31761 - Renewables in Electricity Markets

Day-Ahead Market in DK1 and DK2.

Eléa Foulgoc s192478
Reda Lahlou s192431
Théo Dullin s192446

31761 - Renewables in Electricity Markets
March 12, 2020

Contents

1 Introduction

In this paper, the mechanism of day-ahead electricity markets has been studied through the example of the danish spot market in November 2019 and January 2020. The main goals were to model and analyse a simplified - albeit realistic - electricity market composed of two zones, and supplied by conventional and renewable producers. The possibility of exchange between the two areas DK1 and DK2 has been considered with a limited capacity of 600 MW. On another side, some import and export contracts between a specific area and another country have been implemented.
Data for renewable hourly generation (wind) and hourly consumption in DK1 and DK2 have been extracted from the danish website Nordpool [1] [2]. Conventional generation capacity and import/export contract are although depending on the hour of the day. Every data used for the model are presented in the Appendix (A3, A4, A5).

Before implementing the specific model in a software program, a general mathematical model has been written to illustrate the market clearing procedure for each time unit. The electricity demand is considered inflexible at each hour, that is why the problem focuses on a minimization of the total cost of producers in the market, rather than a social welfare maximization.

Two practical examples of market clearing in the case of congestion (or no congestion) in the transmission between DK1 and DK2 have been presented in order to underline the mechanism of the day-ahead clearing. Then, the model has been computed in the software GAMS [3] to solve the Linear Programming problem built for each month November and January. Finally, the extracted results have been analysed to underline the influence of renewables, transmission between zones and support scheme policies on electricity prices and producer revenues.

2 Model

2.1 Formulation of the LP problem

The aim of the day-ahead market is to schedule the power generation between trading zones so as to minimize the total cost and to meet the power demand of each zone at each time unit. The total cost is the addition of every individual cost of each supplier in both zones. It depends on individual bidding price - the determination of bidding prices will be explain in the Section 2.2 - and on generation level. Finally, the spot market goal can be described by the following Objective Function (1a).

In case of insufficient generation in one zone, the load demand has to be shed. In order to take into account the possibility of load-shedding, a new variable has been created $S_{x,t}$. The load-shedding price λ_{shed} has been set higher than any other generation cost to ensure that demand is shed only when the maximum generation capacity is exceeded.

In each zone x and for each time unit t, the demand has to be satisfied by the suppliers of the zone $y^{G}_{x,i,t}$ taking into account the power exported $y^{EXP}_{x,t}$ and imported $y^{IMP}_{x,t}$ from abroad, the load-shedding $S_{x,t}$ and the power exchanged with the adjacent area $\Delta\delta_t$. This balancing constraint between supply and demand is translated through the equation (1b).

$$\min_{y^G_{x,i,t}} Z = [\sum_{x\in A}(\sum_{i\in J_x} \lambda_{x,i,t} \cdot y^G_{x,i,t}) + \lambda_{shed} \cdot \sum_{x\in A}(S_{x,t})] \tag{1a}$$

$$\text{s.t.} \sum_{i\in J_x} y^G_{x,i,t} + y^{IMP}_{x,t} - y^{EXP}_{x,t} - y^D_{x,t} + S_{x,t} = \Delta\delta_t \qquad \forall\, x \in A,\ \forall\, t \in T \tag{1b}$$

$$-L^{max} \leq \Delta\delta_t \leq L^{max} \qquad \forall\, t \in T \tag{1c}$$

$$0 \leq y^G_{x,i,t} \leq P^{max}_{x,i} \qquad \forall\, i \in J_x,\ \forall\, x \in A,\ \forall\, t \in T \tag{1d}$$

$$\Delta\delta_t \in \mathbb{Z} \qquad \forall\, t \in T \tag{1e}$$

$$y^G_{x,i,t} \in \mathbb{R} \qquad \forall\, x \in A,\ \forall\, t \in T \tag{1f}$$

Where the variables are :

$y^G_{x,i,t}$	Hourly production of producer i in the area x at time t
$S_{x,t}$	Load shed in area x at time t
$\Delta\delta_t$	Energy exchanged between areas at time t. This exchange is limited by physical constraints (1c) *As this variable is relative, it has been decided to set the following convention for the case studied between DK1 and DK2 :* $\Delta\delta_t \geq 0$ *if energy goes from DK1 to DK2* $\Delta\delta_t \leq 0$ *if energy goes from DK2 to DK1*

Where the parameters are :

$y^D_{x,t}$	Hourly energy demand in area x at time t
$\lambda_{x,i,t}$	Price bid by producer i in area x for the time unit t
λ_{shed}	Load shedding price
$y^{IMP}_{x,t}$	Energy imported in area x at time unit t
$y^{EXP}_{x,t}$	Energy exported by area x at time unit t
$P^{max}_{x,i}$	Production capacity of producer i in area x

And where the sets are :

A	Set of trading areas *In the case studied* $A = \{1,2\}$ *for DK1 & DK2*
J_x	Set of energy producer in the area x *In the case studied* $J_1 =\{G_1, G_2, G_3, G_4, G_5, G_6, G_7, WW1, WW2\}$ *and* $J_2 = \{G_8, G_9, G_10, G_11, G_12, G_13, G_14, G15, EW1, EW2\}$
T	Set of time units studied in the spot market *In the case studied each hour of November 2019 & January 2020.*

2.2 Methodology: Biding prices and revenues

The biding price is a consequence of a strategic choice made by each producer. If he does not receive any support, he maximizes his profits by biding at his marginal production cost. If he benefits from a support scheme, he can choose a biding price lower than his actual marginal production cost. This is the case for producers WW2 and EW2. Since they benefit from a feed-in-price, their biding price will be equal to their marginal production cost (0 €/MWh for both of them) minus the support they get for each MWh they produce. Thus, their biding prices will be:

- For producer WW2: λ = -17 €/MWh
- For producer EW2: λ = -12 €/MWh

Producer EW1 benefits from a feed-in-tariff. This means that he is not subject to the market price, but sells his electricity at a guaranteed price of 20 €/MWh. His optimal offering strategy would be to bid at a price as low as possible: as long as he is scheduled, he knows that he will be making profits through his support scheme. A bid of -18 €/MWh has been chosen for the LP problem. This is lower than any of the other bids, which ensures that EW1 will be the first to be scheduled.

With the parameters aforementioned taken into account, the LP model is able to give the results of the market clearing. The hourly production of each producer, the hourly exchanges between the 2 zones as well as the hourly load shed are given by the different variables. Hourly market clearing prices in each zones x are given by taking the dual variables of the respective balancing constraints (1b).

For a supplier i producing $y^G_{x,i,t}$ at time t in a zone x where the market price is $\lambda^S_{x,t}$, his revenue for this hour will be equal to:

- For producers G1 to G15 and WW1 (no support): $R_{x,i,t} = y^G_{x,i,t} * \lambda^S_{x,t}$
- For producers WW2 and EW2 (feed-in-price of FIP_i): $R_{x,i,t} = y^G_{x,i,t} * (\lambda^S_{x,t} + FIP_i)$
- For producer EW1 (feed-in-tariff of FIT): $R_{i,t} = y^G_{x,i,t} * FIT$

3 Two examples of Market Clearing

3.1 Case 1 : Without congestion

Firstly, a case where there is no congestion between DK1 and DK2 is studied. The time unit considered is the 1st of January between 00:00 and 01:00, known as t_1 in the linear model. The characteristics of the day-ahead market for this period are reminded in the Appendix (A9). The renewable generation is adjusted with the wind power available, and some suppliers do not run in this time unit. Moreover, Norway is the only country to exchange electricity with Denmark.

The consumption difference between DK1 and DK2 is 422 MW, and both areas can meet their own demand since the global generation is higher than the consumption need. As the exchange is limited to 600 MW, they will be no congestion in the transmission system. The two region will be able to exchange energy without limitation. This way, the two markets can be considered as one global market to clear.

Secondly, the merit order curve of the global market is build by sorting producers from the cheapest bid to the most expensive one. The global demand is the addition of the two regional net consumption. The point where supply and demand curves meet corresponds to the market clearing price and quantity. Building the merit order curve this way allows to meet the demand with the cheapest generation price, and so to maximize social welfare - or to minimise generation costs. Only producers bidding at or under the market price will then participate to the generation.

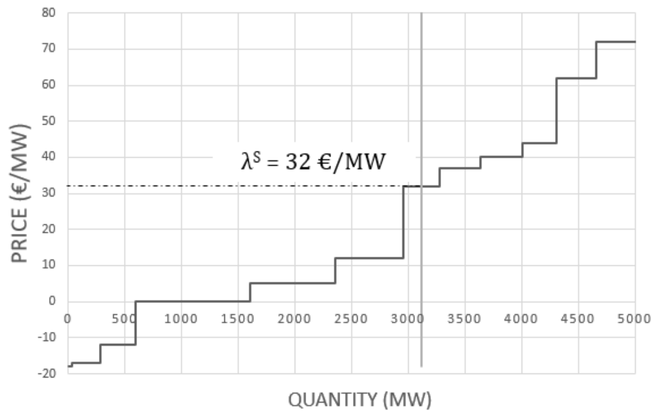

Figure 1: Merit Order curve of the global market at $t = t_1$.

The market clearing price is $\lambda^S = 32$ €/MW in both areas. Only a few producers will be scheduled in the day-ahead, as presented in the following Figure 2. According to the methodology presented in Section 2.2, the revenues of each supplier can be calculated :

Producer i	Area a	$y_{a,i}$ [MW]	$\lambda_{a,i}$	> [€/MW]	Revenue
WW1	1	1004,8	λ^S	32	32 153,6 €
WW2	1	251,2	$\lambda^S + 17$	49	12 308,8 €
EW1	2	34,6	20	20	692,0 €
EW2	2	311,4	$\lambda^S + 12$	44	13 701,6 €
G12	2	162	λ^S	32	5 184,0 €
G13	2	750	λ^S	32	24 000,0 €
G14	2	600	λ^S	32	19 200,0 €

Figure 2: Market Clearing and Revenue of the scheduled producers at $t = t_1$.

Here, DK2 produces more than DK1 and more than its local demand. The exchange between the two areas allows DK1 to import 512 MW from its neighbour in order to have a low market price (λ^S is lower than any conventional producer bidding price in DK1). Moreover, this low price is a consequence of the significant share of wind energy in the generation. The participation of renewable producers drives prices down since their biding price are very low, even negative, and pushes expensive conventional suppliers out of the market.

3.2 Case 2 : With congestion

The chosen time unit is the 1^{st} of January between 13:00 and 14:00 (t_{14}). This time there are more suppliers participating to the local markets, and more exchange with other countries. The market characteristics are presented in the Appendix (A10).

At $t = t_{14}$ the difference between the two demands is 778 MW, which is higher than the exchange limit. This means that the two markets should be consider separately as they will not be able to exchange completely with each other. With the method explains previously, an independent market clearing of DK1 and DK2 determines the individual market prices in both areas without considering any exchange yet :

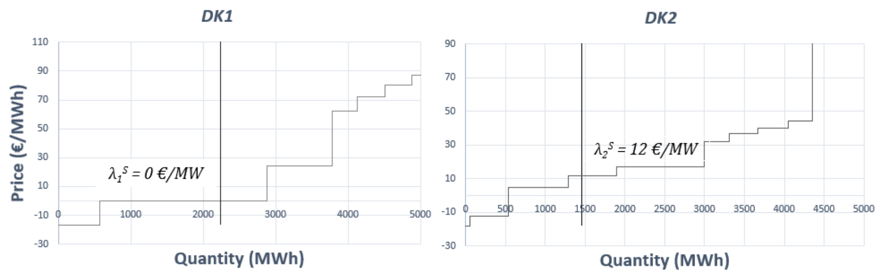

Figure 3: Merit Order curve of both markets at $t = t_{14}$.

DK1 has the cheapest market price of 0 €/MW. This way, it would be interesting that DK1 exports as much as possible (600 MW) to DK2. From DK1 point of view, the demand will increase by 600 MW, while for DK2 a new supplier with a bidding price of 0 €/MW will enter the market. A new market clearing determines the actual local market price with regard to possible exchange between areas :

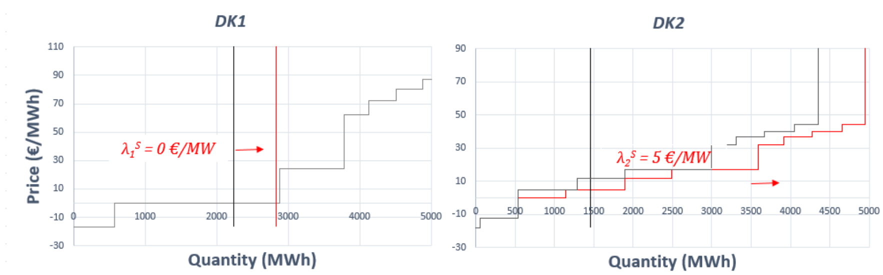

Figure 4: Merit Order curve of both markets at $t = t_{14}$.

Contrary to the first case, DK1 and DK2 have different market prices. Their scheduled suppliers will be rewarded differently according to their own area with the method explained in the previous case, even if they exchange energy :

Producer i	Area a	$y_{a,i}$ [MW]	$\lambda_{a,i}$	> [€/MW]	Revenue
WW1	1	2261,2	λ^S	0	- €
WW2	1	575,8	$\lambda^S + 17$	17	9 788,6 €
EW1	2	54,1	20	20	1 082,0 €
EW2	2	486,9	$\lambda^S + 12$	17	8 277,3 €
G13	2	318	λ^S	5	1 590,0 €

Figure 5: Market Clearing and Revenue of the scheduled producers at $t = t_{14}$.

It is interesting to notice that the price in DK1 is equal to 0 €/MW. This price implies that WW1 (G16) do not have any revenue in producing wind energy, even if it is the supplier that produces 61% of the global electricity circulating in the two region. The other renewable producers can earn money thanks to their support schemes.
Moreover, the low price of DK1 helps DK2 to decrease its own market price to 5 €/MW.

4 Overview of revenues

Tables 1 and 2 show the total revenues generated by the different suppliers for the months of January 2020 and November 2019. These values do not represent the amount of money that producers actually get - production costs would need to be subtracted to get the eventual profits. Distinction has been made between revenues coming directly from the market, and revenues coming from support schemes (namely *feed-in-tariff* for supplier EW1 and *feed-in-price* for suppliers WW2 and EW2).

Supplier	Total revenues from market (k€)	Total revenues from support schemes (k€)	Total revenues (k€)
G1	892	0	892
G2	1912	0	1912
G3	0	0	0
G4	250	0	250
G5	19	0	19
G6	5361	0	5361
G7	0	0	0
G8	3159	0	3159
G9	0	0	0
G10	4	0	4
G11	127	0	127
G12	583	0	583
G13	7208	0	7208
G14	5105	0	5105
G15	0	0	0
WW1	19171	0	19171
WW2	4793	5828	10620
EW1	0	776	776
EW2	3799	4191	7990

Table 1: Overview of revenues in January 2020

Supplier	Total revenues from market (k€)	Total revenues from support schemes (k€)	Total revenues (k€)
G1	1031	0	1031
G2	2031	0	2031
G3	0	0	0
G4	279	0	279
G5	3	0	3
G6	5126	0	5126
G7	0	0	0
G8	2836	0	2836
G9	0	0	0
G10	0	0	0
G11	66	0	66
G12	460	0	460
G13	6883	0	6883
G14	4881	0	4881
G15	0	0	0
WW1	18318	0	18318
WW2	4579	5580	10160
EW1	0	738	738
EW2	3538	3985	7523

Table 2: Overview of revenues in November 2019

It can be noticed that some suppliers are left out of the markets, and never produce any electricity in both months: they are G3, G7, G9 and G15. They are the ones with the highest marginal production cost, hence their inability to compete with other market players. Conversely, the highest revenues are generated from wind farms WW1, WW2 and EW2, which have marginal costs of zero. However, the revenues generated by EW1 are far below the ones generated from the 3 other wind producers. This producer benefits from a feed-in-tariff, implying that he does not participate in the market: he is the first one to be scheduled among the producers, and sells his electricity to a set price of 20 €/MWh. This price is actually higher than the average electricity price in zone East (13,5 €/MWh in January and 13,3 €/MWh in February), which justifies the amount chosen for this support.

It is also interesting to notice that the wind producer generating the highest revenues is WW1, who is the only one not benefiting from a support scheme. Support schemes have probably been designed specifically with attention to the business models of each of the producers, and WW1 may already generate enough revenues from the market. The choice of a feed-in-tariff rather than a feed-in-premium to support WW1 is probably based on solid reasons (for example a desire for revenues security), but it should be noticed that this producer would have generated more revenues if he had benefited from a feed-in-tariff of 17 €/MWh (1198 € in January and 1020 € in November). Overall, support schemes appear as crucial for the producers concerned: WW2 and EW2 generate more than half of their total revenues through support schemes.

5 Market Outcomes

In the part below, some market outcomes are studied to understand what is happening in the market.
First, a deeper analysis of the market prices can be conducted. On the Figure 6, the average prices per hours for both zones at both periods are shown. Several comments can be made. First, once can notice that in both periods, prices in DK1 are always higher, in average, than in DK2. This result is not very surprising as the marginal costs of producers in DK2 are in overall lower than in DK1.
Then, one can notice that in both periods, the prices are the lowest around 6am and the highest around 12am. However, the peak price in November is at 11am whereas it is at 12am in January. These might be caused by the hours and night change between November and January. Also, once might notice other price peaks at the hours around 6pm and mainly 11pm. The average market price fluctuates more for DK1 than DK2 and the price interval is also higher for DK1. As shown in the Figure 7, in November 2019, the maximum price in DK1 is never higher than 80 and never goes negative. For DK2, the maximum price is 37 €/MWh and also never goes negative. One can notice that the hours are more uniform, by studying maximum and minimum price per hour rather than the average one.

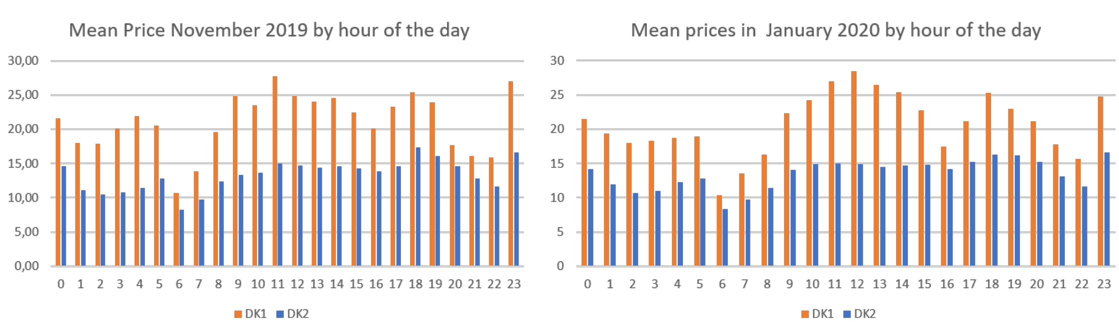

Figure 6: *Average prices*

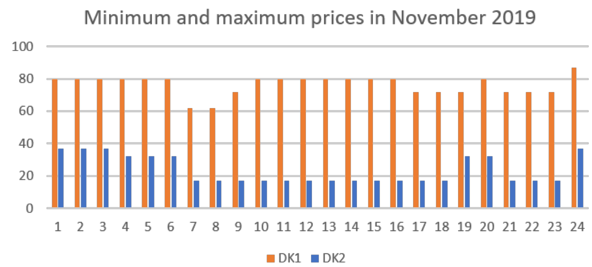

Figure 7: *Minimum and maximum prices per hour*

Also, it would be interesting to have a look at the average price per hour depending on the fact that the exchange pipe is congested or not. These data are shown on Figure 8 for prices of January 2020. It can clearly be seen that the prices depends heavily on the fact that the markets are congested or not. For market DK1, during the night, the congested market leads to an increase of average prices of more than 30 € and even 50 € at 2am. In market DK2, it can be noticed that the biggest price difference is also at night but lower. These data show that DK1 is the market that benefits the most of the possibility of exchange between both zone to have a unique market price.

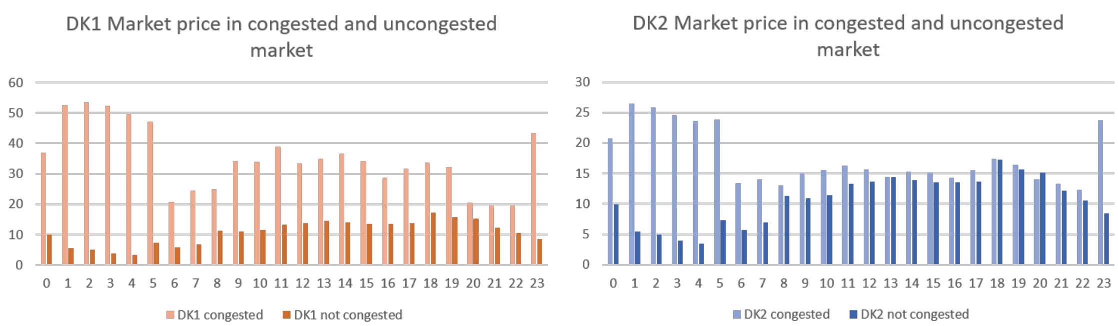

Figure 8: *Average prices depending on market congestion for both zones*

It has just been shown that the congestion has a big impact on the market price. What else could have an impact on it ? Several indicators have been selected.
Have been taken on :

1. the global demand in both zones.
2. the amount exchanged between both zones in relative value (taking into account the direction).
3. the amount exchanged between both zones in absolute value (not taking into account the direction).
4. the wind penetration.
5. a binary variable saying if the market is congested or not.

The correlation between these random variables and the price in DK1 had then been calculated on January 2020. Results are introduced below :

Variable	correlation with price
price	1
global demand	0.152
relative amount exchanged	-0.725
absolute amount exchanged	0.367
wind penetration	-0.861
congestion	0.499

One needs to be very careful because two variables correlated are not necessarily linked. However, the variables chosen were those for which the correlation with the market price can be explain. It can be seen that the the congestion might be correlated with the price : the correlation value is 0.5 which is quite high.
The highest value is met for the correlation with wind penetration, indeed, the wind is the cheapest source and when there is a lot of it, it makes the price go down heavily. Also, it is very interesting to notice that the price is quite highly correlated with the absolute amount of energy exchanged but even more with the relative one. This means that the direction of energy exchanged is very important. Indeed, only DK1 prices are shown here and the prices are decreasing a lot only when the energy goes from DK2 to DK1, because DK2 has lower average prices than DK1.

Finally, a small analysis of wind curtailment and load shedding can be conducted. Load shedding is implemented for when the supply cannot meet the demand. After a run of the simulation, no load shedding happens; the demand is always meet. However, wind curtailment occurs in the simulation. This happens when the wind sources can meet the total demand and even overpass it. Only the producer WW1 has recourse to wind curtailment. It curtails because he is in DK1, the only region where wind overpass demand and because he is the one with the highest bid price of 0 (whereas the others wind producers have negative bid prices). Other wind producers which have negative prices can never meet the demand alone; this explain why the market never have negative prices and also why WW1 is the only producer to curtail wind.

6 Appendices

6.1 Parameters

Table A3: *Conventional Producers Parameters*

Name	Area x	Area Id i	Capacity P_i^{max} [MW]	Biding Price $\lambda_{x,i}^G$ [€/MWh]	Production $y_{x,i,t}^G$
FlexiGas	1	1	380	72	$y_{1,1,t}^G$
FlexiGas	1	2	350	62	$y_{1,2,t}^G$
FlexiGas	1	3	320	150	$y_{1,3,t}^G$
Peako	1	4	370	80	$y_{1,4,t}^G$
Peako	1	5	480	87	$y_{1,5,t}^G$
Nuke22	1	6	900	24	$y_{1,6,t}^G \cdot \mathbb{1}_{5\leq t\leq 22}$
CoalAtLast	1	7	1200	260	$y_{1,7,t}^G$
Nuke22	2	1	1100	17	$y_{2,1,t}^G \cdot \mathbb{1}_{5\leq t\leq 22}$
RoskildeCHP	2	2	300	44	$y_{2,2,t}^G$
RoskildeCHP	2	3	380	40	$y_{2,3,t}^G$
Avedovre	2	4	360	37	$y_{2,4,t}^G$
Avedovre	2	5	320	32	$y_{2,5,t}^G$
BlueWater	2	6	750	5	$y_{2,6,t}^G$
BlueWater	2	7	600	12	$y_{2,7,t}^G$
CoalAtLast	2	8	850	235	$y_{2,8,t}^G$

Table A4: *Wind Producers Parameters*

Name	Area x	Area Id i	Support Scheme	Support [€/MWh]	$\lambda_{x,i}^G$ [€/MWh]
WestWind1	1	8	None	0	0
WestWind2	1	9	FIP	17	-17
EastWind1	2	9	FIT	20	-18
EastWind2	2	10	FIP	12	-12

Table A5: *Importation and Exportation*

Type	Zone x	Country	Quantity [MWh]	Parameter $y_{x,t}^{IMPorEXP}$ [MW]
Importation	1	Norway	100	$y_{1,t}^{IMP} = 100$
Exportation	1	Germany	120	$y_{1,t}^{EXP} = 120 \cdot \mathbb{1}_{8\leq t\leq 15}$
Importation	2	Sweden	80	$y_{2,t}^{IMP} = 80 \cdot \mathbb{1}_{11\leq t\leq 17}$

6.2 Market Clearing Examples

DK1

Generation		
Producer	P_i^{max} *[MW]*	$\lambda_{1,i}$ *[€/MW]*
G1	380	72
G2	350	62
G3	320	150
G4	370	80
G5	480	87
G7	1200	260
WW1	1004,8	0
WW2	251,2	-17
Demand		
y_1^D [MW]		1868
Imp_{Norway} [MW]		100
Final Demand [MW]		***1768***

DK2

Generation		
Producer	P_i^{max} *[MW]*	$\lambda_{2,i}$ *[€/MW]*
G9	300	44
G10	380	40
G11	360	37
G12	320	32
G13	750	5
G14	600	12
G15	850	235
EW1	34,6	-18
EW2	311,4	-12
Demand		
y_2^D [MW]		1346
Final Demand [MW]		***1346***

Figure A9: Generation and consumption in both areas at $t = t_1$, 1st of January at 00:00

DK1

Generation		
Producer	P_i^{max} *[MW]*	$\lambda_{1,i}$ *[€/MW]*
G1	380	72
G2	350	62
G3	320	150
G4	370	80
G5	480	87
G6	900	24
G7	1200	260
WW1	2303,2	0
WW2	575,8	-17
Demand		
y_1^D [MW]		2217
$Exp_{Germany}$ [MW]		120
Imp_{Norway} [MW]		100
Final Demand [MW]		***2237***

DK2

Generation		
Producer	P_i^{max} *[MW]*	$\lambda_{2,i}$ *[€/MW]*
G8	1100	17
G9	300	44
G10	380	40
G11	360	37
G12	320	32
G13	750	5
G14	600	12
G15	850	235
EW1	54,1	-18
EW2	486,9	-12
Demand		
y_2^D [MW]		1539
Imp_{Sweden} [MW]		80
Final Demand [MW]		***1459***

Figure A10: Generation and consumption in both areas at $t = t_{14}$, 1st of January between 13:00 and 14:00.

References

[1] "Market Data : Power System Data - Wind production" https://www.nordpoolgroup.com/

[2] "Market Data : Power System Data - Consumption" https://www.nordpoolgroup.com/

[3] GAMS software - https://www.gams.com/