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Flexible International Exchanges: a Possible Solution for Large – Scale Wind Power Integration

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***Abstract* – A production cost simulation model for the North-Western part of the UCTE system is developed in this paper. Information from various sources was gathered and combined to produce an integrated representative model of the areas under study. Specifically, the technical and economical limits of wind power integration within the power system are highlighted, by means of observing and analyzing various unit commitment schedules under different scenarios. The main question refers to which level of wind penetration the power system can operate in a safe and reliable fashion, while the incoming wind power is completely integrated and correlations between system variables in adjacent areas are taken into account. By answering this question, the system planner will have the flexibility to arrange in the future the power system operation accordingly so as to decrease the operation costs to a minimum and increase the efficiency of the total system to maximum. An investigation of this problem statement can only be executed with global models, which take into account both technical and economic constraints and further optimize the operation of the power system.**

***Index Terms* – power system planning, unit commitment, economic dispatch, wind energy.**

I. INTRODUCTION

This paper will focus on one important aspect of the transitional wave towards the future, which is the current issue of large-scale wind integration within the power system. More specifically, the approach aims to illustrate the significance that international exchange can play in wind power's integration. A computational tool, PowrSym3, is used, which is a production cost simulation model capable of high levels of optimization. In order to achieve this, a relevant model of the power system seen from a high perspective will be constructed and the system's response to different levels of wind penetration will be measured mainly in terms of (un-)used wind energy, system operating costs and emission levels.

A wide range of models has been developed by academia and commercially for the simulation of UC–ED or electricity market operation, ranging from weekly operations planning, to generation-unit investment planning. Even though these models have different characteristics, making them more suitable for different applications, they all have the objective of simulating the generation system operation, while optimizing total costs from a system perspective. More specifically, the Danish tools SIVAEL [1] and EnergyPlan [2], which may be used for large-scale wind system integration studies and assessment of strategic regulating mechanisms respectively. Balmorel [3] is a bottom-up partial equilibrium tool that can provide estimates of future electricity spot prices. It comprises the most important technical aspects of power system operation, including transmission lines and emissions. A similar model, WILMAR tool [4], is using stochastic linear programming to optimize scenario trees (transition probabilities) for possible wind power generation forecasts for each hour. The use of linear programming however limits its application for the modeling of large systems or international studies because calculation times increase exponentially.

The reason for using PowrSym3 in this paper will be highlighted in section II-C, as soon as an insight is given and the framework of the study is described.

II. SIMULATION MODEL

A. Basics of Power System Operation

Due to daily load variations, a coordinated control of the generators' outputs is mandatory for balancing total generation to the total load, so as the system frequency does not deviate from the nominal operating frequency (50 or 60 Hz) [5]. Because of this tenuous balance between supply and demand, the monetary value of electricity also changes continually with time over a day and over the year [6]. Therefore, the economic operation of the system under these conditions gains high significance in ensuring that the involved market parties will receive a return on the invested capital.

Unit commitment (UC) refers to the computational procedure for making decisions in advance, upon which generators to start up and when to connect them to the grid, along with the sequence in which the operating units should be shut down and for how long. Unit commitment is a complex problem which combines data and information on fuel prices, generators' or transmission lines' maintenance schedules,

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ramp rates, idle periods, start-up and shut-down costs. The next step, after unit commitment has been decided, is the economic dispatch (ED), the process in which the system load is matched against the total generation output of the committed units such that the total operating costs are minimized. UC-ED refers to the economic operation of the generating units, bound by technical limitations. Moreover, UC and ED, even if they are interrelated, they comprise different time frames (UC: once or twice per day, ED: throughout the day) and different procedures.

In liberalized markets, the generation unit owners are responsible only for supplying their own customers (i.e. long-term contracts and short-term trading agreements). Each individual owner therefore optimizes the UC–ED of the generation units under its control, taking into account foreseen market prices. Perfect markets in principle lead to the same outcome regarding the scheduling of generation as would have been the case with central optimization. In the absence of market power, there is merely a conceptual difference between market and traditional generation scheduling (i.e. by market participant price bids instead of operating cost minimization). Therefore, solutions for the traditional central optimization of UC–ED based on cost are still highly relevant.

B. *Large-Scale Wind Power Implications*

In the present study the focus shall be on dealing with the impacts of large-scale wind integration on the planning and operation of the power systems. Consequently, the main technical implications are related to the allocation of extra spinning reserve requirements and the satisfaction of ramp rate and minimum up and down constraints that arise from a more dynamic operating regime for conventional units.

1) *Technical Impacts*

a) *Power balancing:* As the capacity of installed wind power increases, significant power fluctuations and uncertainty about the energy volumes arise. Since, ordinarily, the supply-demand balance is maintained by conventional generation, the stochastic nature of wind induces conspicuous uncertainty in the planning especially of spinning reserves. Namely, with the presence of wind for longer time periods, the amount of conventional generation available for system balancing is reduced. Thus, UC-ED are affected, as the existence of wind energy reduces the output and/or the operating hours of conventional generation units, while these units are crucial for the compensation of the wind power's variability and limited predictability [7]. If the fluctuations in wind power production are not appropriately (fast and reliably) smoothed by thermal stations, adverse situations cannot be excluded. Therefore, the system planner has to find an optimum balance between keeping sufficient reserves to confront wind's variability and operating the total system with as low CO_2 emissions as possible in the most economic fashion.

b) *Minimum-load periods:* In periods when the load is low – especially at night – the wind is high and the conventional units cannot reduce adequately their output for various reasons (deployment obligations etc), the aggregate of total supply then can exceed the demand. Under such minimum-load situations, wind-powered production needs to be curtailed to some extent to avoid stability problems [8]. The question that arises refers to which level of wind penetration the power system can operate in a safe and reliable fashion, while the incoming wind power is completely integrated and correlations between adjacent power systems are taken into account.

2) *Economical Impacts*

Aside from the apparent technical implications of integrating wind energy in large-scale within the power system, economics are also of importance, especially, because the wind-produced electricity has a low marginal cost. Likewise, it can be inferred that the market design has also an influence in the way that wind energy is participating in the daily transactions. The dimensions of the market, along with the generation mix, the market gate closure time (after this the international exchange schedules are fixed), the geographic position and the flexibility of the conventional generation units are of concern.

In day-ahead spot markets, the bids including wind power are typically cleared for the 12-36 hours ahead horizon. For conventional generation, apart from some less frequent unplanned outages, the planning is much easier than for wind power, which is susceptible to an intermittent source, as the wind. Hence, the inevitable forecast error bears the power producer or the TSO with the cost of regulation in the ancillary services market, which can vary from low to high values depending on which generation technologies are used. In systems with available hydro power the cost is relatively low, whereas in systems where regulation is performed with combined-cycle gas turbines (CCGT), the cost for regulation is significantly higher. Moreover, from an international exchange perspective, a large forecast error prevents a suitable and precise scheduling of import – export energy volumes.

Especially for systems that include large hydro reservoirs, such as Norway and Sweden, high wind penetration can have an additional repercussion. Since wind is a resource with a low marginal cost, and the compensation for its irregularities is performed by hydro units with also low price, it can be observed that the marginal cost of the total system is decreasing significantly, and can reach almost zero in windy periods [9]. This, in turn affects mostly the condensing power plants, but also the combined heat and power (CHP) units, which are operated less. Further price reductions make the future or contemporary investments in electricity generation not profitable, since the revenues are significantly diminished.

C. *Simulation Model and Database*

1) *Existing Database*

Currently, the prevailing concept is that the transition to the future power systems will be based on two main pillars: the integration of RES and especially wind, along with the sustainable development, which is related to high efficiency, lowering of emissions, optimum maintenance schedules and overall consumption decrease. However, all the previous concepts introduce an additional complexity upon the already complex issues of optimizing the unit commitment and economic dispatch (UC-ED) schedules. Before the integration of stochastic generation and prior to the market influence, unit commitment decisions were relatively easy to take; UC was almost fixed, except for cases of unexpected, generator outages or demand variations that needed re-assessment. Nonetheless, the integration of wind power and the liberalization of electricity markets add more uncertainties (market prices, wind forecast) in the optimization.

Therefore in order to depict and subsequently simulate such a complex situation, a global view is required, which will be provided by PowrSym3. PowrSym in its newer version (PowrSym3) is a multi-area, multi-fuel, chronological generation cost simulation tool for electrical power systems including combined heat and power, energy storage and energy limited fuel contracts [10], which was developed from the 1980s onwards by Operation Simulation Associates, Inc. and the former Dutch utility SEP with support from the Tennessee Valley Authority, U.S. PowrSym3 has been used in the central optimization of the UC–ED of Dutch generating units up until 1998, when the deregulation of the Dutch power sector started. Since then, the database has been maintained by TenneT TSO and the model continues to be used for a range of system studies and adequacy forecasts. The main reason for using PowrSym3 in this study is that it is an existing tool, procured along with a database with validated models for the existing conventional generation in the Netherlands and descriptive models of generation units in four neighboring countries (Germany, France, Belgium, United Kingdom), by the Dutch TSO, TenneT. This will be called the W-UCTE database (Western – European Power System).

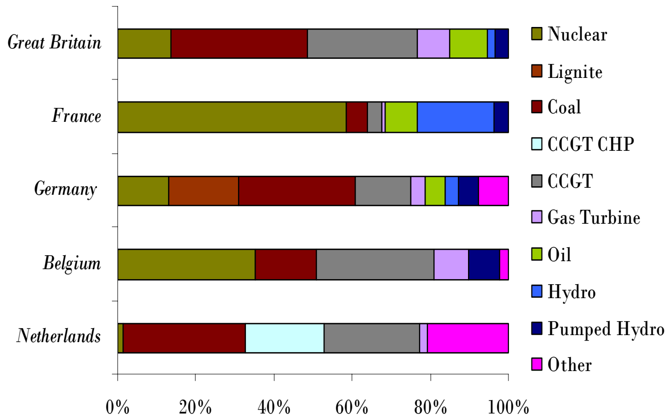

Fig. 1. Generation mix percentages for W-UCTE countries assumed for 2014 (percentages exclusive of wind power) [11]-[12].

a) Conventional generation: The existing database contains models for all the range of conventional generation technologies for various fuels such as coal, natural gas, oil and uranium. Each technology is modeled in clusters of records that define the operational characteristics of each power plant. The types of thermal power plants modeled are: combined-cycle-gas units (CCGT), combined-heat-power units (CCGT CHP), nuclear units, coal or lignite condensing power plants and oil & gas turbine units. The estimated break-down by technology for 2014 is shown in Fig. 1. The most important technical parameters defined within the model for conventional generation units are: minimum up- and down-times; commitment & dispatch status; ramp rates; start-up and running costs; emission levels; heat-rate levels for CHP.

b) *Hydro power:* For hydro power, the modeling concept obeys the basic operating principle of hydro-electric plants which is based on the conversion of potential energy of a water mass from a given height to electricity in the zero reference level, where the generators are located, with a specific efficiency. The absence of thermodynamic processes, fuels and emissions make hydro power models a relatively straightforward concept. The weakness of this approach is that the amount of hydro energy allocated each week under the existing framework before this study, was just a constant fraction of the expected annual hydro energy yield.

c) *Wind power:* Wind power for this study is modeled as a resource with zero marginal cost that can be fully integrated, unless technical constraints require its curtailment. For the representation of wind power in the Netherlands, simultaneous wind speed measurements (time-series) throughout the country were used, followed by interpolation of the wind speeds to foreseen wind power locations and to the correct hub-height, and estimation of the hourly wind park output at these locations. Correlations in time and space between the different wind parks are correctly taken into account. Wind power in Germany is based on one year of measurements collected from the German TSO's, which was then scaled up to the 32 GW installed capacity assumed here.

TABLE I
INSTALLED CAPACITIES BY GENERATION TECHNOLOGY W-UCTE 2014 [11-12]

Technology	NL GW	BE GW	DE GW	FR GW	GB GW
Nuclear	0.4	5.9	14.1	64.9	11.9
Lignite	-	-	18.9	-	-
Coal	9.5	2.6	32.0	6.0	30.4
CCGT CHP	6.2	-	-	-	-
CCGT	7.5	5.0	15.1	4.0	24.4
Gas Turbine	0.6	1.5	4.0	1.1	7.0
Oil	-	-	5.3	9.2	8.4
Hydro	-	-	3.7	21.5	1.8
Pump-Hydro	-	1.3	5.5	4.2	3.0
Other	6.3	0.4	8.2	-	-
Total	30.6	16.7	106.8	110.9	86.9
Wind Power	0.0-12.0	-	32.0	-	-
Max. Load	21	15.2	80.5	87.1	65.5
Demand(TWh)	126	97.0	518.0	550.0	367.0

The case that this paper focuses on is the UC-ED of wind power with perfect prediction. Perfect prediction refers to a flexible market design with 1-hour ahead market clearance. Even if this is not realistic for the moment, the results can help to illustrate the technical limits of wind integration (influencing parameters: transmission capacity, minimum load, spinning reserves and non-spinning reserves limitations). Under this perfect market scheme, all feasible transactions are made and the scheduling is performed almost until the moment of operation.

The information on installed capacities by generation technology is summarized in Table I.

2) *Extending the W-UCTE Model with Nordel*

In order to investigate the impacts of the NorNed cable on wind integration in the Netherlands, the first step is to develop representative models for the generation and load of each country of Nordel, namely Norway (NO), Sweden (SV), Finland (FI), Denmark-West (DKW) and Denmark-East (DKE). The approach was based on the same logic followed in the formation of the W-UCTE system in order to generate a new compatible model, which on the one hand would represent effectively the Nordel region divided into 5 regions and on the other hand would meet the requirements that the existing model posed. For calculating the parameters of the extra inserted regions, extensive data analysis has been conducted. The analysis was based on several official publications and reports on the future generation mix of power systems in Europe [11]-[16], in order to decide the values for the system in 2014, of installed capacities per technology and the system load. The reference year for the load data is 2007; however the simulations are conducted for the year 2014, hence the need to extrapolate the data accordingly, for the future horizon of 7 years ahead.

Furthermore, for the development of wind power data, no wind speed or correlated wind power time-series were available for Scandinavia in the short time-frame of this study. Therefore, a first-order approach has been followed to at least include wind power for Nordel somehow. Wind power in Nordel is perceived solely as negative load, which is subtracted hourly in equal amounts from the load. Consequently, the new load-less-wind profiles are formed, which are the product of the hourly subtraction of load in 2007 and estimated wind power available for each hour in 2014.

For modeling the generation units in Nordel, decision had to be taken first, upon the generation mix and the installed capacities of each technology, foreseen for 2014. Based on information about the current installed capacities of generation units and on reliable estimates by Nordel [15], the final predictions are shown in Table II.

TABLE II
INSTALLED CAPACITIES BY GENERATION TECHNOLOGY IN 2014, NORDEL [15]

Technology	NO GW	SV GW	FI GW	DK-W GW	DK-E GW
Nuclear	-	12.5	4.0	-	-
Coal	-	-	2.5	1.9	1.9
CCGT CHP	-	1.2	8.1	14.1	4.3
CCGT	1.0	1.3	1.0	1.0	0.3
Hydro	30	18.5	3.4	-	-
Other	-	2.7	1.9	-	-
Total	31.0	36.2	21.0	17.0	6.5
Wind Power	0.8	2.1	0.22	2.6	1.4
Max. Load	21.6	26.5	14.8	3.7	2.6
Demand (TWh)	124.3	144.5	88.9	21.2	14.4

As it is evident, from Fig. 2 the Nordel power-mix in 2014 will continue to be dominated by hydro power, followed by thermal power in terms of coal condensing power plants, CHP (Combined-Heat and Power) stations and Combined-Cycle Gas Turbines (CCGT). Investments in nuclear power are not excluded in Sweden and Finland and hence nuclear power is the third generation option of Nordel. From 2% in 2007, wind power is expected to reach 6% of total generation in 2014, which is in line with the predicted sustainable future.

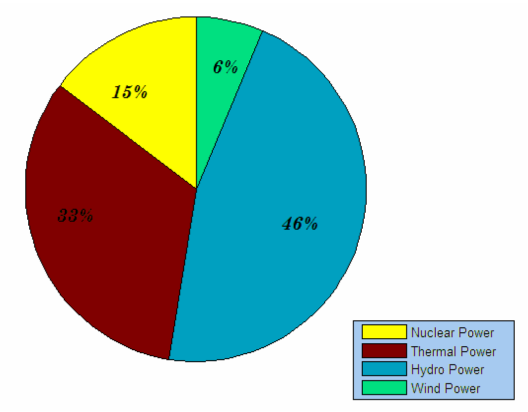

Fig. 2. Estimated distribution of generation in Nordel by energy source, 2014.

The resultant multi-area model where the UC-ED simulations are performed is depicted schematically in Fig. 3. On the one hand the extension of the W-UCTE model increases significantly the complexity and consequently the amount of calculations required, but on the other hand enables a more global view of the power system under study and opens new possibilities for model validation. Fig. 3 also shows the transmission limits for international electricity trade as enforced in the model, taking into account the most probable reinforcements in effect by 2014.

D. *Optimization Structure*

The execution of the optimization model includes three time horizons and has a holistic approach; the annual horizon, which corresponds to reliability calculations and maintenance scheduling, the weekly horizon, which is used for the inclusion of forced outages and the scheduling of hydro and energy storage units. The weekly horizon can also be used for production cost optimization. Finally the basic operation time step can be chosen by the user, in this study it is 1 hour.

The simulations start with reading the input data, consisting of heat areas and loads, system load for all nodes, wind power data and specific user defined attributes about the power system. The first step before weekly optimization starts is the determination of the weekly random outage draws. The outage model selects in a random manner which generators will be tripped for each time-step for a specified number of iterations (Monte Carlo draws); each iteration is then saved and consequently used, as input for a weekly simulation.

For the weekly optimization, first hydro stations are scheduled using a price leveling algorithm, which refers to the time-related constraints such as generation cost, operational aspects of thermal units (maximum or minimum generation levels, ramp rates etc.) and hydro reservoir size. Consequently, the hydro schedule is optimized based on the system marginal cost, while taking into account reservoir size limits, load prediction and wind power forecasts. The model then uses heat demand for different areas, system load, wind power and wind power forecasts for the scheduling of thermal generating units, which are also subject to technical constraints. Based on the operational cost estimates obtained thus far, energy storage is scheduled such that the total operating costs over the week are minimized [10].

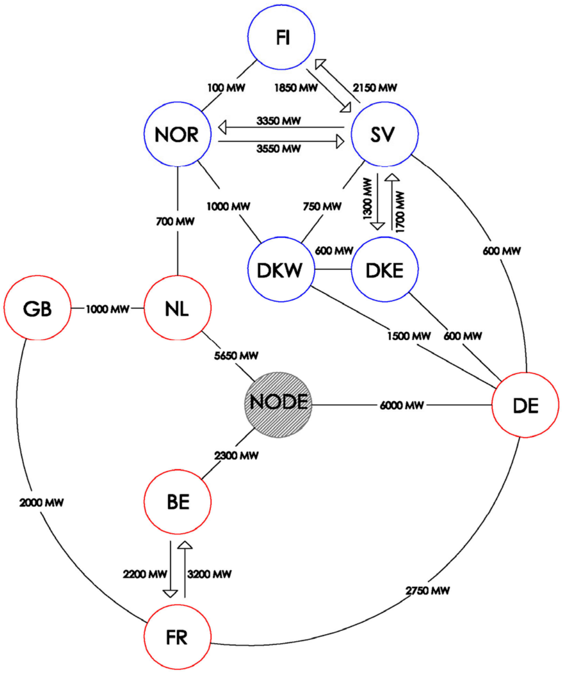

Fig. 3. Simulation model of the Western part of UCTE and Nordel, year 2014.

For the hourly optimization which is a part of the weekly optimization, it is sufficient to mention that the heuristic optimization approach is finding the most expensive units planned to meet the load and de-commits them or ramps them down until no further units can be decremented.

These approaches, for the weekly and hourly horizon along with the annual horizon are the three different optimization tasks that PowrSym3 performs and they are coupled to each other by means of marginal costs and outage schedules. However when the focus is applied on hydro-power, the problem is that the optimization of hydro power is performed only for the weekly and hourly horizon. These two correspond to the short-term scheduling of hydro, whereas for long-term hydro scheduling no provision was taken before this research.

E. Hydro Allocation

The issue with long-range hydro scheduling can be observed only from a higher perspective, given the limitations of the optimization tool used. More specifically, in the existing W-UCTE model, the hydro power inflow is modeled as energy available for dispatch [GWh/week], bound by technical constraints (minimum and maximum power levels, ramp rates etc). While, internally for each week, PowrSym3 optimizes the dispatch of this amount of energy under the operational constraints of the basic (1-hour) time step, the decision for the amount of hydro energy to be delivered every week is left arbitrarily to the user. This decision is important e.g. for a country such as Norway with almost entire hydro power generation. The chosen model must capture the operational characteristics of the area and its reservoirs. With a view to choose the amount of available weekly hydro energy for dispatch, the proposed hydro allocation methods will be a first order approximation of the complex long-term hydro scheduling problem. The common characteristic of all described hydro allocation methods is the prioritization of covering the inland demand. At this point, it must be noted that such methods are almost deterministic (based on high occurrence probability patterns) however for further research stochastic variables should be used instead, to depict inflow probabilities, load prediction forecast errors and future power market prices.

In order to include the effects of load, inflow and price difference (between APX and NordPool) in the scheduling of hydro energy, three indicators are formed, which are depicted in Fig. 4, with equal weight factors: the Load factor, the Inflow factor and the Price factor. All three indicators are fractions of the week input (load, inflow and price respectively) divided by the year input.

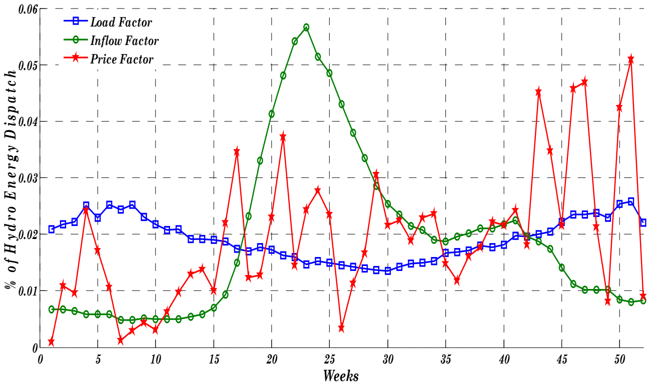

Fig. 4. Influencing factors in long-range hydro scheduling of the Norwegian hydro-power (based on 2007 data).

The decomposition of the problem in different influencing factors can be used to scale the factors in priority sequence. In other words, the operator of the Norwegian aggregated reservoir taking into account the expected energy yield, which is based on load and inflow predictions as well as on future prices of energy imports/exports, can decide how to distribute hydro energy optimally in 52 weeks so as to meet the prioritized targets that were initially set. The limitations are the amount of inflow and the reservoir capacity.

F. Simulation Parameters

The objective of a simulation is to present a yearly optimization unit commitment and economic dispatch (UC-ED) schedule, for a given scenario. In order to assess the output of the simulation, some variables must be defined, which permit the monitoring and evaluation of each simulation. The variations of these variables in different scenarios will be also of importance to quantify, validate and confirm the modeling approach.

1) *Technical Dimension*

In section II-A, power balancing and minimum load situations were highlighted from a global power system's perspective, as key limitations for the large-scale wind integration in the Dutch power system. The model therefore will include these limitations by monitoring a set of technical parameters: ENS (Energy-Not-Served); spinning reserve violations; wasted wind energy in the Netherlands; international exchanges; energy and emission savings. The operation of NorNed in the interconnected power systems of Nordel and W-UCTE can significantly impact any of the above-mentioned parameters.

2) *Economic Dimension*

The economic impacts of wind energy on power system operation are mostly related to its low marginal cost. For example, in Germany which has quite a high wind penetration, it has been reported that wind energy integration reduces spot market prices [17]. Also, in markets where the emission of CO_2 comes at a certain price, the environmental benefits of wind power have a direct financial benefit, which corresponds with the levels of emissions that the thermal generation released during production of both load covering and regulation. The simulation variables for monitoring economic and environmental impacts of large-scale wind integration are: total operating costs (M€/year); utilization factors for conventional generation units; emissions level (Mton/year), in terms of CO_2, SO2 and NOx.

III. RESULTS

A. *Technical Impacts*

The simulation results for all defined variants of wind power implementation, do not report neither energy-not-served (ENS), nor spinning reserve violations in any area within W-UCTE or Nordel. The only case with some ENS reported is when no hydro allocation strategy for the Norwegian reservoir is applied, which in turn enhances the opinion that long-range hydro scheduling strategies should be adopted in the future. Moreover, it can be concluded that sufficient up-ward and down-ward regulation capacity is available at all times during the year in order to balance the aggregated load & wind power variations. This was expected, since the total installed capacity in the specific model design is large compared to the maximum load.

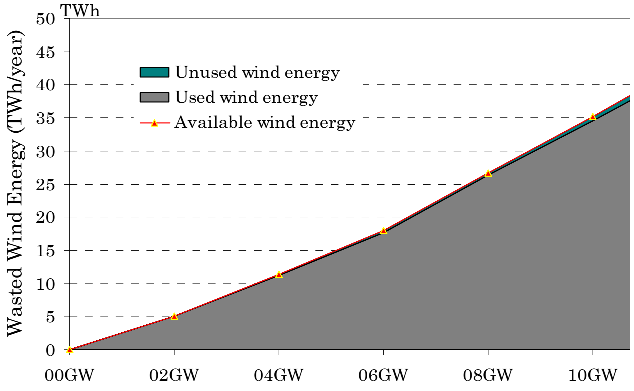

Fig. 5. Wasted wind energy in the Netherlands for 0-12 GW of installed wind power and flexible international exchange.

The amount of wasted wind energy due to minimum-load problems, when a flexible market design (1 hour ahead, market gate closure time) is applied is depicted in Fig. 5. When compared to earlier studies to depict wasted wind with fixed import volumes instead of flexible international exchange, which is presented in the Quality and Capacity Plan 2006-2012 [8], the situation is clearly improved with significant lower wasted wind levels.

Moreover, it is clear from Fig. 6, that the wind power increase in the Netherlands turns the country from net importer to net exporter. Especially, when France and Germany are considered, it can be observed that in periods of high wind in the Netherlands, German imports from France decrease. On the contrary, for the countries of the hydro-dominated Nordel, the increase in wind power does not influence their traded energy volumes significantly as a result of the hydro's zero marginal cost. Therefore since wind has also zero marginal cost, during the optimization of the UC-ED schedule, wind and hydro resources are acting competitively.

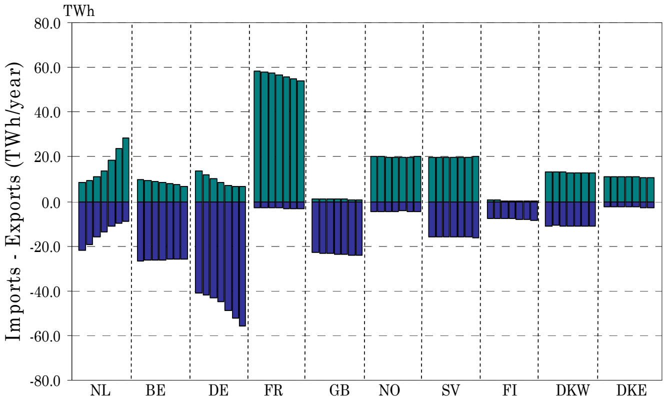

Fig. 6. International exchange in Western-UCTE and Nordel areas for 0-12 GW wind power installed in the Netherlands for all links including NorNed and average inflow in Norway.

This can be seen especially in Germany, where the presence of cheap energy in neighboring areas decreases the full-load hours of German coal-fired and to a lesser extent of CCGT units. The levels of competition are defined by the amount available for exchange, wind or hydro energy at each time-step and by the transmission capacities between Germany and the neighboring areas. In other words, since the Netherlands and Nordel have both large interconnection capacities with Germany, wind power and hydro power will also compete on an international level.

B. *Economic Impacts*

In Fig. 7 the operating cost savings in the Netherlands are depicted for various cases. The highest cost savings, when there is no international exchange, can be explained by the higher marginal cost of the Dutch isolated system, if compared to the marginal cost of the total system. Indeed, even if this would mean more wasted wind energy, the savings by wind power are much higher for isolated systems. However, this may be balanced by the additional amounts of wind energy which are integrated within the system when international exchanges are present, with higher overall socio-economic benefits. As it is evident, the operation of NorNed increases the savings for the total system.

Especially for the case of Netherlands where the wind power revolution is realized, the cost savings resulting from wind integration correspond with approximately 35% of the total system cost. This in turn means that the rest of the nine operation areas are realizing the 65% of the total operating cost savings, given the impact that the high correlation between the German and Dutch wind power has on the results. When compared to the cost savings without NorNed, the overall economic benefit is clearly higher in favor of the cable.

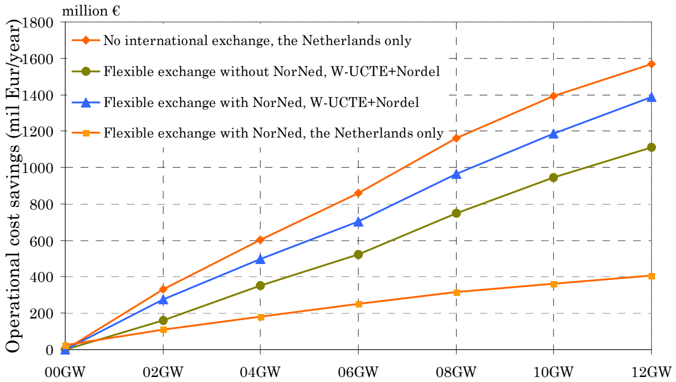

Fig. 7. Annual operating cost savings of wind power and NorNed.

The simulation results clearly demonstrate that wind power leads to saving of significant amounts of CO_2 emissions. It can be noted that emission savings also positively impact operating costs, since CO_2 emission savings are part of the total operating cost. The results for emission savings for SO2 and NOx show similar trends as CO_2.

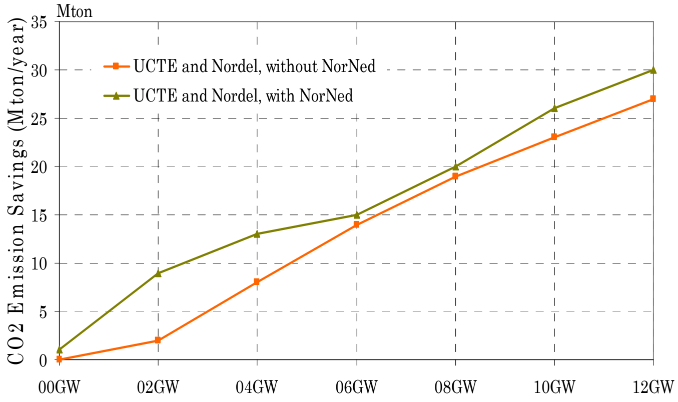

Fig. 8. CO_2 emission savings of the overall system (UCTE and Nordel) for 0-12 GW of wind power in the Netherlands.

In Fig. 8, the emission savings of NorNed are higher for lower wind penetrations. In the range from 6 – 8 GW, the reduction is probably due to the high capacity factor of off-shore wind, but at high wind penetrations again the total emission savings increase. This happens because from 8 - 12 GW the amount of available wind energy is so high, that it can compete in the same terms with hydro power.

IV. CONCLUSIONS

A general criticism of the modeling approach applied in this research is that simulation models are usually highly complex, with many parameters, decision variables and non-linear relations. Under the best circumstances, such models have many degrees of freedom and, with judicious fiddling, can be made to produce virtually any desired results, often with a plausible structure and plausible parameter values [18]. In developing simulation models, it must therefore be borne in mind that all models have limitations and use assumptions to simplify the analysis. The target of the simplifications is to facilitate complex procedures without inserting errors in the results. In the end, the responsibility of determining the applicability of a simulation model to the real world lies with the model developer. This reflection serves as a reminder of this.

Wind power integration within the power system is partly facilitated by the presence of strong international links between countries. International links undoubtedly increase the security of energy supply and may have lower capital investments costs than the energy storage integrated options for wind power [7]. The optimum benefits from international exchanges are obtained when the market closure time is moved to 1 hour, ahead. In this way, the negative effect of wind power forecast errors on system operation costs can be minimized.

Moreover, the technical limits of the power system may be highlighted. Indeed, minimum-load situations during high wind – low load periods are expected to present the first technical integration limit for wind power. One more barrier is posed by the high correlation of German and Dutch wind power. International exchange (availability of transmission capacity for exports) may therefore not be available at all times, which results in wasted wind energy in the Netherlands. The wind power variations additional to those of the load are integrated within the power system effectively, since sufficient ramping capacity is present at all times.

Especially for NorNed, the operation of the cable clearly favors the system in terms of cost/emission savings. With the chosen minimum output levels of the hydro reservoirs in Norway, there is more wasting of available energy sources, either wind or hydro. This can be also perceived as an implicit competition between wind power from the Netherlands and specifically hydro power from Norway. The reason for that is that both generation technologies are considered to have the same, zero marginal cost and therefore, they are competing in the transmission level and the availability period.

Specifically for the Netherlands and Norway, which are linked by NorNed, an optimum management of the Norwegian hydro power based on the price difference can lead to even higher cost/emission savings especially for the Netherlands. This difference is sustained by the limited transmission capacity between the two systems. However, if interconnections are extended with additional links, it is expected that the benefits obtained will not be equally proportional to the increased capacity, but tend to saturate after a certain level of MW.

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