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Combining capacity mechanisms and renewable energy support: A review of the international experience

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ABSTRACT

To ensure sufficient power generation capacity and minimize the risk of blackouts, many countries have introduced capacity mechanisms that provide payments for power plants according to their installed generation capacity. Capacity mechanisms can have different designs, but all have the same purpose—to incentivize sufficient infrastructure investment to meet future electricity demand and, thus, assure mid- and long-term electricity system reliability. Some countries allow renewable energy generators to participate in such capacity mechanisms. Thus, policymakers must choose how to combine capacity mechanisms and renewable energy support. This paper reviews the international experience of combining the two policy types. This is the first review that considers all countries that had some kind of capacity mechanism in place as of 2021. The review reveals a variety of policy mixes. The decision to permit renewable energy producers to participate in a capacity mechanism largely depends on the type of capacity mechanism and the type of renewables support in place. As capacity mechanisms become more widespread and the share of renewable energy in the electricity mix grows, this is one of the largest and most difficult choices that policymakers face. If left unharmonized, the two policies might work against each other, leading to an inefficient and unsustainable scenario, where a rising share of renewables creates a need to increase conventional power generation capacity, undermining cost-efficient decarbonization.

1. Introduction

To meet future electricity demand and avoid blackouts, countries around the world have been introducing measures to ensure the reliability of their electricity systems. The purpose of these so-called capacity mechanisms is to ensure that there is sufficient electricity generation infrastructure by remunerating power plants for the installed capacity, on top of regular revenues from electricity sales. Thus, capacity mechanisms originated as an unconventional way of incentivizing investment in the power sector and providing mid- and long-term reliability to energy systems.

After the turn of the millennium, capacity mechanisms gradually became a standard energy market design element [1]. Initially implemented only in two electricity systems in the United States and in the Unified Energy System of Russia around the year 2000, the number of countries with capacity mechanisms had grown to over 20 by 2020. At that point, they covered around 40% of installed power capacity in the United States, 50% in South America, and 80% in Europe [2].[1] During the same period, the share of renewables in energy systems also expanded. Total renewable power capacity more than doubled between 2008 and 2018, growing beyond 2000 GW and generating a quarter of electricity worldwide [3]. Much of this renewables growth has been bolstered by government support in the form of feed-in tariffs, tax breaks, or targeted auctions.

These parallel trends give rise to difficult choices for policymakers. Does it make sense to allow renewables to participate in capacity mechanisms? If so, should current subsidies for renewables be wholly or partially scaled back to avoid double payment? Furthermore, since capacity mechanisms and renewable energy support have different economic purposes, should they coexist? As capacity mechanisms are introduced in more countries and the share of renewables in the electricity mix also grows rapidly, this is one of the pressing questions that policymakers and electricity system designers face.

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[1] These are our own rough estimates based on country/region power capacity and production data from the official websites of the regional transmission organizations in the United States, country information for South America, and systematic European data [6].

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Abbreviations

CM	capacity mechanism
EU	European Union
GW	gigawatt
MW	megawatt
RE	renewable energy
UK	United Kingdom
US	United States

While a vast literature exists on capacity mechanisms and renewable energy support, the two areas are usually dealt with separately. Most of the few publications that do touch on the intersection of these areas develop into a discussion of how a growing share of intermittent production from renewable energy *adversely* affects energy system reliability and what type of capacity mechanisms can better tackle the problem. For example, based on a simulation exercise, Bhafgwat et al. [4] conclude that a simple strategic reserve scheme would fail to attract sufficient investment in the presence of a high share of renewable energy sources and would have to be replaced with a more sophisticated type of capacity mechanism. A European Commission study [5] adds to this argument by showing that Norway, with over 90% hydropower in its energy mix, incurred the highest cost for maintaining its strategic reserve. A subsequent study by Bhagwat et al. [6] shows that if a capacity mechanism is carefully designed, the uncertainty of electricity supply due to a high share of renewables does not significantly affect the ability of the capacity mechanism to secure sufficient capacity investment. Lara-Arango et al. [7] conclude that the increased uncertainty of the electricity supply due to a high share of renewables makes a capacity mechanism inefficient regardless of its type.

Although most studies consider intermittent renewables to be a threat to the energy system reliability, a handful of emerging studies indicate that renewables can be included in capacity mechanisms. Mastropietro et al. [8] show that some countries have already allowed renewables to participate in their capacity mechanisms. By mapping in detail how the intermittent nature of renewable energy is addressed in capacity mechanisms in several countries, they make the case for including renewables in capacity mechanisms. Nevertheless, they include the caveat that proper capacity de-rating procedures should be implemented. Therefore, the nominal installed capacity of a renewable energy power plant should be reduced to reflect how much it can realistically contribute to system capacity adequacy. For example, if solar panels, on average, produce electricity at only 15% of their installed capacity, their capacity contribution and corresponding remuneration should be set to 15% of their installed capacity. A variety of de-rating approaches exist. One notable approach uses historical data on electricity production from a renewable energy source within a given region. Even when de-rating is carried out, solar and wind capacity can fail due to weather issues; thus more sophisticated de-rating approaches are required to simulate and predict the behavior of the entire energy system. In the same vein, Söder et al. [9] highlight the importance of including renewables in system adequacy assessments. In their recent review of how different countries account for wind energy in their energy reliability calculations, they note that selected jurisdictions choose to pay wind power producers for their contribution to system reliability. These jurisdictions include Great Britain, Ireland, France, Italy, and the regional transmission organization PJM (the United States). However, the question of how these payments are combined with renewables-specific support is not dealt with in their paper. Our analysis builds on and continues this emerging discussion of the role of renewables in system reliability mechanisms.

How different countries handle the integration of renewable energy support and capacity mechanisms has not been systematically analyzed previously. We fill this gap by reviewing how capacity mechanisms and support for renewable energy are combined in all countries where a capacity mechanism is present, a total of 24 countries. Around half of these countries introduced their capacity mechanisms after 2016, and many modified their mechanisms in 2019–2020. Accordingly, the issues dealt with in this review are in large part new. As steadily more countries are adopting capacity mechanisms and renewable energy is growing fast, these issues will also be relevant in the future in many more than the 24 countries studied in this paper. It is therefore useful and important to try to learn lessons from those countries that have already handled this issue.

This review brings out the variety of policy choices and reveals patterns in them. We also discuss the reasoning behind those policy choices, the economic incentives involved, the effects policy designs can have on the energy technology mix, as well as their implications for policy efficiency. This is the first overarching review of all capacity mechanisms worldwide. In addition, the interface between renewable energy and capacity mechanisms has never previously been the main focus of an academic analysis. We believe such a review may be helpful for academics and policymakers alike. For academics, our study can form the empirical basis for further research in the fields of energy system reliability, renewable energy support and transition to low carbon economies. For policymakers, an overview of what choices other countries have made and the contexts for those choices can help inform their own policymaking.

The remainder of the paper is structured as follows. Since capacity mechanisms and renewable-energy support mechanisms are usually treated separately and researchers and policymakers may not be familiar with both fields, we first provide a brief overview of the two topics in Section 2. Section 3 describes the relevant policy mix in the selected countries. Section 4 summarizes the results, presents them graphically and in tabular form, and provides an extensive discussion. Section 5 highlights the policy implications of the conducted analysis. Finally, the concluding section outlines the contribution of the paper and directions for further research.

2. Background on capacity mechanisms and renewable energy support

2.1. Capacity mechanisms

Blackouts are a risk for energy systems worldwide; losses from a single blackout can amount to billions of USD [10]. Blackouts occur when generators are unable to produce enough electricity to meet demand. Events that can contribute to such a situation include a nuclear power plant undergoing unscheduled maintenance; a hydropower reservoir that is empty because of a drought; absence of sunshine or wind; a heatwave causing all households to switch on their air conditioners at the same time; or the transmission facilities of a neighboring country already being at maximum load. Combined, such developments can cause spikes in electricity prices. To protect consumers, policymakers may introduce a price cap. However, those price spikes were part of the revenues for power generators. When prices are capped, incentives to maintain and/or expand generation capacity are lost. Unaddressed, the situation becomes cyclical and worsens with every cycle. This is known as the “missing money problem” [11].

There are several types of capacity mechanism. One of the simplest solutions is to maintain a strategic reserve, usually in the form of several power plants that neither produce electricity nor participate in the market on a daily basis, but are always available to start producing electricity in times of scarcity (defined by either a threshold electricity price or a physical balance of electricity in the system). Which power plants constitute the strategic reserve and how much generators are paid for this service is normally determined through competitive auctions. Often, aging power plants constitute the reserve since building new plants only for reserve purposes is costly. However, the latter option is still possible, and has, for example, been chosen by Norway. The size of the strategic reserve is defined centrally based on system needs and the projected development of the electricity sector. Strategic reserves can involve demand-side operators too, in which case their role is to reduce their consumption when needed [5].

Direct capacity payments are another simple approach to support capacity adequacy. They can have a variety of designs, can be applied to all capacity on the market or only a specific type (e.g. peak generators), or target new capacity to incentivize investments. The type and amount of payment is usually decided by a regulatory body. Unlike strategic reserves, generators that receive direct capacity payments are not outside the electricity market and continue selling electricity on the exchange or through bilateral contracts [5]. A more sophisticated class of capacity mechanisms is the various types of capacity market. The underlying principle here is that the price of capacity is defined by market forces to ensure the long-term dynamic and sustainable adequacy of the energy system [12].

Capacity markets can be arranged through capacity obligations, capacity auctions, or reliability options. A capacity obligations scheme is a decentralized market where utilities and retailers who sell electricity to the end consumer are obliged to have enough capacity available to meet demand. Capacity availability can take the form of ownership of power generators, bilateral contracting with other power generators and/or holding capacity certificates. Capacity certificates are a standardized form of capacity contract and can be tradable, in which case their price is defined by supply and demand. Capacity auctions are a market arrangement where by required capacity volumes are procured centrally, resulting in a single consistent price for the capacity buyers. Both capacity auctions and obligations can be designed for existing or new capacity. The capacity contract can be designed as a call option, usually an option held by the electricity consumer to acquire electricity from the generator at a specified price during a defined period in the future. This type of capacity market is referred to as trade in reliability options. Such a mechanism incentivizes new investment and is intended to ensure an optimal long-term capacity mix, but requires a well-functioning wholesale electricity market [5].

Parmar and Darji [13] provide a detailed description of the different features of capacity mechanisms and a systematic overview of capacity mechanism designs in selected jurisdictions: Brazil, Colombia, Russia, the UK, and the New England ISO, PJM, and NYISO in the United States. Parmar and Darji argue that a growing share of renewables reinforces the need for a capacity mechanism, but they omit the fact that renewables themselves might also participate in the capacity mechanisms and thus contribute to system reliability. The literature on capacity mechanisms is still fledgling and researchers highlight a need for more descriptive studies to provide a foundation for deeper analysis [14].

2.2. Renewable energy support schemes

The most straightforward way to support renewables is to pay extra for the electricity produced from renewable energy sources. Such subsidies usually come in the form of feed-in tariffs or a fixed premium (over the electricity price). Both require the price to be set administratively and adjusted regularly as conditions change, for example when technological developments lower prices. In tendering schemes, the price is set through competitive auctions. Alternatively, the level of support for renewable energy can be determined by market forces. One approach is to oblige utilities to produce a certain share of electricity from renewable energy sources and create a market for *renewable energy certificates*. Thus, entities can choose whether to build their own renewable energy power plants or obtain certificates from other entities, allowing market forces to determine the profile and distribution of renewable energy support that is both sufficient and cost-efficient. As with capacity mechanisms, several types of renewable energy support are often combined. For example, tendering for large-scale projects might be combined with feed-in tariffs or premiums for small-scale installations [15].

The vast academic literature on renewable energy policy analysis comprises both qualitative [16,17] and quantitative studies [18–20]. Targets for installed renewable energy or the share of renewables in the energy mix are often used as the main indicators of policy success [21]. However, policy *cost-efficiency* in terms of the burden on electricity buyers is sometimes also considered. In a metareview of quantitative studies [19], feed-in tariffs were found to be the most effective policy but certificates trading and tendering performed better in terms of cost-efficiency. None of these studies considered outcomes based on system adequacy. Real-world trends and academic findings converge in this area. The rapid pace of renewable energy adoption and falling technology costs has caused many countries to reconsider their support policies and a global shift is ongoing from feed-in tariffs to tendering [22,23].

3. International experience of combining capacity mechanisms and renewable energy support

In this section, we look at the experiences of different countries in integrating (or not) renewable energy support with capacity mechanisms. We start in the Americas and move East. All countries in the world that have implemented any type of capacity mechanisms prior to 2020 are covered.

3.1. North America

The history of capacity markets started in the *United States* in 1999 with the Pennsylvania–New Jersey–Maryland Interconnection (PJM) [24]. Over time, several independent system operators (ISOs) in the United States have established different types of capacity markets: ISO New England; Midcontinent Independent System Operator (MISO); New York ISO (NYISO); and California ISO (CAISO). All of these capacity markets are open to renewables, including wind and solar, regardless of whether renewables receive any other benefits, for example, from the United States' renewable portfolio standard scheme. The exception is ISO New England, where measures were introduced to prevent double payment [8].

A review of capacity markets in the United States [25] reveals that there are still many controversial design issues, for example, whether and how to apply non-compliance penalties to renewables when they fail to supply electricity despite being paid for capacity availability. This challenge derives from the basic problem of how to estimate the reliable capacity of renewables from the system point of view. Some authors note that this issue is becoming increasingly critical as the share of renewable energy electricity rises in most energy systems [8,25].

Two countries in Central America have capacity mechanisms in place: *Guatemala* and the *Dominican Republic*. In Guatemala, renewable energy tenders are part of a wider auction-based capacity market, and every auction has a minimum quota for renewables. Winning bids receive 15-year capacity contracts, and consequently, the mechanism promotes new renewable energy investments. Two auctions in 2016 provided shorter contracts of one to five years for biomass and hydropower projects [26].

The Dominican Republic supports renewables through tariffs, tax relief, and subsidies for distributed energy generation. Combined with the general vulnerability of the Dominican energy system, high penetration of renewables could undermine the stability of the electricity supply. Direct capacity payments therefore target specific power plants to maintain system adequacy and do not include renewables [27].

3.2. South America

Some South American countries, such as Brazil, Chile, Colombia, and Peru, organize long-term energy auctioning alongside electricity markets to attract new investment and meet future electricity demand [28]. Although these market arrangements cannot strictly be called capacity mechanisms, they target the long-term adequacy of the respective country energy systems [8]. The Chilean and Peruvian mechanisms can be described as direct capacity payments, while Brazil and Colombia operate schemes resembling capacity markets that are auction and obligation-based, respectively [5].

With respect to renewable energy support, these four countries have moved from price-based to quantity-based mechanisms [29]. Brazil runs capacity auctions for renewables with 20 to 30-year contracts awarded, a similar scheme exists in Peru, and capacity auctions for renewables were launched in Colombia in 2019. Chile has taken a different approach and has a renewable energy certificate market that requires electricity companies to annually increment the share of renewables [26].

In these countries, long-term energy auctions and renewable support schemes are run separately. It might make sense to connect them more closely with each other, but several barriers would have to be overcome before that could be achieved [29]. Nevertheless, Brazilian, Colombian, and Chilean adequacy mechanisms have de-rating procedures in place that allow participation of renewables in their capacity mechanisms [8].

3.3. Europe

A rapidly growing share of intermittent renewable energy sources in European countries has created a need for greater energy-system flexibility, including flexible power generation, storage, demand response, and interconnectors [30]. To facilitate the introduction of such measures, capacity mechanisms have been introduced. Since 2012, the European Commission has advocated the use of capacity mechanisms [31,32]. The European Union (EU) member states have started adopting a variety of solutions depending on their current situation of the energy system, renewable energy targets, and legal system. Although the European Commission recognizes security of supply as a national matter to be handled by each member state, it strives to enforce convergence to preferred features of a capacity mechanism [33]. These features have been introduced incrementally and include the capacity mechanism being based on market principles; having market-wide coverage, meaning that all kinds of technology should be allowed to participate; including cross-border capacity exchange; having an emphasis on demand response programs; and phasing out capacity support for power plants that emit more than 550g CO_2/kWh to gradually abolish the biggest polluters [34]. Therefore, before implementation, all proposed capacity mechanisms should be approved by the European Commission [33].

In Northern Europe, Finland, Norway, and Sweden historically maintain strategic reserves [5], and together with other North European countries operate the Nordpool regional electricity market. Additionally, they are developing a common platform for assessing long-term electricity generation adequacy [35]. As for renewable energy support, Norway and Sweden have a joint renewable certificates market and Finland switched the promotion of renewables from feed-in tariffs to auctions in 2018 [26]. In these countries, renewable energy support is not connected with capacity mechanisms.

The United Kingdom launched its capacity market in 2014 [36] [2] as part of an electricity market reform process that also included a new support instrument for renewables, a so-called “contracts for difference” feed-in tariff scheme [37]. The new scheme remunerates renewable energy investments through a variable premium on top of the electricity price with a pre-defined cap. Until 2017, the scheme coexisted with the previous renewable energy certificates trading scheme (called “renewables obligations”). During the 2014–2017 transition period, generators were given a choice of which renewables support scheme to draw upon. Renewable energy generators operating under contracts for difference are excluded from the capacity market [38]. However, renewable generators that are supported through tradable certificates can participate in the capacity mechanism if they forgo the certificate payments. Nevertheless, during the first four years of the capacity market, no renewable generators participated [39]. However, their participation has been agreed to start from 2020 as long as they do not receive other support [40].

France, *Germany*, and *Greece* introduced capacity mechanisms in 2016. The French capacity mechanism stands out with its decentralized capacity market design and the option of longer contracts. Alongside standard one-year contracts, seven-year contracts can be granted in order to facilitate new investments [41]. In 2018, this scheme was upgraded with an emphasis on demand response [42]. In negotiations with the European Commission, the *French* authorities initially proposed to keep renewables out of the capacity mechanism, arguing that feed-in premiums already covered the full project costs, while the Commission asserted that there should be no exceptions from the capacity mechanism. Nevertheless, it was ultimately decided to reduce renewables compensation by the equivalent of the capacity revenue in order to avoid double subsidization [43]. A comprehensive capacity de-rating procedure is implemented for renewables to enable inclusion of their capacity on a par with other power generators [8]. Inclusion of renewables in the French capacity market has proven successful in attracting new investments and reducing their cost [44].

Germany created a strategic reserve as a temporary measure to ensure energy system reliability during the phase-out of nuclear power [42,45]. Renewables are in practice not included in the mechanism and are remunerated only by feed-in tariffs since one of the reasons for creating the strategic reserve was to ensure electricity supply in periods when there is no sun and wind, which both account for a growing share of the German energy mix. Similarly to *Germany*, Belgium established a temporary strategic reserve to cope with aging nuclear plants [42]. As in Germany, renewables are not included in this capacity mechanism. They are however supported separately through tradable certificates.

Greece has gradually adopted a flexibility remuneration mechanism to ensure reliability of the energy system. In the first stage, its coverage included such flexible generators as gas-fired power plants and hydropower plants [46]; in the second stage demand response and storage operators were also included [47]. Generators and operators are selected through centralized auctions. Renewables are remunerated through a feed-in premium and are not considered to be flexible generators, and thus excluded from the capacity mechanism. A growing share of intermittent renewable energy is noted as one of the reasons for implementing the capacity mechanism in Greece.

Ireland introduced a reliability option scheme in 2017 as a long-term solution for the security of the energy system. The Irish design of the capacity mechanism allows participation of all demand response operators and any generating capacity, including renewables, regardless of any other support schemes in which they participate. The Irish 2018–2019 subsidy scheme for solar projects automatically accounts for any increase in revenues from either electricity or capacity sales [48]. A similar mechanism was included in the new tendering scheme launched in 2019 [49]. The renewables support arrangements thus avoid double remuneration. *Northern Ireland* has a different support scheme for renewables—tradable certificates. Since renewables support is not interlinked with the capacity mechanism, the rule for renewables is to choose either certificates or the capacity mechanism [48].

Italy and Poland are implementing market-wide capacity mechanisms to address electricity-only market failures and provide an incentive for new capacity investments [42]. Their mechanisms are open to all types of capacity providers and demand response operators, with capacity contracts allocated through regular competitive auctions. The Italian capacity mechanism is a centralized capacity market where reliability options are traded. It has been the subject of criticism in the academic literature due to apparent overcapacity and the fact that there

[2] Northern Ireland is a part of the Irish “all-island single electricity market” (including the Republic of Ireland) and introduced a different type of capacity mechanism in 2017.

are seemingly no problems with the flexibility of the energy system [50]. Interestingly, Italy introduced stringent CO_2 emissions limits, both per kWh and a ceiling on annual total emissions. This applies to all newly built and existing power plants, and was applied already from 2020 [51]. By contrast, EU electricity regulations prescribe such limits for power plants of any age starting only from 2025. Until then, only those built after 2019 have to comply with the limit per kWh under EU rules [52]. This makes the Italian capacity mechanism not only a system adequacy measure, but also a tool for energy system transition to carbon neutrality. Renewable energy producers are allowed to submit bids to the Italian capacity market and their capacity is de-rated based on the historical performance of the corresponding technology. To avoid double subsidization, the capacity mechanism forces participants to relinquish other subsidies corresponding to the amount of capacity remuneration [53]. Although this rule applies to any generating capacity, for renewables it implies giving up part of the feed-in tariff. Although the Polish capacity mechanism also allows for the participation of renewables, it does not permit combining capacity payments with any other operational support, such as a feed-in premium or tariffs. Along with the capacity bid, renewable energy generators have to submit a declaration stating that if a capacity contract is won, the tariff or premium will be forfeited [54].

Portugal and Spain operate a direct capacity payments scheme [5], with the capacity to be remunerated determined through auctions. *Spain* holds renewable energy capacity auctions and remunerates renewables per capacity installed. However, the decision to stage each auction is made separately, and the total amount of renewables to be selected is defined centrally [26]. After closing its feed-in tariff support for renewables in 2012, *Portugal* opened its capacity auctions to such power generation. However, a lack of detailed rules for renewable energy sources has resulted in the inability of renewables to participate in the auctions [55].

3.4. Russia

While some of the countries covered above face the question of whether to align their capacity mechanism with renewables support, *Russia* chose the capacity mechanism approach as the means of renewable energy support in the first place. The *Russian* capacity market is organized through two types of auction: short-term auctions for existing operators, where capacity for a year ahead is traded; and auctions awarding long-term capacity contracts to stimulate new investments. The capacity price for end consumers is calculated centrally as a weighted average of short and long capacity contracts [56].

These long-term auctions were established as the foundation for renewable energy support from 2013 onwards. The approach is unique in that the capacity price is project-specific and dynamic during the duration of the capacity contract, reflecting the changing market environment and project production performance. The capacity price calculation was specifically designed to provide a return on investment equivalent to long-term capacity contracts for conventional energy. The capacity contract does not oblige renewable energy projects to start producing at a specific time. On the contrary, there is a requirement to stop producing electricity upon the order of the system operator, with fees imposed for failure to do so [57].

The first series of *Russian* renewable energy auctions was completed in 2019, and in 2020, the design of the support mechanism is being reconsidered in light of the experience gathered. Interestingly, one of the options considered for the second stage is technology-neutral auctions, not just among renewables, but in one pool with conventional energy. It has been suggested that projects do not compete by investment costs but rather by levelized cost of energy (LCOE), thus taking technology efficiency into account. With this approach, renewables would compete directly with conventional energy technologies, which should help optimize the geographical distribution of electricity generators. For example, solar plants would more likely be built in the sunnier southern part of the country where their LCOE will be lower [58].

3.5. Asia and Oceania

Only three countries in the region have adopted capacity mechanisms. Turkey introduced capacity payments mechanism in 2018 to ensure the long-term reliability of the energy supply [59]. English-language information on this capacity mechanism is scarce and is limited to a few short, non-academic articles. Under the Turkish capacity mechanism, renewables are not eligible for capacity payments since they cannot qualify for the mechanism's requirement to provide base-load generation [60]. Renewable energy is supported separately in Turkey through feed-in tariffs [55].

South Korean capacity payments are paid on a daily basis to generators that declare their availability. Together with the system marginal price, the capacity payment is a component of the total market price on the day-ahead market [61]. The system marginal price reflects the operational costs of electricity production, and capacity payments aim to cover the investment costs of generating units. Renewable energy sources are allowed to trade on the market, and they therefore also receive capacity payments as a part of the overall market price [62]. Renewables are further supported through the certificate market with a growing obligatory share of the energy mix for Korea's 13 largest power companies. The share is set to grow from 2% in 2012 to 10% by 2023 [26]. No mention of restricting the overlap of the two schemes was found in the extant literature.

Until 2014, Australia had a carbon pricing mechanism that benefitted many different emission-reducing actions, including renewable energy investments. However, in 2014 the mechanism was abolished, and renewable energy no longer received any special support [26]. As for capacity mechanisms, Western Australia has a decentralized obligation-based market of capacity credits as well as centralized auctions if insufficient capacity has been allocated through bilateral contracts. Capacity contracts have a duration of one year. Special procedures have been established to determine the technical capabilities of different types of power plants [63]. Renewables are allowed to participate in the capacity market. For example, the certified capacity for the year 2020–2021 includes over 200 MW from 15 wind farms and about 35 MW from five solar power plants, representing 4% and 0.7% of the total, respectively [64].

4. Policy choice patterns

Different countries secure capacity adequacy in different ways, use different mechanisms to support renewables, and combine them in different ways. The variety of practices is summarized in Table 1, where countries are grouped by geographic location. The share of intermittent renewable energy capacity in their electricity mix is presented, as is the type of capacity mechanism and renewable energy support, and the way the two elements are combined (or not). This information is graphically illustrated in Fig. 1, where we show which countries have capacity mechanisms in place, their typology, and whether or not renewables are allowed to participate in the mechanisms in one way or another. The presented countries had on average over 40% intermittent renewable energy capacity at the end of 2019 (not including hydropower with dams).

When the most basic types of capacity mechanisms are used, such as a strategic reserve or direct payments, the reasoning is often that there is only a temporary need. In most of these cases, renewables are excluded from the capacity mechanism and are only entitled to receive support specifically for renewables. Countries with this setup include *Belgium*, the *Dominican Republic*, *Finland*, *Germany*, *Greece*, *Norway*, *Sweden,* and *Turkey*. Exceptions are *Chile* (there is a tradeable certificate market to support renewables that can also participate in the capacity payment scheme); *Peru* and *Spain* (renewable energy tenders are in practice part of the capacity mechanism); *Portugal* (there is no support for renewables

Table 1
Summary of arrangements for capacity adequacy and renewable energy support. Countries are grouped by location, sorted by capacity mechanism type (color-coded) and by the share of renewable energy capacity in the country's power mix (hydro [blue], solar [yellow], wind [green]; compiled from Ref. [66]). The interaction of capacity mechanism and renewables support is color-coded and explained in the comments.

Region	Country	Share of RE in power mix: 2019	Type: Capacity mechanism	Type: Renewables support	Renewables allowed: RE support only	Renewables allowed: Capacity mech. only	Renewables allowed: Combi-nation	Comment
North America	US	21%	capacity market (all three types in different areas)	tradable renewable energy certificates (REC)			X	Renewables are allowed to receive both renewable energy support and capacity payments, except ISO New England, where there is a cap on the generation capacity of renewables receiving subsidies.
North America	Guatemala	43%	capacity market (auctions)	tendering (part of capacity market)			X	Regular capacity auctions have a minimum quota for renewable energy. Winners receive 15-year capacity contracts.
North America	Dominican Republic	22%	direct payments	feed-in tariff	X			Renewables are supported through tariffs, tax relief, and subsidies for distributed energy. Capacity payments target specific power plants and do not include renewables.
South America	Brazil	75%	capacity market (auctions)	tendering			X	Long-term energy auctions for conventional sources are held in parallel with renewable energy support (except Chile, which has renewable energy certificate trading). Brazil and Colombia have comprehensive simulation-based de-rating procedures.
South America	Colombia	67%	capacity market (reliability options)	tendering	X	X		
South America	Chile	45%	direct payments	tradable REC	X	X		
South America	Peru	42%	direct payments	tendering			X	
Europe	UK	35%	capacity market (auctions)	feed-in premium	X	X		As of 2019, the UK capacity market is not open to renewables, but the plan is to allow them from 2020. No renewables with subsidies will be allowed, only fully subsidy-free projects can participate in the capacity market. Proper de-rating procedures are to be implemented for renewables.
Europe	Ireland	38%	capacity market (reliability options)	subsidies & tradable REC			X	Renewables are allowed to participate in the capacity market, but if they receive a subsidy it is adjusted according to capacity revenues. Northern Ireland is an exception, where a tradable REC scheme is in place, resulting in a choice between either REC or capacity mechanism. A comprehensive simulation-based de-rating procedure is implemented for the capacity mechanism.
Europe	Italy	41%	capacity market (reliability options)	feed-in tariff			X	Renewable generators are allowed to bid in the capacity auctions, and if selected, they have to forgo feed-in tariffs corresponding to what they are paid for capacity. A de-rating procedure based on historical performance is in place.
Europe	Poland	17%	capacity market (auctions)	feed-in tariff/premium	X	X		Renewables are allowed to participate in capacity auctions, but only if they do not receive a feed-in tariff. Together with the bid, renewables have to submit a declaration that they will not combine any other aid with capacity payments.
Europe	France	34%	capacity market (obligations)	feed-in premium			X	Renewables are allowed to participate in the capacity trade, but total revenues are reduced according to their capacity income to avoid double subsidization. A comprehensive simulation-based de-rating mechanism is in place.
Europe	Spain	44%	direct payments	tendering			X	Renewable generators are selected through auctions. The winners are remunerated per unit of capacity. The decision to hold an auction is made for one year at a time and the amount of renewable energy is defined centrally.
Europe	Portugal	49%	direct payments	-		X		No specific support for renewables. In theory they can get extra revenues from capacity auctions, but the participation rules for renewables are not specified, so no renewables have obtained capacity payments to date.
Europe	Greece	45%	direct payments	feed-in premium	X			Only flexible capacity is included in the capacity mechanism. Renewables are excluded and only receive payment via a feed-in premium.
Europe	Germany	48%	strategic reserve	feed-in tariff	X			Only designated generators are allowed to participate in the reserve mechanism, while remuneration of renewables goes through the feed-in tariff scheme.
Europe	Belgium	35%	strategic reserve	tradable REC	X			Only designated generators are allowed to participate in the reserve mechanism, while remuneration of renewables goes through tradable REC.
Europe	Norway	93%	strategic reserve	tradable REC	X			All three countries have strategic reserves and together assess the adequacy of the energy system. Renewables are not part of the reserve and are supported separately through tradable certificates (Norway and Sweden) or feed-in tariffs (Finland). Norway has a very low share of solar and wind capacity, but if hydropower is taken into account, the contribution of renewables to the electricity mix is around 93%.
Europe	Sweden	61%	strategic reserve	tradable REC	X			
Europe	Finland	33%	strategic reserve	tendering	X			
Europe	Russia	19%	capacity market (auctions)	tendering			X	A capacity market design was used to create a support mechanism for renewable energy. However, the amount of renewables to be supported is centrally predetermined, they do not compete on a par with conventional energy sources and they do not contribute directly to system adequacy by committing to produce electricity in times of scarcity.
Asia	Turkey	46%	direct payments	feed-in tariff	X	X		The capacity mechanism is in the form of direct capacity payments. Renewables are not eligible to take part in the capacity mechanism. Renewable energy is supported separately via a feed-in tariff.
Asia	S. Korea	10%	direct payments	tradable REC			X	The capacity payment is a component of the day-ahead price in the electricity market and is received by all generators that declare themselves to be available for a particular day. In addition, renewables are supported through tradable certificates. No restrictions on receiving both types of payment are mentioned in the available market rules.
Oceania	S.-W. Australia	35%	capacity market (obligations)	-		X		No renewable energy support. Renewables participate in the decentralized capacity market (one-year contracts) on equal terms with other technologies, with specific procedures to determine available capacity.

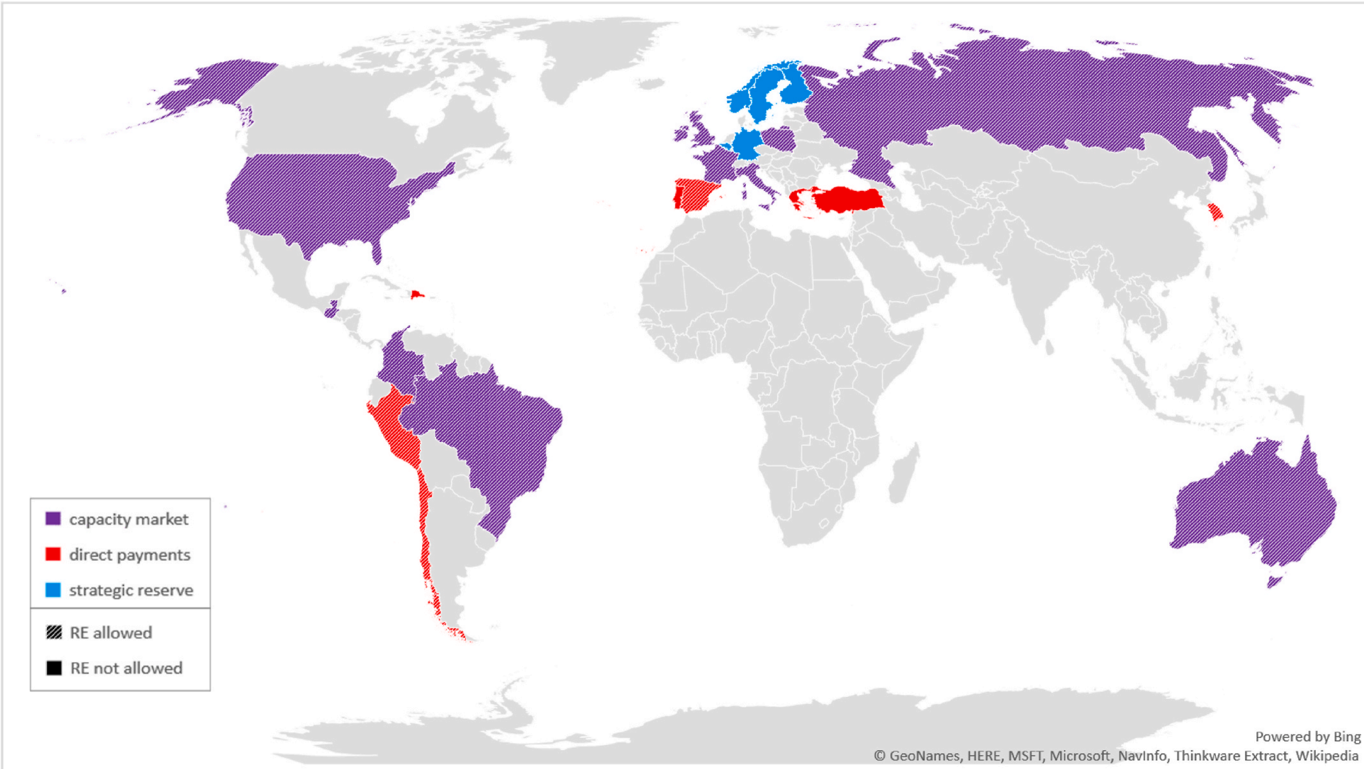

Fig. 1. Capacity mechanisms by type and renewable energy inclusion. The capacity mechanisms in Australia and the United States do not cover the whole country. See details in Table 1. Color-coding by capacity mechanism type combined with pattern if renewables are allowed to participate in the capacity mechanism, solid color if not.

and the capacity mechanism is not effectively adapted for them); and *South Korea* (capacity payments are part of the daily energy pricing mechanism and the payments can go to renewables, along with payments from tradable certificates).

By contrast, capacity markets, as a market-wide capacity mechanism, also welcome the participation of renewables, while de-rating them to reflect the intermittent nature of their power production. The only capacity market design that has not been adapted for renewables is in the *UK*; however, this flaw has been acknowledged by policymakers, who have decided to include renewables from 2020 [40]. Among this group of countries, there are three options for how to treat revenues from renewables support when such generators enter the capacity market: (i) no limitations; (ii) a reduction in support corresponding to the amount of capacity revenue earned; and (iii) revoking support or its absence in the first place. Most of the capacity markets in *the United States* impose no limitations on renewables for revenue from tradable certificates. The absence of intervention to the renewables support is the expected design solution in this case, since prices on the renewables certificate market are supposed to be adjusted automatically by market forces. *Ireland*, however, bars renewables from the renewables certificate trading scheme, as this scheme also covers *Northern Ireland,* which is part of *the UK*. In *Northern Ireland*, therefore, expecting a price response is futile. Nevertheless, the two revenue sources are aligned in the renewable energy support subsidy scheme in Ireland, so that the remuneration for renewables is automatically adjusted to any revenues accruing from the capacity market. *Portugal* and South West Interconnected System of *Australia* are examples of renewables-friendly capacity markets operating in the absence of specific renewable energy support. *Poland* bars renewables from receiving feed-in tariffs if they sell capacity. In *Guatemala* and *Russia*, tendering schemes for renewable energy support form part of the capacity market itself. *France* and *Italy* lower the remuneration of renewables from feed-in tariffs or premiums by an amount corresponding to the capacity revenue earned.

Several countries, including most *South American* states, *France*, *Guatemala*, *Russia*, and the *UK*, introduced long-term capacity contracts for renewables specifically to encourage new investment. However, in spite of being attractive to renewable energy investors [65], this approach is questionable in terms of its actual contribution to the capacity adequacy of the energy system. For example, in *Russia*, the system operator does not have the legal power to order renewable energy generators with long-term capacity contracts to provide this capacity (or to start producing electricity). As Mastropietro et al. [8] have argued, this is therefore just a renewable energy support mechanism and not a proper capacity mechanism. On the other hand, Russia does have an explicit requirement for renewable electricity generators to shut down when requested by the system operator, and if they fail to do so, the generators are fined. Indeed, capacity mechanism penalties for non-performance of renewables is a challenging design issue, and even the more established capacity markets in the *United States* struggle to find a consistent and efficient way to treat renewables when capacity that has been paid for being available cannot supply electricity, for example, when the wind does not blow or the sun does not shine [25].

The choice of policy design is shaped by multiple factors. Path dependency certainly plays an important role. For example, the Scandinavian countries were using strategic reserves long before the European Commission started to promote capacity mechanisms. By contrast, the mechanisms adopted more recently in the EU tend to be capacity markets in some or other form in order to comply with the European Commission's recommendation that member states adopt market-based and market-wide mechanisms.

Russia is another example where policy choices are heavily influenced by history. In Russia, the capacity market existed before renewable energy support. When the authorities faced a choice of which type of renewable energy support to introduce, a feed-in premium scheme was rejected because it would require too many changes in the electricity governance system. Instead, capacity market rules were taken as a basis and extended to long-term capacity contracts for new renewable energy projects.

Since a growing share of renewable energy is often the trigger for the introduction of a capacity mechanism, it might affect the choice of *type* of capacity mechanism and the decision on how to integrate renewables and the capacity mechanism. Fig. 2 shows the choice of the type of capacity mechanism (on the y-axis), whether renewables are allowed to participate in the capacity mechanism or not (pattern vs solid fill), along with the share of intermittent renewable energy in the system (on the x-axis).

Although visually a slight pattern can be noticed in Fig. 2, the difference between the means of the different groups is not statistically significant. The visual pattern can partly be attributed to the fact, already stated above, that the countries which have a strategic reserve in place bar renewables from participation in the capacity mechanism. They also happen to have a relatively high share of renewables, which was one of the reasons for the early creation of those reserves in the first place.

One might expect that only countries with a low share of intermittent renewables in their systems would allow renewables to participate in capacity markets, since their combined effect would be too small to cause disruption in the system. However, this is not the case. Fig. 2 shows that many countries with over 30% renewables in the electricity mix choose to allow them to take part in the capacity mechanism. This indicates that capacity mechanisms could be not only a *mitigation measure against* a high share of renewables, but also a *way to support* a high share of renewables. The debate on whether the transition to renewables and carbon-neutral energy systems requires system reliability measures or is slowed down by these measures is gaining momentum in the industry [33] and academic literature [67,68]. This contradiction arises from the notion that capacity mechanisms tend to support conventional energy power generation based on fossil fuels. However, the recent introduction by the European Commission of the CO_2 emissions limit for capacity mechanisms in EU countries strengthens the outlook for a clean transition. On the other hand, fast development of renewables can be self-destructive and harm overall efficiency [69], if not supported by conventional power generation, flexibility technologies, or system reliability measures.

Bioenergy can be considered a natural solution that contributes both to the transition away from fossil fuels and to maintenance of energy system reliability. In addition, biomass contributes to the removal of carbon dioxide from the atmosphere [70]. However, the sustainability of large-scale bioenergy production is debated and depends on further innovation [71]. Among the possible concerns related to large-scale bioenergy are threats to biodiversity and competition with food production and other land use [72,73].

The European Commission, having accumulated experience with capacity mechanisms from several EU member states [74], still sees intermittent renewables as a cause of system inadequacy rather than part of its solution. Developing flexibility on the demand side has been proposed as a way to offset the intermittency of renewables. Demand-side flexibility is important because it can contribute to market reliability without the need for more generation capacity. Formal measures to promote demand responses within capacity mechanisms have so far been implemented in *France*, *Germany*, and *Greece*.

Along with demand-side flexibility and interconnectivity, storage solutions play an important role in offsetting the intermittency of renewables. A recent study suggests that solar power, from being almost useless for purposes of system reliability, can become a fully reliable generation source if combined with just a 4-h battery [75]. However, commonly used lithium-ion batteries carry a risk of fire or explosion, which may hold back their widespread adoption as an industrial-scale solution for energy storage [76,77]. Hydrogen could potentially play a role not only in the storage of electricity but also in its transmission [78, 79]. However, extensive use of hydrogen technologies faces many challenges [80]. In the meantime, market-based capacity mechanisms support the development of these storage technologies.

Additionally, geopolitics comes into play when designing capacity mechanisms. If a country partly relies on the import of electricity, then its system reliability is also to some extent dependent on that foreign capacity. Limited interconnection capacity between neighboring EU member states restrains the flow of electricity and, thus, trade in electricity and capacity. Moreover, interconnection can be feared for political security reasons [33]. Although the European Commission assesses the influence of local capacity mechanisms on competition and cross-border trade on a case-by-case basis, some researchers have argued that adverse effects are inevitable and a viable solution could be either the imposition of a common model on all local capacity mechanisms or the introduction of a single EU-wide capacity mechanism [81]. Nevertheless, creating a unified mechanism could be complicated by differences in the legislative context, energy system, and system reliability targets. As noted by Mastropietro et al. [29], creating a single

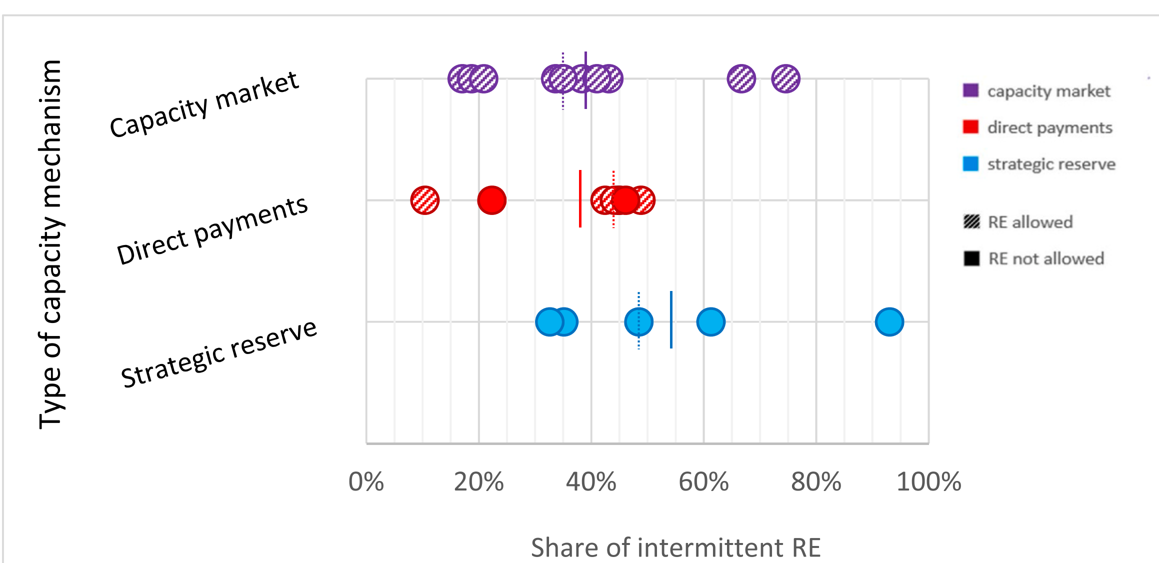

Fig. 2. Policy choice and share of intermittent renewable energy in 24 countries. Color-coding by the type of capacity mechanism, combined with pattern fill if renewables are allowed to participate in the capacity mechanism and solid fill if not.

mechanism across Latin America was deemed impossible for these reasons. However, enabling cross-border capacity trade is a reasonable step towards securing free trade and competition. In the EU, so far only the *Italian* and *Polish* capacity mechanisms are open to foreign capacity providers. Nevertheless, the European Commission continues promoting cross-country cooperation and connectivity [14].

5. Policy implications

In the introduction we indicated three choices that policymakers face and that are the subject of this review. The first one was: *Does it make sense to allow renewables to participate in capacity mechanisms?* The growing share of intermittent renewable energy in power systems clearly creates a need to introduce capacity mechanisms; however, many countries choose to include renewables in their system reliability arrangements. The attitude towards this phenomenon—and thus the policymaking—seems to be narrowed down to a simple choice: either renewables are seen as a threat to system reliability or as a potential ally whose contribution to system reliability should be remunerated. The two options have different consequences and the choice is self-reinforcing. When renewables are left out of the system adequacy mechanism, their development is dictated by the intentions of investors to gain maximum benefit from available renewable energy resources. For example, a sunny country will get increasing amounts of solar power and will face a steadily greater challenge meeting evening peaks in electricity demand when solar does not provide enough energy. By contrast, when renewables are part of a system reliability mechanism, their development would be dictated by the value of complementarity to achieve overall system adequacy. For example, in a sunny country with a lot of solar power, wind and small-hydro capacity will be worth more, which will shift investment incentives from solar to wind and hydropower, thus improving system reliability. In order to achieve such an effect, system adequacy calculations and technology-specific capacity evaluation should be performed based on a sophisticated energy system simulation approach. However, theoretically ideal solutions often fail in practice due to imperfections in policy design and system constraints. Therefore, a capacity mechanism should be carefully adapted to the needs and limitations of the country where it is to be introduced.

The second policy choice noted in the introduction was: *Should subsidies for renewables be wholly or partially canceled to avoid double payment?* A summary of existing policy designs for combining capacity mechanisms with renewable energy support is presented in Table 2 and discussed below.

If the level of renewable energy support is defined centrally, for example in the form of feed-in tariffs or premiums, the aim is to ensure sufficient profitability for renewable energy investments. Any extra revenues will therefore result in windfall profits for such investments and an unnecessary burden on taxpayers. Reducing the level of remuneration for renewables in accordance with the amount of revenues received from capacity mechanisms, as in the *French*, *Irish*, and *Italian* policy mixes, appears to be a viable solution. In such cases, system reliability requirements can potentially determine the technological mix of renewables in the system. Total prohibition of support for renewables if they participate in the capacity mechanism avoids over-subsidization. But, in contrast to the partial reduction of the support, the total removal of the support for renewables will reduce the profitability of new renewable energy investments and thus may slow down their rollout. Such a solution is implemented in *Poland* and the *UK*. It is reasonable to expect that in this policy design, new renewable energy investments will opt for renewables support, but after their expiration will seek to join the capacity mechanism. In this case, system reliability requirements would not affect the development of renewables, which, nevertheless, can be managed manually by technology-specific renewables support policy.

Renewable energy support in the form of tenders is often implemented in parallel with conventional capacity market auctions or direct payments. In such cases, the remuneration gained by renewables at the auction often represents both renewables support and capacity remuneration simultaneously. Technological mix development can be handled centrally by allowing different quotas for different technology types. This policy choice has been made in *Brazil*, *Colombia*, *Guatemala*, *Peru*, *Russia*, and *Spain*.

Table 2
Summary of policy choices on combining capacity mechanism and renewable energy support.

Capacity mechanism	RE support	Combination of the two	Capacity mechanism can steer RE-technology mix	Countries
Capacity market & direct payments	Centrally defined (feed-in tariffs, premiums, direct subsidy)	Diminishes RE support on capacity revenues	Yes	France, Ireland, Italy
		Prohibits RE support if entering a capacity market	No	Poland, UK
		RE is not allowed to participate in a capacity mechanism	No	Dominican Republic, Greece, Turkey
	Tendering	Occur in parallel but do not overlap	No	Brazil, Colombia, Guatemala, Peru, Russia, Spain
	Market-based (tradable REC)	No constraints on receiving both	Yes	South Korea, United States
		Prohibits RE support if joining capacity mechanism	No	Chile, Northern Ireland
Strategic reserve	Any type	RE is not allowed to participate in a capacity mechanism	No	Belgium, Germany, Finland, Norway, Sweden
Any type	No support	RE can participate in a capacity mechanism	Yes	Portugal, SW Australia

Market-based renewable energy support, such as renewable energy certificate trading, should in theory automatically adjust the levels of renewables remuneration in response to extra revenues from capacity mechanisms. This is, perhaps, the most logical solution for the combination of capacity revenue and renewable energy support, where the levels of both are defined by market forces and fulfill both low-carbon targets and energy system reliability requirements. Such a policy design exists in *South Korea* and the *United States*. However, the benefits of this policy choice can only be achieved in a well-developed and efficient electricity market. Market imperfection considerations are taken into account in *Northern Ireland*, where renewables are not allowed to participate in the capacity mechanism if they receive renewable energy support.

When renewables are able to compete with conventional energy on equal terms, because renewable energy technology costs are sufficiently low and/or renewable energy resources are abundant in a specific location, specific support is no longer needed, and the capacity mechanism alone provides additional revenues for renewables. This is the case in *Australia* and *Portugal*. While Australia is an example of a country with frequent renewables participation in its capacity market, Portugal has not yet succeeded in this sense.

If a capacity mechanism takes the form of a strategic reserve, renewables are excluded. However, a rising share of renewables may lead to a need for an increasingly large and expensive reserve. Therefore, excluding renewables from the capacity mechanism can potentially reduce energy system reliability in the long run.

The third policy choice we set out to review was: *Since the economic purposes of capacity mechanisms and renewable energy* support *are different, should they coexist?* The purpose of renewable energy support is to decarbonize the energy sector, while a capacity mechanism is meant to ensure the reliability of the entire energy system. However, the feasibility and the modus of coexistence depend on the types of mechanisms in place. If both are market-based, they can coexist without interventions. If renewable energy support is centrally defined, its level should be reduced according to the revenue received from the capacity mechanism.

All other types of existing policy arrangements in practice exclude the coexistence of the capacity mechanism and renewable energy support, with the exception of tendering. In the case of tendering for renewable energy support, the determinant of the energy-technology mix is shifted from market forces to the authorities. Such a policy arrangement is a practical solution for less efficient markets.

Coordination of capacity mechanisms with renewable energy support, either ensured centrally through auction-based schemes or balanced by market forces, is crucial for balanced development of the energy system and cost-efficiency of both schemes. If not harmonized, the two policies might work against each other leading to an inefficient and unsustainable scenario, where a rising share of renewables creates a need to increase conventional power generation capacity.

As we can see, a variety of approaches exist. Currently, however, there are not enough empirical and simulation studies to enable general recommendations. Furthermore, many capacity mechanism designs have only recently been introduced and there is insufficient evidence to judge the relative merits of the different designs and which design performs best in which circumstances. The very definition of success in this area where different economic aims coexist remains to be established. Extensive further research is required to assist policymaking.

6. Limitations of the study

This review is limited in its geographic scope to countries that had in place some kind of capacity mechanism as of 2021. The review focused on the interaction between capacity mechanism and renewable energy support. When classifying capacity mechanisms, some simplifications are necessary to avoid operating with too many categories, and two instruments classified as one type in our review can have some differences in the details of their design [5]. We did not dwell on the instruments themselves and their history in each country. Instead, our focus was on the current or officially planned state of the policy mix. In particular, we checked whether renewable energy installations are allowed to participate in a capacity mechanism, and if yes, what happens with any renewable energy support for which they are eligible. We did not assess the efficiency nor attempt empirical analysis of the outcomes of the various policy mixes. Many of the policy mixes covered in the review have not produced any relevant outcomes yet as they were only recently implemented or only planned for implementation in the near future. Nevertheless, we did discuss the potential effects of different policy mixes and their policy implications.

7. Conclusions and prospects

With the growing number of capacity mechanisms worldwide and the growing share of renewables in the energy mix, states face a policy design challenge: How should they combine support for renewables with a capacity mechanism, while simultaneously ensuring the cost-efficiency of renewable energy support and energy system adequacy. By providing a systematic review of practices on this issue, this paper gives academics and policymakers alike an overview of the global landscape and the options that have been tried out so far. A variety of approaches have been implemented in different countries, including keeping the two schemes separate, prohibiting support for renewables when they participate in the capacity mechanism, adjusting the level of renewables support according to the amount of capacity revenue received, letting markets define the level of both, shutting down renewable energy support entirely, and using capacity mechanism principles to support renewables. The choice of approach is determined by multiple factors, including the type of capacity mechanism and renewable energy support in place, energy system characteristics, the efficiency of the electricity market, and the political context in the country. Without harmonization with capacity mechanisms, renewable energy support may lead to inefficient policy and unbalanced energy system development—including, paradoxically, a need for more fossil energy.

There remains an evident gap in the literature concerning the *effect* of policy decisions at the country and regional levels. In future research, each country's legal framework and institutional design could be explored in greater detail as a descriptive case study. Empirical studies are required to compare the effectiveness of different capacity mechanism arrangements, to elucidate whether renewables contribute to market adequacy, and to establish whether renewable energy investors are able to pay off under different approaches to combining capacity mechanisms and renewable support. Such empirical investigation is necessary for every country where capacity mechanisms are present. A meta-analysis then would create a strong foundation for comparative characterization of different policy arrangements.

A large body of literature exists comparing the performance and influence of different renewable energy support mechanisms [19,20] but none of these analyses takes capacity markets into account or considers them as an alternative. Therefore, modeling how the behavior of renewable energy investors is shaped by the presence of a capacity market would be an important addition to the literature on renewable energy. Again, different policy design options can have different effects and create different incentives for renewable energy investments. These differences should be carefully studied in order to draw a holistic picture of how different policy designs affect the investment atmosphere and technology mix development. Simulation and empirical studies that focus on whether capacity mechanisms can effectively dictate the renewable energy technology mix would be valuable.

Finally, it would be interesting to design a type of renewable energy support that takes into account energy system reliability needs independently of the presence and of a capacity mechanism and its type. Such a support mechanism should make it possible to raise the share of renewable energy in the electricity mix with less impact on energy system reliability, less need for backup capacity, and thus, in a more cost-efficient way.

Author contributions

Mariia Kozlova: Conceptualization, Formal Analysis, Data curation, Methodology, Investigation, Visualization, Writing - Original Draft. Indra Overland: Conceptualization, Writing - Review & Editing.

Declaration of competing interest

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

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