Influence of Non-harmonized Capacity Mechanisms in an Interconnected Power System on Generation Adequacy

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***Abstract*—Insufficient incentives from the market lead to threats to generation adequacy. In order to create more steady investment signals, capacity mechanisms (CMs) are discussed in many European countries. CMs are discussed to complement energy-based market designs and ensure long-term generation adequacy. The introduction of a CM has an impact, both in the implementing but also in interconnected neighbouring countries. Hereby, the participation of non-domestic capacity at the CM through interconnection to enhance generation adequacy is often only limited or not at all possible. Current discussion is mostly based on qualitative studies. The possible joint impacts are discussed applying economic theory and transferred experience from world-wide implementations. This paper introduces an equilibrium model that allows for quantitative studies directly aiming on the possible interaction on interconnected countries with no, different or equal market designs including CMs. Changing market settings and increasing interconnection capacities can be researched to underpin the qualitative discussion. The cross-border effects are studied that arise if harmonization of CM or cross-border participation are neglected. A case study simulates two interconnected countries in a symmetrical set up to trace down the changes in the results to changes of market design and interconnection capacity. Results show that the change of market design in neighbouring countries has a strong impact on domestic generation adequacy. Increased interconnection capacity can have counter-intuitive effects on the overall generation adequacy.**

***Index Terms*—capacity mechanism, mixed complementarity problem, cross-border effect, interconnection**

NOMENCLATURE

Sets

$t \in \mathcal{T}$	Set of time steps
$c \in \mathcal{C}$	Set of countries
$k \in \mathcal{K}$	Conventional technologies
$j \in \mathcal{J}$	RES technologies

Parameters

$V_{c,k}$;$V_{c,j}$	Variable cost of technology k or j
$I_{c,k}$	Investment cost of technology k
$R_{c,k}$	Ramping capability of technology k
$A_{c,j,t}$	Availability of RES technology j at time t
$C_{c,j}$	Installed capacity of RES technology j
$IC_{c,c}$	Interconnection capacity between two countries
E_c	Elasticity in inverse demand function
$f_c^{\text{p,ccm}}$	Factor for target price at cCM
$f_c^{\text{d,ccm}}$	Factor for target capacity demand at cCM
f_c^{sr}	Factor for share of SR
$\overline{P}_c^{\text{em(,sr)}}$	Price cap for different markets
P_c^{T}	Target price for cCM
$D_{c,t}$	Reference demand on energy-based market
P_c^{R}	Reference price on energy-based market

Variables

$d_{c,t}$	Demand (energy-based)
$z_{c,t}$	Market intervention (energy-based)
$\beta_{c,t}$	Dual variable of demand (energy-based)
d_c^{crm}	Capacity demand at CM
z_c^{crm}	Shortage at CM
β_c^{crm}	Dual variable of demand at cCM
$f_{c,c,t}$	Flow over the interconnection in time step t
$\mu_{c,c,t}^{\text{f}}$	Marginal value of interconnection capacity
$g_{c,k,t}$;$g_{c,j,t}$	Generation of technology k or j at time t
$cp_{c,k}$	Installed capacity of technology k
$\mu_{c,k,t}$;$\mu_{c,j,t}$	Marginal value of capacity (energy-based)
$\rho_{c,k,t}^{\text{up}}$;$\rho_{c,k,t}^{\text{dn}}$	Marginal value of flexibility (up- & downward)
$cp_{c,k}^{\text{crm}}$	Capacity of technology k accepted at CM
$\mu_{c,k}^{\text{crm}}$	Marginal value of capacity at CM
$g_{c,t}^{\text{sr}}$	Generation from SR
$\mu_{c,t}^{\text{sr}}$	Marginal value of SR capacity
$\mu_{c,t}^{\text{crm}}$	Marginal value of demand reduction at dCM
$\lambda_{c,t}$	Hourly price at energy-based market
λ_c^{crm}	Price at the applicable CM

Glossary

cCM	Centralized capacity market
dCM	Decentralized capacity market
EOM	Energy-only market
SR	Strategic reserve

I. INTRODUCTION

The European electricity sector is facing a new challenge. The integration of renewable energy sources (RES) increases the shares of intermittent injections. The low marginal cost of RES, often at zero or below due to subsidies, may threat generation adequacy both on the short- and long-term. The absence of new investment in conventional capacity is observable. In fact, a reduction of power system flexibility due to divestment

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of non-profitable existing capacities is ongoing. For example, although a nuclear phase was announced in Belgium intending a reduction of 6 GW (peak demand in 2015: 13.8 GW) in the following 9 years, substantial investments in new dispatchable generation units have not taken place. To the contrary, gas-fired power plants announced to decommission because of ageing and/or their non-profitability. In consequence, the nuclear phase-out has been postponed to 2022-2025, a strategic reserve is implemented to keep existing power plants available and incentives for new gas-fired power plants are discussed [1].

In a well-designed market, both, long-term generation adequacy and short-term reliability have to emerge from market incentives, i.e., remuneration for energy output, providing flexibility, or ensuring availability. The remuneration can be energy- or capacity-based. Energy-based remuneration (in €/MWh) is most common in current market designs. Capacity-based remuneration (in €/MW) is realized through CMs. The introduction of CMs changes the market design from energy-only markets that were predominant in Europe. The interaction of CMs and policy targets for RES are modelled and discussed in [2] and [3]. In future low-carbon power systems, CMs may offer one possible option to ensure generation adequacy.

CMs are implemented in European countries to help to achieve national generation adequacy targets. National CMs may introduce distortion in neighbouring countries and implicit competition between market designs. The objective to reach an European-wide economically efficient mix might not be reached due to inefficient investment signals originating from different market designs [4]. The aim for national generation adequacy rather than aiming for regional coordination can significantly hamper potential benefits of an integrated long-term expansion of the European power system [5]. Therefore, the possible effects with neighbouring markets makes the implementation of CM complicated [6]. First results after the introduction of the GB capacity market show that ignoring the contribution of interconnectors leads to inefficiencies. It impedes the harmonization process by weakening the business case for interconnectors [7]. A possible coordination of capacity policies such as implementing a CM and integration policies including increased transmission capacity is highlighted in [8]. The role of the interconnector and market is shown in a system dynamics model for two countries. Similar studies on the impact of CMs in interconnected markets use different modelling approaches. A study on cross-border effects including a centralized capacity market and a strategic reserve using agent-based modelling can be found in [9]. The model focusses on long-term dynamics. An additional study based on a system dynamics model is presented in [10]. It includes a detailed discussion on the investment decision and studies among others also the influence of a price cap and security margins in the energy-based market.

The research question of this paper is focussed on the interaction of interconnection capacity and changing market designs including a CM. The market design refers to an energy-only market (EOM) or a possible combination of an energy-based market and a complementary capacity mechanism (CM). The considered CMs in this paper are a strategic reserve (SR), a centralized capacity market (cCM), or a decentralized capacity market (dCM). The effect of a given market design on the generation mix, generation adequacy and the economic efficiency is already researched in [11]. The focus of this paper is put on market configurations with different market designs in countries that are interconnected with transmission capacity used for market harmonization aiming at price convergence on the energy-based market.

To answer the stated research question, this paper introduces an equilibrium model that allows for quantitative studies directly aiming on the possible interaction on interconnected countries with no, different or equal market design including CMs. Changing market settings and increasing interconnection capacities can be researched to underpin the qualitative discussion. The equilibrium reveals prices for the energy- and capacity-based market, installed capacities, and indicators on the generation adequacy such as energy non-served.

Section II briefly introduces the modelled market designs including the CMs. The transfer into the mathematical formulation is presented in Section III. The case study is introduced in Section IV. The discussion of results follows in Section V. Section VI concludes the findings of the paper.

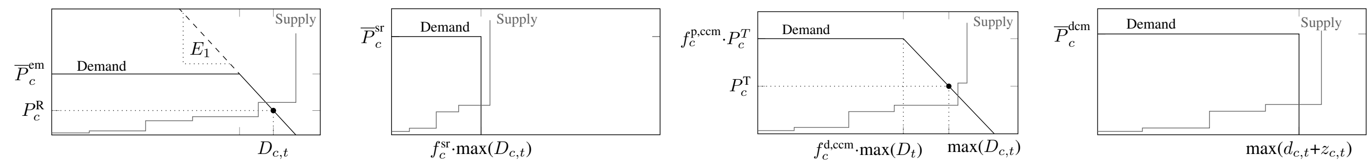
II. Modelling approach

This section briefly justifies the choice for mixed complementarity problem (MCP) and introduces the modelled CMs. A detailed discussion of the different concepts is not in the scope of the paper. The important elements of the market designs for the modelling approach are outlined. A more detailed discussion of the differing CMs is done in [11].

A. Mixed Complementarity Problem (MCP)

Mixed complementarity problems (MCPs) can be used to model energy and network-based markets. Specific applications of MCPs to model capacity mechanisms can be found in [11], [12] and [13]. Because of the perfect competition assumption, same results can be achieved by modelling a cost minimization if the sloped demand curve are incorporated. The presented MCP is chosen because the modelling technique ensures good traceability of results. Direct economic links can be derived from the mathematical formulation of the different market designs due to the interpretation of the dual variables. The interpretation of the dual variables in the discussion of the model highlights the different revenues to justify generation, offering capacity to the CM and to invest in the installation of capacity. For a further relaxation of the perfect competition assumption, such as modelling risk-averse behaviour, the presented formulation offers a starting point.

The model is a market equilibrium model. Producers, consumers and the interconnection operator with opposing objectives are incorporated. Generation technologies maximize their producer surplus, while the demand maximizes its consumer surplus over different markets. The market participants are connected via hourly clearings of energy-based markets and yearly capacity-based markets, if applicable. The flows over



(a) Energy-based Market (b) Strategic Reserve Market (c) Centralized Capacity Market (d) Decentralized Capacity Market

Figure 1. Overview for different markets (w/o import/export)

the interconnection are optimized to arbitrage the price difference on the energy-based market between the two connected countries. The solution of the optimization problem satisfies the first-order conditions (Karush-Kuhn-Tucker (KKT) conditions) and reflects the behavioural conditions of all market participants [14].

B. Modelled Market Designs

In total four different market designs are modelled, namely an energy-only market (EOM), strategic reserve (SR), a centralized capacity market (cCM), and a decentralized capacity market (dCM). The distinguishing parameters are discussed in what follows.

1) Energy-only market (EOM): In each country, the modelled EOM is defined by an hourly market clearing based on traded energy (Fig. 1a). This results in an hourly uniform market clearing price $\lambda_{c,t}$. The demand curve is modelled with two parts. It is partly price elastic. The level of price responsiveness is defined with a given elasticity E_c, a reference price P_c^{R}, and an initial demand profile $D_{c,t}$. The demand is price responsive until the maximum price $\overline{P}_c^{\text{em}}$. If the price reaches the price cap and the supply is not sufficient, market intervention, i.e., a partial load shedding, is necessary. The supply is given by the offered available generation. Additionally, import and export flows with interconnected countries may occur. If there is an additional CM implemented, this market is referred to as energy-based market.

2) Strategic Reserve (SR): A SR is contracted in an additional market next to the energy-based market (Fig. 1b). The SR market is defined by a given inelastic demand which is set as a share of the initial peak demand $f_c^{\text{sr}}{\cdot}\max(D_{c,t})$. In the case study a predetermined share of 10 % is chosen. The SR contracting in an annual market yields one capacity-based price λ_c^{crm}. The upper limit of the capacity price $\overline{P}_c^{\text{sr}}$ is set to twice the Cost of New Entry (CONE), i.e., the annualized fixed costs of the *Peak* technology. The supply side is defined by the offered conventional generation from the domestic generation technologies. The contracted capacity $cp_{c,j}^{\text{crm}}$ cannot be used on the energy-based market by the capacity owner any more, but the SR $g_{c,t}^{\text{sr}}$ is activated by the system operator if the price reaches the price cap $\overline{P}_c^{\text{em}}$ to avoid otherwise necessary partial load shedding.

3) Centralized Capacity Market (cCM): In the cCM design, an additional annual market clearing complements the energy-based market (Fig. 1c). The demand is set by an authority based on two factors. The first reference point is given by the capacity target which is defined as the initial peak demand $\max(D_{c,t})$ and the associated target price P_c^{T} equal to the CONE. The second reference point depends on the two design parameters $f_c^{\text{d,ccm}}$ and $f_c^{\text{p,ccm}}$. The point is set at the minimum capacity demand $f_c^{\text{d,ccm}}{\cdot}\max(D_{c,t})$ at which the authority is willing to pay the maximum price $f_c^{\text{p,ccm}}{\cdot}P_c^{\text{T}}$. The case study uses the two factors $f_c^{\text{d,ccm}}$=0.97 and $f_c^{\text{p,ccm}}$=2. The supply side is formed by domestic generation capacity. Each conventional generators still operates its generating unit on the energy-based market independent of the contracted capacity to the capacity market. The decision of activation is only influenced by the variable cost and the energy-based price.

4) Decentralized Capacity Market (dCM): The dCM is an additional annual market next to the energy-based market. In contrast to the other mechanisms, the determination of capacity demand is linked with consumption at the energy-based market. Consumers are obliged to back their peak energy demand with obligations at the dCM. The volume of obligations is modelled as the peak consumption on the energy-based market and therefore only materializes during the model run. The determination results in a capacity demand which is equal to the maximum of elastic demand and market intervention at the energy-based market $\max(d_{c,t}{+}z_{c,t})$ (Fig. 1d). It is assumed that consumers are aware of the market mechanism and the calculation of obligations. Consumers can react to the energy-based market outcome to reduce peak energy demand and consequently the capacity demand. This introduces a direct link between peak demand levels at the energy-based market and capacity obligations. The price cap $\overline{P}_c^{\text{ccm}}$ is set to twice the CONE. The supply side for the obligations is formed by the domestic generation technologies. Each conventional generators still operates its generating unit on the energy-based market independent of the contracted capacity to the capacity market. The decision of activation is only influenced by the variable cost and the energy-based price.

III. Methodology

This section introduces the model assumptions and mathematical formulation of the market designs. An elaborate description of the EOM model is given. The other market designs are described based on the changes to the equations compared to the EOM. An overview of the used equations for each market design is given in Table I. Multiple countries can be implemented by using the appropriate equations per country for the chosen market design and incorporate the conditions for the interconnector. The following model formulation is presented in [11] and extended for this paper to facilitate multiple interconnected countries. The formulation of the primal problems for each market participant is attached in appendix A

A. Model assumptions

For every market design, perfect competition and perfect information for all market participants are assumed. The exercise of market power is not possible. Each technology and the operator of the interconnector act as price taker. The information includes the demand profiles and investment costs for the whole span of simulation. Hence, the future revenues from the hourly market clearing are known at the time of investment. A one-time investment decision is taken.

B. Energy-Only Market (EOM)

This section briefly describes the EOM model. The EOM only incorporates the energy-based market. The reader is refereed to [12], [13] for a detailed discussion on such a model.

1) Conventional Generation Technologies: Each conventional generation technology is clustered in one producer indexed by k in each country c. The technologies differ in variable costs $V_{c,k}$, annualized investment cost $I_{c,k}$ and ramping rate $R_{c,k}$, i.e. flexibility. The objective of a producer is to maximize its producer surplus, i.e., the difference of achieved revenues and the minimum required revenues. The minimum required revenues cover the cost for generation and investing in capacity. The formulation of the problem in KKT-condition yields the following constraints:

$$\begin{aligned}
\forall c,k,t: 0 \leq & -\lambda_{c,t} + V_{c,k} + \mu_{c,k,t} + \rho^{\text{up}}_{c,k,t} \\
& -\rho^{\text{up}}_{c,k,t+1} - \rho^{\text{dn}}_{c,k,t} + \rho^{\text{dn}}_{c,k,t+1} \quad \perp g_{c,k,t} \geq 0 \quad \text{(1a)} \\
\forall c,k: \quad 0 \leq & -\sum_{t\in T} \left[\mu_{c,k,t} + R_{c,k} \cdot (\rho^{\text{up}}_{c,k,t} + \rho^{\text{dn}}_{c,k,t})\right] \\
& + I_{c,k} \quad \perp cp_{c,k} \geq 0 \quad \text{(1b)} \\
\forall c,k,t: 0 \leq & \; cp_{c,k} - g_{c,k,t} \quad \perp \mu_{c,k,t} \geq 0 \quad \text{(1c)} \\
\forall c,k,t: 0 \leq & \; g_{c,k,t\text{-}1} - g_{c,k,t} + R_{c,k} \cdot cp_{c,k} \perp \rho^{\text{up}}_{c,k,t} \geq 0 \quad \text{(1d)} \\
\forall c,k,t: 0 \leq & \; g_{c,k,t} - g_{c,k,t\text{-}1} + R_{c,k} \cdot cp_{c,k} \perp \rho^{\text{dn}}_{c,k,t} \geq 0 \quad \text{(1e)}
\end{aligned}$$

Eq. (1a) shows that producers generate electricity if the hourly price $\lambda_{c,t}$ covers the sum of variable costs ($V_{c,k}$), the scarcity rent $\mu_{c,k,t}$ and flexibility rents $\rho^{\text{up}}_{c,k,t}$, $\rho^{\text{dn}}_{c,k,t}$. Installed capacity is only justified if the fixed costs $I_{c,k}$ are covered by sufficient accumulated scarcity rents and flexibility rents (1b). Eq. (1c)-(1e) represent the capacity and ramping limits for each conventional technology, with corresponding scarcity rent and flexibility rents, respectively.

2) Renewable Energy Sources: The RES indexed by c, j maximize the producer surplus as well. In contrast to the conventional technologies, only the generation schedule is determined by the model. The installed capacities are fixed. The optimization problem is described with the following KKT-conditions:

$$\begin{aligned}
\forall c,j,t: 0 \leq & -\lambda_{c,t} + V_{c,j} + \mu_{c,j,t} \perp g_{c,j,t} \geq 0 \quad \text{(2a)} \\
\forall c,j,t: 0 \leq & -g_{c,j,t} + A_{c,j,t} \cdot C_{c,j} \perp \mu_{c,j,t} \geq 0 \quad \text{(2b)}
\end{aligned}$$

RES generate electricity if the hourly price $\lambda_{c,t}$ covers the variable costs $V_{c,j}$ and the marginal value of available capacity $\mu_{c,j,t}$ (2a). Eq. (2b) shows that the injection is limited by the installed capacity $C_{c,j}$ times the hourly availability $A_{c,j,t}$, the underlying solar or wind profile per country. The KKT-conditions are independent from the market designs.

3) Demand Side of the Market: The demand side decides on the demand $d_{c,t}$ and regulated market intervention $z_{c,t}$, e.g., partial load shedding, if there is not sufficient supply. The objective is to maximize the consumer surplus. The following KKT-conditions are derived:

$$\begin{aligned}
& \forall c,t: 0 \leq -1/2 \cdot \overline{P}^{\text{em}}_{c} + 1/2 \cdot \lambda_{c,t} + \beta_{c,t} \perp \; d_{c,t} \geq 0 \quad \text{(3a)} \\
& \forall c,t: 0 \leq \beta_{c,t} \quad \perp \; z_{c,t} \geq 0 \quad \text{(3b)} \\
& \forall c,t: 0 = d_{c,t} + z_{c,t} - (\lambda_t - P^0_{c,t})/E_c \quad , \quad \beta_{c,t} \in \mathbb{R} \quad \text{(3c)} \\
& \text{with: } P^0_{c,t} = P^{\text{R}}_c/(E_c \cdot D_{c,t}), \qquad E_c < 0 \quad \text{(3d)}
\end{aligned}$$

Eq. (3a) and (3b) ensure that the demand level and market intervention are chosen so that the total consumer surplus is maximized. The sum of both must be equal to the sloped demand curve (3c). Two possible outcomes depending on demand and supply level are possible. If the demand level lies in the sloped part of the demand curve, the market intervention is zero. If the suppliable demand is below the minimum demand achievable by price response, the gap is filled by market intervention $z_{c,t}$.

4) Energy Balance: The energy balance represents the hourly market clearing for country c. Eq. (4) ensures that the demand $d_{c,t}$ is covered by generation from conventional and RES generation. The energy balance might also be influence by imports or exports.

$$\begin{aligned}
\forall c,t: & \sum_{k\in K} g_{c,k,t} + \sum_{j\in J} g_{c,j,t} + \sum_{cc\in C} (f_{cc,c,t} - f_{c,cc,t}) \\
& = d_{c,t}, \qquad \lambda_{c,t} \in \mathbb{R} \quad \text{(4)}
\end{aligned}$$

C. Interconnection between Market Areas

The operator of the interconnection can purchase on the energy-based market in one country and sell in the interconnected other one. The objective is arbitraging the price difference most optimal with a given interconnection capacity. Additional investment in capacity is not foreseen for the scope of the paper but could be implemented. The optimization problem yields the following constraints:

$$\begin{aligned}
\forall c_1, c_2, t: 0 \leq & -\lambda_{c_2,t} + \lambda_{c_1,t} + \mu^{\text{f}}_{c_1,c_2,t} \perp f_{c_1,c_2,t} \quad (5) \\
\forall c_1, c_2, t: 0 \leq & \; IC_{c_1,c_2} - f_{c_1,c_2,t} \quad \perp \mu^{\text{f}}_{c_1,c_2,t} \quad (6)
\end{aligned}$$

As a result of a flow $f_{c_1,c_2,t}$ between two countries, either prices converge or the interconnection capacity is used fully, so that the dual variable $\mu^{f}_{c_1,c_2,t}$ takes a positive value (6). The dual variable can be interpreted as congestion rent. In this case, flows only occur if the price in importing country c_2 covers the price of the exporting country plus this rent (5).

D. Strategic Reserve (SR)

To fit the model for the SR market design, model changes need to be made for conventional generators and the contracting and activation of SR. A new decision variable for conventional generators is introduced, namely the capacity offered to SR $cp_{c,k}^{\text{crm}}$. The decision on the activation of SR $g_{c,t}^{\text{sr}}$ is taken from the generators.

$$\begin{aligned}
\forall c,k: \quad & 0 \leq -\sum_{t\in T}\left[\mu_{c,k,t} + R_{c,t}\cdot(\rho_{c,k,t}^{\text{up}} + \rho_{c,k,t}^{\text{dn}})\right] \\
& \quad -\mu_k^{\text{crm}} + I_k \qquad \perp \quad cp_{c,k} \geq 0 \qquad (7a) \\
\forall c,k: \quad & 0 \leq -\lambda_c^{\text{crm}} + \sum_{t\in T}\left[\mu_{c,k,t} + R_{c,k}\cdot(\rho_{c,k,t}^{\text{up}} + \rho_{c,k,t}^{\text{dn}})\right] \\
& \quad +\mu_{c,k}^{\text{crm}} \qquad \perp \quad cp_{c,k}^{\text{crm}} \geq 0 \qquad (7b) \\
\forall c,k,t: & 0 \leq (cp_{c,k} - cp_{c,k}^{\text{crm}}) - g_{c,k,t} \quad \perp \quad \mu_{c,k,t} \geq 0 \qquad (7c) \\
\forall c,k,t: & 0 \leq g_{c,k,t\text{-}1} - g_{c,k,t} \\
& \quad +R_{c,k}\cdot(cp_{c,k} - cp_{c,k}^{\text{crm}}) \quad \perp \quad \rho_{c,k,t}^{\text{up}} \geq 0 \qquad (7d) \\
\forall c,k,t: & 0 \leq g_{c,k,t} - g_{c,k,t\text{-}1} \\
& \quad +R_{c,k}\cdot(cp_{c,k} - cp_{c,k}^{\text{crm}}) \quad \perp \quad \rho_{c,k,t}^{\text{dn}} \geq 0 \qquad (7e) \\
\forall c,k: \quad & 0 \leq cp_{c,k} - cp_{c,k}^{\text{crm}} \qquad \perp \quad \mu_{c,k}^{\text{crm}} \geq 0 \qquad (7f)
\end{aligned}$$

The condition for generation remains and is given by (1a). The capacity available for generation and ramping is reduced by the capacity contracted by the SR $cp_{c,k}^{\text{crm}}$ (7c)-(7e). Capacity is offered to SR if the capacity price λ_c^{crm} equals the sum of scarcity rents from the capacity limits (7c),(7f) and flexibility rents (7d),(7e). Eventually, both the rents from energy-based market and SR have to justify the installation of capacity (7a). The equations show the interaction of the two markets for the decision of the conventional generators.

An additional market clearing is introduced (9). The offered capacity from conventional generators equals the predetermined capacity demand. The demand level is set to the maximum of $D_{c,t}$ times a SR sizing factor f_c^{sr}. The marginal value is the capacity price λ_c^{crm}:

$$\begin{aligned}
\forall c,t: & \sum_{k\in K} g_{c,k,t} + \sum_{j\in J} g_{c,j,t} + \sum_{cc\in C}(f_{cc,c,t} - f_{c,cc,t}) \\
& +g_{c,t}^{\text{sr}} = d_{c,t} \qquad , \ \lambda_{c,t} \in \mathbb{R} \qquad (8) \\
\forall c: \quad & 0 = \sum_{k\in K} c_{c,k}^{\text{crm}} + z_c^{\text{crm}} - f_c^{\text{sr}}\cdot\max(D_{c,t}), \ \lambda_c^{\text{crm}} \in \mathbb{R} \qquad (9)
\end{aligned}$$

The SR contracting and activation is modelled individually. A price cap for SR is introduced and a price cap approach is applied:

$$\begin{aligned}
\forall c: \quad & 0 \leq \overline{P}_c^{\text{sr}} + \sum_{t\in T}\mu_{c,t}^{\text{sr}} - \lambda_t^{\text{crm}} \qquad \perp z_c^{\text{crm}} \geq 0 \qquad (10a) \\
\forall c,t: & 0 \leq (\overline{P}_c^{\text{sr}} - \delta) - \lambda_{c,t} + \mu_{c,t}^{\text{sr}} \qquad \perp g_{c,t}^{\text{sr}} \geq 0 \qquad (10b) \\
\forall c,t: & 0 \leq f_c^{\text{sr}}\cdot\max(D_{c,t}) - z_c^{\text{crm}} - g_{c,t}^{\text{sr}} \perp \mu_{c,t}^{\text{sr}} \geq 0 \qquad (10c)
\end{aligned}$$

If there is insufficient capacity during SR contracting ($z_c^{\text{crm}}>0$), the price λ_c^{crm} reaches the price cap $\overline{P}_c^{\text{sr}}$. The SR activation requires the price at the energy-based market $\lambda_{c,t}$ to be at its price cap $\overline{P}_c^{\text{em}}$. The negligible δ ensures that SR are activated prior to market intervention $z_{c,t}$ (10b). The generation from SR is limited by the contracted capacity (10c).

E. Centralized Capacity Market (cCM)

The cCM model requires changes for the conventional generators and demand side. Similar to the SR model, conventional generators additionally decide on the capacity sold to the capacity market $cp_{c,k}^{\text{crm}}$. However, in contrast to SR, the decision on the generation is not affected. Consequently, the KKT-conditions for the producers are a mix from the previous market designs. Eq. (1a),(1c)-(1e) apply for the generation, capacity limit and ramping. The decision on the installed capacity and the limitation of offered capacity to the cCM is taken from the SR model (7a),(7f). The difference is the missing link of the generation and the capacity offered to the cCM. Consequently, the offered capacity only has to be justified by the price at the cCM:

$$\forall c,k: 0 \leq -\lambda_c^{\text{crm}} + \mu_{c,k}^{\text{crm}} \perp cp_{c,k}^{\text{crm}} \geq 0 \qquad (11)$$

A capacity balance representing the cCM market clearing is added. The capacity market results in a market clearing at the market price λ_c^{crm}:

$$\forall c: 0 = \sum_{k\in K} cp_{c,k}^{\text{crm}} - d_c^{\text{crm}}, \quad \lambda_c^{\text{crm}} \in \mathbb{R} \qquad (12)$$

The demand side of the cCM is similar to the energy-based market with a partly sloped demand curve. The shape of the curve is predetermined. This results in the following:

$$\begin{aligned}
& \forall c: \text{(applies for (13a)-(13c))} \\
& 0 \leq -1/2\cdot f_c^{\text{p,ccm}}\cdot P_c^T + 1/2\cdot\lambda_c^{\text{crm}} + \beta_c^{\text{crm}} \perp d_c^{\text{crm}} \geq 0 \ (13a) \\
& 0 \leq \beta_c^{\text{crm}} \qquad \perp z_c^{\text{crm}} \geq 0 \ (13b) \\
& 0 = d_c^{\text{crm}} + z_c^{\text{crm}} - (\lambda_c^{\text{crm}} - P_c^{0,\text{crm}})/M_c^{\text{crm}} \qquad \beta_c^{\text{crm}} \in \mathbb{R} \ (13c) \\
& \text{with } M_c^{\text{crm}} = \frac{((f_c^{\text{p,ccm}} - 1)\cdot P_c^{\text{T}})}{((f_c^{\text{d,ccm}} - 1)\cdot\max(D_{c,t}))} \\
& \text{and } P_c^{0,\text{crm}} = P_c^T - M_c^{\text{crm}}\cdot\max(D_{c,t})
\end{aligned}$$

Similar to the energy-based market, Eq. (13a) and (13b) ensure that the demand level d_c^{crm} and market intervention z_c^{crm} are chosen so that the consumer surplus is maximized. A market intervention z_c^{crm} occurs if the supplied capacity is below the minimum targeted capacity $f_c^{\text{d,ccm}}\cdot\max(D_{c,t})$. In that case, the price reaches the price cap $f_c^{\text{p,ccm}}\cdot P_c^{\text{T}}$. Eq. (13c) requires that the sum of demand and market intervention is equal to the predetermined inverse demand function. The demand side for the energy-based demand remains the same and equations (3a)-(3c) are added.

F. Decentralized Capacity Market (dCM)

The dCM model only differs from the cCM for the demand side. Hence, the equations for the producers and RES are unchanged (see Table I). The market clearing of the dCM requires that the offered capacity is equal to the demand of obligations d_c^{crm}. Eq. (15a) ensures that the demand of

TABLE I. USED EQUATIONS IN MODELS PER MARKET DESIGN

Type	Conventionals	RES	Demand Side	Inter-connector	Market
EOM	(1a)-(1e)	(2a)-(2b)	(3a)-(3c)	(5)-(6)	(4)
SR	(1a),(7a)-(7f)	(2a)-(2b)	(3a)-(3c), (10a)-(10c)	(5)-(6)	(8),(9)
cCM	(1a),(1c)-(1e), (7a),(7f),(11)	(2a)-(2b)	(3a)-(3c), (13a)-(13c)	(5)-(6)	(4),(12)
dCM	(1a),(1c)-(1e), (7a),(7f),(11)	(2a)-(2b)	(3a)-(3c), (15a)-(15e)	(5)-(6)	(4),(14)

obligations is larger than the energy-based peak demand and market intervention if applicable.

$$\forall c: \quad 0 = \sum_{k \in K} cp_{c,k}^{\text{crm}} + z_c^{\text{crm}} - d_c^{\text{crm}}, \quad \lambda_c^{\text{crm}} \in \mathbb{R} \qquad (14)$$

$$\forall c,t: 0 \leq -d_{c,t} - z_{c,t} + d_c^{\text{crm}} \quad \perp \quad \mu_{c,t}^{\text{crm}} \geq 0 \quad (15a)$$

If the supply at the dCM is lower than the capacity demand d_c^{crm}, the gap is filled by a market intervention z_c^{crm}. The price for capacity is then set to the price cap $\overline{P}_c^{\text{crm}}$ (15b).

$$\forall c: 0 \leq \overline{P}_c^{\text{crm}} - \lambda_c^{\text{crm}} \quad \perp z_c^{\text{crm}} \geq 0 \qquad (15b)$$

$$\forall c: 0 \leq \lambda_c^{\text{crm}} - \sum_{t \in T} \mu_{c,t}^{\text{crm}} \perp \overline{d}_c^{\text{crm}} \geq 0 \qquad (15c)$$

The interaction of the dCM with the energy-based market is also reflected in the conditions for the demand at the energy-based market:

$$\forall c,t: 0 \leq -1/2 \cdot \overline{P}_c^{\text{em}} + 1/2 \cdot \lambda_{c,t} + \beta_{c,t} + \mu_{c,t}^{\text{crm}} \perp d_{c,t} \geq 0 \quad (15d)$$

$$\forall c,t: 0 \leq \beta_{c,t} + \mu_{c,t}^{\text{crm}} \qquad \perp z_{c,t} \geq 0 \quad (15e)$$

The marginal value from the capacity demand $\mu_{c,t}^{\text{crm}}$ introduces the link between energy-based market and dCM. If demand at the energy-based market $d_{c,t}$ is at the maximum, the marginal value is positive (15d), thus, the increase of consumer surplus by additional demand is also weighted against the increase of capacity demand.

IV. CASE STUDY

A case study is done to illustrate the application of the model on a small scale power system with two interconnected market areas. The case study is organized in 5 scenarios. Firstly, the reference scenario is the situation with an EOM in both countries. Secondly, one country introduces a dCM to address the problem of generation adequacy. Thirdly, the other country implements a CM with the decision known of the other country resulting in 3 more scenarios.

A. Case: Three Country System

The case study applies the model on two identical market areas, named A and B. The two countries are interconnected with a given transmission capacity available for exporting respectively importing energy. Hence, a symmetrical system is created, so that the model results focus on the changing market designs. Fig. 2 illustrates the three examined stages. As reference scenario serves a situation with an EOM in both

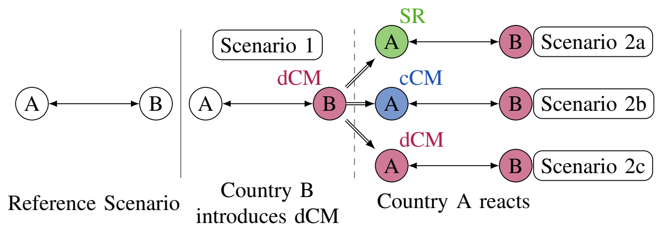


Figure 2. States of market design configuration

countries. As the countries are perfectly symmetrical, the size of the interconnection does not influence the result of the reference scenario.

Scenario 1 represents a change to the market situation. Country B introduces a dCM, while country A still organizes its market as an EOM. As the change of market design in country B changes the situation in country A, country A determines the optimal response. The response could include keeping the EOM (Scen. 1) or also change the market design to either SR (Scen. 2a), cCM (Scen. 2b) or dCM (Scen. 2c). For all scenarios, sensitivities on the interconnection capacity are conducted. This analysis reaches from no interconnection to an interconnection capacity one third the size of the initial peak demand.

B. Data Input

The case study uses data from the Belgian system, retrieved from the Belgian transmission system operator (TSO) Elia [15]. Demand, wind and solar profiles are taken and equally applied on both countries. This is an assumption of the case study to enable the tracing of the model results back to the change of market design. The generation technologies are grouped into three groups, namely *Base*, *Mid* and *Peak*. The technologies differ in their economic parameters, namely annualized fixed costs ($I_{c,k}$) and variable costs ($V_{c,k}$), as well as in their technical flexibility, i.e., the ramping rate ($R_{c,k}$). Similar to the input profiles, the parameters are chosen the same for both countries. The used input parameters are shown in Table II. Additionally, two RES technologies are introduced exogenously. The arbitrarily chosen installed capacities ($C_{c,j}$) for *PV* and *Wind* are given in Table II. The demand is assumed to have a given elasticity of E_c=-0.1 in each country. The reference price P_c^{R} for the demand is calculated for each individual scenario with inelastic demand (E=∞) [11]. In case of energy non-served (ENS), the energy non-served is valued with the maximum market price at the energy-based market, i.e., 3 000 €/MWh, and added to the total cost of the system. This is a conservative assumptions as the value of lost load is considered higher which would lead to even more impact of the ENS on the total cost.

V. RESULTS

The results of the case study are presented along three indicators. Firstly, the installed capacities give insight on the shift of capacity due to different market configurations. Secondly, the flows over the interconnection are examined. Thirdly, the market configurations are discussed with respect

TABLE II. Input parameter for market technologies

Type	$V_{c,k(,j)}$ [€/MWh]	$I_{c,k}$ [€/MW.year]	$I_{c,k}$ [€/MW.20d]	$R_{c,k}$ [%/h]	$C_{c,j}$ [MW]
Base	36	179 865.55	9 855.65	20	-
Mid	53	101 095.36	5 539.47	50	-
Peak	76	68 779.16	3 768.72	100	-
PV	0	-	-	-	5100
Wind	0	-	-	-	2000

TABLE III. Cost per energy served (Energy-based) [€/MWh]

	Country A			Country B		
	Interconnection IC [MW]			Interconnection IC [MW]		
	0	1500	3000	0	1500	3000
Reference	57.90	57.90	57.90	57.90	57.90	57.90
Scenario 1	57.90	57.91	57.85	49.67	49.73	57.96
Scenario 2a	58.01	58.03	58.09	49.67	49.73	55.56
Scenario 2b	49.67	49.67	49.67	49.67	49.67	49.67
Scenario 2c	49.67	49.67	49.67	49.67	49.67	49.67

to the energy non-served. Finally, a system cost comparison based on the cost per energy-served is done.

A. Reference Scenario

In the reference scenario the installed capacities and generation mix are equal for both countries and do not change with increasing interconnection capacity (Fig. 5). This is due to the symmetrical design of the case study. Consequently, the interconnection has no value and there are no flows over the interconnection (Fig. 3). Moreover, the cost for energy served is equal in both countries (Table III). As a result, the total cost (energy-based) (Table IV) are the same, as there are no capacity-based costs in a scenario with an EOM. In both countries, the installed capacity is not sufficient to supply the demand in all time steps. The consequence is energy non-served (Fig. 4). The resulted energy non-served is relatively small compared to the total served demand (0.14 %). As the ENS does not change with the interconnection capacity the total cost including the cost for ENS (Table IV) are equal for all interconnection capacities. The total cost including ENS are highest for *B* compared to all other scenarios. For country *A*, the reference scenario shows the second highest cost, only the Scenario 1 gives higher costs for consumers in *A*. The results of the reference scenario serves as baseline to evaluate the decision taken to change the market designs in the following scenarios.

B. Scenario 1

In the following scenario 1, *B* introduces a dCM which leads to an opposed change in installed capacities in both countries. Due to the obligation to back up energy peak demand by capacity in *B*, the installed capacity increases in *B*. If interconnection is available, the installed capacity in *A* is reduced (Fig. 5). This can be explained by the cheaper offered

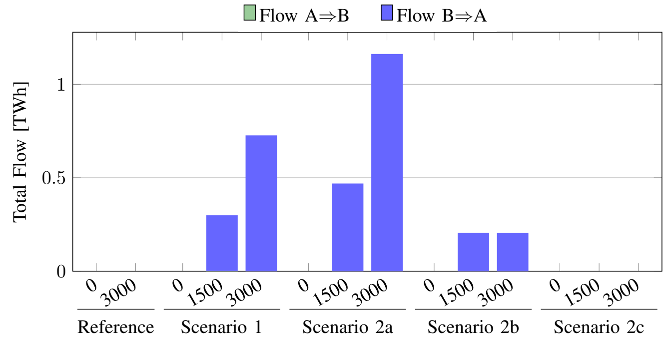


Figure 3. Cross-border flows for market configurations

energy on the energy-based market in *B* because of the complementary remuneration from the dCM. This consequently leads to cross-border flows from *B* to *A* making investment in *A* less attractive (Fig. 3). In terms of energy non-served, two effects can be observed. First, with no or low interconnection, *B* solves its problem of energy non-served. For *A*, the amount stays unchanged, as both the reduction of installed capacities and imported energy balance out. Second, if there is a lot of interconnection capacity, the reduction of capacity in *A* outweighs the benefit of cross-border flows and energy non-served increases again to the observed level of the reference scenario. Although *B* introduces a dCM energy non-served occurs because there is no mechanism in place that prevents the burden sharing in case of simultaneous peaks. In terms of total costs the same distinction as for the energy non-served can be done (Table IV). With no or low interconnection, an increase of the total cost per energy served for *B* is observed, while costs for *A* stay nearly unchanged compared to the corresponding reference scenario. The increase in cost for *B* originates from the dCM. At same time, the dCM ensures a reduction the energy non-served. With higher interconnection, total costs converge again. Shared use of capacity and sharing of energy non-served can be given as reason. The total cost including the ENS shows that the situation for *A*, in which it relies on a EOM while the interconnected country introduces a CM, gives the highest costs. Due to the leakage of capacity to *B* in case of large interconnection capacity, the ENS is largest and consequently also the associated costs.

C. Scenario 2a

The scenario 2a introduces SR for *A* as contrast to the dCM in *B*. The installed capacity result in similar capacity than Scenario 1, with the difference, that the generation mix of *A* is extended with the capacity from the SR (Fig. 5). The price differentials are larger on the energy-based market in the two countries (Table III), partly due to the activation of the SR at the maximum market price. Consequently, this leads to larger cross-border flows (Fig. 3). The problem of energy non-served could be avoided for both countries (Fig. 4). Only for the large interconnection capacity, limited energy non-served occurs in *A*. This can be interpreted as mismatch of the SR size. The reduction of capacity due to imported flows could

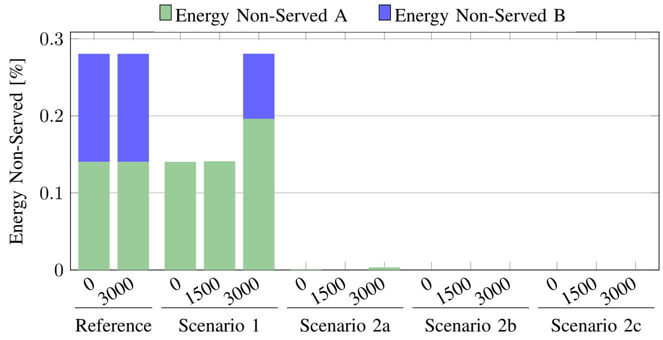


Figure 4. Energy non-served for market configurations

be covered by a slightly increased SR volume. Summarized, the total cost is higher for both countries than in the previous scenarios, which, again, has to be weighted with the absence of energy non-served. If the ENS is incorporated in the total cost (Table IV), this scenario offers the solution with the lowest cost for *A*. It is important to note that *A* strongly relies on the import from the neighbouring country *B*. A domestic generation capacity in *A* is not ensured.

D. Scenario 2b

As alternative to the introduction of SR, in Scenario 2b, *B* introduces a cCM. The generation mix is now linked to the capacity demand due to the two capacity-based markets in the countries. The total installed capacity is higher in *A* as the capacity demand does not depend on the peak energy demand (Fig. 5). As consequence, the energy non-served in both countries is brought to zero (Fig. 4). Costs per served energy on the energy-based markets are identical for all interconnection capacities. This can be explained by the cross-border flows below the interconnection limit that occur and ensure price convergence on the two countries (Fig. 3). The reason that there are cross-border flows can be explained by different generation mixes which originate from the different market mechanisms, especially, the feedback of the capacity demand on the energy-based market price with a dCM in *B*. In terms of total cost, this scenario leads to the most expensive solution among the scenarios with CMs in both countries, mainly due to the highest costs in *A* due to fixed capacity demand in the cCM. The costs for *B* are comparable to the other scenarios in which a dCM is introduced (Table IV). However, taken into account the cost for ENS, the scenario still shows lower costs than the reference scenario with EOM in both countries.

E. Scenario 2c

The Scenario 2c introduces a symmetric market setting. Both markets include a dCM. Generation mix and total cost per energy served are the same for both countries. Similar to the reference scenario, the interconnection has no additional value and there are no cross-border flows observable. Energy non-served does not occur, as sufficient capacity is ensured in both countries (Fig. 4). In contrast with Scenario 2a, both countries do not rely on the import from the neighbouring country but sufficient domestic capacity is installed. Compared to Scenario 2b, the costs are lower due to the higher efficiency of a dCM than a cCM by implicitly linking energy- and capacity-based demand.

TABLE IV. COST PER ENERGY SERVED (ENERGY- & CAPACITY-BASED) [€/MWH] AND TOTAL COST INCLUDING COST FOR ENS (ENERGY- & CAPACITY-BASED, ENS) [€/MWH]

	Country *A*			Country *B*		
	Interconnection *IC [MW]* 0	1500	3000	Interconnection *IC [MW]* 0	1500	3000
Reference	57.90	57.90	57.90	57.90	57.90	57.90
incl. ENS	*62.11*	*62.11*	*62.11*	*62.11*	*62.11*	*62.11*
Scenario 1	57.90	57.91	57.85	59.95	59.94	57.96
incl. ENS	*62.11*	*62.13*	*63.73*	*59.95*	*59.94*	*60.50*
Scenario 2a	59.08	59.07	59.14	59.95	59.95	58.73
incl. ENS	*59.08*	*59.07*	*59.24*	*59.95*	*59.95*	*58.73*
Scenario 2b	60.46	60.46	60.46	59.95	59.95	59.95
incl. ENS	*60.46*	*60.46*	*60.46*	*59.95*	*59.95*	*59.95*
Scenario 2c	*59.95*	*59.95*	*59.95*	*59.95*	*59.95*	*59.95*
incl. ENS	*59.95*	*59.95*	*59.95*	*59.95*	*59.95*	*59.95*

VI. CONCLUSIONS

The qualitative discussion on the introduction of CMs and their interaction with interconnection capacity needs to be supported by quantitative studies. The presented equilibrium model enables the user to model two or more interconnected countries with the same or different CMs. The case study serves as a theoretical model application to analyse the cross-border effects of non-harmonized CMs. It reveals the outcome in case of lack of harmonization, and absence of either implicit or explicit cross-border participation.

The paper presents a case study with two identical interconnected countries with reduced presentation of the generation technologies. The market areas are identical in demand, RES potential and available technologies. Due to the symmetrical set up and the simplification on the input parameters, the changes in the results can be traced down to the change of the market designs in the 5 different scenarios. Four conclusions can be extracted exemplary.

Firstly, the impact of changing market designs in neighbouring countries can not be neglected in the assessment towards generation adequacy in the other country. Cross-border flows triggered by cheaper energy-based prices in the country with dCM lead to a reduction of capacity in the interconnected country. An adequate adaptation of the market design is required to achieve generation adequacy. Here, two options for the adapting country exist, namely relying on import or installation of domestic capacity.

As a second conclusion, the outcome of the chosen options is linked to the choice of market design. SR avoid the problem of energy non-served by adding the additionally needed capacity which can not be covered through imports. In contrast, dCM and cCM give incentives to install domestic capacity,

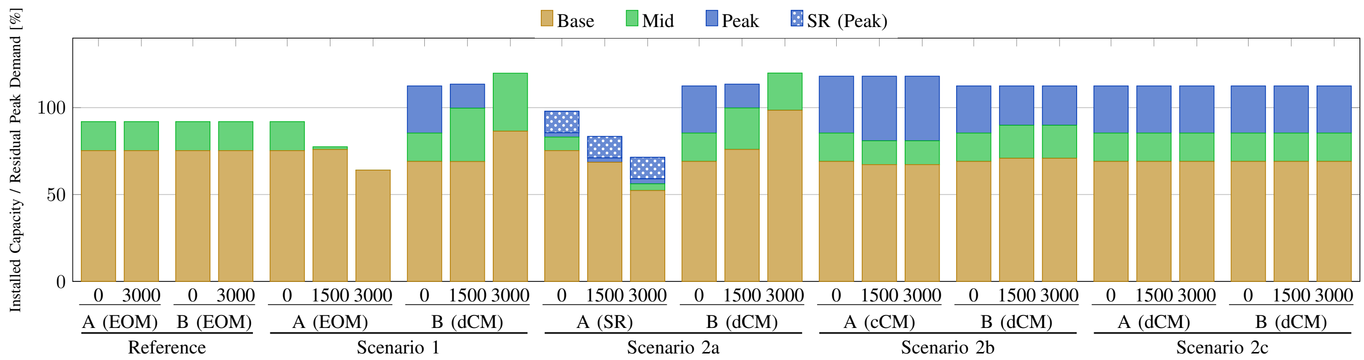


Figure 5. Installed capacities for different market configuration

i.e., capacity within the country neglecting interconnection capacity.

Thirdly, the model reveals that in situations in which one country with its market design relies on the import from the neighbouring country (Scenario 1 & 2a), increased interconnection capacity actually worsens the situation. This is counter-intuitive to the assumption that increased market coupling improves the overall situation. In the theoretical model, the adaptation of the generation mix, namely the reduction of installed capacity in one country, to the largely increased interconnection capacity outweighs the impact of cross-border flows on avoided energy non-served.

Fourthly, the case study contributes to the discussion of harmonization of CMs. The model results show that the scenario with the least costs for both countries is a setting with two different mechanisms (Scenario 2a). If domestic generation adequacy is chosen as policy goal, a harmonization of a dCM (Scenario 2c) yields least costs for consumers in both countries.

The application of the model on the case study with the theoretical set up is a first step to quantify the interaction of CM and interconnection. The model can be scaled up to e.g. an European model with multiple interconnected market zones investigating the existing market framework or plans for upcoming implementations for CMs. It offers therefore a valuable contribution on the discussion of the need for harmonization of CMs and the role of interconnection in a setting with different market designs.

In a next step, cross-border participation, i.e., the participation of non-domestic demand in the CM either directly or via the interconnector needs to be incorporated to represent the full extent of the ongoing discussion in the model. The development towards a model representation of an European market system has to be the goal to give solid policy advice.

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Appendix

The formulation of the individual primal problems for the market participants and market designs are listed below. Sections A-D list the primal problems for the conventional generators, the demand side and the required market balances. The problem formulations for RES and interconnection capacities are identical for all market designs and given in Section E. In combination with one formulation of the preceding sections, these formulation are combined to represent the requested market models.

A. Energy-only Market

1) Conventional Generators:

$$\max_{g_{c,k,t}, cp_{c,k}} \quad \sum_{t \in T} \left[(\lambda_{c,t} - V_{c,k}) \cdot g_{c,k,t} \right] - I_{c,k} \cdot cp_{c,k}$$

$$\forall c,k,t: \quad g_{c,k,t} \leq cp_{c,k} \qquad (\mu_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \leq g_{c,k,t\text{-}1} + R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{up}}_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \geq g_{c,k,t\text{-}1} - R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{dn}}_{c,k,t})$$

2) Demand Side of the Market:

$$\max_{d_{c,t}, z_{c,t}} \quad \sum_{t \in T} \big[(\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot In_{c,t} + 1/2 \cdot (\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot (d_{c,t} - In_{c,t}) \big]$$

$$\forall c,t: \quad d_{c,t} + z_{c,t} = (\lambda_{c,t} - P^{0}_{c,t})/E_c \qquad (\beta_{c,t})$$

$$\text{with: } P^{0}_{c,t} = P^{\text{R}}_{c}/(E_c \cdot D_{c,t}), \qquad E_c < 0$$

3) Market Balance:

$$\forall c,t: \quad \sum_{k \in K} g_{c,k,t} + \sum_{j \in J} g_{c,j,t} + \sum_{cc \in C} (f_{cc,c,t} - f_{c,cc,t}) = d_{c,t} \qquad (\lambda_{c,t})$$

B. Strategic Reserve

1) Conventional Generators:

$$\max_{g_{c,k,t}, cp_{c,k}, cp^{\text{crm}}_{c,k}} \quad \sum_{t \in T} \left[(\lambda_{c,t} - V_{c,k}) \cdot g_{c,k,t} \right] + \lambda^{\text{crm}}_{c} \cdot cp^{\text{crm}}_{c,k} - I_{c,k} \cdot cp_{c,k}$$

$$\forall c,k,t: \quad g_{c,k,t} \leq (cp_{c,k} - cp^{\text{crm}}_{c,k}) \qquad (\mu_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \leq g_{c,k,t\text{-}1} + R_{c,k} \cdot (cp_{c,k} - cp^{\text{crm}}_{c,k}) \qquad (\rho^{\text{up}}_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \geq g_{c,k,t\text{-}1} - R_{c,k} \cdot (cp_{c,k} - cp^{\text{crm}}_{c,k}) \qquad (\rho^{\text{dn}}_{c,k,t})$$

$$\forall c,k: \quad cp^{\text{crm}}_{c,k} \leq cp_{c,k} \qquad (\mu^{\text{crm}}_{c,k,t})$$

2) Demand Side of the Market:

$$\max_{d_{c,t}, z_{c,t}, g^{\text{sr}}_{c,t}, z^{\text{crm}}_{c}} \quad \sum_{t \in T} \big[(\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot In_{c,t} + 1/2 \cdot (\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot (d_{c,t} - In_{c,t}) + (\lambda_{c,t} - (\overline{P}^{\text{em}}_{c} - \delta)) \cdot g^{\text{sr}}_{c,t} \big] + (\lambda^{\text{crm}}_{t} - \overline{P}^{\text{sr}}_{c}) \cdot z^{\text{crm}}_{c}$$

$$\forall c,t: \quad d_{c,t} + z_{c,t} = (\lambda_{c,t} - P^{0}_{c,t})/E_c \qquad (\beta_{c,t})$$

$$\forall c,t: \quad g^{\text{sr}}_{c,t} \leq f^{\text{sr}}_{c} \cdot \max(D_{c,t}) - z^{\text{crm}}_{c} \qquad (\mu^{\text{sr}}_{c,t})$$

3) Market Balances:

$$\forall c,t: \quad \sum_{k \in K} g_{c,k,t} + \sum_{j \in J} g_{c,j,t} + g^{\text{sr}}_{c,t} + \sum_{cc \in C} (f_{cc,c,t} - f_{c,cc,t}) = d_{c,t} \qquad (\lambda_{c,t})$$

$$\forall c: \quad \sum_{k \in K} cp^{\text{crm}}_{c,k} + z^{\text{crm}}_{c} = f^{\text{sr}}_{c} \cdot \max(D_t) \qquad (\lambda^{\text{crm}}_{c})$$

C. Centralized Capacity Market

1) Conventional Generators:

$$\max_{g_{c,k,t}, cp_{c,k}, cp^{\text{crm}}_{c,k}} \quad \sum_{t \in T} \left[(\lambda_{c,t} - V_{c,k}) \cdot g_{c,k,t} \right] + \lambda^{\text{crm}}_{c} \cdot cp^{\text{crm}}_{c,k} - I_{c,k} \cdot cp_{c,k}$$

$$\forall c,k,t: \quad g_{c,k,t} \leq cp_{c,k} \qquad (\mu_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \leq g_{c,k,t\text{-}1} + R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{up}}_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \geq g_{c,k,t\text{-}1} - R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{dn}}_{c,k,t})$$

$$\forall c,k: \quad cp^{\text{crm}}_{c,k} \leq cp_{c,k} \qquad (\mu^{\text{crm}}_{c,k,t})$$

2) Demand Side of the Market:

$$\max_{d_{c,t}, z_{c,t}, d^{\text{crm}}_{c}, z^{\text{crm}}_{c}} \quad \sum_{t \in T} \big[(\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot In_{c,t} + 1/2 \cdot (\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot (d_{c,t} - In_{c,t}) \big] + (f^{\text{p,ccm}}_{c} \cdot P^{\text{T}}_{c} - \lambda^{\text{crm}}_{c}) \cdot f^{\text{d,ccm}} \cdot \max(D_t) + 1/2 \cdot (f^{\text{p,ccm}}_{c} \cdot P^{\text{T}}_{c} - \lambda^{\text{crm}}_{c}) \cdot (d^{\text{crm}}_{c} - f^{\text{d,ccm}} \cdot \max(D_t))$$

$$\forall c,t: \quad d_{c,t} + z_{c,t} = (\lambda_{c,t} - P^{0}_{c,t})/E_c \qquad (\beta_{c,t})$$

$$\forall c: \quad d^{\text{crm}}_{c} + z^{\text{crm}}_{c} = (\lambda^{\text{crm}}_{c} - P^{0,\text{crm}}_{c})/M^{\text{crm}} \qquad (\beta^{\text{crm}}_{c})$$

3) Market Balances:

$$\forall c,t: \quad \sum_{k \in K} g_{c,k,t} + \sum_{j \in J} g_{c,j,t} + \sum_{cc \in C} (f_{cc,c,t} - f_{c,cc,t}) = d_{c,t} \qquad (\lambda_{c,t})$$

$$\forall c: \quad \sum_{k \in K} cp^{\text{crm}}_{c,k} = d^{\text{crm}}_{c} \qquad (\lambda^{\text{crm}}_{c})$$

D. Decentralized Capacity Market

1) Conventional Generators:

$$\max_{g_{c,k,t}, cp_{c,k}, cp^{\text{crm}}_{c,k}} \quad \sum_{t \in T} \left[(\lambda_{c,t} - V_{c,k}) \cdot g_{c,k,t} \right] + \lambda^{\text{crm}}_{c} \cdot cp^{\text{crm}}_{c,k} - I_{c,k} \cdot cp_{c,k}$$

$$\forall c,k,t: \quad g_{c,k,t} \leq cp_{c,k} \qquad (\mu_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \leq g_{c,k,t\text{-}1} + R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{up}}_{c,k,t})$$

$$\forall c,k,t: \quad g_{c,k,t} \geq g_{c,k,t\text{-}1} - R_{c,k} \cdot cp_{c,k} \qquad (\rho^{\text{dn}}_{c,k,t})$$

$$\forall c,k: \quad cp^{\text{crm}}_{c,k} \leq cp_{c,k} \qquad (\mu^{\text{crm}}_{c,k,t})$$

2) Demand Side of the Market:

$$\max_{d_{c,t}, z_{c,t}, d^{\text{crm}}_{c}, z^{\text{crm}}_{c}} \quad \sum_{t \in T} \big[(\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot In_{c,t} + 1/2 \cdot (\overline{P}^{\text{em}}_{c} - \lambda_{c,t}) \cdot (d_{c,t} - In_{c,t}) \big] + (\lambda^{\text{crm}}_{c} - \overline{P}^{\text{dcm}}_{c}) \cdot z^{\text{crm}}_{c} - \lambda^{\text{crm}}_{c} \cdot d^{\text{crm}}_{c}$$

$$\forall c,t: \quad d_{c,t} + z_{c,t} = (\lambda_{c,t} - P^{0}_{c,t})/E_c \qquad (\beta_{c,t})$$

$$\forall c,t: \quad d_{c,t} + z_{c,t} \leq d^{\text{crm}}_{c} \qquad (\mu^{\text{crm}}_{c})$$

3) Market Balances:

$$\forall c,t: \quad \sum_{k\in K} g_{c,k,t} + \sum_{j\in J} g_{c,j,t} + \sum_{cc\in C} (f_{cc,c,t} - f_{c,cc,t}) = d_{c,t} \quad (\lambda_{c,t})$$

$$\forall c: \quad \sum_{k\in K} cp^{\text{crm}}_{c,k} + z^{\text{crm}}_{c} = d^{\text{crm}}_{c} \quad (\lambda^{\text{crm}}_{c})$$

E. Applicable for all Market Models

1) Renewable Energy Sources:

$$\max_{g_{c,j,t}} \quad \sum_{t\in T} \left[(\lambda_{c,t} - V_{c,j}) \cdot g_{c,j,t}\right]$$

$$\forall c,j,t: \quad g_{c,j,t} \leq A_{c,j,t} \cdot C_{c,j} \quad (\mu_{c,j,t})$$

$$\forall c,j,t: \quad g_{c,j,t} \geq 0$$

2) Interconnection between Markets Areas:

$$\max_{f_{c,cc,t}} \quad \sum_{t\in T} \left[(-\lambda_{c,t} + \lambda_{cc,t}) \cdot f_{c,cc,t}\right]$$

$$\forall c,cc,t: \quad f_{c,cc,t} \leq IC_{c,cc} \quad (\mu^{\text{f}}_{c,cc,t})$$

$$\forall c,cc,t: \quad f_{c,cc,t} \geq 0$$