Modelling An Integrated Northern European Regulating Power Market Based On A Common Day-Ahead Market

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Abstract—**With an increasing share of wind power production in the northern European countries and as a consequence thereof increasing need of regulating resources an integration of the northern European regulating power market can be socio-economic beneficial, especially regarding to the good regulating capabilities provided by the Nordic hydro power production-based system. After the successful integration of day-ahead markets, being the basis for the regulating markets, their is the next aspired step.**

In this paper an integrated northern European regulating power market is modelled, being based on a common day-ahead market. Different cases of regulating market integration are studied in order to estimate a possible socio-economic benefit of exchanging regulating resources between the northern continental European and the Nordic system.

***Index Terms* – Regulating market integration, Regulating resource exchange, Reserve procurement, Linear optimisation model.**

NOMENCLATURE

BSP	Balance Service Provider
TSO	Transmission System Operator
ENSTO-E	European Network of Transmission System Operators for Electricity
UCTE	Union for the Coordination of the Transmission of Electricity
PTU	Program Time Unit
NTC	Net Transfer Capacity
EMPS	EFI's Multi-area Power-market Simulator

I. INTRODUCTION

THE need for sustainable energy production leads to an increasing share of wind power production especially in northern Europe, notably in Denmark and Germany but also in the Netherlands. This prospectively significant share of intermittent wind power production results in a rising need for balancing services in order to ensure a secure system operation [1]. The Nordic, especially the Norwegian hydro based power production system has capabilities for offering such balancing services to continental Europe, being provided via the increasing interconnection capacity between the Nordic and the continental European power system.

With the Electricity Market Directives 96/92/EC and 54/EC the European Union enforces the contemporaneously process of the liberalisation and integration of the national European power markets. Regulation 1228/2003 thereby explicitly addresses cross-boarder issues [2]. There is already huge progress in coupling and integrating forward, especially day-ahead markets. Examples here are the common Nordic day-ahead market, the trilateral market coupling (TLC) between the Netherlands, Belgium and France or the market coupling between Denmark and Germany (EMCC). In the case of integrating regulating power markets, the first steps are taken by constituting regional cooperations. There still is a long way to go to achieve an integrated European regulating market, whereas an integrated northern European regulating power market would already be an important development. The integration of regulating power markets will be essential in order to exchange regulating reserves [3].

There are several studies done on national regulating markets, mostly investigating price behaviour, forecasting regulating power prices [4] - [6] and optimising the bidding of market participants [7], [8]. A rough estimation of the economic value of exchanging regulating resources between the Nordic system and continental Europe is done in [9]. In order to estimate the possible socio-economic outcome of integrating northern European regulating markets and exchanging regulating resources, in this paper a model of an integrated regulating market is developed, which is based on a common day-ahead market clearing. The modelled areas hereby include the Nordic countries Denmark, Finland, Norway and Sweden and the northern European countries the Netherlands and Germany representing 2008's state of the system, shown in Fig. 1.

This paper is divided into eight sections. In sections II and III a short overview on the system which is modelled and on system balancing is given. Section IV gives an overview of the current state of regulating market integration in Europe. Next the developed model is described in section V with detailed formulations stated in the appendices B to D. To study the integration of the northern European regulating markets, different cases are studied in section VI. Their results are presented in section VII. Finally a conclusion of the paper is given in section VIII.

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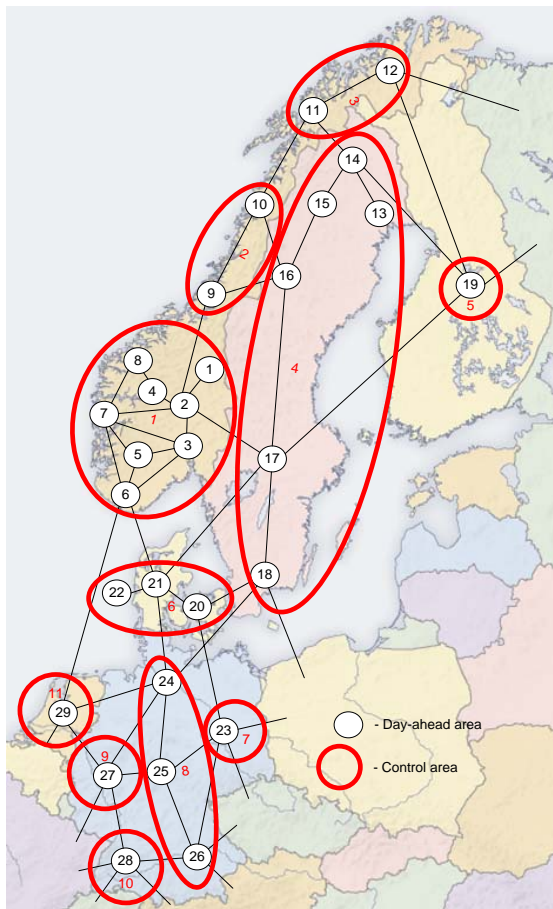* stefan.jaehnert@elkraft.ntnu.no

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Fig. 1.   Geographic overview of the modelled System

TABLE I
CONTROL AREAS

No.	TSO	Abbr.	Comment
1		NO1	
2	Statnett	NO2	
3		NO3	
4	Svenska Kraftnät	SWE	
5	Fingrid	FIN	
6	Energinet.dk	DK	
7	50Hertz Transmission	DE1	formerly known as Vatten-fall Europe Transmission
8	transpower	DE2	formerly known as E.On Transportnetze
9	Amprion	DE3	formerly known as RWE Transportnetze
10	EnBW Transportnetze	DE4	
11	TenneT	NL	

II. SYSTEM OVERVIEW

The modelled system, shown in Fig. 1 comprises the Nordic power system Nordel[1] including Denmark, Finland, Norway and Sweden and the northern part of the continental European power system UCTE including the Netherlands and Germany. An overview of the include control areas and the corresponding transmission system operators (TSO) is given in Table I. For the German TSOs their current and their former names are stated.

The overall power generation in the Nordic part amounts to about 400 TWh annually, whereof 170 TWh are produced by hydro power plants. Still the power generation characteristics in the Nordic system differ significantly from country to country. In Denmark the annual power production of about 40 TWh generation is mainly thermal based, containing a huge share of CHP power plants. It has a rapidly increasing share of wind power production, which supplies about 20% of the total annually energy. Finland has an annual power production of about 80 TWh, where generation is based on a mix of hydro power production and thermal power production, including nuclear, hard-coal and gas power plants. In Sweden power

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[1]In July 2009 ETSO's succeeding organisation ENTSO-E was founded, with Nordel and UCTE as the regional Nordic and Continental Europe subgroups. In the paper it is still referred to this systems as Nordel and UCTE, as also most of the literature include originates from these former organisations

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generation with about 150 TWh per year is mainly supplied by hydro power and nuclear power plants whith an equal share. In Norway with an annual production of about 130 TWh, almost all the power production is based on hydro power [10].

The continental European power system is mainly based on thermal generation. The power production in the Netherlands and Germany sums up to about 740 TWh annually, whereof the Netherlands have a share of 105 TWh. Here power production is based on a mix of hard-coal, gas-fired and oil-fired power plants, with a substantial share of CHP power plants. An increasing share is supplied by wind power generation, which currently is about 3.5% of the total production. The German system as the biggest part of the model has an annual production of about 635 TWh. A substantial share is provided by nuclear and lignite power plants, being approximately 300 TWh per year. The remainder is supplied by a mix of hydro, hard-coal, gas, oil and other power plants and an increasing share of wind power production being 40 TWh annually [11] - [14].

The energy volumes presented here are the total volume settled in bilateral contracts, future as well as forward markets. Thereby the shares between these different alternatives differ quite essential between the northern continental European areas and the Nordic area. In Germany in the day-ahead market run by EEX only about 20% of the total energy volume is settle, whereat via NordPool more than 50% of the energy volume in the Nordic area is settled.

III. SYSTEM BALANCING

The day-ahead market clearing results into a balance between the expected electricity production and the expected consumption. During the real-time operation of the system there quite likely occurs an imbalance between the actual production and the actual consumption. As electricity cannot be stored, the same power has to be produced as is consumed at any point in time. This system balancing is one of the main responsibilities of the transmission system operator (TSO). To be able to balance the system, a TSO needs regulating reserves, also called balancing services. Those services are provided

by either producer or consumer, being called balance service providers (BSP).

Balancing services are divided in different types regarding to their response time and the type of activation. Due to the different characteristics of the Nordic and the northern European system there is a difference in the definition of balancing services in those areas. In the UCTE system balancing services are divided into primary, secondary and tertiary reserves. Primary reserves are fast-responding reserves with an activation time of 30 seconds, which react on frequency deviations in the system. Secondary reserves are automatically activated reserves with an activation time of 15 minutes, which react on the area control error (ACE). They are used to replace activated primary reserves and restore the nominal system frequency. In addition there are tertiary reserves, which are manually activated reserves. Tertiary reserves are used to free activated secondary reserves [15]. In the Nordic system balancing services are divided into frequency controlled reserves (FCR), containing frequency controlled operation reserves (FCNOR) and frequency controlled disturbance reserves (FCDR) with an activation time up to 30 seconds, which are automatically activated reserves, reacting on a system frequency deviation. FCR equal the primary reserves of the continental European system. Further on there are fast disturbance reserves (FADR) with an activation time up to 15 minutes, which are based on the total imbalance of the Nordic system [16]. A detailed overview of different balancing services definitions and specifications can be found in [17].

The provision of balancing services is either mandatory, contracted bilaterally or done via auctions on a regulating power market. There are regulating power markets for the different types of the balancing services. In the regulating power markets there are auctions for reserve capacity, what corresponds to the procurement of regulating reserves. The activation of regulating reserves during real-time system balancing corresponds to the auction of regulating energy (regulating resources), being likewise part of the regulating power market. An analysis of different regulating power market designs can be found in [18]. The time basis for clearing the regulating power markets is the program time unit, which is 15 minutes in the UCTE and 60 minutes in Nordel.

Primary reserves are essential for the operational security. In Netherlands their provision is mandatory for units above a certain capacity [19]. In Germany primary reserves are procured through a biannual auction [20]. In the Nordic area they are contracted either bilaterally or through a market for primary reserves as it was opened in Norway in 2008 [21] & [16].

It is distinguished between the procurement of reserve resources and the actual activation of this regulating resources. As hydro power production has a high regulating capability due to the rapid ramping ability of hydro power plants, there are normally sufficient reserve resources available in the Norwegian system. Thus there is no need to procure them beforehand. During periods with tight capacity a reserve option market (RKOM) is run in Norway, what mainly happens in the winter time. In the Swedish system it is required that all available reserves are bid into the market, what is somehow

similar in the Finish system. In a thermal system the procurement of regulating reserves is essential. In the Danish system reserves are contracted bilaterally [22]. The same accounts for the Netherlands, where this contracting is done annually on a bilaterally basis, wherewith BSPs are contractually obliged to bid into the secondary reserve market, what can be done until one hour before real-time. In Germany the regulating reserve procurement for secondary reserves is done monthly auction-based at [20]. In this auction capacity bids as well as energy bids are specified. The German regulating market for tertiary reserves is held daily.

IV. Integration state of European regulating markets

The successful integration of European day-ahead markets, as it is aspired by the Price Coupling of Regions (PCR) [23] covering 80% of Europe's total power production, can provide experience and a basis in order to integrate European regulating power markets. In order to exchange such balancing services an integration of national regulating markets in necessary to provide a common basis [18].

By now there are proposals from ETSO [24], Nordel [25], Eurelectric [26], ERGEG [27], Bundesnetzagentur (BNA) [28] & [29] and Frontier Economices & Consentec [30] suggesting different approaches for the cross-border exchange of balancing services, i.e. the integration of regulating power markets. An overview on these different approaches is likewise given in [18]. These proposals can generally be divided into two approaches depending on the balancing service exchanging parties. In the first approach exchange of balancing services is done between TSOs and BSPs in neighbouring areas. This is currently implemented by RTE (France) and some of its neighbouring countries (Germany, Switzerland, Spain) and between Germany and Austria, where BSP can provide tertiary reserves mutually [20]. The second approached constituted the exchange of balancing services between TSOs, at a different degree of integration. An exchange of balancing services is currently implemented between RTE and National Grid (UK), which only includes the exchange of regulating resources in the case of available transmission capacity [31]. The recently constituted grid control cooperation (GCC) in Germany, was implemented by four subsequent steps each corresponding to a higher step of regulating market integration [29]. The German regulating market integration was suggested by studies of Consentec [32] and Lichtblick [33] showing possible savings in the case of German wide reserve procurement and imbalance netting. From May 2010 a German wide GCC is enforced by the BNA [34]. In the Nordic system there is a fully integrated regulating power market with a harmonisation of balancing services introduced in March 2009 [25].

In order to exchange balancing services in a European wide area instead of country wise, the transmission system has to be considered, taking into account cross-border congestions. Thus there has to be a trade-off between the day-ahead exchange and the exchange of balancing services. One solution approach is to use a joint market model as implemented by Risø in Wilmar [35], where the day-ahead market and the regulating market is clear at once, taking into account all system constraints.

Comment? Realistic?

V. MODELLING

In order to develop a model of an integrated northern European regulating power market, a generic electricity market design is assumed. The regulating market is based on a day-ahead market, using the day-ahead market's outcome as input to the regulating market. Further on the day-ahead market is assumed to be a common northern European day-ahead market, on which an integrated northern European regulating market can be based. The markets modelled are assumed to be perfect markets, neglecting market power issues. As discussed in the previous section there are different alternatives and sequences of electricity market designs. Sequence refers to the temporal order of clearing the markets, e.g. first running a reserve capacity market and clearing the day-ahead market afterwards or vice versa. The sequence especially concerns the knowledge of the day-ahead prices and dispatch when running the regulating market, particularly when procuring regulating reserves. In the case of procuring reserves before day-ahead market clearing an expected day-ahead market clearing would have to be taken into account, resulting in a stochastic problem. In the here presented model a deterministic approach is implemented. Thus a sequence is chosen, where at first the day-ahead market is cleared and subsequent the regulating market is run. Running the regulating market includes the regulating reserves procurement and finally the system balancing in real-time. The chosen time basis for the day-ahead market clearing is one hour according to NordPool, the APX and the EEX. As PTU length for the regulating market, i.e. the resource procurement and the system balancing 15 minutes are chosen to match the PTU length of the UCTE. In the model the fast reacting primary reserves are neglected and only slower reserves are taken into account.

The systematics of the model are shown in Fig. 2. It consists of the following three subsequent steps: the common day-ahead market, the regulating resource procurement and the system balancing. The common day-ahead market is simulated by the use of EFI's Multi-area Power-market Simulator (EMPS) [36]. The outputs of EMPS are the optimal day-ahead dispatch, taking into account the unit-commitment, the according area prices and water values, which are used as inputs to the subsequent steps. In the second step regulating resources according to defined reserve requirements are procured, resulting in a redispatch of the available generation capacity in order to fulfil the reserve requirements. This generation redispatch then is the input to the last step, the real-time system balancing. In the following subsections V-A to V-C each of these steps with the according model are described in more detail, with a discussion of reserve pricing in subsection V-D.

As shown in Fig. 1 the developed model consists of 29 interconnected day-ahead areas. The areas are defined according to country borders, the geographic distribution of generation capacity and existing bottlenecks in the transmission system. Germany is subdivided according to the suggestion given by [37], [38] and according to areas chosen in [1], [39].
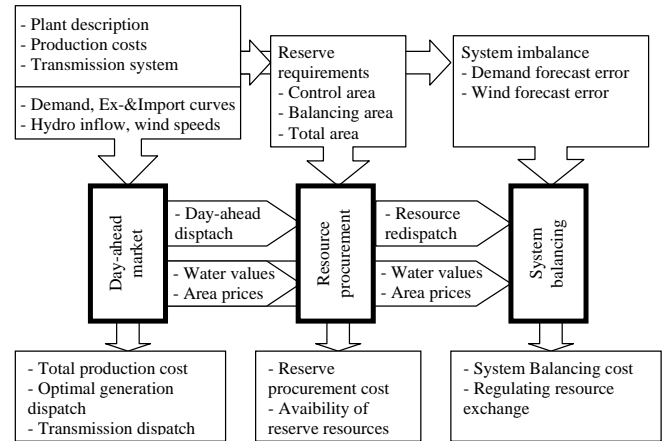

Fig. 2. Schematic diagram of the subsequent model steps

The subdivision of the Norwegian system takes into account different water courses in the hydro system. On a second level, these 29 day-ahead areas are aggregated into 11 control areas, which are in accordance with the current control areas in the UCTE [40] and in Nordel[2] [16]. A further aggregation of these control areas into three balancing areas, being Nordel, the Netherlands and Germany, which complies with the currently defined control blocks is done on a third level. The system is modelled in its 2008's state regarding the installed power plants, the transmission system, the exchange with neighbouring countries, the power production and consumption. To model the stochastic power production 40 different inflow and corresponding wind scenarios covering the years 1951 to 1990 are simulated.

A. Day-ahead market

The day-ahead market is modelled with EMPS [36]. It is an mid- and long-term optimisation model determining the socio-economic optimal dispatch of electricity generation on a weekly basis assuming perfect market behaviour with a time horizon of several years. Weeks can be split into several subsequent periods, by which a hourly resolution of the optimisation process is achieved.

As can be seen in Fig. 1, the modelled system is split into different areas in which production and consumption is aggregated. The transmission lines connecting the areas are modelled by net transfer capacities (NTC) and linear losses, not distinguishing between AC and DC transmission lines.

EMPS was developed for the Nordic system, including Denmark, Finland, Norway and Sweden, thus taking into account hydro based power generation. As there is no real cost for the water, but there is a limited amount of water in the hydro reservoirs, its long term utilization has to be optimised.

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[2]According to Nordel's System Operation Agreement [16] the Nordic area is one control area, with a common Nordic merit order list of regulating bids. Just as the areas defined the day-ahead market clearing by NordPool [41], the Nordic system can be split into areas during real-time system operation, taking into account congestions. In this case the activation regulating bids can deviate from the common merit-order list. The areas during real-time operation can, but does not need to match the day-ahead areas. The division chosen in this model is according to 2008's division.

Thereto EMPS contains a detailed water course description of the hydro power production. Within the optimisation the water values for the hydro reservoirs are determined. They represent the opportunity cost of hydro power production using the water stored in a hydro reservoir. A further explanation of the water value approach is given in [36]. For the hydro power plants, the water values of the according hydro reservoirs are used as the marginal production cost. With these marginal costs for hydro power production, employing a detailed, rule based reservoir draw-down model the optimal dispatch for the hydro power production is determined.

Besides the hydro power generation, thermal power plants are modelled, which are described by a marginal production cost and start up- & shut down costs [42]. Wind power generation is modelled as a fixed input to the system, being defined by the installed wind power generation capacity and nominal wind power production. The nominal wind power production is based on wind speed scenarios gained from reanalysis data as utilized in [1]. In EMPS consumption is defined by curves based on real measurements [19], [43] - [46] and the possibility of including demand elasticity and temperature dependency. Exchange to neighbouring countries is modelled by a scheduled energy exchange [47] rather than a price-dependent exchange.

For a common northern European day-ahead market clearing, the EMPS is expanded to the Netherlands and Germany by including further areas and extending the transmission system, resulting in the model as it is shown in Fig. 1. Both countries are modelled as thermal systems only. Thereby the thermal generation is modelled in two different ways, either as scheduled production, for which a production profile during an year is given or as dispatchable production. The division between scheduled and dispatchable production is shown in Table II. Some of the hard coal, gas- & oil fired power plants are used for district heating thus having a partly fixed production profile. The available dispatchable generation capacity is modelled in the form of single power plants with individual marginal production and start- & stop costs.

TABLE II
POWER PLANT TYPES MODELLED IN THE NORTHERN CONTINENTAL
EUROPEAN AREAS

Non-dispatchable generation	Dispatchable generation
Nuclear	Hard-coal
Lignite	Gas-fired
CHP	Oil-fired
Biomass	
Photovoltaic	
Wind	
Hydro	

Some results of the common day-ahead market clearing are presented afterwards. Fig. 3 shows the area prices for the 40 different inflow and wind scenarios in the form of percentiles for two selected areas. The percentiles give the probability of prices lying below the indicated value. The depicted areas are Southern Norway, which has a high installed hydro power production capacity and the Amprion area, which is a thermal

area with the highest consumption share in Germany. The area price curves clearly show the characteristics for each of the areas. In the hydro area (Fig. 3a) there is a high variation between the different percentiles, which indicates a price dependency on the inflow scenario. There is no high variation of the single percentiles though. However in the thermal area the variation between the percentiles is not high, but the variation of each percentile. This indicates a high price variation between the different periods during a week (e.g. peak, off-peak, weekend). In both areas the prices are around 50 EUR/MWh in average, which matches the average price of the dispatchable thermal power plants. This shows that the marginal production costs of the thermal power plants to a large extent determine the area prices in the Nordic System.
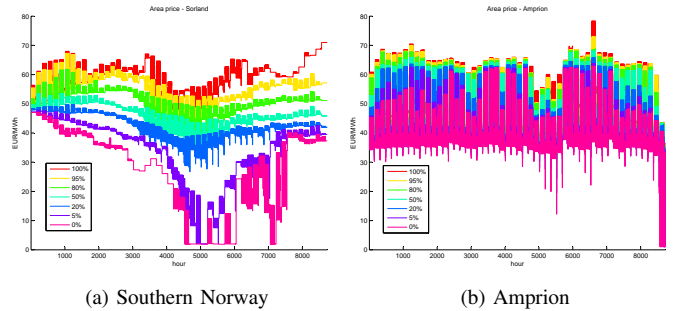

(a) Southern Norway   (b) Amprion

Fig. 3. Percentiles of area prices in a hydro and a thermal area

Fig. 4 and Fig. 5 show a detailed dispatch of generation units during one week in the Amprion area. Here only the dispatchable generation units are plotted. The colour indicates the marginal production cost of the individual units, from blue being cheap units up to the red, the most expensive ones. In each of the blocks ten units are aggregated. The marginal cost stated for the block is the one for the most expensive unit in the block. The plot shows the increasing marginal production costs due to higher production during peaking periods. Due to the consideration of start up costs and the minimum generation capacity of thermal units in the optimisation problem, some of the more expensive units still run during off-peak periods even though the area price is below their marginal production cost, shown in Fig. 5a. Further on the available regulating reserve resources are plotted in Fig. 5b, showing that there is a huge difference between peak and off-peak hours. During peak-hours the available regulating reserve resources are quite few, resulting in the necessity to procure further regulating resources, what is done in the next step.

In Fig. 6 the aggregated day-ahead dispatch of the transmission lines between the Nordic system and Northern continental Europe is depicted. The transmission lines include the Denmark-West Germany interconnection, the NorNed, the Baltic and the Kontek HVDC-cables. The plot shows the percentiles of the annual duration curve of the transmission. It can be seen that the exchange strongly depends on the scenario, i.e. the inflow to the Nordic system. In approximately 40% of the time there is free transmission capacity on the lines, providing the possibility of exchanging up- as well as downward regulating energy. During the rest of the time either
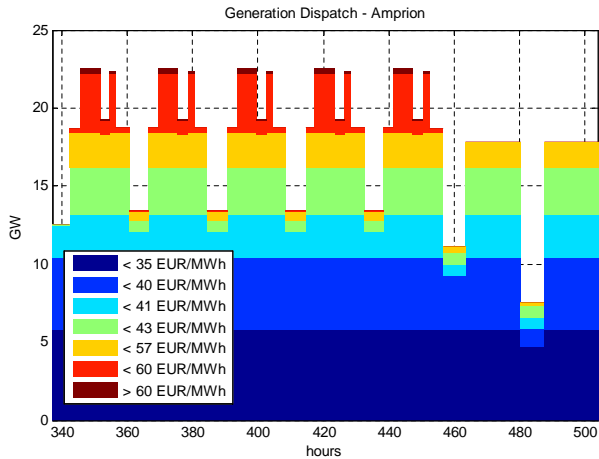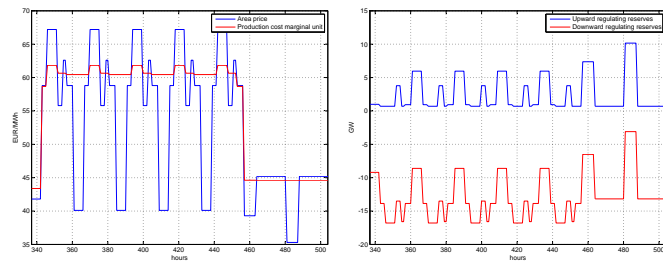
Fig. 4. Generation dispatch of Amprion during week 3

(a) Area price vs. marginal production cost

(b) Reserve resources

Fig. 5. Generation dispatch of Amprion - Analysis

only up- or downward regulating energy can be exchanged between the Nordic and the northern continental European area.
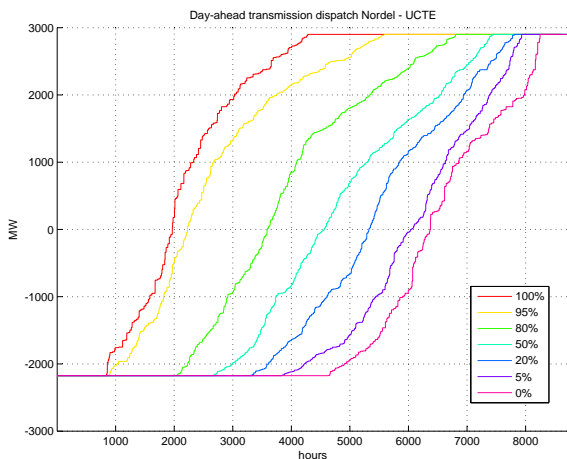

Fig. 6. Day-ahead dispatch of transmission between Nordic and Northern continental European system

B. Reserve procurement

Given the day-ahead market clearing, in the second step, as shown in Fig. 2, required regulating reserves are procured.

This is done by a redispatch of the generation units. The approach of reserve procurement done in this model is different from the reserve capacity markets run in the northern European areas, as described previously in section III. By running the reserve capacity markets, generation capacity is detracted from the day-ahead market beforehand and procured for system balancing, ensuring that enough generation capacity is available during real-time system operation. As perfect market behaviour is assumed in this model, it is assumed that all available generation capacity is bid into the markets, the day-ahead market as well as the regulating power market. Thus it differ if generation capacity is withdrawn from the day-ahead market beforehand or if this generation capacity is procured as regulating reserves afterwards. The only difference in procuring the regulating reserves after the day-ahead market clearing is that in this case the marginal generation capacity is always chosen in order to provide regulating reserves. If the regulating reserve procurement before day-ahead market clearing, the procurement has to be based on an expected day-ahead market outcome, as discussed previously. Thus it is not ensured that the marginal units are chosen in order to provide the regulating reserves. The sequence chosen in this model can be seen as the socio-economic most beneficial approach, what is an idealized reserve procurement, probably resulting in a to low reserve procurement cost estimation.

The reserves being procured comprise up- and downward regulating reserves, but spinning reserves only in the case of thermal power plants. The definition of spinning reserves used throughout this paper is depicted in Fig. 7. There is a distinction between hydro and thermal units providing reserves. For hydro units it is assumed that their start up costs can be neglected and that they do not have a minimum production capacity. Thus their full production capacity can be used as regulating reserves and the units do not need to be started in order to provide regulating reserves. However thermal units do have start up costs and a minimum production capacity. Thus only units that are started up, i.e. producing above their minimum production capacity can provide reserves. They can provide reserves up to their maximum production capacity. Further on downward regulating reserves can only be provided down to the level of the minimum production capacity as indicated in Fig. 7 and not down to zero as it is the case for hydro units.
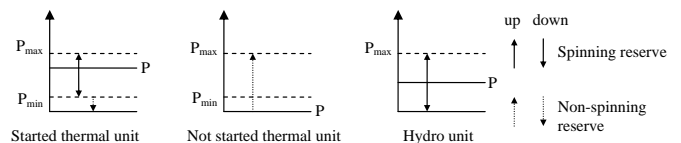

Fig. 7. Definition of spinning and non-spinning reserves

In order to define the required regulating reserves the areas defined in EMPS are aggregated according to the current control areas as described previously. Further on three balancing areas are defined. Reserve requirements are then defined for the control areas, the balancing areas and the total system. The reserve requirements for the single control areas are shown

in Table III. These requirements are based on actual values for the areas, which can be found in [20], [19] and [16]. The values chosen here are the requirements for the fast disturbance reserves (FADR) in the Nordic system and the requirements for secondary reserves in the Netherlands and Germany. In Norway the requirements are defined for the whole country instead of the three control areas.

TABLE III
RESERVE REQUIREMENTS IN MW

	NO1	NO2	NO3	SWE	FIN	DK
Up		520		560	365	175
Down		-520		-560	365	175

	DE1	DE2	DE3	DE4	NL
Up	640	830	1000	540	300
Down	-400	-590	-725	-330	-300

The regulating reserve procurement is modelled with a linear optimization problem. A detailed formulation of the model can be found in appendix B. Below this model is explained.

The aim of the reserve procurement is to change the given day-ahead dispatch in a way to allocate sufficient regulating reserves according to the defined reserve requirements $\bar{r}_k^K$, $\underline{r}_k^K$, $\bar{r}_b^B$, $\underline{r}_b^B$, $\bar{r}^T$, $\underline{r}^T$, see appendix A. These reserve requirements are defined in equation 11 to 14, where the sum over all regulating resources provided by thermal and hydro plants situated in a control area, a balancing area or in the total system has to be higher or equal than the required reserves. Examples for different reserve requirements in balancing areas as well as the total system are given further below in the case study analysis.

In order to fulfil the reserve requirements the day-ahead dispatch has to be changed, which is done by a redispatch of the generating units. Two examples of such a redispatch are explained shortly hereafter. Sketches of them are shown in Fig. 8 for the procurement of upward regulating resources and in Fig. 9 for downward regulating resources. In these examples unit 1 is the cheaper and unit 2 the more expensive one.
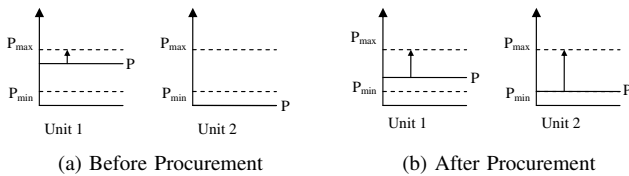

(a) Before Procurement   (b) After Procurement

Fig. 8. Upward regulating resource procurement

In the first case before the reserve procurement, as shown in Fig. 8a, there are not sufficient upward regulating reserves available. To fulfil the requirements unit 2 has to be started up. Due to the minimum production capacity unit 2 has to be started up at least to the minimum capacity resulting in a decrease of production on unit 1, see fig. 8b. This results in increased production costs due to the higher marginal production costs of units 2 compared with unit 1 and additional start up costs due to the start up of unit 2.

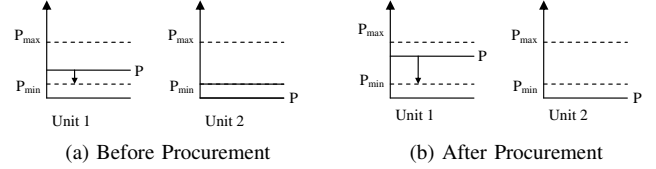(a) Before Procurement   (b) After Procurement

Fig. 9. Downward regulating resource procurement

In the second case before the reserve procurement, as shown in Fig. 9a there are not enough downward regulating resources available. This periodically happens during off-peak periods, where some of the dispatchable generating units are still in operation and operate at minimum production capacity to avoid additional shut down and start up costs. To procure additional downward regulating reserves one of the units has to be shut down, which here is unit 2, see Fig. 9b. This shut down results in a increased production of unit 1 providing sufficient regulating reserves. In this case the cost for procuring the required resources contains the additional shut down costs for unit 2 and an actual reduction of the production costs due to lower marginal production costs of unit 1 compared with unit 2.

The redispatch for hydro units is defined by equation 3 with the production limitations in equation 4, where $y_{h,\omega,\tau}^{hyd^P}$ is the generation dispatch of the hydro unit after the reserve procurement. The available regulating reserves provided by hydro units for upward regulation are $\left(\bar{y}_h^{hyd} - y_{h,\omega,\tau}^{hyd^P}\right)$ and for downward regulation are $\left(y_{h,\omega,\tau}^{hyd^P} - \underline{y}_h^{hyd}\right)$. A minimum production capacity for hydro plants is defined as $\underline{y}_h^{hyd}$, which normally is zero, but can be negative to represent pumping capabilities of a hydro power plant.

The redispatch for thermal units is defined in equation 5. Equation 6 to 10 are necessary in order to include the start up costs of thermal power plants in a way to be solved in a linear optimisation problem. A detailed description of the approach can be found in [42]. $\Delta_\uparrow x_{g,\omega,\tau}^{th}$ and $\Delta_\downarrow x_{g,\omega,\tau}^{th}$ define relative values of provided upward respectively downward regulating reserves. In order to determine the provided reserves, those values have to be multiplied by the free dispatchable capacity of the actual thermal power plant $\left(\bar{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th}\right)$. Equation 9 defines the start up of a thermal power plant between the PTUs $(\tau - 1)$ and τ. Equation 10 defines the whole problem as a round-coupled problem, i.e. the units start up state at the begin of a week are assumed also to be start up state at the end of the week. Thus equations 9 and 10 result in the temporal connection between the PTUs.

During the resource procurement a change of the transmission dispatch is not allowed. Thus the production balance in each individual day-ahead area has to be kept, defined by equation 2. In addition to the possible redispatch of thermal and hydro units, rationing of demand and shut down of scheduled production units is added in order to keep the linear problem feasible. Rationing can be compared to anticipated curtailment of demand in order to maintain the operational security during peak periods. Shut down of lignite or other

base-load plants can be necessary during off-peak periods as well.

The linear problem is solved for a whole week including all of the 674 PTUs. The problem is defined to be deterministic, assuming the generation dispatch, area prices and water values to be known for the whole week.

The objective of the linear optimisation problem is the minimisation of the total redispatch cost. The objective function for $C_\omega^P(y^*)$ is defined by equation 1. In order to determine the total costs, the marginal costs of redispatching a unit are defined by equations 25 to 28. For the thermal units these marginal redispatch costs are based on the marginal production costs of the unit and the area price. They are increased respectively decreased by 5%. For hydro units the marginal redispatch costs are based on the water values and the area price. An cost increase is only done for the thermal units in order to reduce the procurement of regulating reserves provided by them and subsitute it by reserves from hydro units instead. Without such an increase the marginal units of both types would have the same marginal costs after the day-ahead market clearing, whereas it would not make a difference by which units the regulating reserves are provided. However in reality it is seen, that provision of regulating reserves from hydro units is preferred. Thus the increase is a rough emulation of the regulating reserve procurement behaviour in reality.

C. System Balancing

In the final step the system is balanced in real-time. As electricity is not storable, the production and consumption of energy has to be kept in balance during real-time operation of the transmission grid, what is done by activating regulating reserves. The activation of regulating reserves corresponds to the acceptance of energy bids in the regulating power market. In order to achieve the socio-economic best outcome, these bids have to be activated in the order of their bid prices, taking into account remaining transmission capacities after the day-ahead market clearing.

A model of the system balancing is implemented as a linear optimisation problem. The detailed formulation of the model can be found in the appendix C. Input to the system balancing model are the generation dispatch after the resource procurement and results from the day-ahead market clearing, including the transmission dispatch, area prices and water values. A further input is the imbalance of the system. The system imbalance consists of different parts like the load forecast error, hour-to-hour production & consumption changes, unplanned outages and the wind power production forecast error. In the model the imbalance only includes a load forecast error and a wind forecast error, which are represented by recorded imbalance scenarios of 2008 for the Netherlands and Germany [43] - [19] as well as recorded imbalance scenarios of 2007 for Norway and Sweden [48]. As there is a difference between the PTU length in the UCTE and Nordel, the imbalances of Nordel are conerted to a 15 minute resolution to have a matching PTU length. The recorded imbalance scenarios are only available for the whole control areas, however the system balancing model is based on the individual 29 day-ahead areas

to include the available transmission capacities after day-ahead market clearing. Thus the imbalances are distributed by a share according to the ratio of total annual demand of the area to total annual demand in the control area. This results into imbalances for all the individual areas.

The aim of the system balancing is to equal electricity production and consumption in each individual area, including the exchange of electricity between the areas, taking into account the real-time imbalances. The system balance is defined by equation 16 for each area. Included are the possible change in thermal power production, the possible change of the transmission on the lines, the according change of transmission losses, the possible change of hydro power production, rationing of demand and shut down of production. The overall sum of those has to equal the imbalance in the according area consisting of the load forecast error and the wind forecast error.

As mentioned previously, during system balancing the day-ahead transmission dispatch can be changed. The actual real-time transmission is defined in equation 18 with the according transmission losses in equation 17. The predefined constants $\delta_l^B \in \{0, 1\}$ define for each of the lines, if transmission is allowed to be changed during system balancing. This gives the possibility defining whether a line is available for exchanging balancing energy or not, in order to be able to define different regulating market integration levels.

The activated hydro regulating reserves are defined as $\Delta_\uparrow y_{h,\omega,\tau}^{hyd^B}$ $\Delta_\downarrow y_{h,\omega,\tau}^{hyd^B}$, which are determined in equations 19 for upward regulation and 20 for downward regulation respectively. They have to be positive and less or equal to the available reserve for each hydro unit.

The activated thermal regulating reserves are defined in equations 21 to 24. Hereby it is distinguished between spinning reserves $\Delta_\uparrow y_{g,\omega,\tau}^{th_s^B}$ and $\Delta_\downarrow y_{g,\omega,\tau}^{th_s^B}$ and non-spinning reserves $\Delta_\uparrow y_{g,\omega,\tau}^{th_t^B}$ and $\Delta_\downarrow y_{g,\omega,\tau}^{th_t^B}$, as explained previously. Spinning reserves are the reserves available after the resource procurement, as shown in Fig. 7. Non-spinning reserves equal all further generation capacity of dispatchable thermal units. Non-spinning reserves are shown in Fig. 7 likewise. Non-spinning reserves are included in the system balancing model to make all dispatchable thermal generation capacity available for system balancing. The difference for the utilization of spinning and non-spinning reserves is their activation price, which is discussed further down below.

The system balancing's objective is to minimize the socio-economic costs of activating regulating reserves. The according objective function for $C_{\omega,\tau}^B(y^P)$ is stated in equation 15. The linear problem is solved for each PTU individually as there are no temporal dependencies defined, such as ramping or the start up and stopping of units. In addition to the activation of regulating reserves, rationing of demand and shut down of production is defined in the system balancing as well. These can be compared with curtailment of consumption or the shut down of excess wind production during real-time operation of the system.

D. Regulating reserve pricing

In order to estimate the cost for the real-time system balancing the regulating reserves have to be priced. As discussed above in section IV there are only few researches done on estimating or forecasting regulating prices, but none for the determination of actual marginal costs of regulating reserves. As the objective of the system balancing model is a socio-economic optimal activation of regulating reserves, the prices of the regulating reserves used in this paper are based on the marginal production costs of the reserve providing units. The determination of the regulating reserve prices can be found in equations 29 to 34. These are very rough estimates of marginal regulating reserve prices. For hydro units the marginal regulating reserve prices are based on the water value and the area price, being increased or decreased by 10% for upward respectively downward regulating resources. For spinning thermal units the marginal regulating reserve prices are based on the marginal production costs of the regulating reserve providing units and the area price, being increased or decreased by 50% for upward respectively downward regulating resources. The difference between the increase of 10% for hydro units and 50% for thermal units additionally enforces the utilization of hydro regulating reserves instead of thermal ones. To provide all dispatchable thermal capacity for balancing the system in addition to spinning, reserves non-spinning reserves are defined. There are no start up or minimum production requirements on the non-spinning regulating reserves, however these issues are included in the pricing of the non-spinning regulating reserves. The inclusion is done by adding or substracting related start up cost to respectively from the marginal regulating reserve price. This increases the prices quite substantially, which results into utilization of non-spinning reserves in exceptional circumstances only.

Rationing is priced at 10000 EUR/MWh during resource procurement as well as system balancing. The shut down of other than dispatchable production is done at 0 EUR/MWh also during resource procurement as well as system balancing.

VI. CASE STUDIES

To test the model and evaluate the possible benefit of the integrating regulating markets several cases are defined. The cases studied in this paper represent a step wise integration of the northern European regulating markets, distinguishing between a system wide exchange of regulating energy and a system wide procurement of regulating resources.

As the basis for the cases studied, two different years are chosen, a wet and a dry one. This refers to the inflow of the Nordic hydro system. An overview of these years is given in Table IV. It can be seen that there is a 40% difference in inflow to the hydro system. Additionally there is 25% less wind power production in the dry year. These differences impact on the overall operation of the system, which is shown by the net energy export to continental Europe during a wet year and the net energy import from continental Europe during the dry year. Further on it also has an impact on the day-ahead dispatched production of the thermal generation in continental Europe which is substanially higher in a dry year, probably resulting in less available reserves.

TABLE IV
COMPARISON BASIS YEARS

	Wet	Dry
Storable & Non-storable Inflow (TWh)	244.5	146.1
Wind power production (TWh)	74.93	56.1
Net Exchange Nordel - UCTE (TWh)	8.46	-8.39
Production dispatchable thermal generators (TWh)	287.5	319.6

For both years, different steps of regulating market integration are defined, reaching from the current state with no integration up to full integration of regulating markets including system wide regulating reserve procurement and the system wide exchange of regulating resources. The different cases are defined as follows:

a) Case I: is chosen to represent the current state of the system before the integration of the single German regulating markets, as described in section IV. Regulating reserves have to be procured in each control area itself. There is no possibility of exchanging regulating resources between Nordel and UCTE, no exchange possibility between UCTE's control areas, but exchange possibility between the control areas in Nordel.

b) Case II: represents the state of the system after integrating the regulating markets of all the four German control areas as described in [29]. The model is the same as in Case I except that the exchange of regulating resources is allowed between the four German control areas.

c) Case III: represents the state of integration of balancing markets, when regulating resources can be exchanged in system wide, but regulating reserve procurement still has to be done in each single control area.

d) Case IV: allows the procurement of 25% of required regulating reserves for each control area in its according balancing area and the system wide exchange of regulating resources.

e) Case V: additionally allows the system wide procurement of 25% of the required regulating reserves for each control area.

In this paper an amount of 25% of required regulating reserves to be procured outside the control area or the balancing area respectively is chosen. As suggested by UCTE [49] and included in its Policy [15] an amount of maximum 33% of the required secondary reserves is allowed to be procured outside the control area. A substantial share of the required reserves are necessary to be procured in the control area to preserve the operational security. As the model presented in this paper there does not check for available transmission capacity during the reserve procurement process yet, a lower share compared to the UCTE requirements [15] is chosen.

VII. RESULTS

The common day-ahead market is run for 40 different inflow and wind speed scenarios. A wet and a dry year are chosen as the basis for the reserve procurement and the system balancing for the previously defined cases. In this section the results of those cases are presented and discussed.

Fig. 10 and Fig. 11 show the details of two chosen areas being Southern Norway and the Amprion area respectively.

The plots show case V for the wet year. The 34944 PTUs for a generic year of 364 days are plotted.

In the upper diagrams of both figures the prices in the areas are depicted. The plotted prices are the real-time balancing price, the day-ahead area price and for Southern Norway as it is a hydro area the water value. For Southern Norway it can be seen that the day-ahead area price lies around the water value. The real-time balancing price is spread around the area price in a certain band corresponding to the pricing method of the reserves discussed previously. The real-time balancing price is the marginal regulating reserve price of the marginal regulating reserve activated. During summer prices drop down to nearly zero. This happens due to excess inflow to the system and due to low demand resulting in shut down of production, what corresponds to spillage in the hydro system. In the Amprion area, a thermal area, the day-ahead area price and the real-time balancing price are plotted. Likewise in the hydro area the balancing prices are spread around the area prices in a certain band according to the previous regulating reserve price definition. As already discussed for the results of the day-ahead market clearing, it can be seen that the variation of prices during a short period is much higher in the thermal area than in the hydro area. This also results into a higher variation of balancing prices in the thermal area. The drop of prices during summer is not observed in the thermal area. However during the last weeks and the first week of the year a drop of prices can be spotted. Reason for this price drop is the low demand during Christmas holidays. Further on there are some spikes in the balancing prices. These are the times when activation of non-spinning reserves occurs.
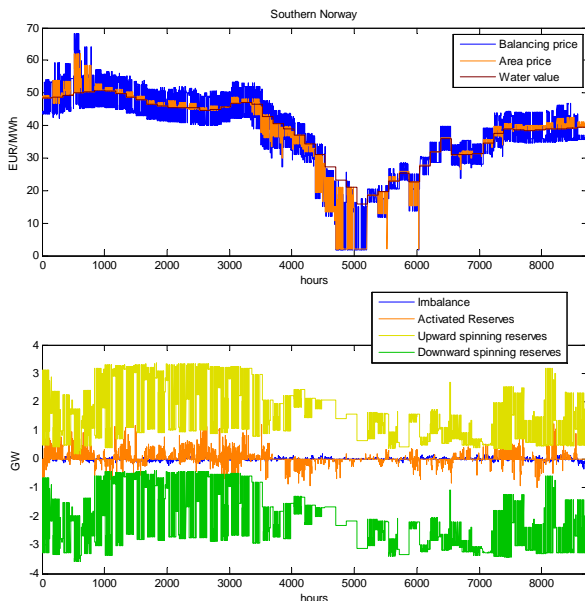

Fig. 10. Result Southern Norway, Case V, Wet Year

In the lower diagrams in Fig. 10 and Fig. 11 operational values of the areas are shown. These area the imbalance in the area, the available spinning upward and downward regulating reserves and the actual activated regulating reserves in the area. In the Amprion area additionally the non-spinning
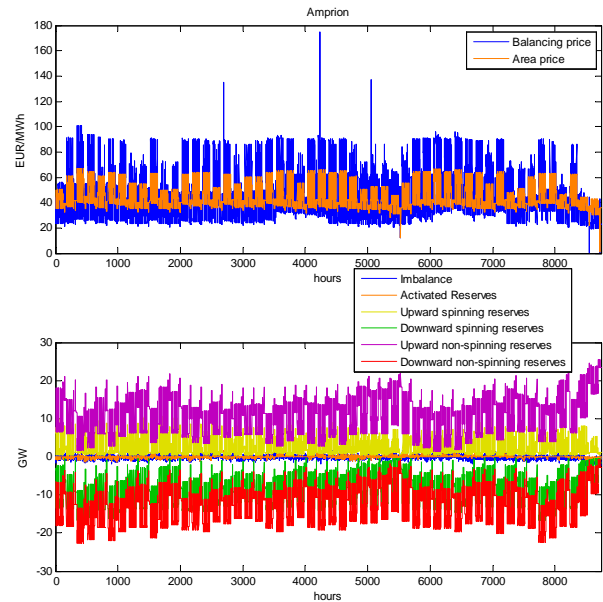

Fig. 11. Result Amprion, Case V, Wet Year

regulating reserves are plotted. As all the hydro power plants can provide regulating reserves, there is an high amount of regulating reserves available in Southern Norway, which shows the good regulating reserve providing capabilities of the hydro system. The actual system imbalance in Southern Norway is much less than the activated regulating reserves in this areas indicating the export of regulating resources. In the Amprion area the situation of regulating reserves is much tighter. Not only spinning upward reserves are quite low and just according to the required volume. Also the availability of downward regulating reserves is quite low periodically, especially during low load periods, as can be seen during the late summer and during the Christmas time. Looking at the relation between the imbalance and the actual activated regulating reserves, it can be seen that the actual imbalance is higher. This indicates the import of regulating resources from other areas.

Fig. 12 shows the difference between the day-ahead transmission dispatch and the actual transmission after the system balancing including the exchange of regulating reserves. The transmission depicted is the aggregated exchange between the Nordic system and northern continental Europe, which includes the West Denmark-Germany interconnection and the NorNed, Baltic and Kontek HVDC-cables. Shown are the transmission duration curves for the wet and the dry year. It can be seen that the duration curves before and after system balancing are approximately the same, what shows that the total exchange of energy is nearly constant. The effect of balancing the system is a smoothing of the duration curves and a reduction of the times where the exchange is at minimum or maximum. This indicates the capability of the cables to exchange regulating reserves. Further on the plots shown in Fig. 12a for the wet year and in Fig. 12b for the dry year show a small shift of the duration curve after system balancing compared to the day-ahead dispatch. The right shift in Fig. 12a indicates a net export of regulating energy from the

TABLE V
RESERVE PROCUREMENT AND SYSTEM BALANCING RESULTS IN A WET AND A DRY YEAR

Year	Case	Reserve procurement				System balancing						
		Cost	Rationing	Shut down	Redispatch	Cost	Upward regulating	Downward regulating	Net exchange	Gross exchange	Rationing	Shut down
		M€	GWh	GWh	GWh	M€	GWh	GWh	GWh	GWh	GWh	GWh
wet	V	49,81	0,015	56,62	2736	62,00	3185	-3327	348	2200	0	0,681
	IV	70,71	0,015	80,27	3900	60,98	3185	-3327	353	2197	0	0,344
	III	91,92	0,555	167,7	4140	60,22	3185	-3328	354	2194	0	0,119
	II	91,92	0,555	167,7	4140	96,00	3991	-4116	0	0	0	0,131
	I	91,92	0,555	167,7	4140	180,7	5865	-5990	0	0	0,036	18,63
dry	V	88,12	3,225	14,28	3062	74,58	3284	-3418	-912,7	1962,6	0	0,121
	IV	110,8	3,225	21,67	4269	74,10	3284	-3419	-903,6	1956,9	0	0
	III	436,1	34,22	50,10	4435	73,69	3284	-3419	-901,7	1956,5	0	0
	II	436,1	34,22	50,10	4435	113,5	3946	-4054	0	0	0,036	0
	I	436,1	34,22	50,10	4435	206,9	5829	-5936	0	0	0,325	12,68

Nordic system, which corresponds to a net export of upward regulation in the wet year. In the dry year there is a left shift, indicating a contrarily behaviour in a dry year.
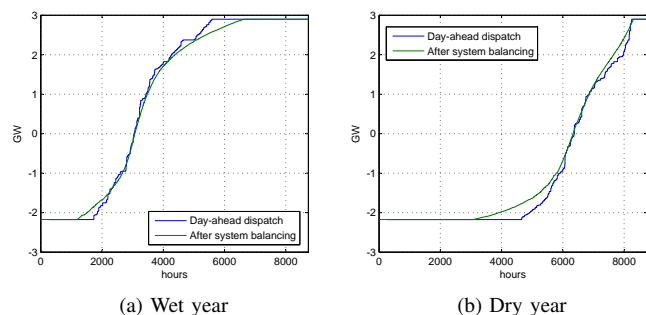

(a) Wet year　　　　　(b) Dry year

Fig. 12.　Duration curve transmission dispatch Nordel-UCTE

In Fig. 13 the difference between the day-ahead transmission dispatch and the actual transmission after system balancing is depicted. As above this is done for the aggregated exchange between the Nordic system and northern continental Europe. This difference can be interpreted as the exchanged regulating resources. During the dry year shown in Fig. 13b there is an exchange of regulating resources between 2.5 GW of upward regulation to -2 GW of downward regulation during the whole year with no significant differences between the seasons. In the wet year shown in Fig. 13a the exchange of regulating resources is between about 3 GW of upward regulation and -2 GW of downward regulation. In this case there is significant difference between the season. During summer there is mostly no export of upward regulating resources. Due to the high inflow to the reservoirs, the day-ahead prices in Southern Norway, as depicted in Fig. 10, as well as all the Nordic system drop to nearly zero. Thus there is already full export to northern continental Europe during the day-ahead dispatch. This results in no available transmission capacity for an additional export of upward regulating energy during the whole summer of this wet year.

Table V shows a summary of all the above described cases. The results are divided into the reserve procurement and the
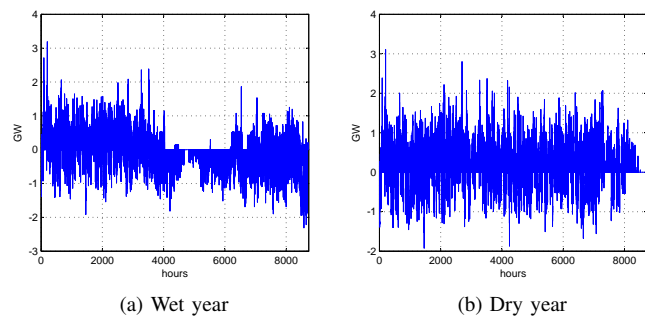

(a) Wet year　　　　　(b) Dry year

Fig. 13.　Regulating resource exchange Nordel-UCTE

system balancing. The results for reserve procurement for case I to III are equal as the procedure of reserve procurement is the same here. Comparing them to case IV there is a decrease in the necessary redispatched energy of about 165 GWh in dry year and 240 GWh in the wet year which comes with a significant reduction of the procurement costs. The difference between these both cases is the ability to procure parts of the required regulating reserves in the balancing areas, which a control area is situated in, instead of procuring all required regulating reserves in the control area. The main reduction of redispatched energy is achieved in Germany. This step can be compared with the recent integration of the German control areas. In [32] and [29] the savings due to German wide procurement are estimated to be around 100M€, which is much more than calculated by this model with approximately 20M€ per year for the wet year. In a dry year the procurement cost are significantly higher. The reason for this is the drastic increase of rationing during the resource procurement resulting in a huge share of the procurement costs.

With the implementation of a system wide possibility of resource procurement the redispatched energy can be decreased additionally by approximately 30% in the wet as well as the dry year. With this further reduction of redispatching energy comes a further reduction of the procurement costs, which are comparable with the previous step, being about 20M€ per year.

Analysing the rationing and shut down during the reserve procurement, a difference can be seen between a wet and a dry year. Rationing during reserve procurement happens in a case when there already is high load near to the total installed generation capacity. Then even when taking into account all available generation capacity, there are not enough reserves available. In order to fulfil the reserve requirements parts of the load have to be curtailed, which happens at a high price.

Rationing is no big issue in a wet year as there are sufficient generation resources. There is significant rationing in dry years though. The rationing only occurs in the northern continental European areas even though its reason the difference in inflow occurs in the Nordic areas. The higher rationing is caused by a export of energy from continental Europe to the Nordic system on average in the dry year. This results in a higher utilization of the dispatchable thermal generation capacity in northern continental Europe. Thus less reserve resources are available in the northern continental European areas. With a system wide reserve procurement the rationing can be decrease significantly.

In reality, the TSO comes in a quite difficult position if a choice must be made between operation with insufficient reserves and rationing of demand or load shedding. In theory, from an economic point of view, the amount of reserves should be chosen such that the marginal cost of the reserves equals the expected marginal outage costs. So if the amount of reserves is optimal with a reserve cost of 50 to 100€/MWh, this amount should obviously be reduces if the cost suddenly increases to 10000€/MWh, indicating that load shedding should not be used to avoid marginal violations of the reserve requirement. In practice, reserve requirements are based on more technical criteria, which are treated as absolute constraints. The ultimate consequence of this is, that load shedding is necessary if there is no other way to satisfy these constraints, and this is the approach taken in the model.

At the shut down during the reserve procurement production of base load power plants like nuclear or lignite is decreased, which is covered by starting up more expensive ones like hard coal. It is done as nuclear and lignite power plants cannot provide reserve resources, but dispatchable power plants are needed to provide the required resources. This applies for upward as well as downward regulating resources. The shut down is only done in northern continental Europe too. It is higher during a wet year, when there is net import of energy to northern continental Europe. A reduction by about 30% can be achieved by a system wide reserve procurement.

Analysing the difference between the studied cases in the system balancing, the main difference occurs between cases I-III. This corresponds to the different steps of exchanging regulating energy. In case I exchange of regulating energy between the German control areas is not allowed whereas this is allowed in case II. This results in a significant decrease of balancing costs by approximately 50% and a reduction of the activated regulating resources by approximately 30%. The reduction of reserves being activated is the result of netting the imbalances of the different areas. The reduction of the balancing costs includes the activation of cheaper regulating resources and the previously mentioned overall

lower activation of regulating resources. The step from case I to case II can also be compared to the recent integration of the German regulating power markets. In [33] and [29] according savings of 100M€ are estimated, which are comparable with the savings calculated by this model. In case III exchange of regulating energy in the whole system is allowed. With that comes a further reduction of the balancing costs and the activated regulting resources. Netting of the total system imbalances results in reduction of activated regulating reserves by approximately 20%. The balancing costs can be reduced further by 30%. Looking on the exchange of regulating resources between the Nordic system and northern continental Europe it can be seen that in an integrated regulating market 30% of the regulating resources are imported to continental Europe. The net exchange of regulating resources depends if it is a wet or dry year, being positive in a wet year, which corresponds to a net export of upward regulating resources. In a dry year the net export is negative. Between cases III-V there are no significant differences which shows that the different methods of reserve procurement do not affect the system balancing.

Due to the procurement of reserve there mostly are enough regulating reserves available in the system. Regarding rationing, it only occurs in the case when there is no exchange of regulating energy allowed between the German control areas during the wet year. During the dry year there also is some rationing in the second case, what happens due to the tighter generation situation. By exchanging regulating energy in the total system rationing can be prevented completely. The shut down of production during real-time system balancing happens more often than rationing. It can be seen that the amount of shut down production can also be decreased significantly by exchanging regulating energy in the total system.

The above presented results are in accordance with estimates of Frontier Economics, which estimated in their 2009 study [50] a possible additional socio-economic benefit of 5.4M€ to 15.9M€ per year in the trade of balancing services by the reservation of 50MW of exchange capacity, taking prices of France the UK, Germany and the Netherlands as a basis. Likewise A. Abbasy et al. in [9] estimated an additional socio-economic benefit of exchanging balancing services between northern continental Europe and the Nordic system at about 80M€.

VIII. Conclusion

In this paper a model is developed which can represent an integrated northern European regulating market, being based on a common northern European day-ahead market clearing. It arises that in the Nordic system ample regulating reserves are normally available, due to the good regulating capability of the hydro power production, which constitutes a high share of power production in the Nordic system. Due to the characteristics of the thermal-based system in the northern continental European area it is necessary to procure upward as well as downward regulating resources. In this paper it is suggested to procure parts of the required regulating reserves in the Nordic system and exchange regulating resources system

wide taking into account available transmission capacity from the day-ahead market.

With different defined cases a stepwise integration of the northern European regulating markets is studied. A comparison with the recent integration of the German regulating markets is done to test the model's consistency. It is shown that by procuring reserves in the system wide the necessary redispatch can be reduced 30%, what indicates that there are ample regulating reserve available in the Nordic system. The activation of regulating reserves can be reduced by 20% due to netting of the imbalances in the system. Further on one third of the activated regulating resources is exchanged between the Nordic system and the northern continental European system.

The socio-economic benefit of procuring regulating reserves system wide and exchanging regulating resources depends on the costs of the regulating reserves. In this paper the costs of regulating reserves are rough estimates, comparing the results with the recent integration of the German regulating markets [29] shows consistency though. The reduction of operation costs is therefore tentative, however it is shown that there are good possibilities of exchanging regulating resources and estimating their amount.

The installation of further intermittent generation capacity like wind power production results in an increased necessity for regulating reserves. As shown in this paper the Nordic, especially the Norwegian hydro based electricity production can provide parts of these regulating reserves. In order to exchange regulating resources between the Nordic countries and continental Europe an integrated regulating market is needed. Modelling such an integrated regulating market, which is based on a common day-ahead market clearing, shows that there is a possible socio-economic benefit in exchanging regulating resources.

APPENDIX

A. Notation

The notation used throughout the paper is stated below.

a) Indicators:

$*$	Day-ahead market
P	Resource procurement
B	System balancing
$\uparrow$ / $\downarrow$	Upward / downward
$^-$ / $_-$	Maximum / minimum

b) Sets and indexes:

$a \in A$	Single areas defined in EMPS
$k \in K$	Control areas
$b \in B$	Balancing areas
$h \in H$	Hydro plants with H_a, H_k being subsets of hydro plants situated in areas a or k respectively
$g \in G$	Thermal plants with G_a, G_k being subsets of thermal plants situated in areas a or k respectively
$l \in L$	Transmission lines with L_a^{to}, L_a^{fr} being subsets of lines transmitting to and from the area a
$\omega \in W$	Weeks
$\tau \in T$	Quarter hours during a week

c) Functions:

$C_\omega^P(y^*)$	Cost function of reserve procurement
$C_{\omega,\tau}^B(y^P)$	Cost function of system balancing

d) Water values and area prices:

$v_{a,\omega}$, $p_{a,\omega}$	Water value and day-ahead price in each area

e) Thermal generation:

$y_{g,\omega,\tau}^{th^*}$	Day-ahead dispatch of thermal plants
$y_{g,\omega,\tau}^{th^P}$, $\Delta_\uparrow y_{g,\omega,\tau}^{th^P}$, $\Delta_\downarrow y_{g,\omega,\tau}^{th^P}$	Redispatch of thermal plants during resource procurement
$\Delta_\uparrow y_{g,\omega,\tau}^{th_s^B}$, $\Delta_\downarrow y_{g,\omega,\tau}^{th_s^B}$	Secondary up- and downward regulating of thermal plants in real-time balancing
$\Delta_\uparrow y_{g,\omega,\tau}^{th_t^B}$, $\Delta_\downarrow y_{g,\omega,\tau}^{th_t^B}$	Tertiary up- and downward regulating of thermal plants in real-time balancing
$\overline{y}_{g,\omega}^{th}$, $\underline{y}_{g,\omega}^{th}$	Maximum and minimum generation capacity of thermal plants
c_g^{th}, s_g^{th}	Marginal cost and start up cost of thermal plants
$\uparrow c_{g,\omega,\tau}^{th^P}$, $\downarrow c_{g,\omega,\tau}^{th^P}$, $s_{g,\omega,\tau}^{th^P}$	Marginal redispatch cost and starting cost of thermal plants in resource procurement

$_{\uparrow}c_{g,\omega,\tau}^{th_s^B}$, $_{\downarrow}c_{g,\omega,\tau}^{th_s^B}$ — Marginal up- and downward regulating costs of thermal plants for secondary reserve

$_{\uparrow}c_{g,\omega,\tau}^{th_t^B}$, $_{\downarrow}c_{g,\omega,\tau}^{th_t^B}$ — Marginal up- and downward regulating costs of thermal plants for tertiary reserve

$x_{g,\omega,\tau}^{th}$, $\Delta_{\uparrow}x_{g,\omega,\tau}^{th}$, $\Delta_{\downarrow}x_{g,\omega,\tau}^{th}$ — Per unit start up and per unit up- and downward provision of thermal plants

f) Hydro generation:

$y_{h,\omega,\tau}^{hyd*}$ — Day-ahead dispatch of hydro plants

$y_{h,\omega,\tau}^{hyd^P}$, $\Delta_{\uparrow}y_{h,\omega,\tau}^{hyd^P}$, $\Delta_{\downarrow}y_{h,\omega,\tau}^{hyd^P}$ — Redispatch of hydro plants during resource procurement

$\Delta_{\uparrow}y_{h,\omega,\tau}^{hyd^B}$, $\Delta_{\downarrow}y_{h,\omega,\tau}^{hyd^B}$ — Up- and downward regulating of hydro plants in real-time balancing

$\overline{y}_h^{hyd}$, $\underline{y}_h^{hyd}$ — Maximum and minimum production of hydro plants

$_{\uparrow}c_{h,\omega,\tau}^{hyd^P}$, $_{\downarrow}c_{h,\omega,\tau}^{hyd^P}$, $s_{g,\omega,\tau}^{th^P}$ — Marginal redispatch cost of hydro plants

$_{\uparrow}c_{h,\omega,\tau}^{hyd^B}$, $_{\downarrow}c_{h,\omega,\tau}^{hyd^B}$, $s_{g,\omega,\tau}^{th^B}$ — Marginal up- and downward regulating costs of hydro plants

g) Transmission lines:

$t_{l,\omega,\tau}^*$, $t_{l,\omega,\tau}^B$ — Day-ahead dispatch and real-time transmission of lines

$\overline{t}_l$, $\underline{t}_l$ — Maximum and minimum transmission limits

α_l, δ_l^B — Linear losses and availability in balancing of transmission lines

$d_{l,\omega,\tau}^*$, $d_{l,\omega,\tau}^B$ — Transmission losses in day-ahead dispatch and real-time transmission

h) Rationing shutdown:

$y_{a,\omega,\tau}^{rat^P}$, $y_{a,\omega,\tau}^{rat^P}$ — Rationing during reserve procurement and in real-time balancing

$y_{a,\omega,\tau}^{sh^P}$, $y_{a,\omega,\tau}^{sh^B}$ — Generation shutdown during reserve procurement and real-time balancing

i) Resource requirements:

$\overline{r}_k^K$, $\underline{r}_k^K$ — Up- and downward reserve requirements in each control area

$\overline{r}_b^B$, $\underline{r}_b^B$ — Up- and downward reserve requirements in each balancing area

$\overline{r}^T$, $\underline{r}^T$ — Up- and downward reserve requirements in the total system

j) Regulating demand:

$\tilde{e}_{a,\omega,\tau}$, $\tilde{w}_{a,\omega,\tau}$ — Demand forecast and wind forecast error in each area

Following the models for the reserve procurement and the system balancing are described in detail.

B. Resource procurement
k) Objective function:

$\forall \omega \in W$:

$$C_\omega^P(y^*) = min \left\{ \sum_{\tau \in T} \left[\sum_{a \in A} \left(\Delta y_{a,\omega,\tau}^{rat^P} \cdot 10000 - \Delta y_{a,\omega,\tau}^{sh^P} \right) \right. \right.$$

$$+ \sum_{g \in G} \left(\Delta_{\uparrow}y_{g,\omega,\tau}^{th^P} \cdot {}_{\uparrow}c_{g,\omega,\tau}^{th^P} - \Delta_{\downarrow}y_{g,\omega,\tau}^{th^P} \cdot {}_{\downarrow}c_{g,\omega,\tau}^{th^P} + s_{g,\omega,\tau}^{th^P} \right) \quad (1)$$

$$\left. \left. + \sum_{h \in H} \left(\Delta_{\uparrow}y_{h,\omega,\tau}^{hyd^P} \cdot {}_{\uparrow}c_{h,\omega,\tau}^{hyd^P} - \Delta_{\downarrow}y_{h,\omega,\tau}^{hyd^P} \cdot {}_{\downarrow}c_{h,\omega,\tau}^{hyd^P} \right) \right] \right\}$$

l) Constraints:

$\forall a \in A, \omega \in W, \tau \in T$:

$$\sum_{g \in G_a} \left(\Delta_{\uparrow}y_{g,\omega,\tau}^{th^P} - \Delta_{\downarrow}y_{g,\omega,\tau}^{th^P} \right) + \sum_{h \in H_a} \left(\Delta_{\uparrow}y_{h,\omega,\tau}^{hyd^P} - \Delta_{\downarrow}y_{h,\omega,\tau}^{hyd^P} \right)$$
$$+\Delta_{\uparrow}y_{a,\omega,\tau}^{rat^P} - \Delta_{\uparrow}y_{a,\omega,\tau}^{sh^P} = 0 \quad (2)$$

$\forall h \in H, \omega \in W, \tau \in T$:

$$y_{h,\omega,\tau}^{hyd^P} = y_{h,\omega,\tau}^{hyd*} + \Delta_{\uparrow}y_{h,\omega,\tau}^{hyd^P} - \Delta_{\downarrow}y_{h,\omega,\tau}^{hyd^P} \quad (3)$$

$$\underline{y}_h^{hyd} \leq y_{h,\omega,\tau}^{hyd^P} \leq \overline{y}_h^{hyd} \quad (4)$$

$\forall g \in G, \omega \in W, \tau \in T$:

$$y_{g,\omega,\tau}^{th^P} = y_{g,\omega,\tau}^{th*} + \Delta_{\uparrow}y_{g,\omega,\tau}^{th^P} - \Delta_{\downarrow}y_{g,\omega,\tau}^{th^P} \quad (5)$$

$$y_{g,\omega,\tau}^{th^P} = \underline{y}_{g,\omega}^{th} \cdot x_{g,\omega,\tau}^{th} + \Delta_{\downarrow}x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) \quad (6)$$

$$\Delta_{\uparrow}x_{g,\omega,\tau}^{th} + \Delta_{\downarrow}x_{g,\omega,\tau}^{th} \leq x_{g,\omega,\tau}^{th} \leq 1 \quad (7)$$

$$s_{g,\omega,\tau}^{th^P} \geq 0 \quad (8)$$

$\forall g \in G, \omega \in W, \tau \in T/\{1\}$:

$$s_{g,\omega,\tau}^{th^P} \geq s_g^{th} \cdot \left(x_{g,\omega,\tau}^{th} - x_{g,\omega,\tau-1}^{th} \right) \quad (9)$$

$\forall g \in G, \omega \in W$:

$$s_{g,\omega,\tau}^{th^P} \geq s_g^{th} \cdot \left(x_{g,\omega,1}^{th} - x_{g,\omega,max(T)}^{th} \right) \quad (10)$$

$\forall k \in K, \omega \in W, \tau \in T$:

$$\overline{r}_k^K \leq \sum_{g \in G_k} \Delta_{\uparrow}x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) + \sum_{h \in H_k} \left(\overline{y}_h^{hyd} - y_{h,\omega,\tau}^{hyd^P} \right) \quad (11)$$

$$\underline{r}_k^K \leq \sum_{g \in G_k} \Delta_{\downarrow}x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) + \sum_{h \in H_k} \left(y_{h,\omega,\tau}^{hyd^P} - \underline{y}_h^{hyd} \right) \quad (12)$$

$\forall \omega \in W, \tau \in T$:

$$\overline{r}^T \leq \sum_{g \in G} \Delta_{\uparrow}x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) + \sum_{h \in H} \left(\overline{y}_h^{hyd} - y_{h,\omega,\tau}^{hyd^P} \right) \quad (13)$$

$$\underline{r}^T \leq \sum_{g \in G} \Delta_{\downarrow}x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) + \sum_{h \in H} \left(y_{h,\omega,\tau}^{hyd^P} - \underline{y}_h^{hyd} \right) \quad (14)$$

C. System balancing
m) Objective function:

$\forall \omega \in W, \tau \in T:$

$$C_\omega^B \left(y^P\right) = min \left\{ \sum_{\tau \in T} \left[\sum_{a \in A} \left(\Delta y_{a,\omega,\tau}^{rat^B} \cdot 10000 - \Delta y_{a,\omega,\tau}^{sh^B} \right) \right. \right.$$
$$+ \sum_{g \in G} \left(\Delta_\uparrow y_{g,\omega,\tau}^{th_s^B} \cdot {}_\uparrow c_{g,\omega,\tau}^{th_s^B} - \Delta_\downarrow y_{g,\omega,\tau}^{th_s^B} \cdot {}_\downarrow c_{g,\omega,\tau}^{th_s^B} \right.$$
$$\left. + \Delta_\uparrow y_{g,\omega,\tau}^{th_t^B} \cdot {}_\uparrow c_{g,\omega,\tau}^{th_t^B} - \Delta_\downarrow y_{g,\omega,\tau}^{th_t^B} \cdot {}_\downarrow c_{g,\omega,\tau}^{th_t^B} \right)$$
$$\left. \left. + \sum_{h \in H} \left(\Delta_\uparrow y_{h,\omega,\tau}^{hyd^B} \cdot {}_\uparrow c_{h,\omega,\tau}^{hyd^B} - \Delta_\downarrow y_{h,\omega,\tau}^{hyd^B} \cdot {}_\downarrow c_{h,\omega,\tau}^{hyd^B} \right) \right] \right\} \quad (15)$$

n) Constraints:

$\forall a \in A, \omega \in W, \tau \in T:$

$$\sum_{g \in G_a} \left(\Delta_\uparrow y_{g,\omega,\tau}^{th_s^B} - \Delta_\downarrow y_{g,\omega,\tau}^{th_s^B} + \Delta_\uparrow y_{g,\omega,\tau}^{th_t^B} - \Delta_\downarrow y_{g,\omega,\tau}^{th_t^B} \right)$$
$$+ \sum_{l \in L_a^{fr}} \left(t_{l,\omega,\tau}^B - t_{l,\omega,\tau}^* \right) - \sum_{l \in L_a^{to}} \left(t_{l,\omega,\tau}^B - t_{l,\omega,\tau}^* \right)$$
$$+ \frac{1}{2} \sum_{l \in L_a^{fr} \cup L_a^{to}} \left(d_{l,\omega,\tau}^B - d_{l,\omega,\tau}^* \right) + \sum_{h \in H_a} \left(\Delta_\uparrow y_{h,\omega,\tau}^{hyd^B} - \Delta_\downarrow y_{h,\omega,\tau}^{hyd^B} \right)$$
$$+ \Delta_\uparrow y_{a,\omega,\tau}^{rat^B} - \Delta_\uparrow y_{a,\omega,\tau}^{sh^B} = \tilde{e}_{a,\omega,\tau} + \tilde{w}_{a,\omega,\tau} \quad (16)$$

$\forall l \in L, \omega \in W, \tau \in T:$

$$d_{l,\omega,\tau}^B \geq \left| t_{l,\omega,\tau}^B \cdot \alpha_l \right| \quad (17)$$

$$\underline{t}_l \leq t_{l,\omega,\tau}^B \leq \overline{t}_l, for \, \delta_l^B = 1$$
$$t_{l,\omega,\tau}^B = t_{l,\omega,\tau}^*, for \, \delta_l^B = 0 \quad (18)$$

$\forall h \in H, \omega \in W, \tau \in T:$

$$0 \leq \Delta_\uparrow y_{h,\omega,\tau}^{hyd^B} \leq \overline{y}_h^{hyd} - y_{h,\omega,\tau}^{hyd^P} \quad (19)$$

$$0 \leq \Delta_\downarrow y_{h,\omega,\tau}^{hyd^B} \leq y_{h,\omega,\tau}^{hyd^P} - \underline{y}_h^{hyd} \quad (20)$$

$\forall g \in G, \omega \in W, \tau \in T:$

$$0 \leq \Delta_\uparrow y_{g,\omega,\tau}^{th_s^B} \leq \Delta_\uparrow x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) \quad (21)$$

$$0 \leq \Delta_\downarrow y_{g,\omega,\tau}^{th_s^B} \leq \Delta_\downarrow x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) \quad (22)$$

$$0 \leq \Delta_\uparrow y_{g,\omega,\tau}^{th_t^B} \leq \overline{y}_{g,\omega}^{th} - y_{g,\omega,\tau}^{th^P} - \Delta_\uparrow x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) \quad (23)$$

$$0 \leq \Delta_\downarrow y_{g,\omega,\tau}^{th_t^B} \leq y_{g,\omega,\tau}^{th^P} - \Delta_\downarrow x_{g,\omega,\tau}^{th} \cdot \left(\overline{y}_{g,\omega}^{th} - \underline{y}_{g,\omega}^{th} \right) \quad (24)$$

D. Reserve pricing
o) Resource procurement:

$\forall a \in A, h \in H_a, \omega \in W, \tau \in T:$

$${}_\uparrow c_{h,\omega,\tau}^{hyd^P} = max \left(v_{a,\omega}, p_{a,\omega,\tau} \right) \quad (25)$$

$${}_\downarrow c_{h,\omega,\tau}^{hyd^P} = min \left(v_{a,\omega}, p_{a,\omega,\tau} \right) \quad (26)$$

$\forall a \in A, g \in G_a, \omega \in W, \tau \in T:$

$${}_\uparrow c_{g,\omega,\tau}^{th^P} = max \left(c_g^{th}, p_{a,\omega,\tau} \right) \cdot 1.05 \quad (27)$$

$${}_\downarrow c_{g,\omega,\tau}^{th^P} = min \left(c_g^{th}, p_{a,\omega,\tau} \right) / 1.05 \quad (28)$$

p) System Balancing:

$\forall a \in A, h \in H_a, \omega \in W, \tau \in T:$

$${}_\uparrow c_{h,\omega,\tau}^{hyd^B} = max \left(v_{a,\omega}, p_{a,\omega,\tau} \right) \cdot 1.1 \quad (29)$$

$${}_\downarrow c_{h,\omega,\tau}^{hyd^B} = min \left(v_{a,\omega}, p_{a,\omega,\tau} \right) / 1.1 \quad (30)$$

$\forall a \in A, g \in G_a, \omega \in W, \tau \in T:$

$${}_\uparrow c_{g,\omega,\tau}^{th_s^B} = max \left(c_g^{th}, p_{a,\omega,\tau} \right) \cdot 1.5 \quad (31)$$

$${}_\downarrow c_{g,\omega,\tau}^{th_s^B} = min \left(c_g^{th}, p_{a,\omega,\tau} \right) / 1.5 \quad (32)$$

$${}_\uparrow c_{g,\omega,\tau}^{th_t^B} = max \left(c_g^{th}, p_{a,\omega,\tau} \right) \cdot 1.5 + \frac{s_g^{th}}{\underline{y}_{g,\omega}^{th}} \quad (33)$$

$${}_\downarrow c_{g,\omega,\tau}^{th_t^B} = min \left(c_g^{th}, p_{a,\omega,\tau} \right) / 1.5 - \frac{s_g^{th}}{\underline{y}_{g,\omega}^{th}} \quad (34)$$

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