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Zonal Pricing in Kazakhstan Power System with a Unit Commitment Model

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ABSTRACT

Developing economies are in process of liberalizing their electricity markets, following similar process in developed economics. This process aims at establishing liquid energy exchanges that provide clear price signals, providing indications on the profitability of different operations: Production, retail, trading in interconnections. This paper aims at developing a unit commitment model for examining zonal market pricing in Kazakhstan. The latter has an extensive landscape but sparsely populated, while is also characterized by the high availability of domestic fossil fuels, but located in different sub-regions of the country. The provision of zonal price signals in such a power system is invaluable, as it enables the provision of clear price signals on the needed infrastructure and the estimation of the zonal hourly energy and technology mix. Moreover, it enables the formation of dynamic bidding strategies by market participants in cases with favourable conditions, such as the implementation of scarcity pricing. This paper presents a unit commitment model that used to assess different bidding strategies and to provide zonal price signals. The strategies are formed, depending on the technology type and fuel prices comparison. Results provide clear signals on needed infrastructure among zones in Kazakhstan. It also shows that dynamic bidding can lead to market coupling. Finally, it indicates the importance of institutional capability to monitor bidding strategies, eliminating speculation.

Keywords: Electricity Markets, Unit Commitment Model, Kazakhstan

JEL Classifications: Q4, Q47, L94

1. INTRODUCTION

A crucial issue in liberalization of electricity markets is the design of the wholesale market. Regulators usually have to choose among zonal and nodal pricing mechanisms, in order to provide the appropriate price signals, as well as to create liquid and competitive markets. Zonal markets are useful in cases where congestion is frequent among power sub-systems, as it provides clear signals for the needed interconnection infrastructure. On the other hand, nodal markets enable the provision of even more detailed price signals to capture local congestion in heavily populated areas. Kazakhstan has an extensive territory, as well as is distributed and sparsely populated. The adoption of a zonal pricing system fits very well to its current needs.

The power system of Kazakhstan has not been extensively examined, besides the fact that Kazakhstan is a very interesting

case in Central Asia. A comprehensive report by World Bank (Aldayarov et al., 2017), examine the case of Kazakhstan power sector, providing evidence on reform experiences and challenges ahead. Kazakhstan has extensive resources of the fossil fuels, which have led researchers to provide sectoral analyses. Kalmykov and Malikova (2017) examine the coal sector on Kazakhstan. This report is a primary review of open sources of information describing the state and prospects of development of coal-mining and energy-generating industries in Kazakhstan and their expected impact on the environment. Energy planning is also an issue that has attracted the interest of researchers. Babazhanova et al. (2017) examine the evolution of a new energy system in the Republic of Kazakhstan. Kazenergy association (KAZENERGY, 2019) in its National Energy Report 2017, provides an updated assessment of the outlook for each energy sector, evaluating the most recent energy industry targets and forecasts contained in official state

documents. Other researchers focus on political issues, namely if nationalization could be a solution for the energy sector. Orazgaliyev (2018) examine the state intervention in Kazakhstan's energy sector, aiming to provide recommendations on the dilemma: Nationalisation or participation? However it focuses on the Kazakhstan's petroleum sector. The quantitative research on Kazakhstan energy system, and especially on the power systems, is limited. A recent economic dispatch model focused on the power system of Kazakhstan is provided by Assembayeva et al. (2018), providing insights in regional scarcity examining the interdependency between production side and network. This work, as the work from the World Bank (Aldayarov et al., 2017), stand as the most comprehensive quantitative recent research on the power sector of Kazakhstan.

The Kazakhstan electricity market has started its liberalization process over two decades ago, as since 2000 the Kazakhstan Operator of Electric Power and Capacity Market (KOREM) has the responsibility to organize and operate the centralized electricity wholesale market (Kazakh government, 2000). However, the retail side is organized through the creation of six regional monopolies where energy supplying organizations (ESOs), established in 2004, are serving as regional single buyers of electricity and as regional monopoly supplier for end consumers in their region (KOREM, 2016). The retail price is regulated by the Natural Monopolies Regulation Agency of Kazakhstan (NMRA), which sets up the regional tariffs for end consumers, indirectly affecting the wholesale prices. The retail prices are differentiated by the annual level of electricity consumption and the temporal consumption pattern (Kazakh government, 2015). This market design has led a high difference among the regions, as average end consumer prices for electricity were in the range between 10.0 KZT/kWh and 19.5 KZT/kWh in 2016, with lowest prices in the Aktau region and highest prices in the Kostanay region (Enegryprom, 2018).

Central Asia region and Kazakhstan have raised the attention of energy modelers over the last decade. However, most application concern energy system models such as the MARKAL/TIMES and the LEAP model. Inyutina et al. (2012) have made projections of greenhouse gas (GHG) emissions, while Sarbassov et al. (2013) have examined the electricity and heating system in Kazakhstan, towards exploring energy efficiency improvement paths. Gomez et al. (2014) have assessed energy saving potential for Kazakhstan, while another report (OECD, 2014) has quantified the effects of reforms for energy subsidies in Kazakhstan. De Miglio et al. (2014) develops a partial-equilibrium MARKAL/TIMES model for the Central Asia region, towards evaluating the benefits from the cooperation between Central Asia and Caspian countries. A TIMES-Kazakhstan model is developed to explore pathways for meeting GHG emission targets in Kazakhstan (Atakhanova, 2007), while a bottom-up electricity sector model (Egerer et al., 2014) examined decarbonization strategies for the Kazakhstan power system. This model provides a nodal power system optimization, but abstracts from technical constraints and a zonal market representation.

Besides the market design, a crucial factor in markets in the existence of companies with market power, as well as the bidding

strategy they implement, namely if there exist regulated caps that impose limits on their strategy. Limits can also exist in the retail side, which indirectly create limits on the wholesale side. Therefore, the level of liberalization of an electricity market is a crucial fact for provision of clear price signals (Nicolli and Vona, 2019). There is a growing literature on liberalization of energy markets either at national or institutional level. Ofuji and Tatsumi (2016) focus on wholesale and retail electricity markets in Japan, providing results of market revitalization measures and prospects for the current reform. Nikoli and Vona (2019) investigate how political factors and energy liberalization affect renewable energy policies. Ciarreta et al. (2016) examine the development of market power in the Spanish power generation sector, by providing perspectives after market liberalization. The methodology applied is ex-post structural and behavioural measures, providing evidence that key dominant companies behaved more competitively in recent periods. Other papers focus on the retail sector, such as Palacios and Saavedra (2017) who examine alternative policies for the liberalization of retail electricity markets in Chile. Koltsaklis and Dagoumas (2018a) reveal the importance of transmission expansion, for relieving congestion and enhancing electricity trade, while Dagoumas (2019) examine the importance of power markets with existence of participant with market power.

The review shows that there is an increasing research on the effects of different stages of liberalization. The review indicates the role of existence of market power, as well as the existence of regulated caps on the bidding strategy of market participants. Moreover, the analysis has revealed that the literature review on Central Asia region and in case of Kazakhstan is increasing over the last decade. Although there is a growing number of official publications/reports and research paper on the Kazakhstan energy system, there is a lack of quantitative assessments, especially related to provision of zonal pricing and assessing different strategies of market participants. This paper aims to provide zonal pricing in Kazakhstan power system with a unit commitment model, through the assessment of different market strategies.

2. METHODOLOGY

As described on the previous section, a unit commitment model is developed to implement zonal pricing for the Kazakh power system. The model builds on the work done at the Energy and Environmental Policy Laboratory of the University of Piraeus on unit commitment modelling (Dagoumas et al., 2017; Koltsaklis et al., 2014). The critical question is if the bidding strategies by market participants in the wholesale market, affect the zonal prices and the energy mix per technology, per fuel and per producer. The simulations are implemented on representative seasonal days. The model elaborates all available public information from institutions such as the Kazakhstan Electricity Association, the Kazakhstan Electricity Grid Operating Company, the Kazakhstan Operator of Electricity Market, KazTransGas and KazAtomProm, as well as information from the above-mentioned reports and papers. The model determines the following outputs: the total hourly energy generation mix per technology type at a daily level (MWh), the hourly system's marginal price at a daily level (\$/MWh), the hourly production (MWh) by power plant and the hourly cross-border

electricity flows (net imports or exports) with each interconnected system (MWh). A critical issue of the model is the determination of the bidding strategy for thermal units from the different market participants. This is done dynamically in the model, considering the capability of the market participants to adopt a scarcity pricing strategy. Different scenarios are formed to capture the impact of fuel type, technology type and power plant ownership.

The paper develops a unit commitment model (Koltsaklis et al., 2018b), formulated it as a Mixed Integer Linear Programming (MILP) model. The objective function is based on the short-term market operation, namely the minimization of the total operational cost of the studied power system at one daily period, solved over a 24-h period. Therefore, the model's objective function includes: (i) marginal production cost of the power units incorporating fuel cost, variable operating and maintenance (O&M) cost, and CO₂ emission allowances cost, (ii) power imports cost, (iii) power exports revenues, (iv) pumping load revenues, (v) units' shut-down cost, and (vi) reserves provision cost, as represented by Equation (1).

$$\begin{aligned}
 \text{Min Cost}^{\text{daily}} = & \underbrace{\sum_{u \in (U^{\text{thh}} \cup U^{\text{z}})} \sum_{z \in Z} \sum_{b \in B} \sum_{t \in T} (CB_{u,z,b,t} \cdot PEO_{u,z,b,t} \cdot L_{z,t})}_{\text{Marginal production cost}} \\
 & + \underbrace{\sum_{n \in N^z} \sum_{z \in Z} \sum_{b \in B} \sum_{t \in T} (ICB_{n,z,b,t} \cdot IEO_{n,z,b,t} \cdot L_{z,t})}_{\text{Power imports cost}} \\
 & - \underbrace{\sum_{n \in N^z} \sum_{z \in Z} \sum_{b \in B} \sum_{t \in T} (ECB_{n,z,b,t} \cdot EEO_{n,z,b,t})}_{\text{Power exports revenues}} \\
 & - \underbrace{\sum_{e \in E^z} \sum_{z \in Z} \sum_{b \in B} \sum_{t \in T} (PMCB_{e,z,b,t}^{\text{pum}} \cdot PMEO_{e,z,b,t})}_{\text{Pumping load revenues}} \\
 & + \underbrace{\sum_{u \in U^{\text{thh}}} \sum_{t \in T} (x_{u,t}^{\text{sd}} \cdot SDC_u)}_{\text{Shut-down cost}} \\
 & + \underbrace{\sum_{u \in U^{\text{thh}}} \sum_{z \in Z} \sum_{t \in T} \left[\begin{aligned} & (PR_{u,z,t}^{\text{up}} \cdot PRO_{u,z,t}) + \\ & (SR_{u,z,t}^{\text{up}} + SR_{u,z,t}^{\text{down}}) \cdot SRO_{u,z,t} \end{aligned} \right]}_{\text{Reserves provision cost}} \quad (1)
 \end{aligned}$$

The problem includes several constraints, concerning the energy balance, system/s energy requirements, corridor limits in case of interzonal systems and reserve type constraints. Those constraints are presented below, whole the nomenclature is provided at the end of the paper.

Energy Balance

Equations (2) describe the energy balance (supply-demand balance) of the overall power system. More specifically, net power injection from all power units $\left(\sum_{g \in G^s} P_{g,m,t}^{\text{net}} \right)$ plus net electricity flow rates $\left(\sum_{s' \in S^s} f_{s',s,m,t} - \sum_{s \in S^s} f_{s,s',m,t} \right)$ and net electricity

imports $\left(\sum_{n \in N^s} im_{n,m,t}^{\text{net}} - \sum_{n \in N^s} ex_{n,m,t} \right)$ to each subsystem $s \in S$, must be equal to the electricity demand of each sector $D_{s,m,t}$ and pumping load, $\sum_{e \in E} pm_{e,m,t}^{\text{pum}}$.

$$\begin{aligned}
 & \sum_{g \in G^s} P_{g,m,t}^{\text{net}} + \underbrace{\sum_{n \in N^s} im_{n,m,t}^{\text{net}} - \sum_{n \in N^s} ex_{n,m,t}}_{\text{net electricity imports}} \quad \forall s \in S, m \in M, t \in T \quad (2) \\
 & + \underbrace{\sum_{s' \in S^s} f_{s',s,m,t} - \sum_{s \in S^s} f_{s,s',m,t}}_{\text{net electricity flow rates}} \\
 & = D_{s,m,t} + \sum_{e \in E} pm_{e,m,t}^{\text{pum}}
 \end{aligned}$$

The overall problem is formulated as an MILP (mixed-integer linear programming) problem, involving the cost minimization objective function (1) subject to constraints (2)-(55).

2.1. System's Energy Requirements

Constraints (3)-(8) model the system's requirements for all energy reserve types, i.e., primary-up, secondary-up and down, tertiary, as well as fast secondary-up and down respectively in each time period $t \in T$. These requirements are assumed to increase linearly with the total installed capacity of renewable units.

$$\sum_{g \in G^{\text{thh}}} r1_{g,m,t}^{\text{up}} \geq R1_{m,t}^{\text{up}} \quad \forall m \in M, t \in T \quad (3)$$

$$\begin{aligned}
 & \sum_{g \in G^{\text{thh}}} r2_{g,m,t}^{\text{up}} \geq R2_{m,t}^{\text{up}} \quad \forall m \in M, t \in T \quad (4) \\
 & + \alpha \cdot (IC_{\text{res}}^{\text{tot}} - IC_{\text{res}}^{\text{int}}) \cdot \frac{R2_{m,t}^{\text{up}}}{R2_{m,t}^{\text{up}} + R2_{m,t}^{\text{dn}}}
 \end{aligned}$$

$$\begin{aligned}
 & \sum_{g \in G^{\text{thh}}} r2_{g,m,t}^{\text{dn}} \geq R2_{m,t}^{\text{dn}} \quad \forall m \in M, t \in T \quad (5) \\
 & + \beta \cdot (IC_{\text{res}}^{\text{tot}} - IC_{\text{res}}^{\text{int}}) \cdot \frac{R2_{m,t}^{\text{dn}}}{R2_{m,t}^{\text{up}} + R2_{m,t}^{\text{dn}}}
 \end{aligned}$$

$$\sum_{g \in G^{\text{thh}}} r3_{g,m,t} \geq R3_{m,t} + \gamma \cdot (IC_{\text{res}}^{\text{tot}} - IC_{\text{res}}^{\text{int}}) \quad \forall m \in M, t \in T \quad (6)$$

$$\begin{aligned}
 & \sum_{g \in G^{\text{thh}}} fr2_{g,m,t}^{\text{up}} \geq FR2_{m,t}^{\text{up}} \quad \forall m \in M, t \in T \quad (7) \\
 & + \delta \cdot (IC_{\text{res}}^{\text{tot}} - IC_{\text{res}}^{\text{int}}) \cdot \frac{FR2_{m,t}^{\text{up}}}{FR2_{m,t}^{\text{up}} + FR2_{m,t}^{\text{dn}}}
 \end{aligned}$$

$$\begin{aligned}
 & \sum_{g \in G^{\text{thh}}} fr2_{g,m,t}^{\text{dn}} \geq FR2_{m,t}^{\text{dn}} \quad \forall m \in M, t \in T \quad (8) \\
 & + \varepsilon \cdot (IC_{\text{res}}^{\text{tot}} - IC_{\text{res}}^{\text{int}}) \cdot \frac{FR2_{m,t}^{\text{dn}}}{FR2_{m,t}^{\text{up}} + FR2_{m,t}^{\text{dn}}}
 \end{aligned}$$

2.2. Corridor Limits

Constraints (9) define that the corridor flow between two interconnected subsystems $s, s' \in S^s$, must be less than or equal to the maximum available power capacity of the corridor $(FL_{s,s',m,t})$

in each time period. Constraints (10) - (13) define the capacity bounds for a proposed electricity interconnection subject to the decision for its construction or not.

$$f_{s,s',m,t} \leq FL_{s,s',m,t} \quad \forall (s,s') \in S^{IS}, m \in M, t \in T \quad (9)$$

$$f_{s,s',m,t} \leq \sum_f CFL_{s,s',f} \quad \forall (s,s') \in S^{CR}, m \in M, t \in T \quad (10)$$

$$cfl_{s,s',f} \leq CL_f \cdot y_f \quad \forall (s,s') \in (S^{IS} \cap S^{CR}), f \in F \quad (11)$$

$$cfl_{s,s',f} \geq CL_{f-1} \cdot y_f \quad \forall (s,s') \in (S^{IS} \cap S^{CR}), f \in F \quad (12)$$

$$\sum_f y_f \leq 1 \quad (13)$$

Reserve-type constraints

Constraints (14) define the upper bounds of primary-up reserve of each unit $g \in G^{hth}$, subject to the decision of its operation (or not) in the dispatchable operational stage ($x_{g,m,t}^{disp}$). Constraints (15) ensure that the sum of the provisions of each unit $g \in G^{hth}$ in secondary-up and down reserves must be less than or equal to the maximum allowable secondary reserve contribution of each unit $g \in G^{hth}$, $R2_g$, subject to the decision of its contribution (or not) to the secondary reserve ($x_{g,m,t}^{sec}$). Constraints (16) and (17) define the upper bounds of tertiary spinning and non-spinning reserves of each unit $g \in G^{hth}$ correspondingly, subject to the decision of its operation (or not) in the dispatchable phase ($x_{g,m,t}^{disp}$), and to the decision for the provision (or not) of tertiary non-spinning reserve in each time period ($x_{g,m,t}^{3ns}$) respectively. Constraints (18) ensure that the provision of each unit $g \in G^{hth}$ in the tertiary non-spinning reserve must be greater than or equal to the unit's technical minimum ($Pmin_i^{dp}$). Constraints (19) define that each unit $g \in G^{hth}$ is able to provide tertiary non-spinning reserve if and only if is non-operational. Equations (20) state that the total provision of each unit $g \in G^{hth}$ in tertiary reserve amounts to the sum of its contribution to tertiary spinning and non-spinning reserves.

Constraints (21) guarantee that the contribution of each unit $g \in G^{hth}$ to fast secondary-up reserve within a period of 1 min must be less than or equal to its contribution to secondary-up reserve. Furthermore, constraints (22) define an upper limit on the fast secondary-up reserve. Constraints (23) and (24) define the same bounds for the fast secondary-down reserve of each unit $g \in G^{hth}$ as constraints (21) and (22) for fast secondary-up reserve correspondingly.

$$r1_{g,m,t}^{up} \leq R1_g \cdot x_{g,m,t}^{disp} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (14)$$

$$r2_{g,m,t}^{up} + r2_{g,m,t}^{down} \leq R2_g \cdot x_{g,m,t}^{sec} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (15)$$

$$r3_{g,m,t}^{sp} \leq R3_g^{sp} \cdot x_{g,m,t}^{disp} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (16)$$

$$r3_{g,m,t}^{nsp} \leq R3_g^{nsp} \cdot x_{g,m,t}^{3ns} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (17)$$

$$r3_{g,m,t}^{nsp} \geq P_g^{min} \cdot x_{g,m,t}^{3ns} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (18)$$

$$x_{g,m,t}^{3ns} \leq 1 - x_{g,m,t} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (19)$$

$$r3_{g,m,t} = r3_{g,m,t}^{sp} + r3_{g,m,t}^{nsp} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (20)$$

$$fr2_{g,m,t}^{up} \leq r2_{g,m,t}^{up} \quad (21)$$

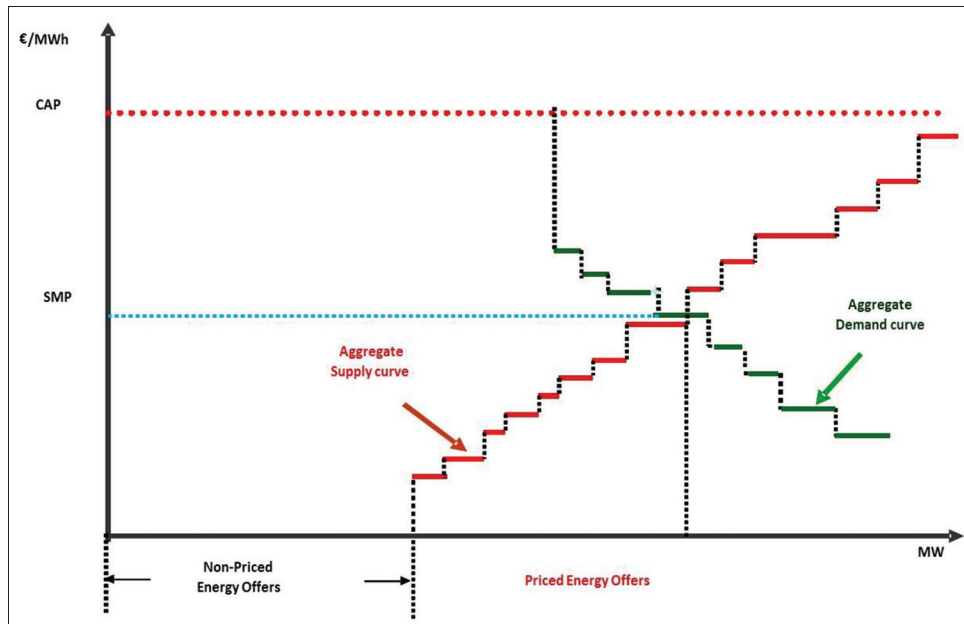
$$fr2_{g,m,t}^{up} \leq R_g^{sc} \cdot 1min \quad \forall g \in G^{hth}, m \in M, t \in T \quad (22)$$

$$fr2_{g,m,t}^{down} \leq r2_{g,m,t}^{down} \quad \forall g \in G^{hth}, m \in M, t \in T \quad (23)$$

$$fr2_{g,m,t}^{down} \leq R_g^{sc} \cdot 1min \quad \forall g \in G^{hth}, m \in M, t \in T \quad (24)$$

The minimization of the objective function leads to the estimation of the System's Marginal Price (SMP), representing the intersection of aggregate sale and purchase curves, as shown in Figure 1. The overall problem is formulated as a MILP problem, involves the cost minimization objective function (1) subject to constraints

Figure 1: Determination of System Marginal Price (SMP), where the aggregate Supply and Demand curves intersect



(2-24) defined above, as well as constraints concerning the typical operational cycle of a hydrothermal unit defined in a recent paper (Koltsaklis et al., 2018b). The operating phases include those of start-up decision, synchronization, soak and desynchronization. Moreover, minimum up and down times are also modelled, while the power output limits are represented in Figure 2. The model is developed in GAMS environment, supplemented by an interface for running the model and showing the results. Figure 3 provides the hourly energy mix of an indicative representative typical day.

3. POWER SYSTEM IN KAZAKHSTAN

Kazakhstan has available domestic resources for all major fuel types: Coal, gas, oil and uranium, as well as for renewables: Hydro, solar and wind. According to World Bank, proven reserves of energy resources in year 2017 for Kazakhstan (in billion tons of oil equivalent) were 15.9, 10.3, 5.2 and 3.5 for coal, uranium, oil and natural gas respectively. The production of primary energy resources at the same year (in million tons of oil equivalent) were 255.8, 79.2, 52.6 and 27.4 for coal, uranium, oil and natural gas respectively. Karatayeva and Clarke provide a review of the current energy resources in Kazakhstan and the future potential of renewables.

However, the power system of Kazakhstan mainly depends on thermal power plants, as the evolution of renewables is limited while the domestic uranium is not used extensively for electricity

production, but for supporting the hydrocarbons explorations in the Aktau region. However, Kazakhstan aims to exploit its domestic uranium and acquire nuclear power production capacity. The plan is to build 1 GW of nuclear capacity by 2030, however this is not captured in the examined scenarios, as the focus of the study concern short-term runs and not long-term planning. Kazakhstan relies mainly on thermal generation from about 10 GW of coal CHPs located near the cities, but it contributes to serious pollution. There is a potential for gasification of power plants in the North and conversion of coal CHPs to gas, which would reduce environmental impact. Concerning interconnections, Kazakhstan has shifted from being a net electricity importer to a net exporter since 2013.

The power system of Kazakhstan is presented in detail by a recent work (Assembayeva et al. 2018; 2019) A developing a spatial electricity market model for the power system of Kazakhstan and providing spatial electricity market data. A recent work (Zhakiyev et al., 2017) present a model for optimal energy dispatch and maintenance of an industrial coal fired combined heat and power plant in Kazakhstan. Moreover, Kerimray et al. (2016) examine climate change mitigation scenarios and policies and measures in the case of Kazakhstan, while Kerimray et al. (2018) investigate the energy transition to a coal free residential sector in Kazakhstan using a regionally disaggregated energy systems model.

The current mix consists of about 11 GW of coal plants, 1.5 GW of coal plants under development, 3.1 GW of gas plants and 0.5 GW of gas plants under development, 2.3 GW of big hydro plants and 0.3 GW of hydro plants under development. The high availability of domestic resources enables Kazakhstan to become a regional exporter of electricity, besides the other resources. This would require considerable investments in interconnections, which however have already been planned and concern interconnection capacity of 10.5 GW with Russia, 2.5 GW and 0.94 GW with Kyrgyzstan and Uzbekistan respectively. The potential for extending domestic power system is also by the rather low reserve margin which was at the level of 11% for year 2014 and is increased with recent capacity additions to more than 20%.

Electricity generation in 2018 in Kazakhstan was 106.8 TWh, including 86.8 TWh from thermal plants, 10.34 TWh from big

Figure 2: Power output limits of each hydrothermal unit (MW)

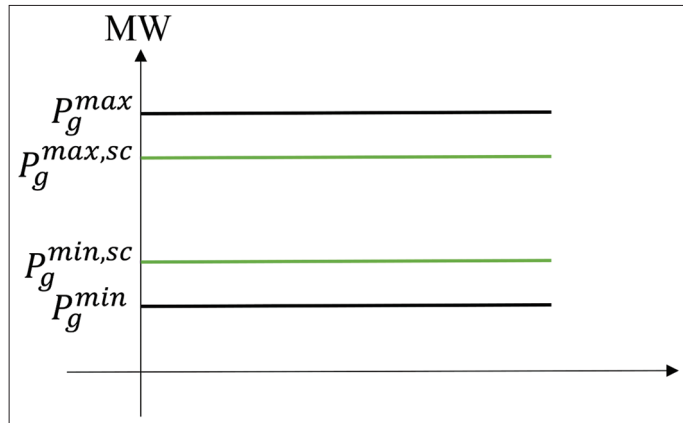
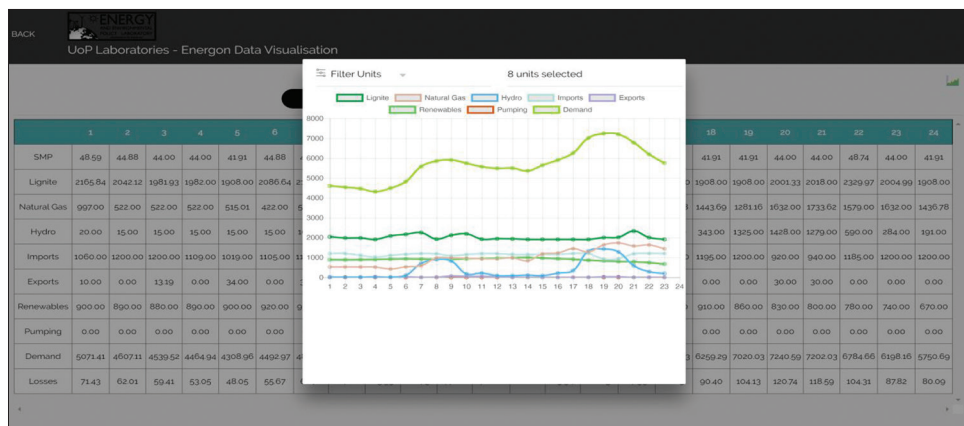


Figure 3: Interface of the model developed, showing the hourly energy mix of indicative day



hydro units, 9.12 TWh from gas plants and 0.54 TWh from solar, wind and biomass installations. Electricity consumption in Kazakhstan in 2018 versus 2017 increased by 5.37 TWh or 5.5% to 103.22 TWh. Concerning its sub-systems, consumption in North zone was 67.86 TWh (65.7%), in South zone 21.94 TWh (21.3%) and in West zone 13.43 TWh (13.0%). The net power flow in 2018 amounted to 3.57 TWh, which concerned exports to Russia and less than 1% to Central Asia (Kyrgyzstan).

However, there are some interzonal constraints within its power system, namely coal is not available in the west and gas is not available in the north. Its power system is divided into three subsystems, north, south and west, where the latter is a rather small system compared to the others. North and south power sub-systems are connected through a transmission corridor of 1.35 GW, which was recently extended to 1.8 GW. The west system is operating rather as an islanded system, as it is far from the other systems and not interconnected. Figure 4 provides the regional power sub-systems in Kazakhstan.

According to the Kazakhstan Electricity Grid Operating Company (KEGOC), the latest available data for year 2018, show that the maximum load was 14.823 MW in 2018, registered on 25 December at 07.00 PM, while the generation capacity was 14.555 MW. Electricity in Kazakhstan is generated by 138 power plants of various forms of ownership. As on January 1, 2019 The total capacity of power plants in Kazakhstan is 21.9 GW and available capacity is 18,9 GW. The power plants are branched into power plants of national importance, power plants of industrial importance and those of regional importance. The power plants of national importance are the large thermal power plants generating and selling electricity to consumers at the electricity wholesale market of Kazakhstan: (1) Ekibastuz GRES-1 LLP named after B.G. Nurzhanov, (2) Ekibastuz GRES-2 Power Plant JSC (3) Power plant of EEC JSC, ERG, Eurasian Group; (4) GRES of Kazakhmys Energy LLP and (5) Zhambyl GRES JSC named after T.I. Baturov, and large hydro power plants used as auxiliary units and to control load schedule profile

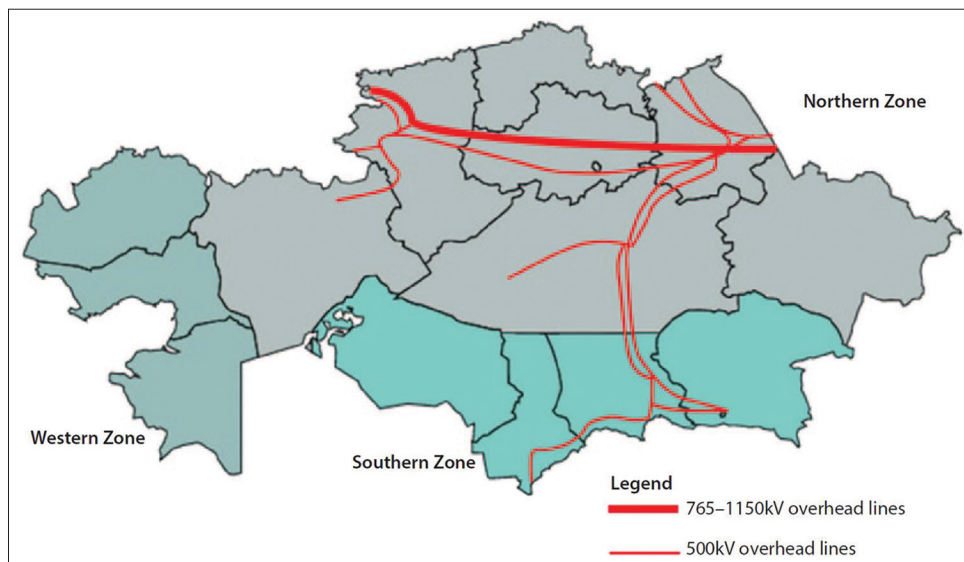
of Kazakhstan UPS: (1) Bukhtarma Hydro Power Complex of Kazzinc LLP, (2) AES Ust-Kamenogorsk HPP LLP, (3) AES Shulbinsk HPP LLP.

The assumptions on the power generation technologies were based on public available info by the Kazakhstan Electricity Grid Operating Company (KEGOC), as well as the accompanying data to the article published by Assembayeva et al. (2018), which provides analytical data for each power plant. However, the presented model does not focus on nodal pricing, but at zonal systems, therefore only corridor limits among the north and south subsystems were used. Assumptions of the reserves were not based on official data by KEGOC, as such could be found. However indicative figures were used based on the experience of modelers from other national power systems.

Concerning the market design, according to the Kazakhstan Electricity Grid Operating Company (KEGOC), electricity market is divided into wholesale and retail markets, the heating energy market is retail only. The functional design of the wholesale electricity market in Kazakhstan includes:

- Market of decentralized purchase and sale of electricity (bilateral contracts of electricity purchase and sale);
- Centralized electricity market, which is based on purchase and sale of electricity for short-term (spot-trade), mid-term (week, month) and long-term (quarter, year) period;
- Real-time balancing market operating for physical and subsequent financial settlement of hourly imbalances arising within the operating day between actual and contractual generation and consumption of electricity in the unified power system of Kazakhstan;
- System and ancillary service market, where the System Operator renders the system services and acquires the ancillary services from the Kazakhstan electric power market entities in order to ensure compliance with the state standards established for reliable operation of Kazakhstan UPS and electric power quality.
- Capacity market.

Figure 4: Regional power sub-systems in Kazakhstan (source: Aldayarov et al., 2017)



The electricity market operator is the System Operator of Kazakhstan UPS, KEGOC JSC. Established with the order of the Ministry of Energy of the Republic of Kazakhstan No. 61, dated 17 October 2014, while with the order No. 106 of the Minister of Energy of the Republic of Kazakhstan, dated 20 February 2015, the rules for organization and operation of the wholesale electricity market, have been approved. The regulatory developments are considerable over the last years, including the approval of the Standard contract for technical dispatching of electricity consumption and production in the network, of the Standard contract for electricity transmission in the National Power Grid, and of the Standard contract for electricity consumption and production balancing, approved by Order No.58 of the Minister of National Economy of the Republic of Kazakhstan dated 24 June 2019.

The domestic market has several market participants, so there does not exist a company with dominant position that can use its market power to manipulate the wholesale market. There exist power plants that have competitive operating costs, that are usually considered as benchmark for the other power plants. Moreover, the regulated prices in the retail market affect indirectly the wholesale prices. Under those data, it is interesting to compare a scenario where power plants operate at their variable cost in order to provide optimum benchmark wholesale prices, with scenarios where thermal power plants bid more aggressively to increase their profitability.

4. RESULTS

Two typical seasonal days are examined. For each day, three scenarios are examined. The first scenario concerns a minimum cost scenario, where all thermal plants bid in their variable cost. This scenario enables the provision of the cost-optimum energy mix and minimum system marginal price for each zonal system. The second scenario examines the case where the thermal plants with the cheapest fuel adopt a dynamic pricing strategy, namely bid only their technical minimum at their variable cost in order to guarantee their operation and to avoid shut-down, while the

remaining capacity between the technical maximum and technical minimum of the power plant are bid in several steps and in increasing prices up to variable cost of the more expensive and competing thermal plants using alternative fuel. This enables guaranteeing their operation and increasing their profitability. The third scenario examines the case where all power plants adopt a dynamic pricing, increasing their bid by up to 40% over from the second scenario. This scenario indicates the case where a power sub-system is dominated by a technology, where plants form a cartel to adopt similar aggressive bidding strategy towards increasing wholesale prices.

The unit commitment model contributes to the simulation of the wholesale market, as it enables the examination of different typical days, different fuel mix, different fuel prices and different bidding strategies by market participants. Figure 5 provides the evolution of regional (zonal) hourly demand for two days examined, namely day 1 a day 2. Figure 6 provide the zonal prices in the West zone, which remain constant at about 15 USD/MWh, namely about 5.8 KZT/kWh, which represents the marginal generation costs of gas-fired power plants. A similar situation is resulted in case of the North system, however with considerably lower SMPs, as the marginal units are the coal units with a marginal cost at the level of 3.5 USD/MWh, namely about 1.35 KZT/kWh. However, the South SMP has a higher evolution. The North zone has high installed competitive capacity, as coal units dominate the system, supplemented by considerable hydro production. The South system is favoured by the corridor inflows from the North system, which represent about 50% of its local consumption. Therefore, it uses its competitive hydro and few renewables resources, as well as competitive electricity imports from the North system, which eliminates the SMP within the price spread among coal and gas plants. This leads to higher deviation on zonal SMPs, as for few hours regional gas stations become the marginal producers. The reserves requirements do not seem to affect the solution in the examined scenarios, due to the availability of base load units and the small penetration of renewables, that would enhance flexibility ramping requirements, facilitating the further penetration of more expensive gas plants. However, we have also examined cases where the market participants have implemented

Figure 5: Evolution of zonal hourly demand for typical days 1 and 2

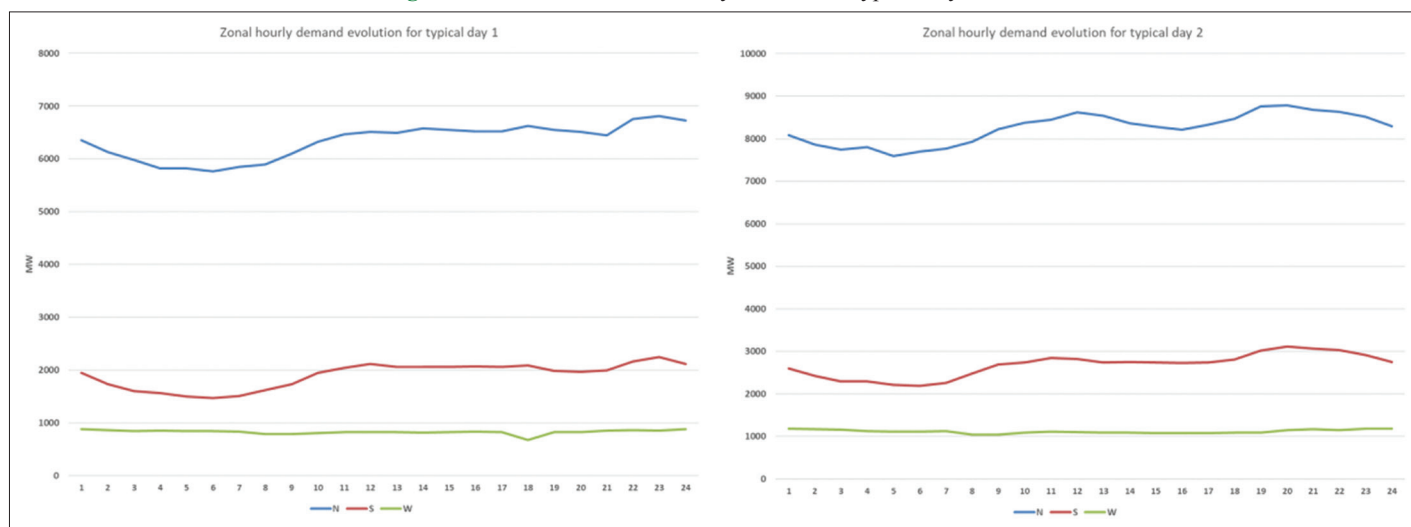


Figure 6: Evolution of hourly zonal system marginal price for typical days 1 and 2

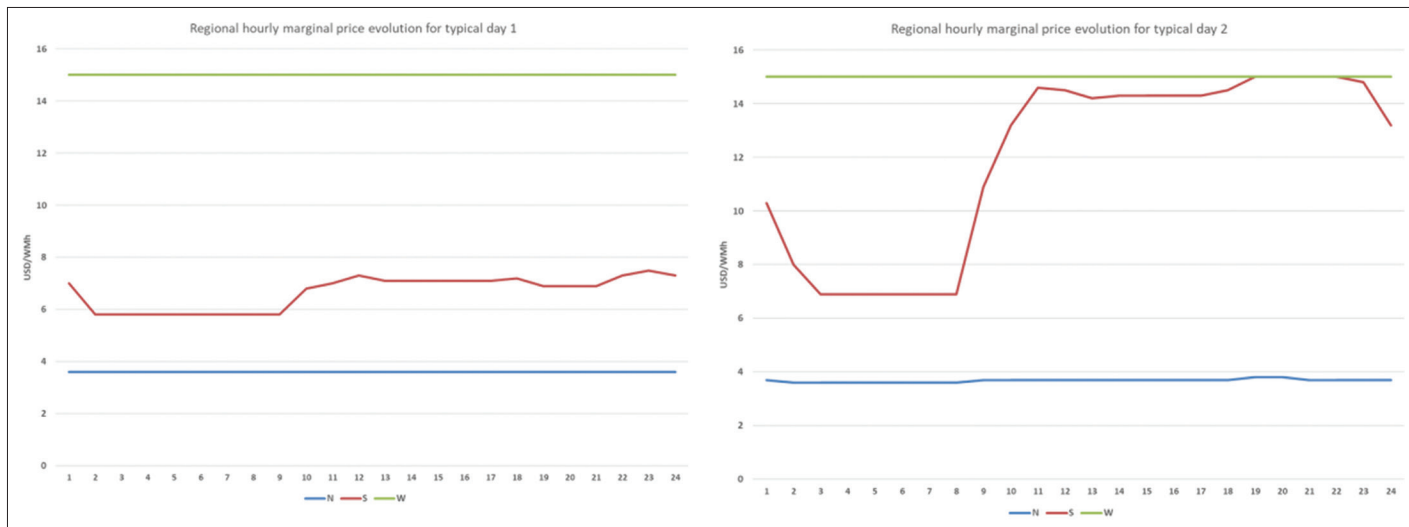


Figure 7: Evolution of hourly zonal system marginal price for typical days 1 and 2, in case of aggressive bidding by coal plant owners

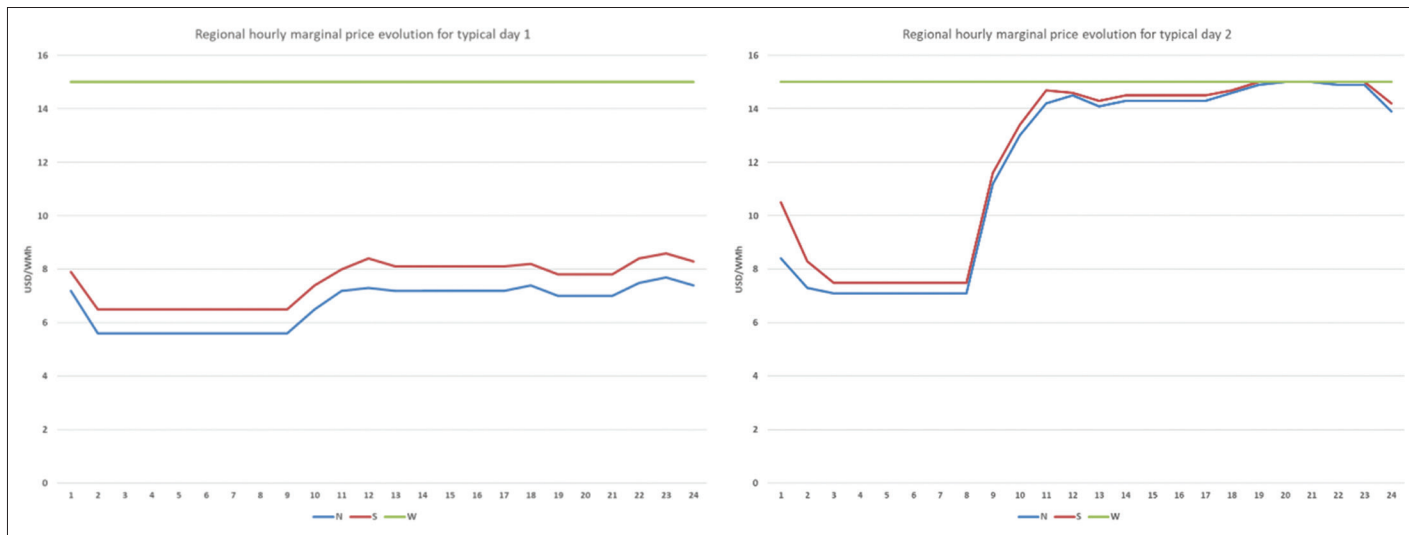
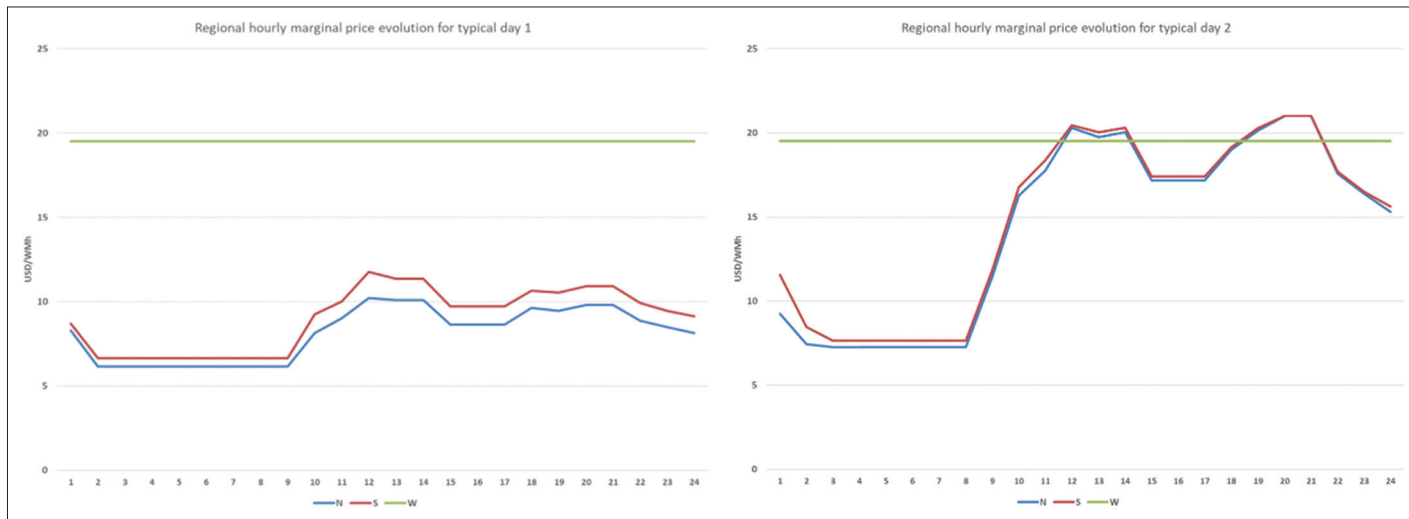


Figure 8: Evolution of hourly zonal system marginal price for typical days 1 and 2, in case of aggressive bidding by all thermal power plant owners



aggressive bidding strategies, which affected considerably the prices especially in the North system. This comes from the fact that market participants with competitive coal plants bid their technical minimum at the levels of short-run production costs and the rest capacity gradually up to the gas marginal prices. Those results represented in Figure 7, show that price evolution could be radically changed if the motivation and focus of market participants is changed. Figure 8 provide the results of the zonal prices in case all thermal power plants adopt a dynamic bidding. This leads to considerable increase of prices up to the level of 40% compared to the previous case. Although such scenario represents a simulation of cartel behavior, it stands as a case where representative agents, namely power plant owners, adopt a homogenized strategy to maximize their profits. This scenario indicates the need for institutional capability, namely the existence of regulating and competition authorities, that monitor bidding strategies from market participants, to eliminate the chances of formatting cartel behavior.

5. CONCLUSIONS

The paper develops a unit commitment model to examine to assess the impact of market strategies on the case of the power system of Kazakhstan. There is lack on quantitative assessments for its power sector, especially related to the provision of zonal price signals and the examination of different bidding strategies of market participants. The paper uses all available public information from official institutions and other reports/papers and aims to provide evidence on the wholesale price and energy mix, per technology and fuel type. The objective function is based on the short-term market operation, namely the minimization of the total operational cost of the studied power system at one daily period, solved over a 24-h period. Therefore, the model's objective function includes: (i) marginal production cost of the power units incorporating fuel cost, variable operating and maintenance (O&M) cost, and CO₂ emission allowances cost, (ii) power imports cost, (iii) power exports revenues, (iv) pumping load revenues, (v) units' shut-down cost, and (vi) reserves provision cost. The problem includes a number of constraints, concerning the energy balance, system/s energy requirements, corridor limits in case of interzonal systems and reserve type constraints. The overall problem is formulated as a MILP problem, involving the cost minimization objective function subject to techno-economic constraints. The model examines different representative seasonal days as well as different bidding strategies. The strategies are formed, depending on the technology type and fuel prices comparison. Results provide clear signals on needed infrastructure among zones in Kazakhstan, that would also enable market coupling among different zones.

The examined scenarios show that the zonal prices in the West zone remain constant at about 15 USD/MWh, namely about 5.8 KZT/kWh, which represents the marginal generation costs of gas-fired power plants. A similar situation is resulted in case of the North system, however with considerably lower SMPs, as the marginal units are the coal units with a marginal cost at the level of 3.5 USD/MWh, namely about 1.35 KZT/kWh. However, the South SMP has a higher evolution. The North zone has high

installed competitive capacity, as coal units dominate the system, supplemented by considerable hydro production. The South system is favoured by the corridor inflows from the North system, which represent about 50% of its local consumption. Therefore, it uses its competitive hydro and few renewables resources, as well as competitive electricity imports from the North system, which eliminates the SMP within the price spread among coal and gas plants. This leads to higher deviation on zonal SMPs, as for few hours regional gas stations become the marginal producers. Moreover, the examined scenarios show that reserves requirements do not affect the solution, due to the availability of base load units and the small penetration of renewables, that would enhance flexibility ramping requirements, facilitating the further penetration of more expensive gas plants. Finally, we have also examined cases where the market participants have implemented aggressive bidding strategies, which affected considerably the prices especially in the North system. The price evolution could be radically changed if the motivation and focus of market participants is changed. Finally, in case where all thermal plants adopt a dynamic, aggressive and homogenized bidding, wholesale prices could increase considerably. This scenario indicates the need for institutional capability, namely the existence of regulating and competition authorities, that monitor bidding strategies from market participants, to eliminate the chances of formatting cartel behavior. To sum up, the market design and robust operation of a power market is a process that should eliminate regulated provisions on bidding strategies, in order to provide clear and realistic price signals. On the other hand, the continuous monitoring of the markets will enable the formation of homogenized strategies that speculate the wholesale market and consequently affect the profitability of the retail sector and the final consumer prices.

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NOMENCLATURE

Sets

$(s, s') \in S$	set of subsystems
$(s, s') \in S^{IS}$	set of subsystems of the interconnected power system
$(s, s') \in S^{CR}$	set of subsystems of the autonomous power system
$(t, t') \in T$	set of hours
$h \in H$	set of pumped storage units
$b \in B$	set of blocks of the energy offer function (bids) of each hydrothermal unit
$e \in E^s$	set of pumped storage units $e \in E^z$ interconnected with sector $s \in S$
$e \in E^z$	set of pumped storage units $e \in E$ interconnected with sector $z \in Z$
$f \in F$	set of transmission capacity range blocks between the mainland and the autonomous power system
$g \in G^h$	set of hydroelectric units
$g \in G^{hth}$	set of hydrothermal units
$g \in G^{res}$	set of renewable units (not including hydro units)
$g \in G^s$	set of units $g \in G$ that are installed in sector $s \in S$
$g \in G^{th}$	set of thermal units
$g \in G^z$	set of units $g \in G$ that are (or can be) installed in sector $z \in Z$
$g \in G$	set of all units
$m \in M$	set of months
$n \in N^s$	set of interconnected power systems $n \in N$ with sector $s \in S$
$n \in N^z$	set of interconnected power systems $n \in N$ with sector $z \in Z$
$n \in N$	set of interconnected power systems
$s \in S^s$	set of sectors $s \in S$ interconnected with sector $s' \neq s \in S$
$w \in W$	set of start-up types {hot, warm, cold}
$z \in Z$	set of zones

Parameters

$AF_{g,z,m,t}$	Availability factor of each unit $g \in G^{res}$ in zone $z \in Z$, month $m \in M$ and hour $t \in T$ (p.u.)
$CB_{g,b,m,t}$	Marginal cost of block $b \in B$ of the energy offer function of each unit $g \in G^{hth}$ in month $m \in M$ and hour $t \in T$ (€/MW)
$CEP_{n,b,m,t}$	Marginal export bid of block $b \in B$ to interconnection $n \in N$ in month $m \in M$ and hour $t \in T$ (€/MW)
$CIP_{n,b,m,t}$	Marginal cost of block $b \in B$ of the imported energy offer function from interconnection $n \in N$, in month $m \in M$ and hour $t \in T$ (€/MW)
CL_f	Capacity range- f of the proposed interconnector between the mainland (interconnected) and the autonomous power system
$CPM_{e,b,m,t}$	Marginal bid of block $b \in B$ of pumped storage unit $h \in H$ in month $m \in M$ and hour $t \in T$ (€/MW)
$D_{s,m,t}$	Power load of subsystem $s \in S$, in month $m \in M$ and hour $t \in T$ (MW)
$EP_{n,b,m,t}$	Quantity of capacity block $b \in B$ of each energy export interconnection $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$FL_{s,s',m,t}$	Upper bound of the flow from sector $s \in S$ to sector $s' \neq s \in S$ in month $m \in M$ and hour $t \in T$ (MW)
$FR_{m,t}^{down}$	System requirements in fast secondary-down reserve in month $m \in M$ and hour $t \in T$ (MW)
$FR_{m,t}^{up}$	System requirements in fast secondary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
IC_{res}^{int}	Installed capacity of renewables in the mainland (interconnected) and power system
IC_{res}^{tot}	Installed capacity of renewables in both the mainland (interconnected) and autonomous power system
INV_f	Investment cost of transmission capacity block $f \in F$ (€/MW)
$IP_{n,b,m,t}$	Quantity of capacity block $b \in B$ of each power import interconnection $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$L_{z,m,t}$	Injection losses coefficient in zone $z \in Z$, month $m \in M$ and hour $t \in T$ (p.u.)

$NP_{g,m,t}$	Fixed (non-priced) component of the energy offer function of each unit $g \in G$ in month $m \in M$ and hour $t \in T$ (MW)
$PCB_{g,b,m,t}$	Power capacity block $b \in B$ of the energy offer function of unit $g \in G^{hth}$ in month $m \in M$ and hour $t \in T$ (MW)
$PC_{g,m,t}$	Available power capacity of unit $g \in G$ in month $m \in M$ and hour $t \in T$ (MW)
$PMB_{e,b,m,t}$	Quantity of capacity block $b \in B$ of pumped storage unit $h \in H$ in month $m \in M$ and hour $t \in T$ (MW)
$P_g^{max,sc}$	Maximum power output (when providing secondary reserve) of each unit $g \in G^{hth}$ (MW)
P_g^{max}	Maximum power output (dispatchable phase) of each unit $g \in G^{hth}$ (MW)
$P_g^{min,sc}$	Minimum power output (when providing secondary reserve) of each unit $g \in G^{hth}$ (MW)
P_g^{min}	Minimum power output (dispatchable phase) of each unit $g \in G^{hth}$ (MW)
P_g^{soak}	Power output of each unit $g \in G^{hth}$ when operating in soak phase (MW)
$R1_g$	Maximum contribution of unit $g \in G^{hth}$ in primary reserve (MW)
$R1_{m,t}^{up}$	System requirements in primary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
$R2_i$	Maximum contribution of unit $g \in G^{hth}$ in secondary reserve (MW)
$R2_{m,t}^{down}$	System requirements in secondary-down reserve in month $m \in M$ and hour $t \in T$ (MW)
$R2_{m,t}^{up}$	System requirements in secondary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
$R3_g^{nsp}$	Maximum contribution of unit $g \in G^{hth}$ in non-spinning tertiary reserve (MW)
$R3_g^{sp}$	Maximum contribution of unit $g \in G^{hth}$ in spinning tertiary reserve (MW)
$R3_{m,t}$	System requirements in tertiary reserve in month $m \in M$ and hour $t \in T$ (MW)
$RC1_{g,m,t}$	Price of the primary energy offer of each unit $g \in G^{hth}$, in month $m \in M$ and hour $t \in T$ (€/MW)
$RC2_{g,m,t}$	Price of the secondary range energy offer of each unit $g \in G^{hth}$, in month $m \in M$ and hour $t \in T$ (€/MW)
R_g^{down}	Ramp-down rate of unit $g \in G^{hth}$ (MW)
R_g^{sc}	Ramp rate of unit $g \in G^{hth}$ when providing secondary reserve (MW)
R_g^{up}	Ramp-up rate of unit $g \in G^{hth}$ (MW)
SDC_g	Shut-down cost of each unit $g \in G^{hth}$ (€)
T_g^{htw}	Non-operational time of unit $g \in G^{hth}$ before going from hot to warm standby condition (h)
T_g^{desyn}	Desynchronization time of unit $g \in G^{hth}$ (h)
T_g^{down}	Minimum down time of unit $g \in G^{hth}$ (h)
T_g^{past}	Extended time period in the past (greater than the higher cold reservation time of all thermal units) (h)
T_g^{rdn}	Non-operational time (after being shut-down) of unit $g \in G^{hth}$ (h)
$T_g^{soak,w}$	Type-w soak time of unit $g \in G^{hth}$ (h)
$T_g^{sync,w}$	Type-w synchronization time of unit $g \in G^{hth}$ (h)
T_g^{up}	Minimum up time of unit $g \in G^{hth}$ (h)
T_g^{wtc}	Non-operational time of unit $g \in G^{hth}$ before going from warm to cold standby condition (h)

Continuous variables

$cf_{s,s',f}$	Capacity of the interconnector between the mainland (interconnected) and the autonomous power system whose bounds are in the determined capacity range- f (MW)
$exb_{n,b,m,t}$	Cleared quantity of power capacity block $b \in B$ exported to interconnected system $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$ex_{n,m,t}$	Total energy withdrawal (exports) to interconnected system $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$fr2_{g,m,t}^{down}$	Contribution of unit $g \in G^{hth}$ in fast secondary-down reserve in month $m \in M$ and hour $t \in T$ (MW)
$fr2_{g,m,t}^{up}$	Contribution of unit $g \in G^{hth}$ in fast secondary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
$f_{s,s',m,t}$	Corridor power flow from sector $s \in S$ to $s' \in S$ in month $m \in M$ and hour $t \in T$ (MW)
$imb_{n,b,m,t}$	Cleared quantity of power capacity block $b \in B$ imported from interconnected system $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$im_{n,m,t}$	Total energy injection (imports) from interconnected system $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)

$im_{n,m,t}^{net}$	Net energy injection (imports) to interconnected system $n \in N$ in month $m \in M$ and hour $t \in T$ (MW)
$pb_{g,b,m,t}$	Quantity of power capacity block $b \in B$ of unit $g \in G^{hth}$, dispatched in month $m \in M$ and hour $t \in T$ (MW)
$p_{g,m,t}$	Energy injection (generation) from unit $g \in G^{hth}$ in month $m \in M$ and hour $t \in T$ (MW)
$p_{g,m,t}^{desyn}$	Power output of unit $g \in G^{hth}$ when operating in the desynchronization phase in month $m \in M$ and hour $t \in T$ (MW)
$p_{g,m,t}^{net}$	Net energy injection from unit $g \in G^{hth}$ in month $m \in M$ and hour $t \in T$ (MW)
$p_{g,m,t}^{soak}$	Power output of unit $g \in G^{hth}$ when operating in the soak phase in month $m \in M$ and hour $t \in T$ (MW)
$pmb_{e,b,m,t}^{pum}$	Cleared quantity of block $b \in B$ of pumping unit $h \in H$ in month $m \in M$ and hour $t \in T$ (MW)
$pmb_{e,m,t}^{pum}$	Total cleared quantity of pumping unit $h \in H$ in month $m \in M$ and hour $t \in T$ (MW)
$r1_{g,m,t}^{up}$	Contribution of unit $g \in G^{hth}$ in primary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
$r2_{g,m,t}^{down}$	Contribution of unit $g \in G^{hth}$ in secondary-down reserve in month $m \in M$ and hour $t \in T$ (MW)
$r2_{g,m,t}^{up}$	Contribution of unit $g \in G^{hth}$ in secondary-up reserve in month $m \in M$ and hour $t \in T$ (MW)
$r3_{g,m,t}$	Contribution of unit $g \in G^{hth}$ in tertiary reserve in month $m \in M$ and hour $t \in T$ (MW)
$r3_{g,m,t}^{nsp}$	Contribution of unit $g \in G^{hth}$ in non-spinning tertiary reserve in month $m \in M$ and hour $t \in T$ (MW)
$r3_{g,m,t}^{sp}$	Contribution of unit $g \in G^{hth}$ in spinning tertiary reserve in month $m \in M$ and hour $t \in T$ (MW)

Binary variables

$x_{g,m,t}$	1, if unit $g \in G^{hth}$ is committed (operational) in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{3ns}$	1, if unit $g \in G^{hth}$ contributes to non-spinning tertiary reserve in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{desyn}$	1, if unit $g \in G^{hth}$ operates in the desynchronization phase in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{disp}$	1, if unit $g \in G^{hth}$ operates in the dispatchable phase in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{sd}$	1, if unit $g \in G^{hth}$ is shut-down in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{sec}$	1, if unit $g \in G^{hth}$ contributes to secondary reserve in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{soak,w}$	1, if unit $g \in G^{hth}$ operates in the type- w soak phase in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{soak}$	1, if unit $g \in G^{hth}$ operates in the soak phase in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{st,w}$	1, if a type- w start-up decision is taken for unit $g \in G^{hth}$ in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{st}$	1, if unit $g \in G^{hth}$ starts-up in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{sync,w}$	1, if unit $g \in G^{hth}$ operates in the type- w synchronization phase in month $m \in M$ and hour $t \in T$
$x_{g,m,t}^{sync}$	1, if unit $g \in G^{hth}$ operates in the synchronization phase in month $m \in M$ and hour $t \in T$
y_f	1, if capacity range- f interconnector is to be installed between the mainland (interconnected) and the autonomous power system