producers is depressed at high-demand realizations, resulting in a decrease in investment incentives and the distortion of the generation mix.

The dominant producer's exploitation of their informational advantage under the complex auction design is highlighted by P.D. Klemperer (2002) and D. Harbord and C. McCoy (2000). V. Grimm et al. (2008) further argues that the high strategic complexity of the PAB set-up can lead to irrational behavior. The reason why PAB is considered less subject to collusion is that bidders cannot use low inframarginal bids as costless threats (Fabra 2003). P.D. Klemperer (2002) argues that the observation of higher prices being paid to high marginal cost producers creates incentives for low marginal cost producers to include a markup in their bid.

Monopolistic competition

In monopolistic competition, due to the interdependence between low demand realizations and high demand realizations, the monopolist engages in second-degree price discrimination, resulting in monopolistic profits and reduced customer surplus according to G. Federico and D. Rahman (2003).

Experimental studies

D. Engelmann and V. Grimm (2009) highlight two types of untruthful bidding prominent in PAB pricing: high flat bidding, when there is little competition, and supply inflation when the degree of competition is high. High flat bids can improve the bidder's revenue, since the prices received for all units sold are brought closer but incur the risk of being completely priced out by rivals. Supply inflation, rather than high flat bidding, allows bidders to avoid zero gain outcomes.

Empirical and simulation results

An empirical analysis conducted by S. Heim and G. Götz (2021) reveals abusive market power exploitation in the German reserve power market, which operates under the PAB auction design. The study suggests that PAB does not prevent collusion and the problem of strategic capacity withholding and can even exacerbate these problems in markets with sufficient market power. Simulation studies conducted by A. Hailu and S. Thoyer (2010) and J. Bower and D. Bunn (2001) confirm the presence of supply inflation and high flat bidding in PAB pricing. Additionally, L. Sugianto and K. Liao (2014) demonstrates that PAB complicates the learning process for bidders.

3.1.3. Discriminatory vs. uniform pricing

In this section, we directly compare two pricing rules: DP and UP. We employ various metrics, including prices, productive efficiency, consumer surplus, and additional arguments related to market power and consumer expenditures.

Prices

The literature suggests that DP auctions generally result in lower average prices compared to UP (Tenorio 1997; Hudson et al. 2000; Xiong et al. 2004; Fabra et al. 2006; Holmberg 2009; Fabra et al. 2011; Ausubel et al. 2014; Sugianto, Liao 2014; Viehmann et al. 2021; Cheng et al. 2022; Zhao et al. 2023). However, there are cases where UP achieves lower average prices, as highlighted by J. Bower and D. Bunn (2001), D.E. Aliabadi et al. (2017), S.F. Tierney et al. (2008), G. Federico and D. Rahman (2003), and B. Willems and Y. Yu (2022). Despite these exceptions, the majority of investigated cases indicate that DP auctions tend to result in lower average prices, providing political relief in the context of an asymmetric oligopoly.

Productive efficiency

Regarding productive efficiency, the results are mixed. Analytical papers demonstrate that under perfect competition and monopolistic setups, UP leads to higher efficiency (Willems, Yu 2022; Federico, Rahman 2003). This result also holds for the duopoly case, as shown by N. Fabra et al. (2002). Even in the oligopolistic case with learning behavior incorporated, L. Cheng et al. (2022) found that UP produces higher productive efficiency. Simulation studies by D.E. Aliabadi et al. (2017) and J. Viehmann et al. (2021) also support the higher productive efficiency of UP. However, L.M. Ausubel et al. (2014) determined that DP achieves higher efficiency in the asymmetric case with flat demand and decreasing marginal utility. While the evidence is mixed, the prevailing consensus leans towards UP's favoring productive efficiency in various scenarios.

Consumer surplus

There are conflicting findings regarding consumer surplus. B. Willems and Y. Yu (2022) found that UP leads to higher consumer surplus in a model with elastic demand and a wide range of technologies under perfect competition. But N. Fabra et al. (2002) (for symmetric duopoly), P. Holmberg (2009) (for symmetric oligopoly), and G. Federico and D. Rahman (2003) (for monopoly and perfect competition) established that DP produces higher consumer surplus. Additionally, D.E. Aliabadi et al. (2017) finds lower consumer surplus for UP. These conflicting findings highlight the complex relation between pricing rules and consumer surplus.

Additional arguments

In addition to the metrics discussed above, other arguments come into play when comparing DP and UP. The literature suggests that exploiting market power is more challenging in DP auctions than in UP (Federico, Rahman 2003). Furthermore, S.F. Tierney et al. (2008) argues that transitioning from UP to DP auctions could increase consumers' overall expenditures due to strategic bidding behavior, inefficient plant dispatch, and inefficient capacity investment. These factors need to be considered when evaluating the impact of different pricing rules on consumer welfare.

In summary, the comparison of UP and DP reveals contrasting findings across different metrics. While DP auctions tend to result in lower average prices and potentially higher consumer surplus, the long-term perspective and investment decisions often favor UP (Willems, Yu 2022). Additionally, UP tends to be associated with higher productive efficiency in various scenarios. The difficulty of exploiting market power in DP auctions and the potential increase in consumer expenditures during the transition from UP to DP are also important considerations. Therefore, the choice between these pricing rules should be based on a comprehensive evaluation of these factors and their implications within the specific context of the electricity market.

3.1.4. Vickrey auction pricing

The Vickrey auction, based on the fundamental insight of W. Vickrey (1961), ensures truthful bidding as the dominant strategy for each player since the price received is independent of their bid. Although the Vickrey auction has yet to be implemented in practice, it has been extensively studied both theoretically and experimentally. Originally designed for single-unit auctions, a modified version called the Vickrey–Clarke–Groves (VCG) pricing rule (Clarke 1971) has been proposed for multi-unit electricity market auctions.

In the VCG setup, a bidder's payoff depends on their bids only to the extent that it affects their probability of being chosen. Generators are incentivized to offer supply at a price equal to marginal cost, as it maximizes their probability of operating, ensuring an efficient dispatch and rendering demand reduction irrational.

The specific implementation of the VCG mechanism varies across the academic literature, but the general method is as follows: starting with the cleared market, where all winning bids and the MCP are known, the price for each unit is not based on the MCP or the bid price. Instead, it is determined by the opportunity costs, representing the value that sellers forego by participating in the auction. More precisely, the price for a unit is determined by the value of the highest losing bid for that unit, reflecting the benefit forgone by the seller.

The VCG mechanism benefits the efficiency and simplifies the bidding strategies, as bidding truthfully becomes the dominant strategy (Sessa et al. 2017).

Analytical studies

N. Fabra et al. (2002) conducted a discrete, multi-unit auction model assuming a duopoly and concluded that VCG auctions guarantee productive efficiency but may result in large payments to firms. V. Grimm et al. (2008) highlighted the potential of VCG to achieve cost-efficiency even in oligopolistic settings with technical restrictions, but they also identified complexity and challenges in price discovery. Their results showed that VCG generates different profits for identical generators and higher prices for larger bidders/generators, which may lead to increased electricity expenditures, incurring high political costs and potentially deterring entry.

Simulation studies

Simulations confirm that bids converge towards truthful bidding in VCG pricing, but there may be sensitivity to heterogeneity among the generators, leading to bid shading (Hailu, Thoyer 2007, 2010).

Comparison to UP and PAB

In the only comparative analytical study (Fabra et al. 2002) considering a duopoly, the welfare ranking between VCG and other pricing rules is inherently ambiguous.

Simulation comparisons largely support VCG pricing. In interesting cases simulating an asymmetric oligopoly, VCG pricing provides prices between those of UP and DP, with the lowest level of price volatility, as shown by L. Sugianto and K. Liao (2014) and S. Lange et al. (2022) in their agent-based simulations. Furthermore, S. Lange et al. (2022) demonstrated that bid shading can increase generators' profits in a VCG auction. However, minor adjustments can render such behavior unprofitable, leading to increased market efficiency and participation. Indeed, S. Lange et al. (2022) proposed a twisted VCG auction that preserves bidders' privacy and guarantees truthful bidding even in an asymmetric oligopoly.

In the case of a symmetric oligopoly, both UP and W. Vickrey pricing result in the lowest average prices, but DP results in the lowest degree of market power and price volatility (Sugianto, Liao 2014). This holds even when considering a more realistic way of capturing generators' learning effects using an Ant Colony Optimization algorithm (Azadeh et al. 2010).

To summarize, the Vickrey auction, through its VCG variant, offers the advantages of efficient dispatch, truthful bidding, and simplified strategies. Analytical and simulation studies highlight the potential benefits and challenges associated with VCG pricing, emphasizing its efficiency and potential for reducing costs. Comparative studies demonstrate that VCG pricing can result in prices and market dynamics between those resulting from UP and DP, with lower price volatility. However, careful considerations of market structure, heterogeneity among generators, and potential gaming strategies are necessary for its effective implementation.

4. Conclusion

This comprehensive literature review addresses the ongoing discussion surrounding pricing rules in the day-ahead market, driven by a significant increase in electricity prices in 2022. The analysis reveals two distinct perspectives based on the general outlook of the electricity market: the political perspective, which prioritizes low electricity costs to protect customers irrespective of future market structure or generation mix, and the efficiency-theoretic perspective, which aims at establishing a well-functioning market that converges towards a fully liberal, self-regulating system despite inherent limitations. These perspectives can lead to different conclusions regarding the choice of a pricing rule.

The pricing rules investigated in this study are uniform pricing (UP), discriminatory pricing (DP), and the Vickrey–Clarke–Groves (VCG) pricing rule. UP, currently the predominantly implemented rule, offers advantages such as transparency, facilitating price discovery, coordination benefits for Over-the-Counter (OTC) contracts, and simplicity, contributing to efficient market operations and reduced transaction costs. However, in the case of imperfect competition, it incentivizes collusion and bid shading, leading to an inefficient dispatch, lower consumer surplus, and possible price spikes, resulting in higher volatility. On the other hand, it benefits smaller bidders and renewable generators as well as converges quickly to perfect competition, albeit with an inefficient dispatch. It also incurs high political costs.

DP, motivated by the goal of reducing wholesale electricity prices and perceived as less susceptible to strategic manipulation by large traders, faces its own challenges. Analytical studies indicate that even under perfect competition, generators include markups in their bids, leading to reduced productive efficiency, consumer surplus, and social welfare. The "guessing the market clearing price" game triggered by DP undermines truthful bidding and results in an inefficient dispatch and reduced production efficiency. Small generators face burdensome estimation costs, while dominant producers can exploit their informational advantage. Empirical and simulation results reveal the existence in markets operating under discriminatory pricing of an abusive exploitation of market power, collusion, supply inflation, and complications in learning.

The Vickrey auction, particularly the VCG pricing rule, ensures truthful bidding even under asymmetric oligopolistic markets. However, it requires side payments and can result in significantly different payments favoring large generators. This incurs high political costs and may potentially increase market power in the long run.

Direct comparison of the three pricing rules finds varying performance across relevant metrics. In terms of average prices, they are minimized under DP, followed by VCG and UP. However, the higher prices in UP actually encourage entry by smaller bidders and renewable generators, which is promising. Regarding price volatility, VCG is the dominant pricing rule, followed by DP and then UP. In terms of productive efficiency, VCG outperforms the others, followed by UP.

In conclusion, the choice of the pricing rule in the day-ahead market depends on the desired outcomes. While each pricing rule has its advantages and disadvantages, further research and careful analysis are needed to determine the most suitable approach that balances efficiency, fairness, and the long-term sustainability of the electricity market.

References

[1] Aliabadi, D.E., Kaya, M. and Şahin, G. (2017) 'An agent-based simulation of power generation company behavior in electricity markets under different market-clearing mechanisms', *Energy Policy*, vol. 100, pp. 191–205.

[2] Ausubel, L.M., Cramtom, P., Pycia, M., Rostek, M. and Weretka, M. (2014) 'Demand reduction and inefficiency in multi-unit auctions', *The Review of Economic Studies*, vol. 81, pp. 1366–1400.

[3] Azadeh, A., Skandari, M.R. and Maleki-Shoja, B. (2010) 'An integrated ant colony optimization approach to compare strategies of clearing market in electricity markets: Agent-based simulation', *Energy Policy*, vol. 38, pp. 6307–6319.

[4] Bower, J. (2002) 'Why did electricity prices fall in England and Wales? Market mechanism or market structure?', The Oxford Institute of Energy Studies, https://doi.org/10.26889/1901795225.

[5] Bower, J. and Bunn, D. (2001) 'Experimental analysis of the efficiency of uniform-price versus discriminatory auctions in the England and Wales electricity market', *Journal of Economic Dynamics and Control*, vol. 25, pp. 561–592.

[6] Bracht van, N., Maaz, A., and Moser A. (2019) Simulating electricity market bidding and price caps in the European power markets. S18 Report, European Commission.

[7] Cheng, L., Chen, Y. and Liu, G. (2022) '2PnS-EG: A general two-population *n*-strategy evolutionary game for strategic long-term bidding in a deregulated market under different market clearing mechanisms', *International Journal of Electrical Power & Energy Systems*, vol. 142, 108182.

[8] Clarke, E.H. (1971) 'Multipart pricing of public goods', *Public Choice*, vol. 11, pp. 17–33.

[9] Cramton, P. and Stoft, S. (2007) 'Why we need to stick with uniform-price auctions in electricity markets', *The Electricity Journal*, vol. 20, pp. 26–37.

[10] Dechenaux, E. and Kovenock, D. (2007) 'Tacit collusion and capacity withholding in repeated uniform price auctions', *The RAND Journal of Economics*, vol. 38, pp. 1044–1069.

[11] Engelmann, D. and Grimm, V. (2009) 'Bidding behavior in multi-unit auctions – an experimental investigation', *Economic Journal*, vol. 119, pp. 855–882.

[12] Evans, J. and Green, R. (2003) 'Why did British electricity prices fall after 1998?', Working Paper, Massachusetts Institute of Technology, Center for Energy and Environmental Policy Research.

[13] Fabra, N. (2003) 'Tacit collusion in repeated auctions: Uniform versus discriminatory', *The Journal of Industrial Economics*, vol. 51, pp. 271–293.

[14] Fabra, N., von der Fehr, N.H. and Harbord, D. (2002) 'Modeling electricity auctions', *The Electricity Journal*, vol. 15, pp. 72–81.

[15] Fabra, N., von der Fehr, N.H. and Harbord, D. (2006) 'Designing electricity auctions', *The RAND Journal of Economics*, vol. 37, pp. 23–46.

[16] Fabra, N., von der Fehr, N.M. and de Frutos, M. (2011) 'Market Design and Investment Incentives', *The Economic Journal*, vol. 121, pp. 1340–1360.

[17] Federico, G. and Rahman, D. (2003) 'Bidding in an electricity pay-as-bid auction', *Journal of Regulatory Economics*, vol. 24, pp. 175–211.

[18] Fehr von der, N.H. and Harbord, D. (1998) 'Competition in electricity spot markets: Economic theory and international experience', Memorandum, No. 05/1998, University of Oslo, Department of Economics, Oslo.

[19] Grimm, V., Ockenfels, A. and Zoettl, G. (2008) 'Strommarktdesign: Zur Ausgestaltung der Auktionsregeln an der EEX', *Zeitschrift für Energiewirtschaft*, vol. 32, pp. 147–161.

[20] Hailu, A. and Thoyer, S. (2007) 'Designing multi-unit multiple bid auctions: An agent-based computational model of uniform, discriminatory and generalised vickrey auctions', *The Economic Record*, vol. 83, pp. S57–S72.

[21] Hailu, A. and Thoyer, S. (2010) 'What format for multi-unit multiple-bid auctions? Agent-based simulation of auction performance and nonlinear bidding behavior', *Computational Economics*, vol. 35, pp. 189–209.

[22] Harbord, D. and McCoy, C. (2000) 'Mis-designing the UK electricity market?', *European Competition Law Review*, vol. 21.

[23] Haucap, J. (2013) 'Braucht Deutschland einen Kapazitätsmarkt für eine sichere Stromversorgung?', *Zeitschrift für Wirtschaftspolitik*, vol. 62, pp. 257–269.

[24] Heim, S. and Götz, G. (2021) 'Do pay-as-bid auctions favor collusion? Evidence from Germany's market for reserve power', *Energy Policy*, vol. 155, 112308.

[25] Holmberg, P. (2009) 'Supply function equilibria of pay-as-bid auctions', *Journal of Regulatory Economics*, vol. 36, pp. 154–177.

[26] Holmberg, P. and Wolak, F. (2015) Electricity markets: Designing auctions where suppliers have uncertain costs. Technical Report. Energy Policy Research Group, University of Cambridge.

[27] Hudson, R. (2000) Analysis of uniform and discriminatory price auctions in restructured electricity markets, Oak Ridge National Laboratory, Oak Ridge TN.

[28] Jamasb, T. and Pollitt, M. (2005) 'Electricity market reform in the European union: Review of progress toward liberalization integration', *The Energy Journal*, vol. 26, pp. 11–41.

[29] Joskow, P.L. and Kahn, E. (2002) 'A quantitative analysis of pricing behavior in California's wholesale electricity market during summer 2000', *The Energy Journal*, vol. 23, pp. 1–35.
[30] Kagel, J.H. and Levin, D. (2001) 'Behavior in multi-unit demand auctions: Experiments with uniform price and dynamic Vickery auctions', *Econometrica*, vol. 69, pp. 413–454.
[31] Kahn, A.E., Cramton, P.C., Porter, R.H. and Tabors, R.D. (2001) 'Uniform pricing or pay-as-bid pricing: a dilemma for California and beyond', *The Electricity Journal*, vol. 14, pp. 70–79.
[32] Klemperer, P. (2002) 'What really matters in auction design', *Journal of Economic Perspectives*, vol. 16, pp. 169–189.
[33] Klemperer, P.D. and Meyer, M.A. (1989) Supply function equilibria in oligopoly under uncertainty, *Econometrica*, vol. 57, pp. 1243–1277.
[34] Lange, S., Sokolowski, P. and Yu, X. (2022) 'An efficient, open-bid procurement auction for small-scale electricity markets', *Applied Energy*, vol. 314, 118867.
[35] Moret, S., Babonneau, F., Bierlaire, M. and Maréchal, F. (2020) 'Overcapacity in European power systems: Analysis and robust optimization approach', *Applied Energy*, vol. 259, 113970.
[36] Ockenfels, A. (2007) 'Electricity exchange and market power; Stromboerse und Marktmacht', *ET, Energiewirtschaftliche Tagesfragen*, vol. 57, pp. 44–60.
[37] Ocker, F., Ehrhart, K.M. and Belica, M. (2018) 'Harmonization of the European balancing power auction: A game-theoretical and empirical investigation', *Energy Economics*, vol. 73, pp. 194–211.
[38] Rassenti, S., Smith, V. and Wilson, B. (2003) 'Discriminatory price auctions in electricity markets: Low volatility at the expense of high price levels', *Journal of Regulatory Economics*, vol. 23, pp. 109–123.
[39] Sessa, P.G., Walton, N. and Kamgarpour, M. (2017) 'Exploring the Vickrey–Clarke–Groves mechanism for electricity markets', *IFAC-PapersOnLine*, vol. 50, pp. 189–194.
[40] Sioshansi, F.P. (2006) 'Electricity market reform: What has the experience taught us thus far?', *Utilities Policy*, vol. 14, pp. 63–75.
[41] Soloviova, M. and Vargiolu, T. (2021) 'Efficient representation of supply and demand curves on day-ahead electricity markets', *The Journal of Energy Markets*, https://www.doi.org/10.21314/JEM.2020.218.
[42] Sugianto, L. and Liao, K. (2014) 'Comparison of different auction pricing rules in the electricity market', *Modern Applied Science*, vol. 8, pp. 147–163.
[43] Tenorio, R. (1997) 'On strategic quantity bidding in multiple unit auctions', *The Journal of Industrial Economics*, vol. 45, pp. 207–217.
[44] Tierney, S.F., Schatzki, T. and Mukerji, R. (2008) 'Uniform-pricing versus pay-as-bid in wholesale electricity markets: does it make a difference?', New York ISO.
[45] Vasin, A. (2014) 'Game-theoretic study of electricity market mechanisms', *Procedia Computer Science*, vol. 31, pp. 124–132.

[46] Vickrey, W. (1961) 'Counterspeculation, auctions, and competitive sealed tenders', *The Journal of Finance*, vol. 16, pp. 8–37.
[47] Viehmann, J., Lorenczik, S. and Malischek, R. (2021) 'Multi-unit multiple bid auctions in balancing markets: An agent-based Q-learning approach', *Energy Economics*, vol. 93, 105035.
[48] Willems, B. and Yu, Y. (2022) Bidding and investment in wholesale electricity markets: Discriminatory versus uniform-price auctions, Working Paper, No. 1462, [Online], Available: https://www.tse-fr.eu/sites/default/files/TSE/documents/doc/wp/2023/wp_tse_1462.pdf [5 Jan 2024].
[49] Wolak, F.A. and Patrick, R.H. (2001) The impact of market rules and market structure on the price determination process in the England and Wales electricity market, Working Paper, No. 8248, National Bureau of Economic Research, [Online], Available: https://www.nber.org/system/files/working_papers/w8248/w8248.pdf [5 Jan 2024].
[50] Wolfram, C.D. (1999) 'Electricity markets: Should the rest of the world adopt the united kingdom's reforms', *Regulation*, vol. 22, pp. 48–53.
[51] Xiong, S., Okuma, S. and Fujita, H. (2004) 'Multi-agent based experiments on uniform price and pay-as-bid electricity auction markets', *IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, vol. 1, pp. 72–76.
[52] Zhao, D., Botterud, A. and Ilic, M. (2023) 'Uniform pricing vs pay as bid in 100%-renewables electricity markets: A game-theoretical analysis', e-Energy'23: Proceedings of the 14th ACM International Conference on Future Energy Systems, June 2023, pp. 236–241, https://doi.org/10.1145/3575813.3595201.

Summary

This literature review delves into the intricate realm of pricing rules in the day-ahead electricity market, spurred by a notable surge in 2022 electricity prices. Employing a comparative analysis of uniform pricing (UP), discriminatory pricing (DP), and the Vickrey–Clarke–Groves (VCG) pricing rule, the study navigates the complexities of these mechanisms. The evaluation unveils contrasting perspectives: the political push for consumer-friendly low prices versus the efficiency aspiration for a self-regulating market. DP, minimizing average prices but increasing volatility, and VCG, excelling in productive efficiency, are pitted against UP, the prevailing yet imperfect norm. The findings underscore the nuances of each rule; DP leads to reduced average prices and heightened volatility, while VCG ensures superior productive efficiency. Despite UP's simplicity, it prompts inefficiencies and political costs. These insights illuminate the pivotal choice faced by policymakers, balancing efficiency, fairness, and market sustainability.

JEL codes: D47, L94, L50

Keywords: *day-ahead market, uniform pricing, discriminatory pricing, Vickrey–Clarke–Groves*