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By Andreas Bublitz, Dogan Keles, Florian Zimmermann, Christoph Fraunholz, Wolf Fichtner

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Andreas Bublitz*, Dogan Keles, Florian Zimmermann,
Christoph Fraunholz, Wolf Fichtner

Chair of Energy Economics, Institute for Industrial Production (IIP),
Karlsruhe Institute of Technology (KIT),
Hertzstraße 16, 76187 Karlsruhe, Germany
*Corresponding author. *Email address*: andreas.bublitz@kit.edu
Tel.:+49 721 608 44544

Electricity markets are currently going through a phase of agitating transition, which is mainly characterized by an increasing share of fluctuating renewable energies. Among policy makers, this has led to growing concerns about generation adequacy and often to the introduction of different capacity remuneration mechanisms to generate less volatile sources of income for investors and, thereby, guaranteeing generation adequacy. However, these mechanisms entail new challenges regarding the best design to avoid any adverse effects. At the same time, it is disputed whether capacity remuneration mechanisms are indeed needed or whether an energy-only market is sufficient. Therefore, after discussing the peculiarities of the electricity markets, which are the starting point of the unique regulatory framework, an up-to-date overview of the debate on the need for capacity remuneration mechanisms is provided. In addition, the current status of capacity remuneration mechanisms in Europe is shown, and initial experience is presented. Furthermore, this article reflects the current state of research about capacity remuneration mechanisms in regards to, for example, cross-border effects, investment cycles or market power. In a conclusive summary, shortcomings of the existing research works and open questions that need to be addressed in future works are discussed.

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

Andreas Bublitz[a,*], Dogan Keles[a], Florian Zimmermann[a], Christoph Fraunholz[a], Wolf Fichtner[a]

[a] *Karlsruhe Institute of Technology, Chair of Energy Economics,*
*Hertzstraße 16, D-76187 Karlsruhe*

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## Abstract

Electricity markets are currently going through a phase of agitating transition, which is mainly characterized by an increasing share of fluctuating renewable energies. Among policy makers, this has led to growing concerns about generation adequacy and often to the introduction of different capacity remuneration mechanisms to generate less volatile sources of income for investors and, thereby, guaranteeing generation adequacy. However, these mechanisms entail new challenges regarding the best design to avoid any adverse effects. At the same time, it is disputed whether capacity remuneration mechanisms are indeed needed or whether an energy-only market is sufficient. Therefore, after discussing the peculiarities of the electricity markets, which are the starting point of the unique regulatory framework, an up-to-date overview of the debate on the need for capacity remuneration mechanisms is provided. In addition, the current status of capacity remuneration mechanisms in Europe is shown, and initial experience is presented. Furthermore, this article reflects the current state of research about capacity remuneration mechanisms in regards to, for example, cross-border effects, investment cycles or market power. In a conclusive summary, shortcomings of the existing research works and open questions that need to be addressed in future works are discussed.

*Keywords:* Electricity market, Market design, Generation adequacy,

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[*] Corresponding author
*Email address:* `andreas.bublitz@kit.edu` (Andreas Bublitz)

Capacity markets, Capacity remuneration mechanisms

# 1. Introduction

A reliable electricity system remains one of the main objectives of energy market regulators, especially after liberalizing the sector, whereas market participants are now responsible for investments in supply capacities. 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, as experienced in Europe, generating adequate price signals becomes more and more challenging during the energy transition phase, which is mainly shaped by three factors: the expansion of renewable energies, the reduction of carbon emissions from fossil power production and the European market integration. In this transition period, electricity prices have strongly decreased. Besides other factors, the rising feed-in from volatile renewable energy sources (RES) with marginal generation costs near zero has strongly contributed to this development (Kallabis et al., 2016; Bublitz et al., 2017).

Furthermore, a reliable electricity system needs to be reached at reasonable costs for end consumers while at the same time greenhouse gases and other emissions are limited to a certain level. These three targets of electricity market regulation—reliability, sustainability, and affordability—are commonly named the energy trilemma (Ang et al., 2015; Hawker et al., 2017), as an efficient balance between these oftentimes conflicting targets is difficult to find and achievable only by accepting trade-offs. However, in practice it looks as if reliability is the trump card in the debate, where the objective is to maintain the high level of security of supply reached in industrialized economies without restrictions (European Commission, 2006; BMWi, 2017), leaving the relative weights given to sustainability and affordability the only thing that remains to be decided (Newbery, 2016b). The challenging trade-off between reaching the set targets of sustainability and affordability is usually made by pricing emissions through dedicated cap and trade schemes, such as the EU Emissions Trading Scheme.

Initially, several exchanges and pool markets were established, on which especially energy quantities were traded forming the energy-only market (EOM). The short-term objective of the EOM is to allocate resources optimally (e.g., Gan and Litvinov, 2003) and to ensure a cost-minimal supply with prices reflecting marginal costs of electricity production, whereas its task in the long-term is to guarantee the demand-supply adequacy by generating investment signals provided by peaking prices at scarcity times (Stoft, 2002; Hogan, 2005). However, motivated by the missing money problem, there is still an ongoing discussion about the ability of the EOM to fulfill these objectives in general (Cramton et al., 2013; Joskow, 2008). In the recent years, the discussion became even stronger due to the expansion of RES electricity generation (Hildmann et al., 2015).

Due to the already large and still quickly growing number of studies on capacity remuneration mechanisms (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, due to 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 review documents on theoretical concepts of market design and CRMs as wells as a review of mechanisms implemented in some countries, to the knowledge of the authors, there still does not exist any comprehensive review on the discussion about and the assessment of different design options for the electricity market in the literature.

Hence, this article aims to guide newcomers and interested researchers through the complex field of electricity market design by providing a broad and up-to-date survey starting with the discussion about the necessity of alternatives to the EOM (Section 2). 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, implemented market design options in different European countries (Section 3) are discussed, as many changes to existing market designs could be observed in

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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 3).

Europe in the last years. The theoretical perspective considers the assessment of the impacts of different design options (Section 4) on regulatory targets, such as generation adequacy and RES integration. The review of the latter perspective will be 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 on-going debate about securing generation adequacy

The electricity sector is characterized by a particular set of features distinguishing it from other sectors often viewed as unique and problematic as these features act as barriers complicating the formation of an efficient market equilibrium between demand and supply in the short term and, even more so, in the long term (Borenstein, 2002; Joskow and Tirole, 2007). These barriers mainly originate from the physical properties of the electricity system as well as specific market properties and have raised growing concerns regarding generation adequacy[2].

In the recent years, especially European policymakers are worried whether the existing markets will generate sufficient price signals to incentivize investments in generation capacity and to ensure security of supply (Léautier, 2016). However, the question remains whether these concerns are justified and if the already introduced instruments are effective and efficient. Therefore, after describing the long-standing barriers (Section 2.1) and more recent challenges (Section 2.2) that lead to numerous adaptations of the existing market design, the current state of the debate on market design is presented (Section 2.3).

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[2] Generation adequacy has a long-term orientation and is defined as the ability of an electricity system to provide sufficient capacities to satisfy the base as well as the peak demand at all times (European Commission, 2017a). Furthermore, generation adequacy also includes the ability to provide sufficient flexibility to follow sharp load changes (Brijs et al., 2016).

## 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. Other reasons, which are briefly discussed in the following, stem from the market organization itself.

One 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 Figure 1a). For this reason, Lynch and Devine (2017)

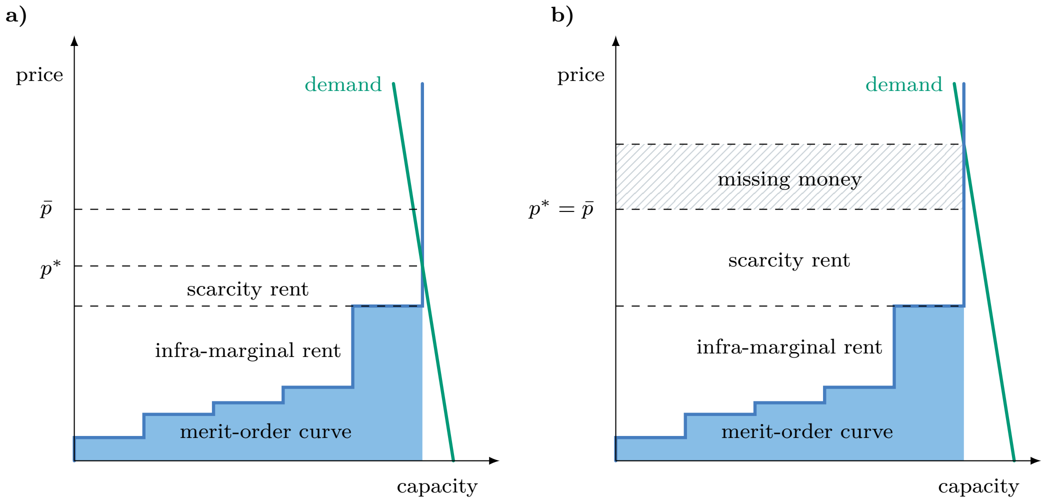

Figure 1: Price setting in scarcity situations. a) The equilibrium price $p^*$ is below the price cap $\bar{p}$ and an efficient outcome is achieved. b) The equilibrium price $p^*$ is above the price cap $\bar{p}$, however, as the resulting price $p^*$ is equal to the price cap, welfare loses occur (missing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

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.

Price caps in spot markets[3] 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)[4] 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 Figure 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[5]. 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

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[3] Whereas in some countries price caps are set directly by the regulator and are legally binding, e.g., Texas ERCOT day-ahead market 9000 USD/MWh (Public Utility Commission of Texas [PUC], 2012), in other countries only a technical limit exists. For example, the limit for the French day-ahead market at the EPEX SPOT is 3000 EUR/MWh (EPEX SPOT, 2018), and for the Spanish daily market at the OMIE the limit is 180 EUR/MWh (OMI-Polo Español [OMIE], 2018). However, for over-the-counter trading, a higher price can be specified.

[4] 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).

[5] 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).

market instead of missing money (Newbery, 1989).

## 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. 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[6]. Based on the regionally varying policy targets, for example, the ambitious EU-wide target of attaining a share of 20 % renewable energy in the final energy consumption by 2020, a further expansion of PV and wind power capacities is expected. 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 Figure 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

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[6] 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)

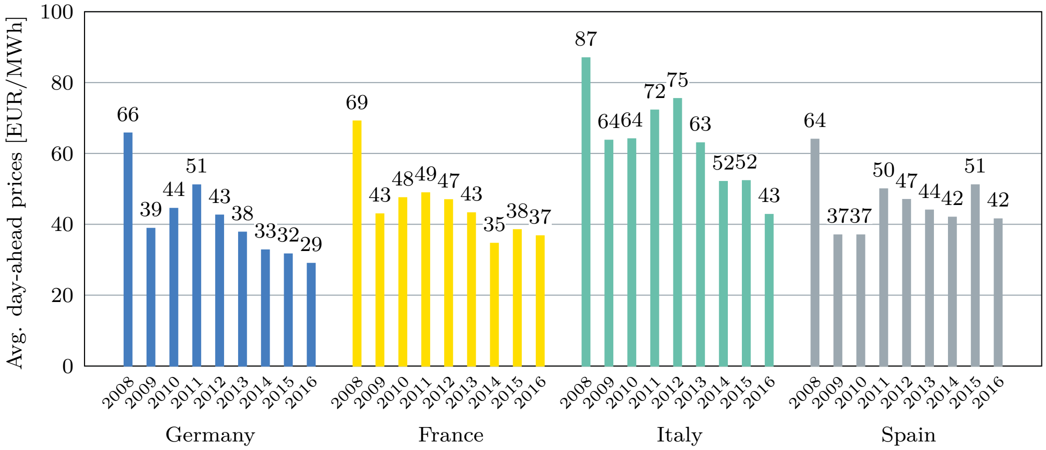

Figure 2: The development of day-ahead prices in major European markets in the last years shows a clear downward trend, apart from the years 2009 and 2010, which can be regarded as outliers due to the impact of the global economic crisis. The comparison of the figures for 2008 and 2016 indicates a decline 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).

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 (VDE, 2012). 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,

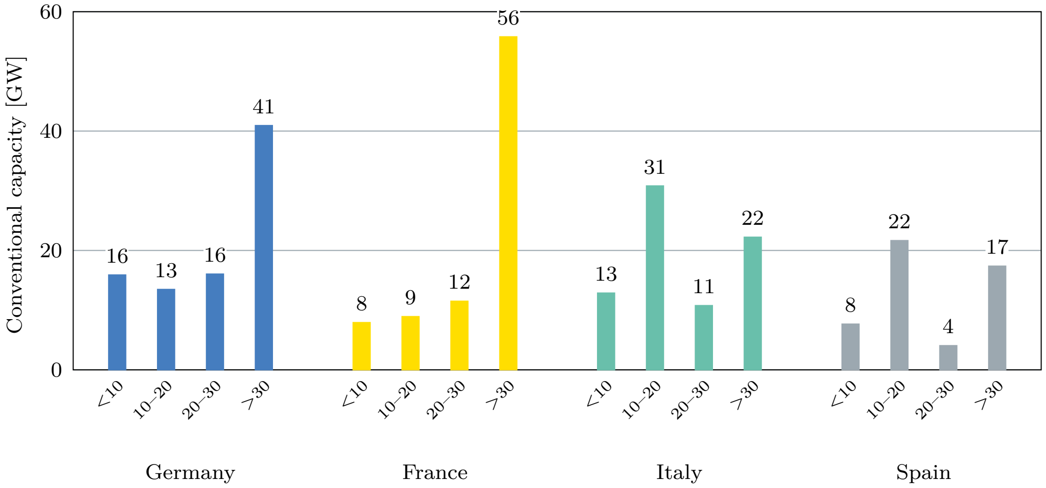

Figure 3: Operating years since the beginning of operation of installed conventional capacities. While large capacities in Germany and France are operating for more than 30 years, in Italy and Spain, the installed capacity of the power plant fleet in the category 10–20 years is higher than the installed capacity in the category of more than 30 operating years.

the national or supranational level. Owing to the aging power plant fleet (see Figure 3), there does not only seem to be a need for maintaining current conventional capacities but also to invest into new units as a large share of the existing units reaches the limits of their technical lifetime.

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. Whereas the nuclear phase-out contradicts the targets of lowering the carbon emissions, the discussions about a phase-out of hard coal and lignite-fired power plants are in accordance (e.g., Knopf et al., 2014; Bruninx et al., 2013). 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). In conclusion, it can be said that investors are exposed to major uncertainties as a result of the described developments, which are further exacerbated, e.g., by volatile energy prices, the growth of e-mobility and the transfer of clean electricity into other sectors (sector coupling). Hence, the question arises whether the required investments in conventional capacities can be handled within the existing market design under the present uncertainties.

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

The scientific discussion on the necessity as well as the design of CRMs arose in the 1990s, a decade that marks the beginning of the restructuring[7] of electricity markets in many countries around the world (e.g., Hogan, 2002), where the first approach chosen often was to rely on the scarcity pricing of energy and, thus, EOMs were established (Sioshansi and Pfaffenberger, 2006).

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

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[7] In this context, in comparison with deregulation, restructuring is the better fitting term as the electricity sector serves as a prominent example, where the replacement of a monopoly with competitive market structures does not lead to less extensive, only to a different regulatory framework (Jamasb and Pollitt, 2005; Newbery, 2005; Vogel, 1998).

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, an excessive risk of load curtailment and high costs for consumers (Réseau de transport d'électricité, 2014a). Moreover, de Vries and Hakvoort (2004) argues that even long-term contracts do not provide a solution as they offer consumers the opportunity to free-ride.[8] 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 under to overinvestment, investors have strong asymmetric incentives and, thus, tend to under- 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

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[8] 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.

of political will to allow for unconstrained electricity prices[9] and periodic shortages (Besser et al., 2002; Hogan, 2005).

However, often it is argued that CRM are inefficient and according to Oren (2000) the least desirable instrument or according to Hogan (2017) only the third best option to ensuring reliability—with the first option being the elimination of the leading underlying causes, e.g., incentivize a flexible demand[10], and the second-best option being an administrative price curve for the usage of reserve energy. Wolak (2004) even claims that the rationale for CRM 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.

Summing up, whether the EOM is able to guarantee generation adequacy is still discussed intensively. It is, however, 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, i.e., the physical properties of the product electricity, the required high level of security of supply, the lack of reactivity to real-time prices, and the missing possibility of individual consumer rationing (Joskow and Tirole, 2007). Moreover, the utilization of real-world experience to draw general conclusions is only 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

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[9] Although price caps are frequently mentioned as a source of the missing money problem, the data on market prices do seem to tell a different story, e.g., since the establishment of the EEX in 2000, the upper price limit of the German spot market (3000 EUR/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), and, thus, it seems rather far-fetched that in the cases price caps are the primary cause of the missing money problem. On the contrary, in France, the price cap has been hit several times, most recently on 19 October 2009, although, the main reason arguably lies in a coordination failure, i.e., a difference of 7000 MW between the consumption and available capacity forecasts resulting in less available capacity on the market (French Energy Regulatory Commission, 2009).

[10] 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).

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 over-capacities. Even though no agreement is found in the literature on the fundamental need for CRM, recent developments have to such an extent cast doubt on the effectiveness of an EOM that in many countries politicians deem the introduction of such mechanisms necessary.

# 3. Market design options and current status of implementation in Europe

In this section, an overview of several CRMs currently implemented or in the planning stage in European countries is presented. After briefly introducing a general classification and the basic principles of different generic mechanisms, further details of the real-world examples in some of the most relevant European countries are described. Based on the presented findings, conclusions from the implemented mechanisms are drawn with a focus on the ongoing efforts of creating a single European electricity market.

## 3.1. Generic market design options

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 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.

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 |

## 3.2. Current status of implementation

In the European Union, the member states themselves decide on whether, when, which and how to implement a CRM (Bhagwat et al., 2017c). Although according to Petitet et al. (2017), the EOM remains the European Commission's preferred approach to trigger new investments and provide signals for decommissioning in case of overcapacities, several European countries have either already implemented CRMs or are currently in the process of evaluating tailored solutions (for an overview see Table 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 the currently active mechanisms are described in the following paragraphs.

Table 3: Overview of implemented CRMs in Europe. Sources: Cejie (2015); Deutscher Bundestag (2016); EirGrid plc and SONI Limited (2017); European Commission (2014, 2016a,b,c, 2017c,b); Hancher et al. (2015); Patrian (2017); Roques et al. (2017); Single Electricity Market Committee (2016); Svenska Kraftnät (2016).

| **Type** | **Country** | **Administrator** | | **Eligible technologies** | | | | **Status**[1] | |
|---|---|---|---|---|---|---|---|---|---|
| | | **TSO** | **RA** | **TPP** | **IRE** | **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 | 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) |
| De-central obligation | France | x | | x | x | x | x | active | (2015) |
| Targeted capacity payment | Spain[5] | x | | x | | | | active | (2007) |

*Abbreviations:* DSM—demand side management, IC—interconnector, IRE—intermittent renewable energies, RA—regulatory authority, TPP—thermal power plant, TSO—transmission system operator

[1] Year of (planned) implementation in parentheses. [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 2.70 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.

### 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).

### Central buyer (United Kingdom)

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).

### 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). 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).

### 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.

## 3.3. Harmonization of the European electricity market

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 and Figure 4a). Yet, the uncoordinated implementation of these local mechanisms might lead to numerous potentially adverse cross-border effects, which are described in detail in Section 4.6.

Bearing in mind the additional mechanisms that are likely to be established within the next few years (see Figure 4b), these potential cross-border effects are expected to further gain in importance. For this reason, Hawker et al. (2017) suggest three different approaches in order to limit potential adverse effects of national mechanisms. Firstly, generators could be permitted to participate in CRMs in their neighboring countries taking into account the respective interconnector capacity. Secondly, all national mechanisms currently in operation could be harmonized and coordinated under a single design. Thirdly, a single EU-wide CRM could be implemented. However, although a European strategic reserve is described as technically feasible by Neuhoff et al. (2016), a realization of the latter two options is unlikely and potentially also not reasonable due to different drivers for the design of the national mechanisms[11] and difficulties in defining a common VoLL despite countries' structural differences in terms of their economy, their energy mix and their potential risk of shortage situations (Réseau de transport d'électricité, 2014a).

The European Commission has already recognized the issue of cross-border effects and, thus, continuously assesses the conformity of planned and implemented mechanisms with EU State aid rules (for an overview of the cases see European Commission, 2017d). For a lawful public intervention in the market, the European Commission (2013) requires 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. Impacts on efficiency and market welfare

In the following, the most significant theoretical and model-based studies along with their key findings are reviewed. First, the design elements of CRMs (Section 4.1) are briefly discussed. Then, it is examined how CRMs are affected by the current characteristics of the electricity market such as market power (Section 4.2), risk aversion (Section 4.3), and investment cycles (Section 4.4). Subsequently, it is discussed how market welfare is influenced by CRMs (Section 4.5) and what effects occur in neighboring market areas (Section 4.6). Finally, the impact of CRMs in a changing electricity market characterized by a higher share of RES (Section 4.7) and a more flexible demand side (Section 4.8) is discussed.

For many analyses, especially for dynamic long-term effects—such as the occurrence of investment cycles—the use of models is highly suitable (Hary

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[11] Although the main drivers behind the implementation of a CRM are usually threats to generation adequacy, the backgrounds may differ, e.g., while Belgium and Germany are phasing out nuclear power and see the need to incentivize new generation capacity, France and Sweden cope with potentially system-endangering demand peaks in winter.

et al., 2016). Numerous different approaches already exist in the literature, which are summarized in Table 4 that also shows the growing interest in electricity market design.

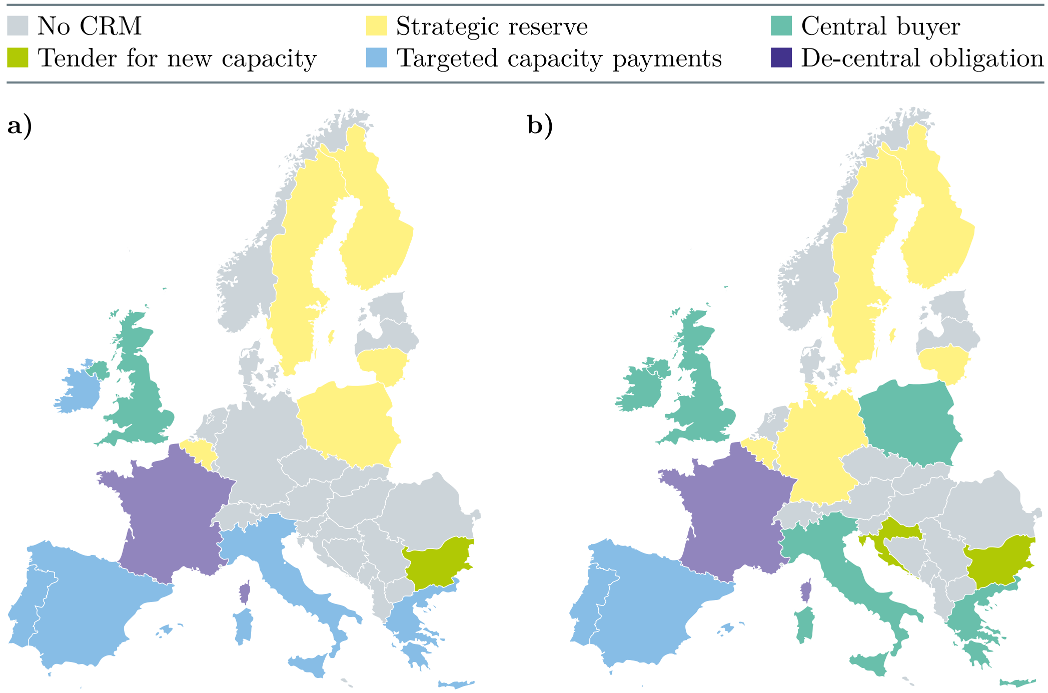

Figure 4: Overview of **a)** current situation of CRMs in Europe and **b)** the status in the future when all planned mechanisms are implemented. Already today, the mechanisms are poorly coordinated, which might intensify due to additional mechanisms being established within the next few years. Sources: ACER and CEER (2017); EirGrid plc and SONI Limited (2017); European Commission (2014, 2016a,b); Hancher et al. (2015); Roques et al. (2016).

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type$^{a,\ b}$** | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Aalami et al. (2010) | analytical | interruptible technologies | Iran | 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 | 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 | 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 | 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) | 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 | 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 | 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 | effectiveness strategic reserve in the presence of a high RES share |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type$^{a,\ b}$** | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Bhagwat et al. (2017a) | agent-based (EMLab) | spot market, decommissions (retirement of unprofitable existing generation)/investments, transmission constraints | hypothetical based on Germany | 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 | 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 | 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 | 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 | 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 | 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 | 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 | firms' optimal behavior and market equilibrium in capacity markets with the possibility to sell to a foreign market under both perfect competition and monopoly |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**$^{a,\ b}$ | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Ehrenmann and Smeers (2011) | stochastic equilibrium | electricty dispatch, investment | hypothetical | effects of risk (fuel prices, carbon market) on investment decisions in generation capacity |
| Fabra et al. (2011) | analytical (Nash equilibrium) | investments | hypothetical | 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 | 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 | 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 | 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 | 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 | 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 | influence of spot market design on firms' investment decision for different regimes of spot market competition (competitive prices and Cournot-Nash equilibrium) |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**[a, b] | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Hach et al. (2016) | single-firm optimization | spot market, decommissions (retirement of unprofitable existing generation)/investments | Great Britain | 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 | 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 | 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 | effect of a (regional) capacity payment mechanism and a price cap on investments in Iranian electricity market |
| Herrero et al. (2015) | single-firm optimization | electricity dispatch, investments | hypothetical | 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 | 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 | 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 | 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 | sources of the missing money problem in imperfect markets |
| Joskow and Tirole (2007) | analytical (Ramsey optimum) | spot market, investments, operating reserve | hypothetical | efficiency of capacity obligations |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**[a, b] | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Keles et al. (2016) | agent-based (PowerACE) | spot market, decommissions (retirement of unprofitable existing generation)/investments, operating reserve, transmission constraints | Germany | 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 | effects of zonal forward capacity markets on investments across market zones |
| Laleman and Albrecht (2016) | statistical | electricity dispatch | Belgium | 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 | 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 | 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 | 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 | relationship between prices, market power and investment under three different regulatory regimes (low price cap, high price cap, capacity market) |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**[a, b] | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Levin and Botterud (2015) | single-firm optimization | electricity dispatch, investments, spinning-up and non-spinning reserve | Texas (ERCOT) | 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 | 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 | impact of refurbishment under capacity payments and reliability options |
| de Maere d'Aertrycke et al. (2017) | stochastic equilibrium | electricity dispatch, investments | hypothetical | 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 | impact of penalty schemes for under-delivery on capacity mechanisms' effectiveness and unit reliability |
| Meunier (2013) | analytical | electricty dispatch, investment | hypothetical | effect of risk and risk-aversion on the long-term equilibrium technology mix |
| Meyer and Gore (2015) | analytical (Nash equilibrium) | spot market, investments | hypothetical | 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 | the rationality of underinvestment if profit-seeking, non-abusive producers construct and operate either one—base or peaking—generation unit (or both) |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**[a, b] | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Mohamed Haikel (2011) | analytical (three stage, Karush-Kuhn-Tucker, Nash equilibrium) | spot market, investments | hypothetical | 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 | benefits of coordinated cross-border strategic reserves |
| Ochoa and Gore (2015) | system dynamics | electricity dispatch, investments, transmission constraints | Finland, Russia | 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 | 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 | 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 | 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 | effects of capacity mechanisms on security of supply objectives assuming risk-averse and risk-neutral investor behavior in power markets undergoing an energy transition |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type$^{\mathbf{a,\ b}}$** | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Ringler et al. (2017) | agent-based (PowerACE) | spot market, investments, operating reserve, transmission constraints | CWE Market area | 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 | 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) | 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 | 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 | 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 | 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 | 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 | market prices, reliability, and consumer costs in different market designs (EOM, capacity market, strategic reserve) |

Table 5: Summarized overview of modeling approaches regarding the development of electricity market design with a focus on capacity remuneration mechanisms.

| **Publication** | **Model type**$^{a,\ b}$ | **Model scope** | **Market area** | **Research subject** |
|---|---|---|---|---|
| Willems and Morbee (2010) | analytical | spot market, investment | Germany | 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 | robustness of various capacity mechanisms to welfare losses caused by regulatory errors |
| Zimmermann et al. (2017) | agent-based (PowerACE) | spot market, decommissions (based on age)/investments, transmission constraints | Belgium,<br>Germany,<br>France | effects of a capacity market and strategic reserve on investments and electricity prices |

[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. 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). Thus, in the following paragraphs, the major design elements[12] of CRMs are discussed.

### 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)[13] 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 future demand, then the required quantity of demand to reach the target for system availability is derived.

### 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.[14] Although in theory, it makes sense to rely on the

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[12] At this point only the most important design parameters as well as selected parameters for specific mechanisms can be 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.

[13] 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).

[14] 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.

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[15]. 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).

### 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

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[15] 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.

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).

#### 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 mechanism, 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 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 countries 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 USA, 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 ongoing 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, afterward, an up-to-date overview of the debate was given. Subsequently, a classification of the different mechanisms was shown, the current status of implementation in Europe was presented, and initial experiences were discussed.

Although CRMs can improve generation adequacy, they also bring with them 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 a complex 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 the cross-border impacts of CRMs are complex and sometimes unambiguous, there seems to be a consensus that a one-sided implementation leads to negative spillover effects on a neighboring market without a CRM, which thereby increase the pressure to either introduce an own CRM or to chose a coordinated approach. Compared to an EOM, the value of flexible resources that is closely related to volatile prices 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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Karlsruher Institut für Technologie

Institut für Industriebetriebslehre und Industrielle Produktion (IIP)
Deutsch-Französisches Institut für Umweltforschung (DFIU)

Hertzstr. 16
D-76187 Karlsruhe

KIT – Universität des Landes Baden-Württemberg und
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