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A survey on electricity market design: Insights from theory and real-world implementations of capacity remuneration mechanisms

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ABSTRACT

In recent years, electricity markets have been characterized by a growing share of fluctuating renewable energies, which has increased concerns about the security of electricity supply. As a consequence, existing market designs are adapted, and new capacity remuneration mechanisms are introduced. However, these mechanisms entail new challenges, and it is disputed whether they are indeed needed. In this article, an overview of the current debate on the necessity of capacity remuneration mechanisms is provided. Furthermore, initial experiences of real-world implementations are discussed, and common findings in the literature, categorized by their economic implications, are derived. Finally, shortcomings in existing research and open questions that need to be addressed in future works are pointed out.

1. Introduction

A reliable electricity system remains one of the main objectives of energy market regulators. This objective requires the stimulation of adequate investments on the supply side by market prices, which are to be high enough to finance not only the operational but also the fixed costs. However, generating adequate price signals becomes more and more challenging during the energy transition phase mainly shaped by the expansion of distributed renewable energies sources (RES). This intensified the discussion on demand-supply adequacy and lead to the proposal and in some cases introduction of mechanisms to remunerate capacity providers. However, the necessity and the design of these so-called capacity remuneration mechanisms (CRMs) are diversely evaluated in the literature.

Due to the already large and still quickly growing number of studies on CRMs[1], it is increasingly hard to keep an up-to-date overview. As several real-world experiences in the implementation and administration of CRMs have been gained, reviews have already been carried out focusing on the practical lessons learned (e.g., Batlle and Rodilla, 2010; Beckers et al., 2012; Bhagwat et al., 2016b; Karacsonyi et al., 2006; Spees et al., 2013). However, because of the rapid development and frequent regulatory changes, some of the presented information is already obsolete. Other more broadly oriented studies provide a systematic description of CRMs as well as a descriptive comparison (e.g., Doorman et al., 2016; DNV GL, 2014; European Commission, 2016b; Hancher et al., 2015; de Vries, 2007) or focus on the fundamental economic principles of CRMs, (e.g., Cramton et al., 2013; Stoft, 2002). Beside these studies on theoretical concepts of market design and CRMs as well as a review of mechanisms implemented in some countries, to the best knowledge of the authors, there does not exist a comprehensive review of the discussion and assessment of different design options for the electricity market in the literature.

Therefore, this article aims to guide both, new entrants and advanced researchers, through the field of electricity market design by providing a comprehensive and up-to-date overview of market design options. As the topic is well discussed in the literature and there are several real-world implementations of CRMs today, this paper aims not only to review theoretical studies on electricity market design but

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[1] In the literature, two other terms—capacity mechanism and capacity markets—are commonly used as synonyms for capacity remuneration mechanisms. In this article, however, capacity markets have a narrower definition and are considered as a specific variant of the different mechanism to enumerate capacity (see Section 3).

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also to describe a selection of real-world implementations of CRMs as alternative design options. This enables the potential reader to gain insights from theoretical approaches and related studies as well as from practical implementations.

In order to understand why there are so many approaches in theory and practice and how the discussion about the requirement for alternative design options evolved, Section 2 provides a review of the discussion about generation adequacy and about the performance of the energy-only-market (EOM). Afterward, the focus is set on the assessment of market design options in the literature, both from a practical perspective and theoretical perspective. In the practical case, a selection of the most relevant design options implemented in electricity markets around the world is discussed (Section 3). The theoretical perspective considers the assessment of the impacts of different design options on regulatory targets, such as generation adequacy and RES integration (Section 4). The review of the latter perspective is carried out in focusing on the qualitative discussion of limitations and benefits of each market design option, as well as on the model-based analysis of impacts on different criteria, e.g., market welfare, security of supply or incentivizing flexibility. Finally, the main common findings are discussed, open questions with which researchers are currently confronted are pointed out, and a set of policy implications is derived (Section 5).

2. The ongoing debate about securing generation adequacy

The question of whether EOMs generate sufficient price signals to incentivize investments in generation capacity is closely linked to the specific characteristics of electricity markets, i.e., their long-standing barriers and more recent challenges. Therefore, after describing these characteristics, the discussion on generation adequacy is summarized to show the motivation behind CRMs, to make the review more comprehensive and to present the latest findings from the fast-growing literature in a broader context.

2.1. Existing barriers to generation adequacy

The barriers in the electricity sector can be clustered in physical and market-related ones. Physical barriers are mainly based on the fact that electricity systems need to balance generation and consumption in each node of the electricity grid at every point in time, as the disruption of electricity frequency can lead to severe damages, such as the destruction of connected devices or even the collapse of the entire power system (Kwoka and Madjarov, 2007). Usually, the most substantial amount of electricity is already traded several months or years in advance via forward contracts and over-the-counter (OTC) markets that allow energy suppliers to hedge their portfolio (Meeus et al., 2005). As the possibilities to store electricity economically are still limited, and deviations from the expected consumer demand as well as the unexpected unavailability of generation capacity induce a need for short-term trading, spot markets usually possess high liquidity. However, as a certain time between spot market clearing and fulfillment is still necessary to organize the delivery, current wholesale markets are unable to capture these temporal and spatial requirements in their clearing process. Hence, other market or regulatory mechanisms are required. Furthermore, due to the nature of the electricity network, a free-rider problem occurs as up to now the network cannot differentiate between customers with and without contracts guaranteeing a reliable supply (Lynch and Devine, 2017). Therefore, an EOM design without reliability contracts cannot discriminate between customers who are willing to pay for reliability and those who are not (Joskow and Tirole, 2007). These technical properties are one reason why electricity prices as the outcome of market equilibrium cannot carry all information and signals necessary for the reliable long-term operation and the required investments in the generation infrastructure.

One example for market-related barriers are price caps in spot markets, which are a regulatory barrier introduced to protect consumers and to avoid the abuse of market power in the absence of demand elasticity (Stoft, 2002). However, as Petitet et al. (2017) point out, price caps are usually set below the value of lost load (VoLL)[2] for political reasons, and the resulting investments in generation capacity are likely not sufficient to cover the electricity demand at all times. Even though it is theoretically possible to set shortage prices or price caps sufficiently high, i.e., equal to the VoLL, in practice its specific value would have to be determined first, a task often described as difficult or even impossible to perform (e.g., Cramton et al., 2013; Willis and Garrod, 1997).

Therefore, other measures may be required to replace signals coming from price spikes and to generate sufficient incentives for investments (Doorman et al., 2016). These additional measures are to be implemented to address the so-called missing money problem, which can be defined as the lost earnings beyond the price cap, especially for peak load power plants (see Fig. 1b). More detailed, missing money is that part of these lost earnings that is necessary to cover the investment and all other fixed costs. For Joskow and Tirole (2007), missing money may also occur due to premature technical decisions of system operators to avoid market disequilibrium and brownouts[3]. Furthermore, Newbery (2016a) argues that even if earnings from price spikes are sufficient to cover fixed and capital costs, investors might not be willing to bear the associated risks and are unable to lay them off through futures and contract markets. In this case, the problem is referred to as missing market instead of missing money (Newbery, 1989).

Another problem in current wholesale electricity markets is that large parts of electricity demand are inelastic from a short-term perspective, e.g., households have a fixed rate for energy consumption in combination with a base rate tariff (Dütschke and Paetz, 2013) and, thus, do not actively participate in the volatile wholesale market or show any reaction even to drastic prices changes (Cramton and Stoft, 2005). Therefore, the marginal costs of base load and with increasing demand peak load power plants set the market price until the entire demand can no longer be met by the existing generation capacity (see Fig. 1a). For this reason, Lynch and Devine (2017) state that the price signal for reliable supply and generation adequacy can be considered weak. Keppler (2017) even argues that many problems regarding security of supply could be solved if the demand side became more elastic and participated in the market efficiently. Furthermore, Aalami et al. (2010) claim that the implementation of demand response programs will lead to the reflection of wholesale prices in retail prices, especially, if new developments change the need for electric services and new business models are developed for the demand response measures. However, currently, the main burden of balancing the system to guarantee the reliable operation of the electricity grid in the short term and to ensure generation adequacy in the long term lies on the supply side.

2.2. Recently emerging challenges

In addition to the already mentioned long-standing barriers that exist on wholesale electricity markets, several recent developments revive the debate about mechanisms remunerating generation capacity, e.g., the rise of intermittent RES or the market-related and political uncertainties, such as the phase-out of specific technologies.

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[2] The value of lost load describes the average willingness of customers to pay for the reliability of their electricity supply. The individual willingness to pay is not an unlimited value but can vary between close to zero and tens of thousands of Euros per MWh, especially for critical infrastructures such as hospitals (Hogan, 2017).

[3] In the electricity system major failures result in brownouts or blackouts. A blackout is a disruption in a wider range of an electricity system up to a total collapse of the whole supply whereas a brownout implies an excessively reduced voltage that can result in equipment failure, e.g., overheating of electric motors (Blume, 2007).

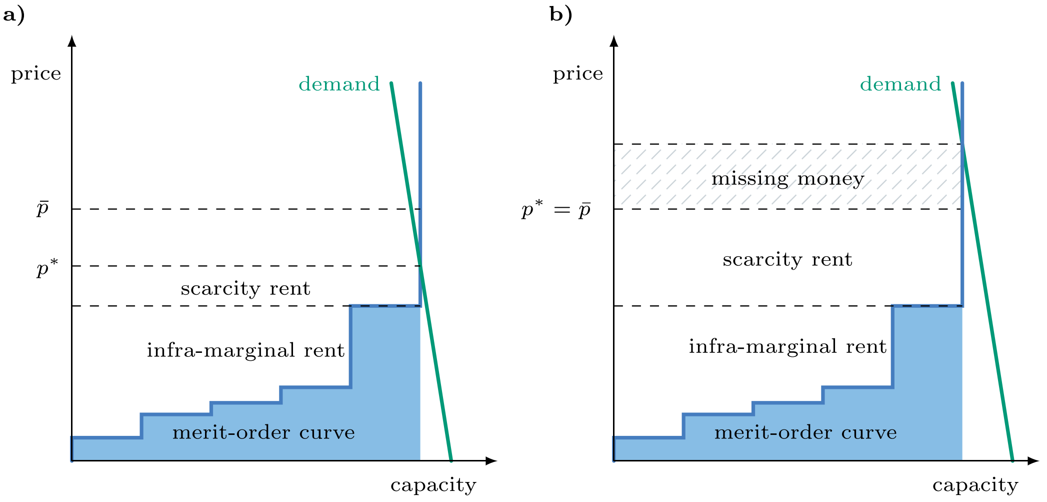

Fig. 1. Price setting in scarcity situations. a) The equilibrium price p^* is below the price cap $\bar{p}$ and an efficient outcome is achieved. b) The equilibrium price p^* is above the price cap $\bar{p}$, however, as the resulting price p^* is equal to the price cap, welfare losses occur (missing money).

The aim of the following paragraphs is, thus, to shed light on these developments.

Driven by the introduction of various subsidy programs, RES have experienced a remarkable rise[4]. PV and wind power are highly capital intensive (e.g., Newbery, 2016b; Schmidt, 2014) but feature marginal costs close to zero (Milligan et al., 2016; Osorio and van Ackere, 2016). The low generation costs of RES result in decreasing electricity prices—also known as the merit-order effect (Sensfuß et al., 2008). Lower electricity prices in turn reduce the yields of conventional generation and, at the same time, the larger share of RES decreases the load factors of thermal capacities. Combined with the priority dispatch of RES implemented in many European countries (Hu et al., 2017; Newbery et al., 2017), this effect can even lead to negative prices (Nicolosi, 2010). Furthermore, as scarcity situations occur less often, renewable generation reduces the profitability of peak-load plants that depend on recovering their capital costs during a limited number of hours (Keppler, 2017). In Europe, the expansion of RES in combination with several other factors, e.g., decreasing prices for hard coal and carbon emission certificates, caused a significant drop in electricity prices (see Bublitz et al., 2017; Hirth, 2018; Kallabis et al., 2016) that drastically complicated the recovering of operating expenses for conventional capacities (see Fig. 2). For instance, in the last years, gas-fired generation was often unprofitable. As a consequence gas power plants are being mothballed and decommissions are already carried out or being considered (S&P Global Platts, 2013; Bloomberg, 2015; Réseau de transport d'électricité, 2014b).

Due to the dependence on weather conditions, the generation of PV and wind power is highly intermittent, and especially wind generation is hard to predict (Newbery, 2016b). As their level of electricity generation is semi-dispatchable, only a reduction is possible (Lynch and Devine, 2017; Di Cosmo and Lynch, 2016), an additional need for flexibility is created, which, for example, can be provided by demand response measures, large-scale storage capacities or power plants with the ability to quickly ramp up or down (Pollitt and Anaya, 2016; Cepeda and Finon, 2013). Therefore, without further advancements, intermittent RES are currently unable to replace dispatchable conventional power plants adequately (Hach et al., 2016; Doorman et al., 2016) and the need for dispatchable generation capacity remains high. Moreover, as RES are often located away from the demand centers and the locations of capacities they replace, grid constraints will play a more pronounced role. RES are already mentioned as the main driver for grid congestions (Bruninx et al., 2013), and in the future, supply and demand need to be balanced at different geographical levels, e.g., at the local, the national or supranational level.

Finally, investors face different uncertainties regarding fuel and electricity prices and the regulatory framework, e.g., the nuclear phase-out decision, fossil fuel reduction or carbon emission targets. Even though the phase-outs affect supply security, Becker et al. (2016) claim that neither politicians nor scientists discuss lowering the level of security of supply to achieve a sustainable and affordable system. Beyond that, in case of an investment decision, the prompt commissioning of generation capacity—especially for controversial technologies (e.g., carbon capture and storage)—proves to be another obstacle, as the licensing process is tedious and adds another layer of uncertainty (Doorman et al., 2016).

2.3. *The optimal functioning of energy-only markets and the necessity of capacity remuneration mechanisms*

One, maybe the most persuasive, argument in favor of an EOM is that—even in the absence of an active demand response—resulting market prices are efficient and, thus, lead to sufficient long-term investments guaranteeing the least-cost long-term system if several key assumptions are met (Caramanis et al., 1982; Oren, 2005; Schweppe et al., 1988; Stoft, 2002): (1) the market is perfectly competitive, (2) market participants have rational expectations and (3) follow a risk-neutral strategy. However, in the light of the present state of electricity markets that feature several imperfections (Cepeda and Finon, 2011), these assumptions seem rather unrealistic, maybe even impossible to realize in practice. In real-world markets, a small number of producers often dominate the market, resulting in a duopoly or oligopoly (e.g., Schwenen, 2014), and invest strategically (Grimm and Zöttl, 2013; Zöttl, 2010). Furthermore, investors are usually rather risk-averse, i.e., building less capacity than risk-neutral investors would (Neuhoff and de Vries, 2004). Moreover, market participants may not always have rational expectations, and in the presence of the large uncertainties, e.g., about the development of electricity prices, and the long lead times for new investments, electricity markets are prone to suffer investment cycles (Arango and Larsen, 2011; Ford, 2002; Olsina et al., 2006). The alternation between overcapacity and under-capacity results in inefficient market allocations, i.e., in the former case, unprofitable investments and, in the latter case,

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[4] The rise of RES is, for example, illustrated by the fact that between 2006 and 2016, the worldwide installed photovoltaic (PV) and wind power capacity grew by a compound annual rate of 48% respectively 21% to a worldwide installed capacity of 303 GW respectively 487 GW by the end of 2016 (REN21, 2017).

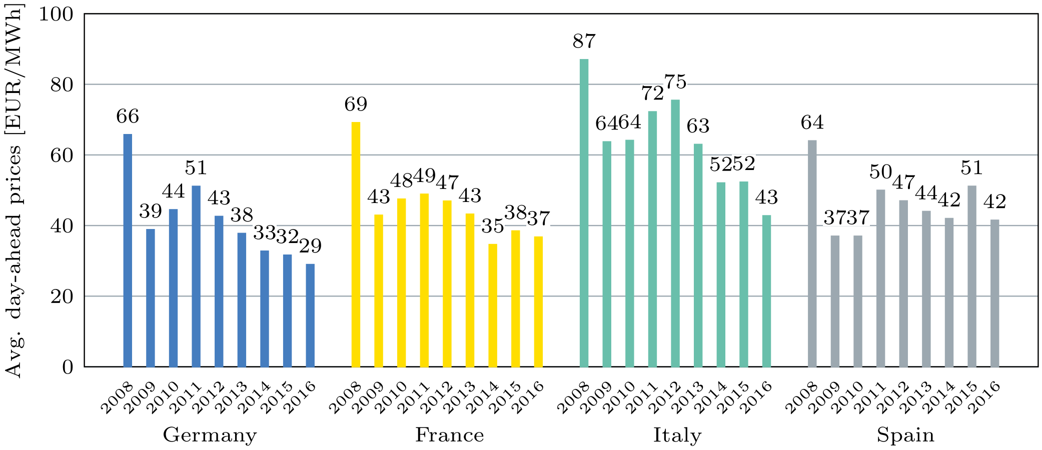

Fig. 2. The development of day-ahead prices in major European markets in the last years shows a clear downward trend, apart from the years 2009 and 2010, which can be regarded as outliers due to the impact of the global economic crisis. The comparison of the figures for 2008 and 2016 indicates a decline of about 50% in Germany, France, and Italy, whereas the decline in Spain is about 33%. Sources: ENTSO-E (2017), EPEX SPOT (2018), Gestore dei Mercati Energetic (2017), OMI-Polo Español S.A. (2017).

an excessive risk of load curtailment and high costs for consumers (Réseau de transport d'électricité, 2014a). Moreover, de Vries and Hakvoort (2004) argue that even long-term contracts do not provide a solution as they offer consumers the opportunity to free-ride.[5]

In addition, Keppler (2017) shows two other independent problems of an EOM. On the one hand, demand-side externalities in the form of transaction costs and incomplete information ensure that the social willingness-to-pay is greater than private willingness-to-pay for additional capacity. On the other hand, investments in generation capacities are not arbitrarily scalable, but rather take discrete values. In combination with dramatically lower revenues in the transition from underinvestment to overinvestment, investors have strong asymmetric incentives and, thus, tend to underinvest rather than to overinvest. Besides, Joskow and Tirole (2007) argue that scarcity rents are very sensitive to regulatory changes and that even minor mistakes are likely to have a significant impact on market prices.

Some of the more critical voices stress that market imperfections, especially the lack of demand response, will always persist in EOMs, and lead to the exercise of market power, which results in high price peaks. Thus, a different framework or additional measures, e.g., CRMs, are required to help to ensure generation adequacy efficiently (Cramton and Stoft, 2005; Joskow and Tirole, 2007). Others reply that the main problem of EOMs is the lack of political will to allow for unconstrained electricity prices[6] and periodic shortages (Besser et al., 2002; Hogan, 2005).

However, often it is argued that CRMs are inefficient and according to Oren (2000) the least desirable instrument or according to Hogan (2017) only the third best option to ensure reliability, with the first option being the elimination of the leading underlying causes, e.g., incentivizing a flexible demand[7], and the second-best option being an administrative price curve for the usage of reserve energy. Wolak (2004) even claims that the rationale for CRMs is essentially a holdover from the regulated regime of the energy sector that encourages over-investment and is highly susceptible to market power, thus, frequently requiring regulatory intervention to set a non-distorted capacity price. In a recent publication, Wolak (2017) instead argues that generation adequacy can be ensured by establishing a market for standardized forward contracts and mandating retailers to participate in order to provide sufficient liquidity. He states that in this way generation adequacy can be ensured at the lowest possible cost, as scarcity is reflected in the forward prices and investors are provided with the necessary financing.

Summing up, whether the EOM is able to guarantee generation adequacy, is still discussed intensively in the literature. It is apparent that the efficient allocation of resources by an EOM is a highly challenging task, given the particular combination of the unusual characteristics of the electricity market. Here, the utilization of real-world experience to draw general conclusions is of limited use. In case, some analysts argue that the developments on a particular market serve as an example for the inherent shortcomings of an EOM, advocates respond that the market has not been able to function well due to regulatory mistakes (Doorman et al., 2016). Beyond that, Hogan (2017) states that the financial distress present in many European as well as North American electricity markets, can be attributed to overcapacities. Nonetheless, recent developments have raised serious doubts on the effectiveness of an EOM so that many politicians deem the introduction of CRMs necessary.

3. Market design options and current status of real-world implementations

In order to highlight the practical relevance of the market design concepts developed in the literature, an overview of several CRMs currently implemented or in the planning stage around the world is provided in the following. These real-world implementations are classified with respect to some key characteristics. Then, conclusions and implications for future implementations are presented. Thereby, this section provides a helpful backdrop for a deeper understanding of the literature reviewed in Section 4.

3.1. Generic types of capacity remuneration mechanisms

Typically, CRMs are designed to incentivize investments and thus improve generation adequacy, i.e., avoid shortage situations. This is implemented by offering capacity providers income on top of the

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[5] A problem with long-term contracts is that they are not contracted directly between consumers and utilities, but rather through load-serving entities as intermediaries. However, rational consumers prefer the cheapest retailer, which by avoiding long-term contracts does not contribute to the financing of peaking capacities.

[6] Although price caps are frequently mentioned as a source of the missing money problem, the data on market prices often tells a different story, e.g., since the establishment of the EEX in 2000, the upper price limit of the German spot market (3000 Euro/MWh) was not once hindering the price formation (EPEX SPOT, 2018), the same seems to be the case in several US market areas from 2000 to 2006 (Joskow, 2008).

[7] In the future, if end consumers start to participate directly in the market via smart meters, they could specify in detail what price they are willing to pay for each consumption level. If the price is too high, the smart meter will switch off individual consumers directly, for example, the washing machine, while leaving others connected, e.g., the lights and refrigerator. Thereby, the missing money problem could be avoided (Newbery, 2016a).

earnings from selling electricity on the market (Hawker et al., 2017). Yet, the mechanisms vary in the way the required quantities that are supplied and the corresponding capacity prices are determined (Hach et al., 2016).

The European Commission (2016b) distinguishes between volume-based mechanisms, where a specific capacity sufficient to guarantee the desired level of generation adequacy is set and then results in a market-driven price, and price-based mechanisms, where the amount of the procured capacity is steered by setting a target price. Both categories can also be subdivided into market-wide and targeted approaches. Whereas market-wide mechanisms provide support to all capacity in the market, targeted mechanisms aim at supporting only a subset, e.g., newly built capacity or capacity expected to be required additionally to the one already provided by the market. More specifically, six different types of mechanisms can be differentiated (for typical characteristics, see Table 1):

(1) *Tender for new capacity.* Financial support is granted to capacity providers in order to establish the required additional capacity. Different variations are possible, e.g., financing the construction of new capacity or long-term power purchase agreements.
(2) *Strategic reserve.* A certain amount of additional capacity is contracted and held in reserve outside the EOM. The reserve capacity is only operated if specific conditions are met, e.g., a shortage of capacity in the spot market or a price settlement above a certain electricity price.
(3) *Targeted capacity payment.* A central body sets a fixed price paid only to eligible capacity, e.g., selected technology types or newly built capacity.
(4) *Central buyer.* The total amount of required capacity is set by a central body and procured through a central bidding process so that the market determines the price. Two common variants of the central buyer mechanism include the forward capacity market (Cramton and Stoft, 2005, 2006) and reliability options (Perez-Arriaga, 1999; Vázquez et al., 2001; Batlle et al., 2007).
(5) *De-central obligation.* An obligation is placed on load-serving entities to individually secure the total capacity they need to meet their consumers' demand. In contrast to the central buyer model, there is no central bidding process. Instead, individual contracts between electricity suppliers and capacity providers are negotiated.
(6) *Market-wide capacity payment.* Based on estimates of the level of capacity payments needed to bring forward the required capacity, a capacity price is determined centrally, which is then paid to all capacity providers in the market.

3.2. *Current status of implementation around the world*

While the first CRMs in the US date back to the 1990s, European countries only rather recently started implementing such mechanisms or are currently evaluating tailored solutions. However, the European trend towards applying CRMs stands in contrast to the European Commission's preference for the EOM as an approach to trigger new investments and provide signals for decommissioning in case of overcapacities (Petitet et al., 2017). Some further countries outside of Europe and the US, such as Australia and Colombia, are also relying on CRMs in order to guarantee generation adequacy.

An overview of several real-world implementations of CRMs as well as planned mechanisms is provided in Table 2 and Fig. 3. The country-specific approaches differ not only with regard to the chosen type of the mechanism but also with regard to the respective administrators and the eligible technologies. Further characteristics of some currently active mechanisms can be found in Appendix A.

3.3. *Discussion and implications for future implementations*

An expert survey conducted by Bhagwat et al. (2016b) reveals that the CRMs implemented in the US have effectively—but likely not efficiently—contributed to reaching the different regions' respective reliability goals. For this reason, the experts generally advise the EU to rely on EOMs and not implement CRMs. If, however, CRMs are to be implemented in Europe, they recommend using consistent and transparent rules with minimum subsequent modifications. Moreover, based on the US experience, it seems advisable to base the capacity remuneration on the availability of the respective resources in actual scarcity conditions. Since these recommendations are quite generic, they are also applicable to any country outside of Europe which is considering the implementation of a CRM.

Bhagwat et al. (2016b) further state that cross-border inefficiencies are currently not considered a major issue in the US, even though the introduction of the PJM mechanism has likely been a key driver for the subsequent implementation of a CRM in the neighboring MISO region. In this respect, the situation is different in Europe, where the European Commission (2011) considers a single European electricity market—also termed "internal electricity market"—essential in order to ensure competitive, sustainable and secure energy supply in the future. This is contrasted by several European countries already using or currently implementing individual mechanisms to increase generation adequacy on a national level (see Section 3.2). Yet, in a highly interconnected electricity system like the European one, the uncoordinated implementation of local mechanisms might lead to numerous potentially adverse cross-border effects, which are described in detail in Section 4.6.

Table 1
Typical characteristics for different types of CRMs. However, due to specific requirements, the concrete specifications may vary in different countries. Sources: European Commission (2016b), Hancher et al. (2015), Neuhoff et al. (2013, 2016).

Type	Category	Procurement/ market type	Participation in other markets	Product	Main regulatory parameters
Tender for new capacity	Volume-based/ targeted	Centralized/ auction	Yes	Firm capacity	Capacity volume
Strategic reserve	Volume-based/ targeted	Centralized/ auction	No	Reserve capacity	Capacity volume, activation rule, trigger event
Targeted capacity payment	Price-based/ targeted	Centralized/ auction	Yes	Firm capacity	Capacity price, eligibility criteria
Central buyer	Volume-based/ market-wide	Centralized/ auction	Yes	Call option	Capacity volume, strike price
De-central obligation	Volume-based/ market-wide	Decentralized/ bilateral	Yes	Reliability certificate	Security margin, penalties
Market-wide capacity payment	Price-based/ market-wide	Centralized/ auction	Yes	Firm capacity	Capacity price

Table 2
Overview of implemented CRMs around the world. Sources: Bhagwat et al. (2016b), Byers et al. (2018), Cejie (2015), Chow and Brant (2018), Deutscher Bundestag (2016), EirGrid plc and SONI Limited (2017), European Commission (2014, 2016a,b,c, 2017a,b), Government of Western Australia (2017), Hancher et al. (2015), Harbord (2016), Midcontinent Independent System Operator, Inc. (2019), New York Independent System Operator (2018), Patrian (2017), PJM (2018), Roques et al. (2017), Single Electricity Market Committee (2016), Southwest Power Pool, I. (2018a,b), Svenska Kraftnät (2016).

Type	Market area	Administrator		Eligible technologies				Status[1]	
		TSO/ISO	RA	TPP	VRES	DSM	IC		
Strategic reserve	Belgium	x	x	x		x		Active	(2014)
	Germany	x	x	x		x		Planned[2]	(2018)
	Sweden	x		x		x		Active	(2003)
Central buyer	Colombia		x	x	x			Active	(2006)
	Ireland[3]	x	x	x	x	x	x	Planned	(2017)
	Italy[3]	x	x	x		x	x	Planned	(2018)
	Poland[4]	x	x	x	x	x	x	Planned	(2018)
	UK	x	x	x	x	x	x	Active	(2014)
	US – ISO-NE	x		x	x	x	x	Active	(1998)
	US – MISO	x		x	x	x	x	Active	(2009)
	US – NYISO	x		x	x	x	x	Active	(1999)
	US – PJM	x		x	x	x	x	Active	(2007)
De-central obligation	Australia – SWIS	x	x	x	x	x		Active	(2005)
	France	x		x	x	x	x	Active	(2015)
	US – CAISO	x	x	x	x	x	x	Active	(2006)
	US – SPP	x		x	x	x	x	Active	(2018)
Targeted capacity payment	Spain[5]	x		x				Active	(2007)

Abbreviations: CAISO—California ISO, DSM—demand side management, IC—interconnector, ISO—independent system operator, ISO-NE—ISO New England, MISO—Midcontinent ISO, NYISO—New York ISO, PJM—Pennsylvania-New Jersey-Maryland Interconnection, RA—regulatory authority, SPP—Southwest power pool, SWIS—South West interconnected system, TPP—thermal power plant, TSO—transmission system operator, VRES—variable renewable energy sources

[1] Year of (planned) implementation in parentheses. The year refers to the respective mechanism currently in place, however, other mechanism may have been used before.

[2] In Germany, two separate mechanisms have been discussed that can be classified as a strategic reserve. In 2016, a security stand-by arrangement for lignite-fired power plants with a total capacity of 2.7 GW was introduced in order to attain national climate targets. Furthermore, an additional so-called capacity reserve is supposed to be active in winter of 2018/19 to ensure generation adequacy. However, as the European Commission still assesses whether the capacity reserve complies with EU state aid rules, it is unclear whether the planned schedule can be met.

[3] To date, targeted capacity payments are used.

[4] Currently, a strategic reserve is implemented.

[5] This refers to the now in place "availability service" mechanism. An additional mechanism named "investment incentive" was abolished in 2016.

The European Commission has already recognized this issue and therefore continuously assesses the conformity of planned and implemented mechanisms with EU State aid rules (for an overview of the cases see European Commission, 2017c). For a lawful public intervention in the market, the European Commission (2013) asks for the respective member state to demonstrate the essential need for any capacity remuneration. Moreover, any mechanism must ensure that distortions of competition are minimized and technology neutrality is guaranteed. The latter aspect includes the eligibility of demand-side measures or foreign generation capacity, which, for example, has led to several adjustments of the French decentralized capacity market mechanism.

4. Findings on capacity remuneration mechanisms in the literature

After analyzing real-world implementations of CRMs, the findings in the literature are discussed below. In view of the large number of studies, the findings have been structured based on the specifically investigated topics. This allows to compare similar studies and to derive common results. In many of the analyses, e.g., for evaluating dynamic long-term effects—such as the occurrence of investment cycles—the use of models is highly suitable (Hary et al., 2016). Table 3 gives a quick overview of the existing approaches available in the literature including the regarded market characteristics or the considered research topics. For example, this allows determining which model type is particularly suitable for the assessment of specific research questions.

The summary of all the findings in the literature, including but not limited to the mentioned models in the table, is structured by the economic implications of CRMs in the following subsections. At first, the design elements of CRMs are briefly discussed. Then, it is examined how CRMs are affected by market power, risk aversion, and investment cycles. Subsequently, it is analyzed how CRMs influence market welfare and neighboring market areas. Finally, the impact of CRMs in an electricity market characterized by a higher share of RES and a more flexible demand side is evaluated.

4.1. Generic design criteria for a capacity remuneration mechanism

The design of a CRM is a complex challenge where the ideal solution depends on the particular market conditions, e.g., the existing capacity mix and the demand characteristics (Batlle and Rodilla, 2010; Cepeda and Finon, 2011; Keppler, 2017; Spees et al., 2013). Here only the most important design parameters as well as selected parameters for specific mechanisms are discussed, for further criteria, e.g., see Batlle and Pérez-Arriaga (2008), Ausubel and Cramton (2010) for different design criteria, Herrero et al. (2015) for pricing rules, Neuhoff et al. (2016) for the design of a strategic reserve or Schwenen (2015) for the design of capacity auctions.

4.1.1. Target for system availability

Once the decision to introduce a CRM has been made, a system-wide target for system adequacy is often set, which helps to determine in the case of volume-based mechanisms the required capacity level or in the case of price-based mechanisms the targeted capacity price (Hogan, 2017). Here, the loss of load expectation (LOLE)[8] is frequently used and often a value of 1 day in 10 years is targeted (NERC, 2009), which however has been criticized as arbitrary and too strict to be economically optimal (Cramton and Stoft, 2006). Taking into account correlated outages among generators and the expected

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[8] However, the LOLE is not free of criticism, for example, as it refers only to curtailment and does not indicate to what absolute or relative extent in relation to the market size the curtailment occurs. Here, the unserved energy (UE) metric provides more insight (Lueken et al., 2016). An overview of further reliability target can be found at Milligan et al. (2016).

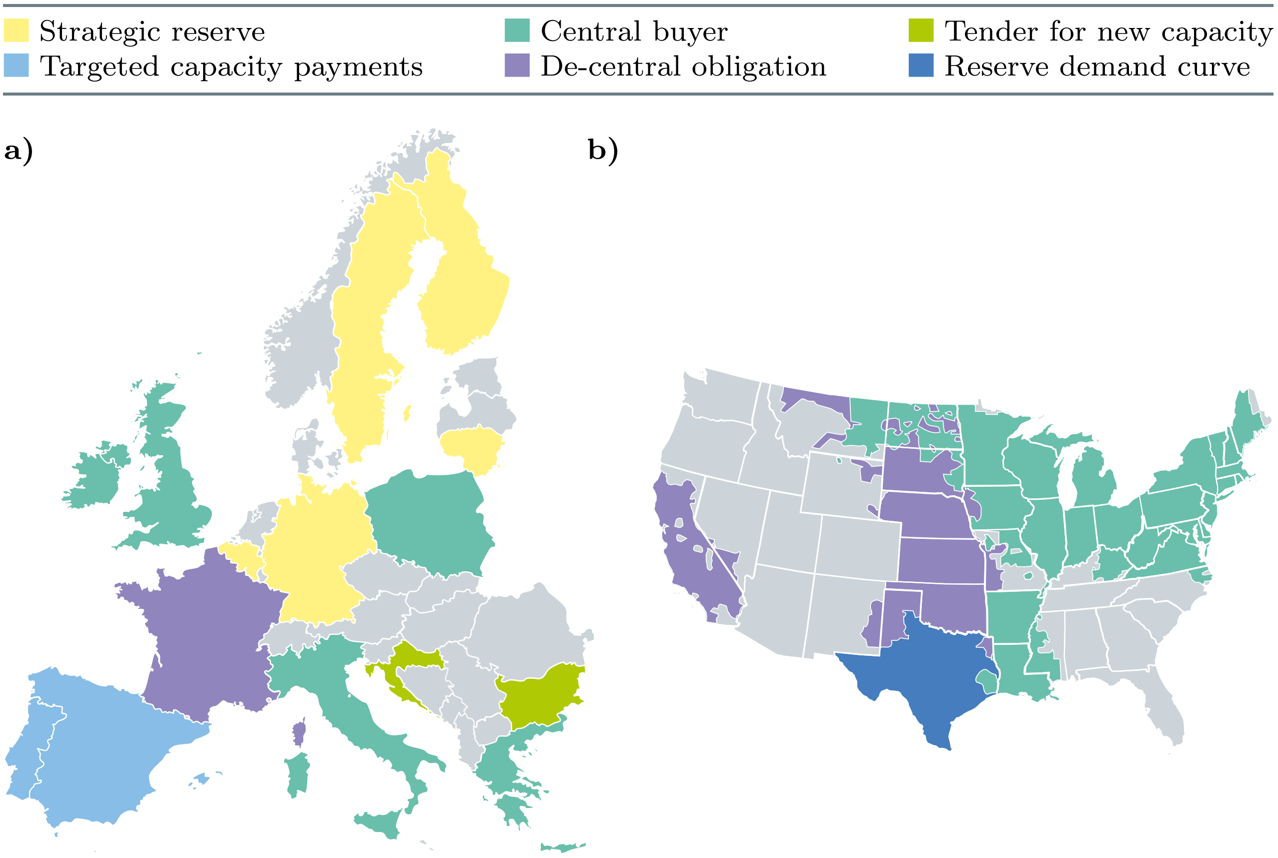

Fig. 3. Overview of a) the future situation of CRMs in Europe when all planned mechanisms are implemented and b) the current situation in the US. The situation is more diverse in Europa due to uncoordinated national approaches and diverging interests. Whereas only two different types of CRMs are found in the US, a specific case is the Texas ERCOT market, where the EOM is supported by an artificial reserve demand curve that produces high price signals to incentivize new investments or DSM. Sources: ACER and CEER (2017), Chow and Brant (2018), EirGrid plc and SONI Limited (2017), European Commission (2014, 2016a,b), U.S. Government Accountability Office (2017), Midcontinent Independent System Operator, Inc. (2019), Hancher et al. (2015), Roques et al. (2016).

future demand, then the required quantity of demand to reach the target for system availability is derived.

4.1.2. Demand curve

In quantity-based CRMs, a demand curve—usually referred to as the variable resource requirement demand curve—must be defined that sets the price for each capacity level.[9] Although in theory, it makes sense to rely on the declining marginal value of capacity (Cramton and Stoft, 2007), in practice, due to the difficulty of estimating this value, usually, a linear curve based on an upper and a lower price limit is used (Spees et al., 2013). The upper price cap needs to be high enough to incentivize sufficient investments when the system is tight and typically equals a multiple of the Net CONE[10]. The lower price cap is usually set equal to zero and marks the capacity level when the desired reserve margin is reached. However, sometimes, in order to avoid a total price collapse or prevent market manipulation from large purchasers of capacity, a higher price is set, e.g., 75% of the Net CONE (Miller et al., 2012). When setting the upper and lower price limit, it also needs to be taken into account that a steep demand curve may lead to more volatile prices and, thus, greater uncertainty for investors (Bhagwat et al., 2017b).

4.1.3. Eligible technologies

In a next step, the definition of the capacity product needs to be established, and it has to be decided which capacity resources are eligible. de Sisternes and Parsons (2016) argue that CRMs should be technology-neutral and allow for the participation of all elements that can reliably provide capacity (conventional and renewable generation, storage technologies, demand-side measures). If certain technologies were to be excluded, the mechanisms would introduce hidden subsidies for the technologies eligible for the CRM, which in turn would lead to higher costs for consumers. At the same time, however, it must be noted that this can possibly lead to conflicts regarding the reduction of carbon emissions, for example, in Great Britain highly emission-intensive diesel-fueled generators received capacity payments (S&P Global Platts, 2015). Moreover, Hach and Spinler (2016) propose to consider the specific policy targets and only consider a technology-neutral selection if generation adequacy is to be achieved at the lowest possible cost. However, if particularly flexible capacities are required or an ambitious emission reduction target needs to be achieved, this should be reflected in the selection of technologies. Although it is cheaper to only pay for new generation capacities, it must be noted that this strategy works only once as investors will adjust their behavior onwards and demand additional protection and risk premiums (Cramton et al., 2013).

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[9] Instead of demand curves sometimes a fixed capacity is set. However, Hobbs et al. (2007) advise against this practice as sloped demand curves bear lower risks for consumers.

[10] Similar to the determination of the VoLL, the determination of the CONE or the Net CONE, which is usually carried out by the regulator, is also a controversial matter. The choice or the cost-basis of the reference technology, and, thus, its value is often adjusted over time (Cramton and Stoft, 2007, 2008; Jenkin et al., 2016). Regarding the related uncertainty, Spees et al. (2013) propose to better set a higher value to avoid unreliable outcomes.

Table 3
Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms or generation adequacy.

Publication	Model type[a,b]	Model scope	Market area	Design criteria	Market power	Uncer-tainty	Investment cycl.	Efficiency	Cross-border	High RES	Flexible Res.	Research subject
Aalami et al. (2010)	analytical	interruptible technologies	Iran								x	impact of capacity market programs on the load level and shape
Abani et al. (2018)	system dynamics	spot market, decommissions (retirement of unprofitable existing generation)/ investments	hypothetical			x						impact of risk aversion on the performances of capacity remuneration mechanisms (competitive EOM, capacity market and strategic reserve) with investors facing an uncertain peak load
Abani et al. (2016)	system dynamics	spot market, decommissions (retirement of unprofitable existing generation)/ investments	hypothetical			x		x				impact of investors' risk aversion on investments in generation capacity in a competitive EOM and a capacity market
Assili et al. (2008)	system dynamics	electricity dispatch, investments	hypothetical				x					influence of capacity payments on market prices and the reserve margin
Bajo-Buenestado (2017)	analytical (perfect competition, subgame perfect Nash equilibrium)	spot market, investments	Texas (ERCOT)		x			x				welfare effects of introducing capacity payments in a competitive market and a market with dominant firms
Bhagwat and de Vries (2013)	agent-based (EMLab)	spot market, investments, transmission constraints	Germany, Netherlands				x					effect of a strategic reserve in Germany on investment behavior and leakage of reserve benefits to the Netherlands
Bhagwat et al. (2014)	agent-based (EMLab)	spot market, decommissions/investments, transmission constraints	hypothetical based on Germany						x			cross-border impact of a capacity market and a strategic reserve on consumer costs and on investments in the affected markets
Bhagwat et al. (2016a)	agent-based (EMLab)	spot market, decommissions (retirement of unprofitable existing generation)/ investments, transmission constraints	hypothetical based on Germany		x	x	x					effectiveness strategic reserve in the presence of a high RES share
Bhagwat et al. (2017a)	agent-based (EMLab)	spot market, decommissions (retirement of unprofitable existing generation)/ investments, transmission constraints	hypothetical based on Germany			x	x			x		effectiveness of a capacity market in the presence of imperfect information and uncertainty, declining demand shocks resulting in load loss, and a growing share of RES
Bhagwat et al. (2017b)	agent-based (EMLab)	spot market, decommissions (retirement of unprofitable existing generation)/ investments	hypothetical based on the United Kingdom			x	x					effectiveness of a forward capacity market with long-term contracts in the presence of a growing share of RES
Bhagwat et al. (2017c)	agent-based (EMLab)	spot market, decommissions (retirement of unprofitable existing generation)/ investments, transmission constraints	hypothetical based on Germany						x			cross-border effects of a capacity market and/or a strategic reserve
Briggs and Kleit (2013)	analytical (Ramsey optimum)	spot market, investments, transmission constraints	hypothetical		x			x				efficiency of capacity payments
Bublitz et al. (2015)	agent-based (PowerACE)	spot market, decommissions (retirement of unprofitable existing generation)/ investments, operating reserve, transmission constraints	Germany		x			x				effects of the proposed strategic reserve in Germany on security of supply and costs
Cepeda and Finon (2011)	system dynamics	spot market, investments, transmission constraints	hypothetical			x	x					cross-border effects of an EOM (with/without price cap) and a forward capacity market

Cepeda and Finon (2013)	system dynamics	spot market, investments	hypothetical based on France							x	x	effects of large-scale deployment of wind power generation on spot prices and reliability of supply
Creti and Fabra (2007)	analytical (perfect competition, monopoly)	spot market, transmission constraints	hypothetical					x				firms' optimal behavior and market equilibrium in capacity markets with the possibility to sell to a foreign market under both perfect competition and monopoly
Ehrenmann and Smeers (2011)	stochastic equilibrium	electricty dispatch, investment	hypothetical		x	x						effects of risk (fuel prices, carbon market) on investment decisions in generation capacity
Fabra et al. (2011)	analytical (Nash equilibrium)	investments	hypothetical			x		x				effects of price caps and auction formats (uniform-price/discriminatory) on investments and the capacity ratio between two firms
Fan et al. (2012)	stochastic equilibrium	electricity dispatch, investments	hypothetical			x						effects of uncertainty and risk aversion on investments in high and low-carbon capacities
Franco et al. (2015)	system dynamics	electricity dispatch, decommissions (retirement of unprofitable existing generation)/investments	Great Britain				x					effect of central buyer capacity market on investment cycles and long-term market stability
Genoese et al. (2012)	agent-based (PowerACE)	spot market, investments, operating reserve, transmission constraints	hypothetical based on Spain					x				impact of a capacity payment mechanism on the long-term development of investments in conventional capacities and on electricity prices
Gore et al. (2016)	single-firm optimization	spot market, transmission constraints	Finland, Russia					x	x			short-term effects of an EOM and an energy-plus-capacity market on cross-border trade and efficient allocation of transmission capacity
Grave et al. (2012)	single-firm optimization (DIME)	electricity dispatch, decommissions (based on age)/investments	Germany								x	development of security of supply under the increasing penetration of intermittent RES and the need for backup capacity and electricity imports
Grimm and Zöttl (2013)	analytical (perfect competition, Nash equilibrium)	spot market, investments	Germany					x				influence of spot market design on firms' investment decision for different regimes of spot market competition (competitive prices and Cournot-Nash equilibrium)
Hach et al. (2016)	single-firm optimization	spot market, decommissions (retirement of unprofitable existing generation)/investments	Great Britain		x							affordability, reliability, and sustainability of a central buyer capacity market (for new or new/existing capacity)
Hach and Spinler (2016)	real options for single investor	spot market, investments	Europe	x		x						effect of capacity payments on investments in gas-fired power plants under rising renewable feed-in
Hary et al. (2016)	system dynamics	spot market, decommissions (retirement of unprofitable existing generation)/investments	hypothetical			x	x	x				dynamic effects of a capacity market and a strategic reserve mechanism on investment cycles
Hasani-Marzooni and Hosseini (2013)	system dynamics	electricity generation, investments, operating reserve, transmission constraints	Iran				x	x				effect of a (regional) capacity payment mechanism and a price cap on investments in Iranian electricity market

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Table 3 (*continued*)

Publication	Model type[a,b]	Model scope	Market area	Design criteria	Market power	Uncer-tainty	Investment cycl.	Efficiency	Cross-border	High RES	Flexible Res.	Research subject
Herrero et al. (2015)	single-firm optimization	electricity dispatch, investments	hypothetical	x								effects of the implemented pricing rule (linear and non-linear) on long-term investment incentives
Hobbs et al. (2007)	agent-based (single agent)	investments	hypothetical	x		x						effects of alternative demand curves in the PJM market on reserve margins, generator profitability, and consumer costs
Höschle et al. (2017)	analytical (Karush-Kuhn-Tucker)	electricity dispatch, investments, green certificates	Belgium					x				effect of central buyer capacity market and strategic reserve on the reserve margin and non-participating RES
Jaehnert and Doorman (2014)	single-firm optimization	electricity dispatch, investments, transmission constraints	Netherlands, Germany							x		effect of a capacity mechanism or an increased price cap on generation capacity under rising renewable feed-in
Joskow (2008)	analytical (Ramsey optimum)	spot market, investments	hypothetical		x						x	sources of the missing money problem in imperfect markets
Joskow and Tirole (2007)	analytical (Ramsey optimum)	spot market, investments, operating reserve	hypothetical		x	x		x				efficiency of capacity obligations
Keles et al. (2016)	agent-based (PowerACE)	spot market, decommissions (retirement of unprofitable existing generation)/ investments, operating reserve, transmission constraints	Germany					x				generation adequacy in different market designs (EOM, central buyer capacity market, strategic reserve)
Kim and Kim (2012)	single-firm optimization	electricity dispatch, investments, transmission constraints	South Korea					x				effects of zonal forward capacity markets on investments across market zones
Laleman and Albrecht (2016)	statistical	electricity dispatch	Belgium								x	occurrence of electricity shortages and surpluses in the presence of a high share of nuclear combined with a high share of intermittent RES
Lara-Arango et al. (2017a)	analytical (joint maximization, Nash equilibrium, perfect competition) combined with scenario experiments	spot market, investments	hypothetical				x	x				economic welfare of a central buyer capacity market and a strategic reserve
Lara-Arango et al. (2017b)	agent-based	electricity dispatch, decommissions (based on age)/investments	hypothetical			x	x					influence of uncertainty on producer surplus and market stability in case of capacity payments and a capacity auction
Léautier (2016)	analytical (two-stage, Nash equilibrium)	spot market, investments	hypothetical		x	x		x				optimal investment in different market designs (financial reliability options, physical capacity certificates, single market for energy and operating reserves)
Le Coq et al. (2017)	analytical combined with scenario experiments	spot market, investments	hypothetical		x			x				relationship between prices, market power and investment under three different regulatory regimes (low price cap, high price cap, capacity market)
Levin and Botterud (2015)	single-firm optimization	electricity dispatch, investments, spinning-up and non-spinning reserve	Texas (ERCOT)							x		ability of three different market mechanisms (Operating Reserve Demand Curves, Fixed Reserve Scarcity Prices and fixed capacity payments) to provide generator revenue sufficiency and resource adequacy with increasing amounts of renewable energy

Lueken et al. (2016)	statistical	spot market	PJM	x		x				resource adequacy requirements in the PJM market area assuming plant failures are either independent or correlated
Lynch and Devine (2017)	analytical (Karush-Kuhn-Tucker)	spot market, decommissions (retirement based on higher maintenance costs)/investments, refurbishment	hypothetical				x			impact of refurbishment under capacity payments and reliability options
de Maere d'Aertrycke et al. (2017)	stochastic equilibrium	electricity dispatch, investments	hypothetical			x	x			impact of incomplete risk trading (Contracts for Difference, Reliability Options with and without physical back-up) on investments
Mastropietro et al. (2016)	agent-based (two-stage)	spot market, investments	hypothetical	x						impact of penalty schemes for under-delivery on capacity mechanisms' effectiveness and unit reliability
Meunier (2013)	analytical	electricty dispatch, investment	hypothetical			x				effect of risk and risk-aversion on the long-term equilibrium technology mix
Meyer and Gore (2015)	analytical (Nash equilibrium)	spot market, investments	hypothetical		x		x	x		influence of competition and market power on market welfare of CRMs (strategic reserve and reliability options)
Milstein and Tishler (2012)	analytical (Nash equilibrium)	spot market, investments	Israel				x			the rationality of underinvestment if profit-seeking, non-abusive producers construct and operate either one—base or peaking—generation unit (or both)
Mohamed Haikel (2011)	analytical (three stage, Karush-Kuhn-Tucker, Nash equilibrium)	spot market, investments	hypothetical		x	x	x			comparison of three CRM (reliability options, forward capacity market, and capacity payments) in regard of efficiently assuring long-term capacity adequacy in Cournot oligopoly, collusion, and monopolistic situations
Neuhoff et al. (2016)	single-firm optimization	electricity dispatch, transmission constraints	hypothetical	x			x	x		benefits of coordinated cross-border strategic reserves
Ochoa and Gore (2015)	system dynamics	electricity dispatch, investments, transmission constraints	Finland, Russia				x	x		effects of maintaining a strategic reserve in Finland in combination with the different scenarios of interconnection expansion and trading arrangements with Russia
Osorio and van Ackere (2016)	system dynamics	electricity dispatch, investments, transmission constraints	Switzerland					x	x	impact of the nuclear phase-out and the increasing penetration of variable RES on security of supply
Ozdemir et al. (2013)	single-firm optimization (COMPETES)	electricity dispatch, decommissions (based on age)/investments, transmission constraints	Europe					x		cross-border effects (investments, electricity generation, market prices, and import export flows) of a unilateral introduction of a German capacity market
Park et al. (2007)	system dynamics	spot market, investments	South Korea				x			effects of capacity incentive systems—loss of load probability or fixed capacity payments—on investment in the Korean electricity market
Petitet et al. (2017)	system dynamics (SIDES)	electricity dispatch, decommissions (retirement of unprofitable existing generation)/investments	hypothetical			x	x			effects of capacity mechanisms on security of supply objectives assuming risk-averse and risk-neutral investor behavior in power markets undergoing an energy transition

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Table 3 (*continued*)

Publication	Model type[a,b]	Model scope	Market area	Design criteria	Market power	Uncer-tainty	Investment cycl.	Efficiency	Cross-border	High RES	Flexible Res.	Research subject
Ringler et al. (2017)	agent-based (PowerACE)	spot market, investments, operating reserve, transmission constraints	CWE Market area					x	x			effects of cross-border congestion management and capacity mechanisms on welfare and generation adequacy in Europe (potential development of the CWE Market)
Schwenen (2014)	analytical	spot market	hypothetical		x			x			x	effect of market structure (duopoly with symmetric and asymmetric firm size) on security of supply in a capacity market and an EOM
Schwenen (2015)	analytical	capacity auction	New York (ICAP)	x								strategic bidding to coordinate on an equilibrium in multi-unit auctions with capacity constrained bidders
See et al. (2016)	single-firm optimization	electricity dispatch, transmission constraints	hypothetical						x			reinforcing cross-border competition for the supply of capacity generation with the help of a flow-based forward capacity mechanism
Tashpulatov (2015)	log-linear regression	spot market	England and Wales		x							effects of regulatory reforms on incentive and disincentive to exercise market power
Traber (2017)	analytical (Karush-Kuhn-Tucker)	spot market, decommissions (based on age)/ investments/retrofitting, transmission constraints	Germany, France, and Poland					x				effects of capacity remuneration mechanisms on welfare and distribution (consumers/producers) with a focus on conventional power plants
de Vries and Heijnen (2008)	agent-based	spot market, decommissions (based on age)/investments, interruptible technologies	The Netherlands		x	x	x					effectiveness of different market designs (an EOM with and without market power, capacity payment, operating reserves pricing, capacity market) under uncertainty about demand growth
Weiss et al. (2017)	hybrid (single-firm optimization/ agent-based)	spot market, investments	Israel							x	x	market prices, reliability, and consumer costs in different market designs (EOM, capacity market, strategic reserve)
Willems and Morbee (2010)	analytical	spot market, investment	Germany			x		x				effects of an increasing number of derivatives on welfare and investment incentives in electricity market with risk averse firms
Winzer (2013)	agent-based	spot market, investments	Great Britain			x		x				robustness of various capacity mechanisms to welfare losses caused by regulatory errors

[a] Here, the column “model scope” excludes all CRM as these are mentioned in the column “Research subject”.

[b] If only marginal costs are regarded to determine, which capacity is operating, the term “electricity dispatch” is used. However, the term “spot market” is used if the strategic behavior of market participants is explicitly modeled.

4.1.4. Verification system

In order to enhance the performance of CRMs, a performance incentive system is required, which ensures that the capacities actually provide the contracted capacity when the system is tight (Vazquez et al., 2002; Mastropietro et al., 2016). This can either be implemented through a financial penalty for non-compliance (Cramton and Stoft, 2005) or by restricting the amount a resource can provide to its firm capacity (Batlle and Pérez-Arriaga, 2008). The experiences from the United States show that despite the existence of explicit penalties, underperformance has occurred, which underlines the importance of designing and implementing a performance incentive system (Mastropietro et al., 2017). If a financial penalty is chosen, it needs to be high enough to incite investors to compliance, which, however, increases the risk of investors and this is reflected in their bids. For the exact amount of the penalty, it is possible to rely on the VoLL, the capacity price or the Net CONE.

4.2. Potential and effects of market power

Central buyer mechanisms, e.g., reliability options, are able to lower the potential for market power in wholesale electricity markets (Le Coq et al., 2017; Léautier, 2016) and thereby improve the efficiency and reduce the total bill of generation, which is defined as the sum of the revenues realized by the electricity generators (Hach et al., 2016). By contrast, compared to an EOM, Bhagwat et al. (2016a) claim that a strategic reserve increases the possibility to exercise market power as the opportunities to withhold capacities, which can result in an activation of the reserve and extreme market prices, become more frequent compared to an EOM where market power is primarily exercised during capacity shortage hours.

In addition, as Mohamed Haikel (2011) points out, market power might be exerted when introducing non-market based mechanisms, e.g., capacity payments. However, the possible entry of a new competitor makes them less vulnerable to market power than, e.g., day-ahead markets, where in the short term no additional competition can emerge (Schwenen, 2014). Therefore, it seems unlikely that the additional potential of market power within a CRM will compensate for the lower potential in the wholesale markets. Nonetheless, Joskow (2008) advocates that the capacity price could be reduced by the quasi-rents earned by a hypothetical peaking unit, thereby disincentivizing the exercise of market power. Furthermore, Cramton and Stoft (2008) argue that only new investments could be allowed to set the capacity price to mitigate market power, existing capacity must either submit a zero bid or is not allowed to participate at all. The rationale behind this approach is that although established market players might possess market power, they are unable to exercise it if there is competitive new entry and only new investments set the price.

4.3. Influence of uncertainty and risk aversion

In the majority of the considered analyses, it is assumed for simplification purposes that all decision-makers act risk-neutral, although several theoretical arguments (Neuhoff and de Vries, 2004; Banal-Estanol and Ottaviani, 2006) as well as real-world observations suggest that decision-makers in the energy sector are usually risk-averse or at least behave accordingly (Meunier, 2013). This seems to be the case not only for economic but also for political decision-makers (Finon et al., 2008; Neuhoff et al., 2016). However, several studies explicitly consider risk-aversion and their findings are described in the following.

As the electricity market reacts very sensitively to the level of risk aversion of the investors (e.g., Petitet et al., 2017), risk aversion causes the market to deviate from the installed capacity in the welfare optimal case (Winzer, 2013). Given the high social costs of capacity shortages and the uncertainty associated with the development of the electricity market, de Vries and Heijnen (2008) point out that the socially optimal level of generation capacity is higher than the theoretical optimum under perfect foresight. Moreover, Ehrenmann and Smeers (2011) find that in an EOM with a low price cap as well as in a CRM, uncertainty and risk aversion aggravates the generation adequacy problem, which in turn can dramatically increase the costs for end consumers. This is caused by delaying investments and shifting from high- to less-capital intensive investments. Similar findings are made by de Vries and Heijnen (2008) who state that CRMs can contribute to a more balanced generation portfolio by reducing the investment risk and, thus, counteracting the tendency of risk-averse investors towards low-capital technologies with short lead times. Fan et al. (2012) conclude that a CRM could prove to be beneficial as their findings indicate that risk aversion tempts investors to adopt the decisions that would have been taken if the worst-case scenario had materialized thereby avoiding investments in new uncertain technologies, e.g., concentrating solar power.

As part of an analytical analysis, Neuhoff and de Vries (2004) investigate the influence of weather- and demand-related uncertainty and risk aversion on the investment decisions of electricity generators having a unique technology at their disposal. Their results indicate that an EOM will provide insufficient investment incentives to ensure generation adequacy if investors or final consumers are risk-averse and unable to hedge their portfolio adequately via long-term contracts. de Maere d'Aertrycke et al. (2017) analyze the effect of two reference long-term contracts as well as the impact of a long-term forward capacity market and find that even though long-term contracts and a highly calibrated forward capacity market are able to improve welfare substantially, they also entail severe drawbacks. In all cases, traded volumes need to be far higher than in current energy markets as illiquidity can severely impair the effectiveness of these instruments and increase the risk premiums demanded by investors by about 10%. Besides, Willems and Morbee (2010) find that the liquid trade of derivatives provides sufficient incentives for a risk-averse producer to invest. Here, forward contracts mainly lead to an increase of investments in base-load capacity, and if also options are offered in the market, the investments in peak-load plants will increase as well. In some cases, if no suitable financial substitutes are traded for an investment option, however, overinvestment can occur.

Furthermore, Abani et al. (2016) state that considering the risk aversion of the decision makers involved is crucial when comparing different market designs. Their results demonstrate that when comparing the implementation of a central buyer mechanism and an EOM, the difference in shortage situations increases if investors are regarded as risk-averse instead of risk-neutral. In a more recent study, Abani et al. (2018) investigate an EOM and two CRMs (central buyer, strategic reserve) and find that in case of risk aversion, investors tend to extend the lifetime of existing generation capacity instead of building new, which in turn leads to higher total generation costs. Similarly, Petitet et al. (2017) show that in an EOM the amount of economically motivated decommissions of thermal plants or the level of scarcity prices is dependent on the risk aversion of the investors. However, CRMs are comparatively insensitive to the risk aversion of the market participants due to the fact that the required quantity is directly specified by the regulator and the risk aversion of the market participants is reflected in their bids affecting the total costs. This proves to be a substantial benefit for policy makers as market developments are more predictable.

4.4. Effects of investment cycles

Although fixed or variable capacity payments are unable to abolish investment cycles, they reduce the cycles' amplitude resulting in a high level of market price stability and a reasonable reserve margin (Assili et al., 2008; Ford, 1999). Moreover, Cepeda and Finon (2011) demonstrate that investment cycles can effectively be dampened by capacity obligations, in turn leading to smoother annual average electricity prices and higher reliability.

In case of a strategic reserve, Bhagwat et al. (2016a) and de Sisternes and Parsons (2016) find that investment cycles, e.g., caused by uncertainty about the future electricity demand, may still occur. Similarly, Hary et al. (2016) show that although underinvestment is avoided, overinvestment is not prevented by a strategic reserve as the regulator cannot influence the perceived value of additional generation capacity or enforce investors to postpone their decisions. However, a central buyer mechanism is able to positively influence investor behavior and, therefore, reduce the occurrences of under- and overinvestment. Moreover, Bhagwat et al. (2017a) find that in case of a forward capacity market boom and bust cycles may still occur if the electricity demand drops sharply, consequently leading to the decline of capacity prices and multiple decommissions of existing capacity so that only a high reserve margin initially set by the regulator prevents loss of load situations. In reaction to the resulting shortage, capacity prices spike again, and investments are made. Similarly, Bhagwat et al. (2017b) state that in a forward capacity market investment cycles still exist, but in comparison with an EOM, they extend over longer periods and feature smaller amplitudes. Also, by decreasing the investor risk and reliability risk for consumers, forward reliability markets can prevent boom-bust cycles (Cramton and Stoft, 2008).

Beyond, Franco et al. (2015) claim that the implementation of a CRM together with long-term contracts for low-carbon generators prevent any fluctuations in the price and reserve margin in the British electricity market. However, sudden shocks seem not to be taken into account in the analysis. Also, Hasani and Hosseini (2011) state that a hybrid CRM (periodically using capacity payments and a forward capacity market) is able to prevent over- and underinvestment efficiently.

In summary, the presented results support the assertion that investment cycles, which are caused by uncertainties, e.g., regarding the demand growth, can be damped by CRMs (de Vries and Heijnen, 2008). However, most often they cannot be completely prevented and a sufficient reserve margin mainly depending on market uncertainties needs to be determined by the regulator.

4.5. Efficiency and market welfare of capacity remuneration mechanisms

As a strategic reserve allows the use of all contracted capacities only for a single purpose, inevitably inefficiencies occur, and additional investments are needed to replace the lost flexibility (Höschle et al., 2017). Further, the dispatch of the strategic reserve at any other value than the VoLL can reduce the market welfare analogous to the price caps in the EOM (Finon et al., 2008). Besides, a strategic reserve does not appear to improve the market stability or increase the expected economic surplus in the long term (Lara-Arango et al., 2017a). Therefore, it seems advisable to use a strategic reserve as a short-term solution and replace it by other mechanisms in the long term. However, the distributional effects of a strategic reserve seem to be relatively small (Neuhoff et al., 2016).

Creti and Fabra (2007) state that in order for a CRM to maximize social welfare, gains from reducing load loss situations must exceed the additional capacity costs and the secured capacity procured should be equal to the peak demand. Furthermore, they argue that the price limit should be defined as the opportunity costs of providing full capacity commitment as different parameterizations would lead to a reduction in welfare through either overcapacities or scarcity prices. In a case study for Great Britain, Hach et al. (2016) find that through deliberate overcapacity and, thereby, avoiding extreme prices and lost load occasions, a central buyer mechanism can effectively lower the total bill of generation. Similar results are obtained by Bhagwat et al. (2017b), Höschle et al. (2017), and Keles et al. (2016) in case studies of the electricity market in Great Britain, Belgium, and Germany, respectively. However, Schwenen (2014) argues that in a framework with two firms, in equilibrium capacity prices are non-competitive due to capacity constraints and signals for the entry of new firms are likely being distorted by the regulator.

By employing an analytical model, Briggs and Kleit (2013) find that capacity payments for base-load power plants are never optimal. In the short term, capacity payments will cause prices to fall and competitive base-load power plants to be suppressed, and in the long term incentives to invest in peak load power plants and generation adequacy will decline. Also, the positive short-term price effect might be lower than theoretically expected (Genoese et al., 2012), and the payments might even fail to ensure an adequate reserve margin (Park et al., 2007; Kim and Kim, 2012). Likewise, Milstein and Tishler (2012) find that targeted capacity payments for the peaking technology, which account for 25% of the associated capacity costs, only increase the social welfare by 0.02%. Furthermore, Bajo-Buenestado (2017) show that the benefit of capacity payments depends on the intensity of competition and is less if the market is controlled by dominant companies as in many real-world markets. Joskow and Tirole (2007) state that if market power is present in a market with more than two states of nature, i.e., peak and off-peak, capacity payments are an insufficient instrument.

As results from the literature are not always coherent and often only applicable for specific cases, the question of which CRM is most efficient remains open. For example, often a central buyer mechanism seems to yield significantly better results than a strategic reserve (Hary et al., 2016; Keles et al., 2016; Höschle et al., 2017), but sometimes the results are ambiguous (Traber, 2017). Most likely, this can be attributed to the fact that the results depend among other things on the existing generation structure and their development in time (Batlle and Rodilla, 2010; Traber, 2017) as well as the taken assumptions, e.g., the consideration of uncertainty (Lara-Arango et al., 2017b) or the risk aversion of investors (Petitet et al., 2017). Nevertheless, there seems to be a consensus in the literature that market-based mechanisms are usually advantageous compared to interventionist mechanisms, e.g., capacity payments (Batlle and Rodilla, 2010; Mohamed Haikel, 2011; Lara-Arango et al., 2017a).

4.6. Influence on neighboring markets through cross-border effects

One of the difficulties encountered in the study of cross-border effects is the large number of influence factors such as the regarded markets, generation technologies, different interconnector capacities or asymmetric market sizes. Furthermore, cross-border effects are strongly influenced by competition between market participants and the possibility of exerting market power (Meyer and Gore, 2015). Thus, deriving common conclusions is extremely challenging.

One major short-term cross-border effect is the occurrence of market distortions if a CRM does not adequately consider generation capacities abroad. In this case, through additional capacity payments, domestic producers gain a competitive edge over foreign producers (Hawker et al., 2017). However, the primary focus of the scientific research is on long-term effects, i.e., the development of generation adequacy, distributive effects, and price effects, as CRMs will mainly drive investment decisions (e.g., Ozdemir et al., 2013). For example, with the help of an agent-based electricity market model Bhagwat et al. (2014, 2017c) find that in case of a forward capacity market and strategic reserve in two neighboring markets, the forward capacity market appears to have a negative spillover effect on the strategic reserve. However, a neighboring EOM does not limit the ability of a national forward capacity market or strategic reserve to achieve its objectives. Indeed, vice versa, two effects can be observed. On the one hand, the neighboring EOM operates as a free-rider and benefits from the additional foreign generation capacities. On the other hand, the dependence of the EOM on imports increases, which can be particularly disadvantageous in critical situations. Similar results are obtained by Ochoa and Gore (2015), who show in a case study for the Finnish and Russian electricity market, that if Russian imports were reliably available, abolishing Finland's strategic reserve could lead to lower costs for Finnish consumers. However, as this is not the case, the advantages of maintaining a strategic reserve outweigh the disadvantages, and the interconnection expansion should be avoided—instead, the development of local capacities should be given preference. Furthermore, Cepeda and Finon (2011) find that in the long term an EOM will only marginally benefit from a CRM in an adjacent market. Also, for the EOM, the unilateral introduction of a price cap leads to a reduced level of security of supply as suppliers prefer to offer their generation capacity in neighboring markets. Moreover, by using a simulation model to investigate the unilateral introduction of a strategic reserve and reliability options in a two-country case, Meyer and Gore (2015) show that the overall cross-border welfare effect is most likely negative.

In addition, it can be concluded that the introduction of a CRM in a neighboring country creates considerable pressure on the national regulator to introduce a dedicated CRM as a safeguard against possibly harmful consequences (Bhagwat et al., 2017c; Gore et al., 2016). Therefore, Hawker et al. (2017) are advocating the cross-border coordination of CRMs to provide sufficient new investment in generation and transmission capacities and Neuhoff et al. (2016) claim that a coordinated strategic reserve in Europe should be feasible and, among other things, would have the following advantages: On the one hand, capacities from abroad could be used at times of maximum stress and, on the other hand, the joint calculation of the reserve volume would reduce the required quantity as individual demand peaks usually occur at different times. Furthermore, with the possible expansion of cross-border capacity and the associated strong influence on prices (Osorio and van Ackere, 2016), a coordinated approach seems to be increasingly advantageous. However, solving the dilemma of choosing between a coordinated or national approach is complex. Especially when time is a critical factor, a co-ordinated solution might not be implemented early enough due to the increased need for coordination (de Vries, 2007).

4.7. Impact of a high share of intermittent renewables

One of the central questions associated with the rapid expansion of RES is whether they exacerbate the adequacy problem. First of all, Cramton et al. (2013) point out that price caps present in most EOMs are unaffected as the level is neither lowered nor increased by RES. Nonetheless, increasing low price caps might become more relevant as large investments in peak-load generation capacity are likely to be required as a backup for intermittent RES. However, this could be prevented by a price cap set too low (Cepeda and Finon, 2013; Jaehnert and Doorman, 2014). As RES, due to their marginal costs close to zero, can be regarded as a price-inelastic demand—with the exception of situations where the prices are negative—Cramton et al. (2013) argue that RES increase the volatility of and the uncertainty about the demand and market prices and, thereby, exacerbate the adequacy problem. Similarly, Newbery (2017) claims that a high share of intermittent RES, on the one hand, and the uncertainty about the development of the carbon allowances price, on the other hand, likely require long-term capacity contracts—beyond a horizon of three to four years—for ensuring reliability efficiently.

Jaehnert and Doorman (2014) investigate the development of system adequacy and find that the capacity reserve margins decrease with an increasing share of RES leading to several occurrences of load curtailment. Also, the merit-order effect caused by large-scale employment of wind energy is more relevant in an EOM than in a market with a CRM, where thermal generation capacities are better able to recover the fixed costs of their investment (Cepeda and Finon, 2013). However, in reverse, a CRM that only takes into account the secured available capacity can have a negative impact on the market-driven development of wind power. Still, in a world with 100% renewable energy, Weiss et al. (2017) argue that an EOM can adequately function if market prices take into account the opportunity costs of flexible resources. However, in such a scenario, RES probably still require a dedicated funding mechanism. Besides, a CRM might be necessary to minimize the associated risk of underinvestment in flexible capacities.

4.8. Incentives for flexible resources

As with increasing shares of RES supply fluctuations in the electricity market become more frequent, flexible resources are required (Nicolosi, 2010; Grave et al., 2012), e.g., demand-side management or short-term and long-term storage options that have not yet been sufficiently remunerated in the market design to date (Cepeda and Finon, 2013; Joskow, 2008). An adequate market design needs to pay sufficient attention to flexible resources in order to fully capitalize on their potential (Neuhoff et al., 2016; Weiss et al., 2017). Although flexible resources do not automatically guarantee a reliable level of investment, they ensure reliability under different levels of installed generation capacity and induce an efficient electricity dispatch (Cramton and Stoft, 2005).

Whereas the concept of firm or reliable capacity is already well defined and, moreover, constant, regardless of how the future electricity system develops, the term flexibility is still vague and furthermore has a critical temporal dependency. Sometimes flexibility is required for a few seconds or minutes, but other times for several hours or even days and usually the most suitable options for short-term flexibility are not coherent with those for long-term flexibility (Hogan, 2017). In order to reliably determine the need for and value of flexibility, it is best to compare the value of energy in scarcity with that in abundance situations, which depends on the current state of the electricity system.

In a well-functioning EOM, market participants are exposed to extremely high price signals at times of scarcity or negative prices in times of oversupply, thus, creating incentives for long-term investments in storage technologies as well as incentives for consumers to directly react to price developments (e.g., Hu et al., 2017). For this reason, EOMs can especially benefit from increased flexibility, e.g., through demand response, as the market is then able to react to extreme price peaks and consumers are no longer exposed to the excessive market power of suppliers, thereby reducing the need for regulatory price caps (Schwenen, 2014). Yet, if the market design is severely different, e.g., by a forward capacity market, price spikes will decrease in frequency and amplitude, thus, diminishing the value of flexible resources (Hogan, 2017). Auer and Haas (2016) even argue that the introduction of capacity payments ruins market competition, meaning that flexibility options would not be exploited, thus, leaving their development only in the hands of the regulator. Even though these theoretical findings pose a clear disadvantage for CRMs, practical experiences indicate that decision makers seem to be aware of this issue as, for example in the US, CRMs explicitly include financial support for flexible resources, which in turn lead to a rise of these capacities (Rious et al., 2015).

5. Conclusions and policy implications

Electricity markets are in many respects similar to most other markets; however, they require a specific regulatory framework due to a number of peculiarities such as the physical characteristics of the commodity electricity, an inelastic volatile demand and the missing-money problem. In combination with the transformation from a centralized system with primarily fossil-fuel power plants to a decentralized system with a high share of renewable energies and the sharp decline in electricity prices, concerns among policy makers about generation adequacy have grown and led to the implementation of various CRMs. However, the necessity of CRMs remains the subject of ongoing discussion, and it is often argued that an EOM already offers an efficient solution whereas CRMs tend to be inefficient. To better grasp the arguments of both sides, an up-to-date overview of the debate was given. Subsequently, a classification of the different mechanisms was shown, the current status of real-world implementations was presented, and initial experiences were discussed. While only two types of mechanisms (central buyer and de-central obligations) are used in the United States, the situation is much more diverse in Europe due to uncoordinated national approaches.

The findings in the literature reveal that CRMs can improve generation adequacy, but also bring along new challenges. One major advantage of CRMs is that they are able to effectively reduce or even to solve different problems of existing markets. For example, fluctuations caused by investment cycles can be dampened—even though usually not fully abolished—and, thereby, extreme scarcity events can be prevented. Also, the adverse effects of the abuse of market power can be mitigated, and some mechanisms, for example, a forward capacity market, are able to solve the missing money problem. Also, CRMs usually make market developments less dependent on the risk profile of the investors, thereby, making them more predictable and reducing deviations from the long-term optimum that can be caused by risk-averse decision-makers.

Determining the optimal market design, however, remains an ongoing challenge. As the adequate design depends on a variety of factors such as the existing capacity mix and demand characteristics, no general advantageousness of single mechanisms could be determined so far. For example, often a central buyer mechanism seems to yield significantly better results than a strategic reserve, which is inefficient by design as contracted capacities are used for a single purpose only. However, in exceptional cases the results are ambiguous. Nevertheless, it can be concluded that market-based mechanisms, e.g., a forward capacity market, are usually advantageous compared to interventionist mechanisms such as capacity payments.

Furthermore, the implementation of a CRM can lead to market distortions, e.g., through cross-border effects. Even though cross-border impacts are diverse and the results in the literature are sometimes conflicting, there seems to be a consensus that a one-sided implementation of CRMs leads to negative spillover effects on a neighboring market without a CRM. This increases the pressure in the neighbouring market either to introduce a domestic mechanism or to pursue a coordinated approach. Compared to an EOM, the value of flexible resources is diminished in the presence of a CRM. Therefore, their expansion is largely independent of market forces and left in the hands of the regulator.

Even though a large number of studies has already been carried out, the comparability of the results is often limited and, thus, it is difficult to select the best mechanism to implement. It would therefore be helpful if common criteria or specific scenarios are used to evaluate different market designs. Furthermore, especially the efficiency of the mechanism is all too often neglected. Also, the behavior of market participants as learning, risk-averse agents that interact with each other often does not seem to be adequately addressed and rarely verified by studies or experiments. However, as the investors' risk profile can directly influence the results and the relative advantageousness of different CRM, it would thus be advisable to explicitly consider risk aversion.

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Appendix A. Details on selected real-world implementations of CRMs

In the following, some details on real-world implementations of CRMs additional to the information already presented in Section 3.2 is provided. Not all mechanisms active around the world are described, but the focus rather lies on the mechanisms currently active in Europe as well as the different central buyer implementations in the United States, which is the most common type of CRM used in Northern America.

A.1. Strategic reserve (Belgium/Sweden)

Both Belgium (since 2014) and Sweden (since 2003) have set up strategic reserves to support demand peaks during the winter season (Elia Group, 2015; Svenska Kraftnät, 2016). In Belgium, the capacity is procured through a competitive tendering process, in which market participants intending to shut down capacity are obliged to participate (Hancher et al., 2015). Thus far (until October 2017), the reserve has not been activated (Elia Group, 2017a,b). Contrary, the Swedish reserve has already been used a few times, with yearly costs in 2013 and 2014 amounting to about 14 respectively 13 million Euro. This is significantly lower than the estimated costs of a shortage situation (90 million Euro) (Cejie, 2015).

A.2. Central buyer (United Kingdom/US – ISO-NE/US – MISO/US – NYISO/US – PJM)

In order to maintain generation adequacy, in 2014, the United Kingdom introduced central capacity auctions with the first delivery to take place in winter 2018/2019. The capacity payments are determined via descending clock auctions four years (T−4) and one year (T−1) before the respective delivery period. Despite the technology-neutral approach, the incentives for demand response (0.4–2.5% of the contracted capacity) and new investments (4.2–6.5%) have been limited in the first three T−4 auctions (Office of Gas and Electricity Markets, 2015, 2016, 2017). However, in the latest T−4 auction (2016), existing and new storage capacities won contracts for the first time, accounting for around 6% of the contracted capacity (Office of Gas and Electricity Markets, 2017).

ISO-NE and NYISO were the first market areas in the United States to use central capacity auctions as early as 1998 and 1999, respectively. A few years later, PJM, in 2007, and MISO, in 2009, also introduced such mechanisms in their market areas. All four implementations have in common that capacity is procured in multiple zones in order to account for intra-zonal transmission constraints (Byers et al., 2018). The auction design, however, differs among the mechanisms. While uniform pricing is applied in PJM and NYISO, ISO-NE and MISO use descending clock auctions (Bhagwat et al., 2016b). Moreover, ISO-NE is the only mechanism bundling capacity options with financial call options (similarly to the reliability options model proposed by Vazquez et al., 2002), while NYISO, PJM and MISO conduct forward capacity markets (Byers et al., 2018). An overview of the historical capacity prices of the four markets is provided in Byers et al. (2018), although the authors state that clear trends could not be identified due to the limited amount of data points as well as differences and changes in markets rules.

A.3. De-central obligation (France)

In 2015, France implemented a de-central obligation with the first delivery to take place in 2017. All load-serving entities are obliged to hold a certain number of certificates reflecting the share of electricity consumption of their consumers during times of peak demand, e.g., when extreme winter conditions occur. Certificates can be obtained by certifying own generation and demand-side capacities, which afterward can be traded in a market or using bilateral arrangements (European Commission, 2016a). Within Europe, the French mechanism is the first to explicitly include and remunerate foreign capacities in neighboring countries, however, limited by the expected capacity of the respective interconnectors at peak times (European Commission, 2016c). In the first three auctions, a total volume of 34 GW has been contracted with all auctions resulting in capacity prices close to 10,000 EUR/MW (EPEX SPOT, 2017a,b,c).

A.4. Targeted capacity payments (Spain)

The Spanish mechanism, initially introduced in 1997, was substantially redesigned in 2007 to adapt to the then valid European law (Hancher et al., 2015). The new system was designed to reduce investment risk by offering fixed capacity payments for a period of ten years (investment incentive). Securing generation adequacy in the medium-term (availability service) through contracts of one year or less with peak-load power plants was the other main target. However, to estimate the required generation capacity and long-term capacity payments was made significantly more difficult by unforeseen events like the economic crisis and the resulting low electricity demand, which together led to the reduction of long-term capacity payments for investments in 2012 and ultimately to the abolition of the investment incentive in 2013. Nonetheless, the availability service is still active.

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