

Assessment of Wind Production Impacts to a Power System and Market Formation in Baltic

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Abstract - This paper is related to the topical problem of expanding wind production integration to the power system and electricity markets. The model for simulation of wind production curves according to the development of wind capacities in Baltic is proposed. In order to evaluate the effect of the wind power integration to the price formation as well as level of system penetration by wind, methodology and algorithms taking into account the development scenarios in Baltic are presented.

Keywords – Distributed power, Modeling, System integration, Wind energy

I. INTRODUCTION

A number of wind power projects in the Baltic region were proposed within the last period. Integration of wind generation into power production mix has significant impact to the power system (PS) operation as well as to the electricity market.

The aim of the study is assessment of wind production impacts related with considerable wind installation in future, developing of methods and algorithms enable simulations from wind conditions to final impact on a system. The paper proposes the algorithms and methodology for estimation of those impacts including model which is capable to generate wind production curve assuming real wind conditions in a region. The results of regional wind production modeling presented in this article contain wind production and duration curves with application of different smoothing approaches, estimation of seasonal diversity of wind generation in different stages of future development of wind installations as well as comparison of annual production obtained by the proposed model with expected targets in the field of wind production in Baltic. The final part of the study is aimed to an estimation of power system penetration by wind generation and assessment of merit-order effect according to the development scenarios of the PS in Baltic till 2020. The wind power production is based on real wind conditions in the Baltic region and expected development of installed wind capacities.

II. WIND GENERATION MODELLING

Wind power and thus its modeling is significantly different from the other power technologies. Generation has specific characteristics, including variability and geographical distribution. The methodology and model presented in the next part integrate specific features of large-scale wind generation deployment and regional wind conditions.

A. Tendencies of installed wind capacities in Baltic

The development of wind capacities in Baltic assumed in this study is based on planning and assumptions presented in National Renewable Energy Action Plans (NREAPs)

published by three Baltic states (EE, LV, LT) related to the development of wind generation capacities, both onshore and offshore by 2020 [1]. The offshore installations in Baltic are planned from 2017 mainly in Estonia and to a lesser extent in Latvia. Considering the technical availability of wind turbines which is generally at the very high level compared to other types of production sources, for further assumptions is envisaged at 97% [2]. The values of decreased available wind installed power P_{DEC} in Baltic are in table 1.

TABLE I.
TECHNICALLY AVAILABLE WIND CAPACITY

Year	2011	2016	2020
P_{DEC} (MW)	402	1124	1553

High level of technical availability is one of the significant advantages regarding to reliability of the supply from distributed wind power installations in the power system. The requirements of maintenance or unplanned breakdown of single unit has a negligible effect on the overall wind production.

B. Estimation of regional wind conditions

Annual wind conditions applied for simulation of wind power production were measured at hourly basis in height of 10m at coastal part of Estonia in 3 localities and subsequently recalculated for wind speed conditions in height of 60m by equation 1

$$V_n = V_0 \left(\frac{H}{H_0} \right)^\alpha ; \text{ for } \alpha = 0,35 \quad (1)$$

In further calculations, the averaged wind speed values are used. Occurrence of averaged annual wind speed is demonstrated in Fig. 1.

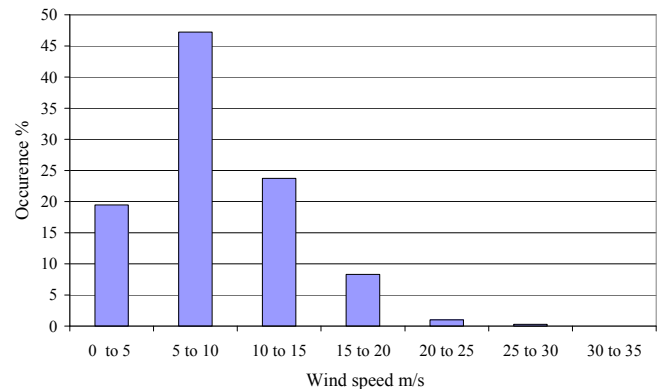


Fig. 1. Averaged wind speed occurrence.

C. Aggregated wind power characteristics modeling

To derive power output of installed wind capacity, the following model expressed by equation (2) has been introduced. This expression merges typical aggregated wind farm power curves both offshore and onshore [2]

$$f(x) = a_1 \cdot e^{-((x-b_1)/c_1)^2} + a_2 \cdot e^{-((x-b_2)/c_2)^2} + a_3 \cdot e^{-((x-b_3)/c_3)^2} + a_4 \cdot e^{-((x-b_4)/c_4)^2} + a_5 \cdot e^{-((x-b_5)/c_5)^2} + a_6 \cdot e^{-((x-b_6)/c_6)^2} + a_7 \cdot e^{-((x-b_7)/c_7)^2} \quad (2)$$

Variable “x” represents averaged wind speed (m/s) per every particular hour. Values of the coefficients to the formula 2 are shown in table 2.

TABLE II. APPLIED COEFFICIENTS

a1	0,03402	b3	16,13	c5	3,818
b1	7,712	c3	0,5106	a6	0,4647
c1	2,281	a4	10,7	b6	13,16
a2	-0,1338	b4	21,43	c6	4,155
b2	19,48	c4	2,496	a7	-10,07
c2	1,606	a5	0,6206	b7	21,45
a3	0,009714	b5	17,15	c7	2,44

In order to obtain generated power according to wind speed via production curve of aggregated wind farm (Fig. 2), the difference in characteristics between onshore and offshore installations are neglected.

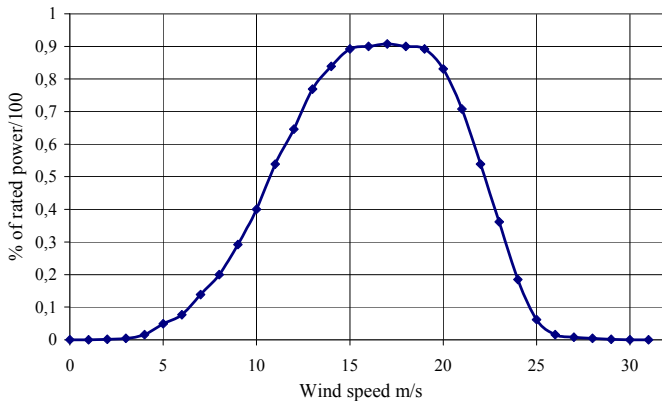


Fig. 2. Production curve of aggregated wind farm.

The resulting production curve is labeled as “raw” production curve with relatively high volatility of production. Averaging of the wind speed has partial impact to the shape of output production curve, so dynamics of variations has been decreased. However, in order to achieve characteristics observed and measured in real conditions, incorporation of so-called large-scale deployment smoothing effect (LSDSE) of wind production is performed in the next step.

D. Large-scale wind generation deployment

Large-scale wind power deployment has a significant impact to the shape of aggregated wind production curve. The more wind deployed the less dynamic fluctuations are achieved and therefore decreasing effect of aggregated wind generation in territory as production from “intermittent” energy source.

In order to incorporate this effect, the output curve of the aggregated wind farm (Fig. 2) is smoothed by the moving average method. A moving average smooths data by replacing each data point with the average of the neighboring data points defined within the span. This process is equivalent to lowpass filtering with the response of the smoothing. Smoothing algorithm applied in this task is given in figure 3 below.

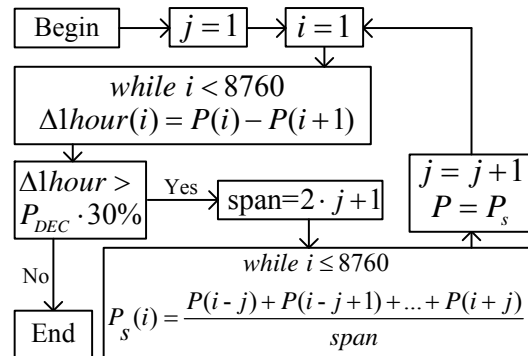


Fig. 3. Flowchart of incorporated smoothing algorithm.

Where, $P(i)$ is the wind production value per hour i , $P_s(i)$ is the smoothed value for the i data point, j is the number of neighboring data points (hours) on either side of $P_s(i)$, and $2j+1$ represents the span.

The moving average smoothing method follows these rules:

- The span must be odd;
- The data point to be smoothed must be at the center of the span;
- The span is adjusted for data points that cannot accommodate the specified number of neighbors on either side;
- The end points are not smoothed because a span cannot be defined.

Taking into account the experience and measurements of extreme variations of large scale regional wind installations also shown in literature [2], the following criteria for dynamics of changes in wind production were selected. The maximally allowed positive and negative ramp rate between neighboring hours is at 30%, within 4 hours at 50% and within 12 hours at 70% of technically available installed wind capacity (P_{DEC}). In addition, the 2 approaches in smoothing of “raw” production curve are applied. The first, labeled as “sequential smoothing” involving all aforementioned criteria for dynamic changes successively, the second labeled as “direct smoothing” employs in smoothing directly only criterion about 70% maximally allowed positive or negative ramp rate within 12 hours. The results of applied smoothing are shown in figure 4.

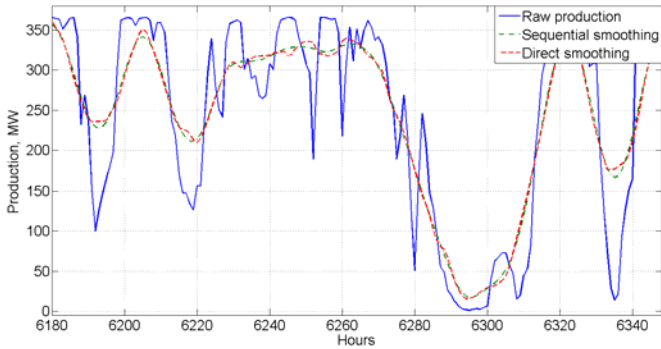


Fig. 4. Example of one week smoothed wind production.

After the smoothing of “raw” production curve has been incorporated the term ‘intermittent’ is for system-wide wind power substituted by the term ‘variable output’ and used instead in further considerations.

The procedure that was used to simulate power production by wind power plants in Baltic is summarized and presented by the algorithm in figure 5. Input data to the simulation of actual wind production comprises, estimated real wind conditions (dashed box) and installed capacity decreased by technical availability. Subsequently, the curve obtained through model of aggregated wind farm is smoothed by the methods in detail described in chapter D.

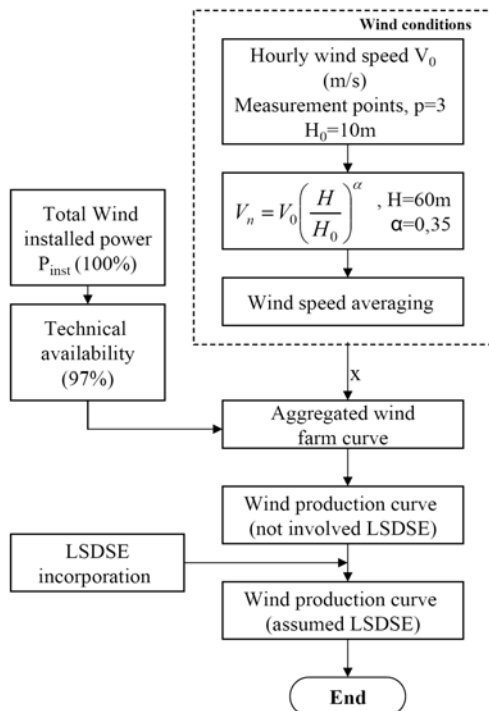


Fig. 5. Wind production curve simulation algorithm.

III. RESULTS OF REGIONAL WIND PRODUCTION MODELING

The deliverables obtained from simulation of the wind production are presented in this part of the article and contain raw and smoothed production curve in Baltic 2020 scenario; monthly diversity of wind generation and duration curves with different smoothing approaches for 2011, 2016, 2020

scenarios; capacity and load factor estimation as well as comparison of the annual Baltic wind production obtained by model and expected values in NREAPs 2011-2020.

Using the algorithm shown in figure 5 according the Baltic wind development scenario 2020 has been generated smoothed wind production curve in Baltic given in figure 6 below. The smoothed production curve should be regarded without curtailment of wind production as physical production.

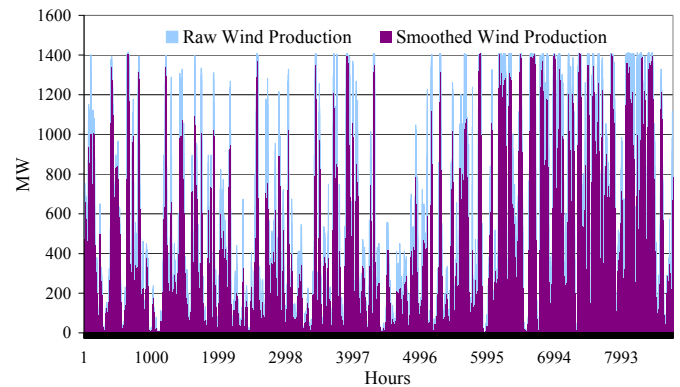


Fig. 6. Annual “raw” and smoothed Baltic wind generation in 2020.

Seasonal diversity of wind production affect proportion of wind impact to a overall PS and exposing needs for power capacity reserves. Result of average monthly generation by wind for assumed development scenarios indicates figure 7.

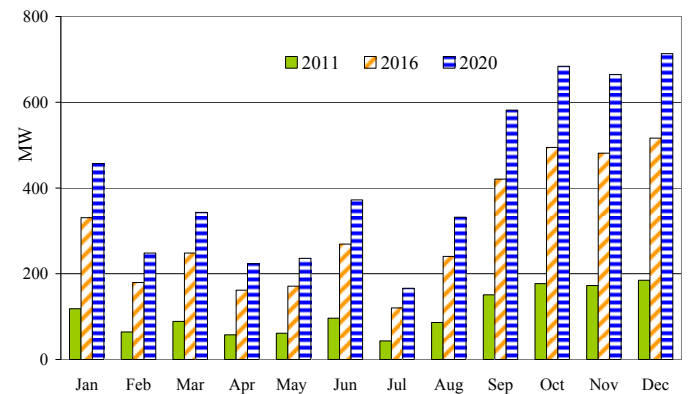


Fig. 7. Average monthly Baltic wind generation.

Within the year considerable variations in average wind generation may be observed. The lowest contribution in compliance with figure 7 is expected during the 1st (January to April) and 2nd (May to August) thirds of the year, however, during the 3rd third (September to December) a substantial contribution of wind production could be expected. Observe the seasonal and inter-annual variation of wind power production is crucial in tasks of wind power integration to a power system. The results are important in strategic power system planning as well as for estimation of long-term impacts to the electricity prices. The less important and significant these results are for a short-term power system management and operation.

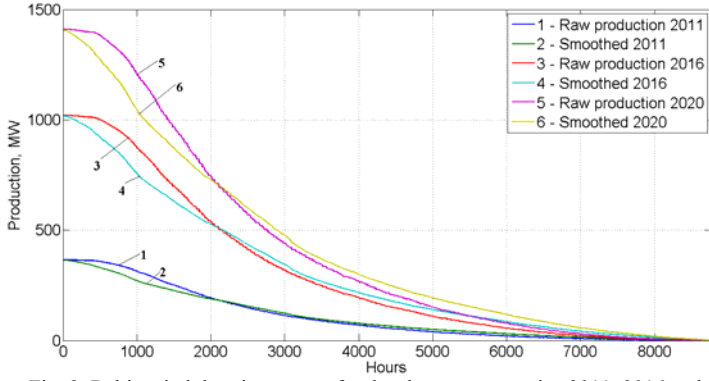


Fig. 8. Baltic wind duration curves for development scenarios 2011, 2016 and 2020.

Duration curves in figure 8 illustrate the relationship between the level of wind generation and the number of hours for 3 development scenarios (2011, 2016, 2020), moreover, with estimation of changes in shapes due to the incorporation of the smoothing effect. The curves are made by sorting all generation values of the 8760 hours in particular year in the order of decreasing. Comparing the shapes of "raw" and "smoothed" production curves is evident that improvement of flatness decreasing production in peak production hours, however, spreading this production to the remaining hours of the year. Capacity utilization rate provides important and easy comprehensible characteristics of production source. In general might be concluded, the flatter generation-duration curve, the better it is for grid operation.

The capacity factor (C_f) and load factor (L_f) of wind generation obtained from simulation and calculated by Eq. 3 and 4 reached the value 0, 26 and 0, 29 respectively.

$$C_f = \frac{\int_0^t p(t) dt}{P_{inst} * t}; \quad (-, \text{MW}, \text{MW}) \quad (3)$$

$$L_f = \frac{P_{av}}{P_{max}}; \quad (-, \text{MW}, \text{MW}) \quad (4)$$

Where, P_{inst} is the total wind installed power; P_{av} is the average wind generation in time period t ; P_{max} represents peak production of wind plants during the time period t .

Results of annual wind production simulation comparing to the targets in National Renewable Energy Action Plans (NREAPs) of the Baltic States are presented in table 2.

TABLE III. SIMULATED AND EXPECTED WIND PRODUCTION

Year	Results MWh	NREAPs MWh	Year	Results MWh	NREAPs MWh
2011	942476	901000	2016	2632868	2385000
2012	1399022	1095000	2017	2850606	2853000
2013	1640172	1579000	2018	2979375	3087000
2014	1914100	1843000	2019	3389096	3251000
2015	2061600	2133000	2020	3637270	3697000

IV. IMPACTS OF THE WIND DEVELOPMENT ONTO A POWER SYSTEM AND ELECTRICITY MARKET

Integration of wind generation into power production mix has impact to the power system operation as well as to the electricity market due to the specific technical/economic features of such type of power source. In this chapter algorithm (Fig. 9) including evaluation of the system penetration and estimation of so-called "merit-order" effect (see Ch. IV-B) according to the PS development in Baltic is proposed.

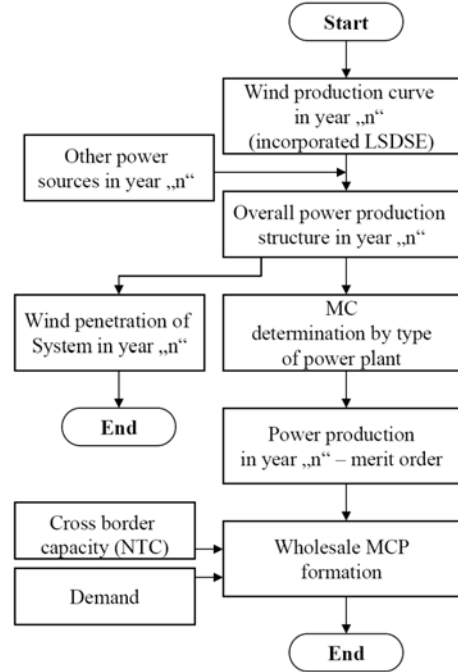


Fig. 9. Merit-order effect & wind penetration of PS – estimation algorithm.

In order to evaluate the effect of the wind power integration to the price formation and level of system penetration by wind, the development changes in power production mix and extension of cross-border transmission capacities in Baltic are based on following assumptions: increase in overall RES production is in compliance with data published in NREAPs [1]. Capacities of other power plants in Baltic generation mix for development scenarios 2016 and 2020, only the main, confirmed projects are taken into account. Marginal costs of production for different types of power production technology are based on present and projected values published in [4]. Assumed new interconnection projects between Baltic and neighboring countries are: By 2013 Estlink II 650 MW (EE-FIN) and by 2016 NordBalt (LT-SWE) 700 MW. The LitPol contribution (LT-PL) is to be considered on 500MW in 2020. Towards non-EU countries, the constant 1500 MW transmission capacity is considered [5][6][7].

A. Wind penetration of power system

The impact of wind power on the electricity system depends mostly on the level of wind power penetration [8]. For Baltic scenarios 2011, 2016 and 2020 are calculated coefficients of wind penetration according to development of generation, transmission capacities and forecasts of system load.

Wind energy penetration is determined as the percentage of total demand $W_{A\ total}$ covered by wind energy $W_{W\ gen}$ in Baltic region estimated on an annual basis according to equation 5:

$$W_{WP} = \frac{W_{Wgen}}{W_{A\ total}} 100; (\%, \text{MWh, MWh}) \quad (5)$$

The wind power capacity penetration shows relation of total installed wind capacity P_{DEC} to the peak load P_{Lmax} in region for the estimated time period (winter/summer) as follows:

$$C_{WP} = \frac{P_{DEC}}{P_{Lmax}} 100; (\%, \text{MW, MW}) \quad (6)$$

The maximum share of wind power focused on power balance assessment in region is based on minimal load value P_{Lmin} , maximal wind load P_{Wmax} and available cross-border capacity P_{NTC} calculated as:

$$S_{Wmax} = \frac{P_{Wmax}}{P_{Lmin} + P_{NTC}} 100; (\%, \text{MW, MW, MW}) \quad (7)$$

$0\% \leq S_{Wmax} \leq 100\%$ - Non-curtailed wind production;

$S_{Wmax} > 100\%$ - Required curtailment of wind production.

However, requirements for the wind production curtailment could appear due to the internal network constrains, therefore, non-curtailed wind production is assumed only in the case when capability of internal network is sufficient

The disproportions in seasonal availability mainly CHP and hydro production could significantly devalue veracity of results, thus, calculation is performed for winter and summer conditions. Results of wind penetration assessment for all scenarios are summarized in table 4.

TABLE IV. BALTIC SYSTEM PENETRATION BY WIND

Scenario/Year		2011	2016	2020
W_{WP}		3,4	8,4	10,4
	C_{WP}			
C_{WP}	Winter	7,7	19,1	23,7
	Summer	11,5	28,2	34,9
S_{Wmax}				
	S_{Wmax}			
S_{Wmax} (Only P _{NTC} to EU)	Winter	7,9	16,1	21,1
	Summer	5,6	11,2	14,5
S_{Wmax} (Only P _{NTC} to EU)				
	S_{Wmax}			
S_{Wmax} (Only P _{NTC} to EU)	Winter	11,7	21,2	27,2
	Summer	9,7	15,8	20,1

B. Merit- order effect of the wind production

Currently, the merit-order effect characterizes influence of the electricity produced under feed-in-tariff (FIT) law to the wholesale electricity price in way that average cost of electricity decreases. The FIT are proposed as temporary system of subsidies, however, in long-term perspectives may be direct merit-order effect caused by wind production (currently covered by FIT) expected as well. The reason is bidding strategies which are used by power producers to join the short-term organized markets (e.g. Nord Pool Spot). The

offer bids of generators on those short-term markets are often placed on level of so-called short-run marginal costs (SRMC) of particular producer [9]. The SRMC of wind production are close to zero, it means that wind production enters bottom of the marginal cost curve i.e. supply curve.

An example of engagement wind production into estimated Baltic merit-order generation at the basis of SRMC extended with transmission capacities for summer (July) and winter (January) conditions in 2020 scenario are shown in Fig. 10 and Fig. 11 respectively. Level of load in the system represents estimated minimal, average and maximal load during January and July in Baltic 2020. To better distinguish situation, the supply curve is shifted at maximally achieved level of wind production in 2020.

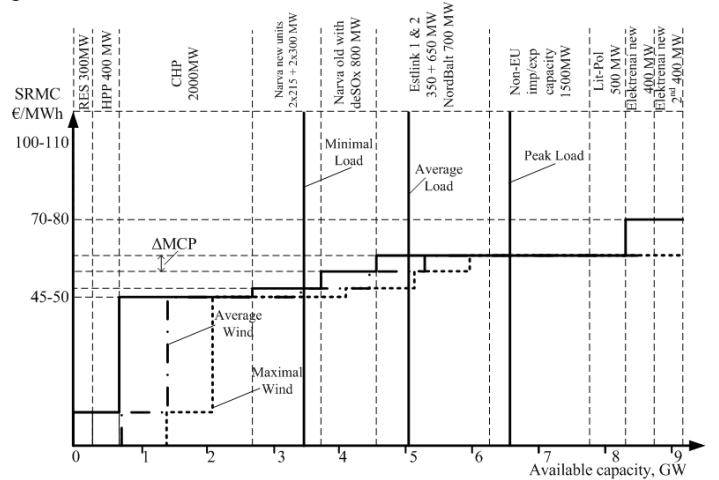


Fig. 10. System price formation in winter scenario 2020.

The most significant difference in the presented snapshots is caused by CHP production, which is for summer scenario considered at 500 MWe and for winter scenario 2000 MWe.

Load of system (demand) is modeled as inflexible, determination of market clearing price (MCP) and market clearing volume is based on power pool principle, so-called one-sided auction.

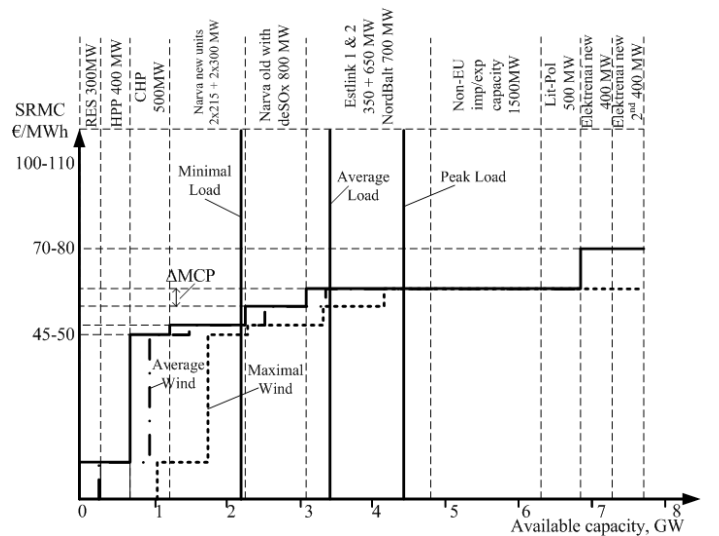


Fig. 11. System price formation in summer scenario 2020.

It is quite evident that shifting of entire production curve due to inclusion of wind power is not constant throughout the year. The variation differs according to the wind condition seasonally and partially from year to year. The range of shifting and its duration might be clarified by duration curves of wind production. These have been on annual basis obtained by wind production modeling and presented also for 2020 scenario in figure 8. However, to the price formation process and thus on the resulting price have impact countless number of factors. In mid and long-term perspectives such as structure, disposition and availability of power sources, level of commercial capacities of cross-border lines and also structure and level of demand. The demand side management programs appear to have a crucial role in future integration of wind, to deal with negative impacts to a power system as well as reduce the price volatility.

V. CONCLUSIONS

The article proposing algorithm and manner of wind production simulation based on real wind conditions. Effect of the large-scale deployment wind generation has been considered through different approaches of wind production curve smoothing and incorporated to the proposed algorithm of wind production modeling. Subsequently, simulated wind production curves were applied in order to calculate wind penetration of Baltic power system according to forecasted state of generation, transmission and load in particular scenario and seasonal conditions with summarized results. According to deliverables and results of this study the several conclusion related to a wind penetration of power system and electricity market could be made: the results obtained by the model are comparable with targets published in NERAPs, the level of system penetration by wind in compliance with methodology and evaluation criteria shows that for all assumed scenarios are values within acceptable range. Though, the considerable difference of the results could be observed in the case of disturbances when substantial amount of generation capacity of conventional power plants or transmission capacities is out of operation. Integration of the wind production will increase price volatility, both seasonal and short-term, however, estimate the exact effect of wind production to the electricity prices is not easy task. One of the expected influences of wind power on electricity market has been presented in Baltic development scenario 2020 through merit-order effect caused by wind production. As could be derived from presented snapshots, integration of wind production will reduce need of most expensive conventional plants which can lead to lower average prices for electricity. Should be noticed that expansion of power production capacities with low marginal costs of production might have also negative impact to the conventional generators, mostly caused by decrease of their load factors, hence, reducing ability sufficiently cover total production costs. From the long-term perspectives, effects of wind integration into generating portfolio could be evaluated as positive, regarding to improved generation and transmission adequacy as well as system reliability.

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Artjoms Obuševs, Mario Turcik, Irina Oļeiņikova, Gatis Junghāns. **Vēja ražošanas ietekmes novērtējums uz energosistēmu un tirgus veidošanos Baltijā**
Pētījuma mērķis ir novērtēt vēja ražošanas ietekmes, saistītas ar ievērojamu vēja elektrostaciju pieaugumu nākotnē, izstrādāt metodes un algoritmus, kuri ļauj veikt simulāciju sākot no vēja apstākļiem līdz galīgai ietekmei uz sistēmu. Rakstā tiek ierosināti algoritmi un metodoloģija šo ietekmju novērtēšanai, ieskaitot modeli kas spēj ģenerēt vēja ražošanas raksturlīkni ievērojot reālos vēja apstākļus reģionā.

Vēja enerģijas modelēšanai ir būtiskas atšķirības no citām enerģijas tehnoloģijām. Ģenerācijai ir specifiskas īpašības, ievērojot vēja nepastāvību un ģeogrāfisko sadalījumu. Metodika un modelis apvieno sevī specifiskas īpašības liela mēroga vēja ģenerācijas izvietošanā un reģionālos vēja apstākļus.

Rezultāti, kas iegūti no vēja ražošanas simulācijas ir izklāstīti dotajā rakstā un ietver neapstrādāto un izlīdzināto ražošanas raksturlīkni Baltijas 2020. gada scenārijam; ikmēneša vēja ģenerācijas nevienādības un ilguma līknes ar dažādiem izlīdzināšanas papēmieniem 2011, 2016 un 2020. gada scenārijiem; caurlaides spējas un slodzes koeficientu novērtējums. un Baltijas gada vēja ražošanas salīdzinājums starp rezultātiem iegūtiem pēc modeļa un sagaidāmām vērtībām pēc NREAPs 2011-2020. Vēja iespēšanās līmenis sistēmā saskaņā ar metodiku un vērtēšanas kritērijiem rāda, ka visiem apskatāmiem scenārijiem vērtības ir pieņemamā robežu diapazonā. Vēja ražošanas integrācija samazinās vajadzību pēc vis dārgākām tradicionālām stacijām, kas var pazemināt elektroenerģijas vidējo cenu. Bet jāievēro to, ka elektroenerģijas ražošanas paplašināšanai ar zemām robežizmaksām var būt arī negatīva ietekme uz tradicionāliem ģeneratoriem, galvenokārt izraisot slodzes koeficienta samazināšanos, tādējādi samazinot iespēju pietiekami nosegt kopējās ražošanas izmaksas.

Артем Обушев, Марио Турчик, Ирина Олейникова, Гатис Юнгханс. **Оценка воздействия производства ветряной энергии на энергосистему и формирование рынка в странах Балтии**

Целью исследования является оценка воздействия производства ветряной энергии, связанным со значительным увеличением количества ветряных электростанций в будущем, разработка методов и алгоритмов, позволяющих произвести моделирование от ветровых условий до окончательного воздействия на систему. В статье предложены алгоритмы и методики оценки этих последствий, включая модель, которая способна генерировать характеристику производства учитывая реальные условия ветра в регионе.

Энергия ветра и ее моделирование существенно отличается от других энергетических технологий. Генерация имеет специфические особенности, включая изменчивость и географическое распределения. Методика и модель объединяет особенности крупномасштабного размещения ветряной генерации с учетом региональных условий.

Полученные результаты, представленные в этой статье, содержат необработанные и сглаженные кривые производства в Балтии для прогноза на 2020 год; ежемесячное различие ветряной генерации и кривые продолжительности при сглаживании для сценариев 2011, 2016, 2020 годов; оценка пропускной способности и коэффициента использования установленной мощности; сравнение ежегодного производства полученного с помощью модели и целями NREAPs для 2011-2020 годов. В соответствии с методикой и критериями оценки, значения уровня влияния ветра на энергосистему для всех сценариев находятся в допустимом диапазоне. Интеграция производства ветряной энергии позволит снизить потребность в самых дорогих традиционных станциях, что приведет к снижению средних цен на электроэнергию. Расширение производственных мощностей с низкими замыкающими затратами, приводит к негативному влиянию на традиционные генераторы, в основном снижением коэффициента использования установленной мощности, следовательно, снижению возможности покрывать общие производственные затраты.