RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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THE STUDY OF WIND ENERGY RESOURCE AND THE ASSESSMENT OF THE ECONOMIC FEASIBILITY OF WIND ENERGY PROJECTS

Summary of the Doctoral Thesis

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Professor Dr. habil. sc. ing.
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERIG SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on July 2, 2019 11:00 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 306.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Deniss Bezrukovs .... (signature)
Date ....

The Doctoral Thesis has been written in English. It comprises Introduction, 5 Chapters; Conclusions; 91 Figures; 20 Tables; 1 Annex; the total number of pages is 141. The Bibliography contains 140 titles.

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GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Topicality

The solution to the problems of modern energetics is inseparable from the increased protection of the environment from pollution and reduction in carbon dioxide emissions caused by fossil fuel combustion. It is, therefore, not a coincidence that technologies based on the efficient utilization of Renewable Energy Sources (RES) are rapidly developing. For instance, the installed capacity of wind energy power plants in the last 20 years grew more than fiftyfold.

The growing interest in the commercial use of wind energy can be attributed to a significant progress in improving the technological design of turbine manufacturing and increasing the height of hubs, that made it possible to significantly increase the nominal capacity of installed generators. At the same time, energy storage technologies are being developed and methods for planning wind power park (WPP) energy generation output based on short-term wind turbine operational efficiency forecasting are being improved. The advancements made in these fields lead to the fact that alternative energy is becoming more profitable every year.

In the process of designing a new WPP, one of the main criteria for choosing the construction site is the existence of a technical report analysing the distribution of wind energy potential up to 200 m. The modern methods of wind power modelling such as Global wind atlas and ERA5, developed on the basis of climatological models, provide information on the global distribution of long-term wind speed averages with resolution 10 km × 10 km. These results allow to select primary locations with relatively high wind energy potential in a particular country that could be promising for the construction of a WPP.

Prospective studies in the field of improving wind energy efficiency are concerned with the possibility of short-term modelling of wind energy for up to 48 hours ahead at the height of 10 m to 500 m. This enables electricity producers to participate in the commercial sale of energy at market prices through the Nord Pool power market. The price of energy in this market depends on concurrent supply and demand, resulting in the fact that in certain periods of time price can significantly deviate from a daily or monthly average.

The Thesis presents the results of applications and further developments of methods aimed at lowering uncertainty associated with wind power project by estimating wind energy resource potential and predicting the efficiency of wind turbines in the conditions of low wind speed typical for Latvia. In order to achieve the proposed goals, in the course of the study of the distribution of wind energy potential in Latvia, a series of physical experiments were carried out using laser measuring complexes and measuring sensors installed on 60–80 m tall masts, in combination with mathematical modelling on the basis of Computational Fluid Dynamics (CFD) methods.

The results obtained in the course of ENER/FP7/618122/NEWA ERA-NET PLUS project enabled the development of a wind energy resource distribution map based on long-term wind speed measurements using the technical capabilities of the Latvian National Hydrometeorological and Climatological Service of the Latvian Environment, Geology and Meteorology Centre (LEGMC), which operates a network of 10 m high meteorological masts. In combination with the study of wind speed distribution over height a wind shear estimation method has been developed using lattice cellular communication masts. The proposed approach makes it possible to predict the effectiveness of wind turbine operation for different generator types at various hub heights.

Aims and Objectives of the Doctoral Thesis

The purpose of the work is to reduce the cost of energy production and increase the feasibility of wind power parks by lowering the level of operational uncertainty associated with the projects. In order to achieve the stated goal, the following tasks were undertaken:

1. To consider forecasting methods of wind energy project revenue streams using stochastic differential equation models.
2. To assess the relationship between wind turbine technical characteristics and the amount of energy production.
3. To perform the study of wind shear based on long-term measurements of wind speed, gathered using laser-based measuring systems Symphonie Plus and SpiDar.
4. To create a long-term average wind speed distribution map for the territory of Latvia at the height of 10 m based on the results of wind speed measurements obtained from LEGMC for the time period 2015–2016.
5. To study the possibility of using the power law function to extrapolate the values of the parameters of the Weibull distribution function to the height corresponding to the location of wind turbine axis.
6. To test a method of carrying out wind shear estimations, using cellular communication masts for installing the sensors of wind speed measuring complexes at multiple height levels.
7. To quantify the impact of lattice masts’ structural design on the results of wind speed measurements using CFD modelling and physical experiments.
8. To show that following the recommendations for placing sensors on the mast to perform wind speed measurements in accordance with the technical standard IEC 61400-12-1 does not ensure the accuracy of measurements of at least 1 % prescribed by the standard.
9. To propose a method for improving the accuracy of wind speed measurements by comparing the results of estimations obtained from two sensors installed at the same height and offset by at least 120° with respect to each other.
10. To create a map of the Weibull distribution parameters for the average wind speed and wind energy resource at the height of 10 m for the territory of Latvia.
11. To perform the assessment of the operational efficiency of low-power wind generators for wind turbines with vertical and horizontal axes at the height of 10 m.
12. To develop a model of the spatial distribution of the relative capacity factor for horizontal axis wind turbine type generator with rated power 2.5 kW at the height of 10 m.

13. To study variations in the efficiency of wind turbines in the conditions of low wind in Latvia depending on the height of the hub and generator type

Research Methods

In order to address the problems that had to be solved in the framework of the Thesis, mathematical simulation methods were used in combination with the performance of physical experimental studies in natural conditions.

The evaluation of the possibility of estimating the feasibility of wind power parks by forecasting price fluctuations in the Nord Pool energy market in combination with short-term wind speed forecasts was made using stochastic differential equation (SDE) models.

The evaluation of the possibility of using a network of lattice cellular communication masts with the height of up to 100 m was performed using CFD modelling on a supercomputer at Ventspils University College. Furthermore, a physical experiment was designed in order to confirm theoretically drawn conclusions. The experiment involved three 100 m high lattice masts located on the Baltic Sea coast and belonging to Latvijas Mobilais Telefons (LMT) network operator.

The study of the dependence of wind turbine efficiency on the hub height was performed using an extrapolation of the results of average wind speed measurements and fitting the Weibull probability density function.

A model of the spatial distribution of wind energy and low-power wind turbine efficiency at the height of 10 m above the ground was developed based on long-term average wind speed measurements obtained from 22 observation sites on the territory of Latvia.

In order to perform the estimates of wind shear based on experimental wind speed measurements at lower altitudes, the power-law extrapolation function was used.

Scientific Novelty of the Doctoral Thesis

1. A proposed model in the form of a density map of Weibull distribution parameters for the average values of wind speed at the height of 10 m for the territory of Latvia.
2. A proposed model in the form of a distribution map of multi-year mean values of wind energy resource at the height of 10 m for the territory of Latvia.
3. A proposed model in the form of a distribution map of operational efficiency at the height of 10 m of low-power generators for wind turbines with vertical and horizontal axis for the territory of Latvia.
4. A model was developed of the spatial distribution of a relative capacity factor for HAWT type generator with rated power 2.5 kW at the height of 10 m above the ground for the territory of Latvia.
5. The variability in the efficiency of wind turbines in the conditions of low winds, depending on the height of the mast and generator type was studied.
6. A method was proposed for improving the accuracy of the measurements of average wind speed by comparing the results of estimations obtained from two sensors

installed at the same height and shifted by an angle of at least 120° with respect to each other.

Importance of the Doctoral Thesis

The research results have found practical application in the following projects:

- Project New European Wind Atlas (NEWA), ENER/FP7/618122/NEWA ERA-NET PLUS, supported by the EUROPEAN COMMISSION under the 7th Framework Programme for Research, Technological Development and Demonstration.
- Project “Future-proof development of the Latvian power system in an integrated Europe (FutureProof)”, project No. VPP-EM-INFRA-2018/1-0005.
- Project “Innovative smart grid technologies and their optimization (INGRIDO)”, project No. VPP-EM-INFRA-2018/1-0006.

The results of evaluation of effectiveness of low-power wind turbines were used in preparation of recommendations for the Ministry of Economics of Latvia in accordance with agreement EM/2018/19 dated 05.03.2018.: “Electricity NETO billing system evaluation and suggestions for system improvements”, developed by a team of researchers of Riga Technical University under the leadership of Dr. habil. sc. ing. Professor Antans S. Sauhats.

Basic Viewpoints Proposed for the Defence

1. A model in the form of a map of spatial distribution of the Weibull distribution parameter values for average wind speed and wind energy resource at the height of 10 m for the territory of Latvia.
2. A model in the form of a map of spatial distribution of operational efficiency at the height of 10 m of low-power wind generators for wind turbines with vertical and horizontal axis for the territory of Latvia.
3. A model of the spatial distribution of relative capacity factor for HAWT type generator with rated power 2.5 kW at the height of 10 m above the ground for the territory of Latvia.
4. The results of the study of variation in the efficiency of wind turbines in the conditions of low winds, depending on the height of the mast and generator type.
5. A methodology of improving the accuracy of average wind speed measurements by combining the results of estimations obtained from two sensors installed at the same height and offset by at least 120° from each other.

Contribution of the Author to the Research

The scientific results presented in the work were carried out in collaboration with the scientific supervisor of the Thesis Dr. habil. sc. ing. Professor A. S. Sauhats. The author has studied the possibility of assessing the economic and operational risks associated with the implementation of wind power projects using stochastic models.

The study of wind energy resource was made by the author on the basis of the results obtained within the framework of scientific project New European Wind Atlas (NEWA), ENER/FP7/618122/NEWA ERA-NET PLUS, supported by the EUROPEAN COMMISSION under the 7th Framework Programme for Research, Technological Development and Demonstration.

The development of a model in the form of a spatial distribution map of wind energy and the efficiency of wind turbines at the altitude of 10 m in the territory of Latvia was carried out based on historical data from long-term measurements of wind speed provided by LEGMC.

The author proposed using the model in the form of a density map of Weibull distribution parameters to gauge the efficiency of wind turbines. The density maps can serve as a reference tool for assessing wind energy resource potential in Latvia at a height of 10 m and estimating operational efficiency of low-power wind generators for wind turbines with vertical and horizontal axes.

At the core of the Thesis are articles prepared and published with the participation of the author, who personally participated in the presentations and discussions of the results in scientific conferences, as well as in the preparation of experimental studies.

Approbation of the Research

The results of the research were presented and discussed in the following conferences.

1. **D. Bezrukovs**, A. S. Sauhats (2016): The Application of Stochastic Differential Equation Models in the Assessment of the Economic Feasibility of Wind Energy Projects in Latvia. October 13–14, 2016, 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON).
2. V. Bezrukovs, Vl. Bezrukovs, A. Zacepins, **D. Bezrukovs** (2016): Forecasting of wind turbine efficiency in Latvia by long-term wind speed measurements. October 13–14, 2016, 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON).
3. **Bezrukovs, D**., Sauhats, A. S. (2017): Economic and Operational Risks in Wind Energy Projects in Latvia. International Conference on Renewable Energies and Power Quality (ICREPQ’17) Malaga (Spain), April 4–6, 2017.
4. Bezrukovs V., Bezrukovs Vl., Upnere S., **Bezrukovs D**., Sauhats A. S. (2017): The assessment of wind speed distortions in a simulated flow around a lattice cellular communication mast. EECS 2017 European Conference on Electrical Engineering and Computer Science, Bern, Switzerland, November 17–19, 2017.
5. Bezrukovs V., Bezrukovs Vl., Upnere S., Gulbe L., **Bezrukovs D**. (2018): The use of cellular communication masts for wind shear research. Conference CYSENI 2018, May 23–25, Kaunas.
6. **Bezrukovs D**., Aniskevich S., Bezrukovs V. (2018): Forecasting the efficiency of small wind turbine generators. The 8th International ENERGY Conference & Workshop – REMOO, 29–31 May 2018, VENICE / ITALY.

7. Bezrukovs V., Bezrukovs Vl., Upnere S., **Bezrukovs D**. (2018): The impact of lattice mast structure on the results of wind speed measurements. Wind Europe the global on&offshore conference, Hamburg, September 24–28, 2018. /PO.065.
8. Bezrukovs V., Bezrukovs Vl., **Bezrukovs D.,** Zacepins A., Volkovs A. (2019): A method of correcting wind speed measurement results obtained from sensors placed on a lattice mast. Wind Europe Conference & Exhibition, Bilbao, 02–04 April 2019. /PO.136.
9. Bezrukovs V., Bezrukovs Vl., **Bezrukovs D**., Zacepins A. (2019): Reducing the uncertainty of wind speed measurements obtained on lattice masts. Wind Resource 2019, Workshops / Resource Assessment / PO.003, Brussels, 27–28 June 2019.

The results of the research were published.

1. **Bezrukovs, D**., Sauhats, A. S. (2017): Economic and Operational Risks in Wind Energy Projects in Latvia. Renewable Energy and Power Quality Journal, 2017, No. 15, pp. 1–6, ISSN 2172-038X; DOI:10.24084/repqj15.326.
2. **Bezrukovs, D.,** Sauhats, A. S. (2016): The Application of Stochastic Differential Equation Models in the Assessment of the Economic Feasibility of Wind Energy Projects in Latvia. In: 2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2016): Proceedings, Latvia, Riga, 13–14 October 2016. IEEE, 2016, pp. 151–156. ISBN 978-1-5090-3732-2; e-ISBN 978-1-5090-3731-5; DOI:10.1109/RTUCON.2016.7763108.
3. V. Bezrukovs, Vl. Bezrukovs, A. Zacepins, **D. Bezrukovs** (2016): “Forecasting of wind turbine efficiency in Latvia by long-term wind speed measurements”. In the proceeding of “2016 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)”. 13–14 October 2016, Riga, Latvia. DOI: 10.1109/RTUCON.2016.7763104.
4. V. Bezrukovs, A. Zacepins, Vl. Bezrukovs, **D. Bezrukovs**. (2016): “The evaluation of wind turbine efficiency in Latvia under low-wind conditions”. Space Research Review. 2016. Vol. 4, pp. 85–96. VIRAC, ISBN 978-9984-48-053-7.
5. Aniskevich S., Bezrukovs V., Zandovskis U., **Bezrukovs D.**, (2017): Modelling the spatial distribution of wind energy resources in Latvia. Latvian Journal of Physics and Technical Sciences N 6, 2017. pp. 10–20. DOI: 1010.1515/lpts-2017-0037.
6. Bezrukovs V., Bezrukovs Vl., Upnere S., **Bezrukovs D**., Sauhats A. S. (2017): The Assessment of Wind Speed Distortions in a Simulated Flow Around a Lattice Cellular Communication Mast, 2017 European Conference on Electrical Engineering and Computer Science (EECS), Bern, Switzerland, 2017, pp. 421–428. DOI:10.1109/EECS.2017.84.
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8. Bezrukovs V., Bezrukovs Vl., Gulbe L., **Bezrukovs D.,** Konuhova M. (2018): The experience of installing wind measuring sensors on cellular communication tall masts. Space Research Review, Vol. 5, 2018, pp. 85–103. ISBN 978-9984-648-89-7.
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10. Petričenko, Ļ., Broka, Z., Sauhats, A. S., **Bezrukovs, D**. (2018): Cost-Benefit Analysis of Li-Ion Batteries in a Distribution Network. No: 2018 15th International Conference on the European Energy Market (EEM 2018), Poland, Lodz, 27–29 June 2018. Piscataway, NY: IEEE, 2018, pp. 1–5.
11. **Bezrukovs D**., Aniskevich S., Bezrukovs V., (2018): Forecasting the efficiency of small wind turbine generators. Proceeding of the 8th International ENERGY Conference & Workshop – REMOO, 29–31 May 2018, VENICE / ITALY, pp. 14. ISBN 978-3-9818275-8-3.

1. ALTERNATIVE ENERGY SOURCES IN MODERN ENERGETICS

1.1. Problems and solutions

Nowadays, the human civilization can exist only by producing and consuming an enormous, ever-increasing amount of energy. At the same time, prior to the industrial revolution at the turn of the 18th–19th centuries humanity was relying practically exclusively on renewable energy sources – energy of water, wind and bio fuel.

Industrial technology development and the associated growth in energy needs led to a rapid increase in the use of, predominantly, non-renewable energy resources – first coal, and then oil and gas. Therefore, the global energy industry of the 20th and early 21st centuries was, and remains, largely hydrocarbon-based that makes the cornerstone of the energy problem that world nations try to tackle.

The global energy problem can be viewed as a task of ensuring a reliable supply of fuel and energy for the humanity, while limiting associated environmental costs. The main reason for the emergence of the energy problem could be attributed to a rapid increase in the consumption of mineral fuels and the volumes of greenhouse gasses emitted in the process of their consumption.

As can be seen from Fig. 1.1, in the course of the last 150 years the rate of energy consumption has increased dramatically. It is notable that the period when the volumes have skyrocketed includes only the last 70 years [1].

It is unarguable that Earth’s crust contains all types of hydrocarbons in huge quantities, but it should be noted that their overall volume is still limited and can be exhausted. In the beginning of the 21st century, the concept of “global energy security” has come into wide use. The strategy of such security rests on the principles of a long-term, reliable, environmentally friendly energy supply at reasonable prices that suits both exporting countries and consumers.

At the same time, global energy security largely depends on practical measures of further ensuring the world economies primarily with traditional types of energy resources that are more stable and predictable. Therefore, the search for sustainable solutions to energy problem remains relevant also nowadays.

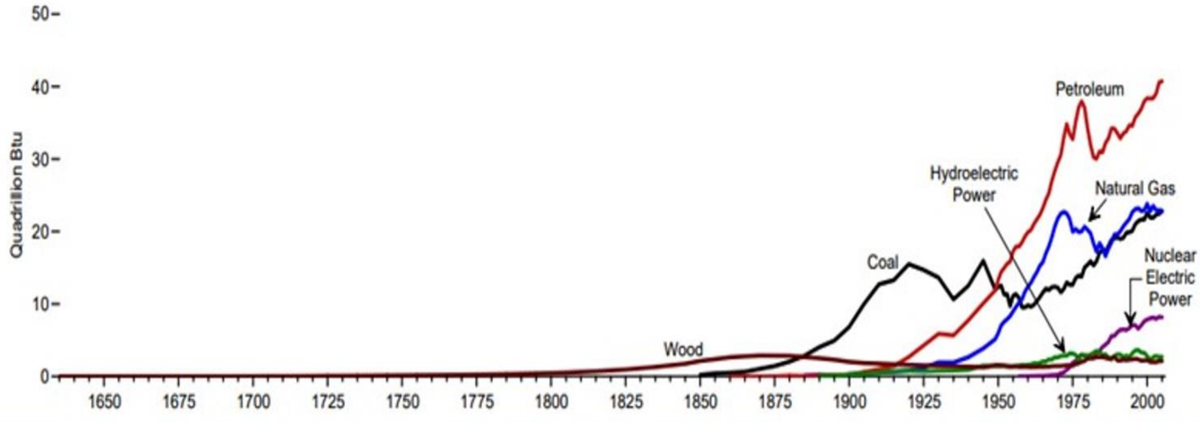

Fig. 1.1. World energy consumption in the period 1630–2005 in British thermal units (Btu) [1].

The path of increasing the stock of fuel reserves has always been the main one, but nowadays, an alternative approach has come to the forefront, which is to use energy resources more rationally and economically, that is to implement energy conservation policies.

In recent years, many technical and technological innovations have been carried out to improve the situation. Energy saving is increasing due to the improvement of industrial and municipal equipment, the production of more efficient cars, thermal isolation of buildings, etc. The range of macroeconomic measures should in the first place include a gradual change in the structure of consumption of energy resources with an emphasis on increasing the share of renewable and non-traditional primary energy resources.

The sharp increase in energy consumption in the world over the past decades has led to the problem of an anthropogenic influence on climate change. In this regard, on 12 December 2015 in Paris, parties to the UNFCCC reached a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future [2], [3].

The share of electricity in total energy use must double, with substantial electrification of transport and heating. Renewables would then make up two-thirds of energy consumption and 85 % of power generation. Together with energy efficiency, this could deliver over 90 % of the climate mitigation needed to maintain a 2 °C limit.

According to the Reference Case (which reflects current and planned policies including Nationally Determined Contributions (NDCs)), energy-related CO_2 emissions will increase slightly year on year to 2040, before dipping slightly by 2050 to remain roughly at today's level. The assessment suggests that renewable energy and energy efficiency can provide over 90 % of the reduction in energy related CO_2 emissions [4].

1.2. The use of renewable energy resources

Overall trends in the power production suggest that the transition to renewable energy is feasible, as in 2016 renewables accounted for 18.2 % of final energy consumption, while modern renewables, not including traditional use of biomass, contributed approximately 10.4 % [5]. Renewable energy sources are mainly used to produce electrical energy (Fig. 1.2), as they provided 26 % of global electricity demand at the end of 2017 [5].

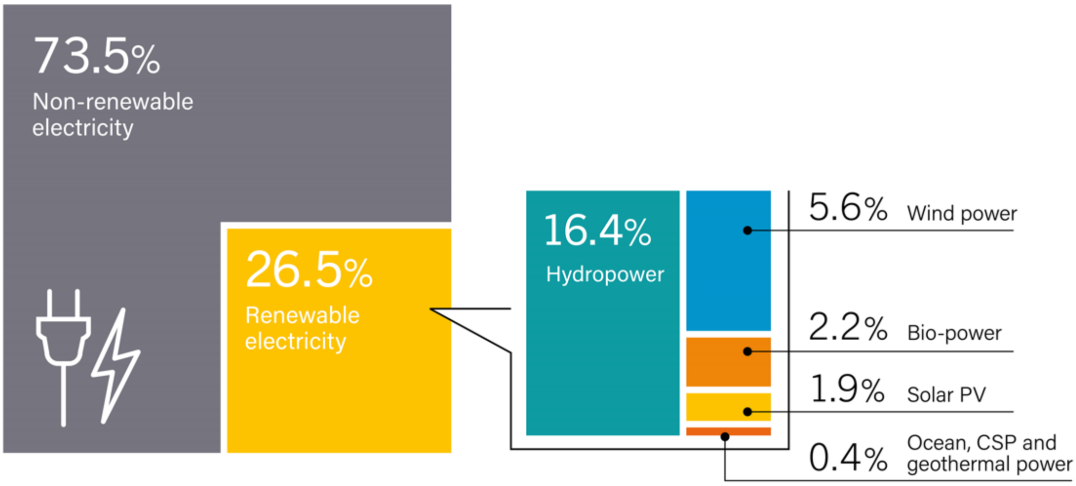

Fig. 1.2. Estimated renewable energy share of global electricity production, end 2017 [5].

The speed and magnitude of the structural changes in wind energy sector can be seen from long-term statistics on the penetration of wind energy globally and in Europe. As reported by Global Wind Energy Council [6], in the last 20 years wind energy power globally grew more than fiftyfold (Fig. 1.3).

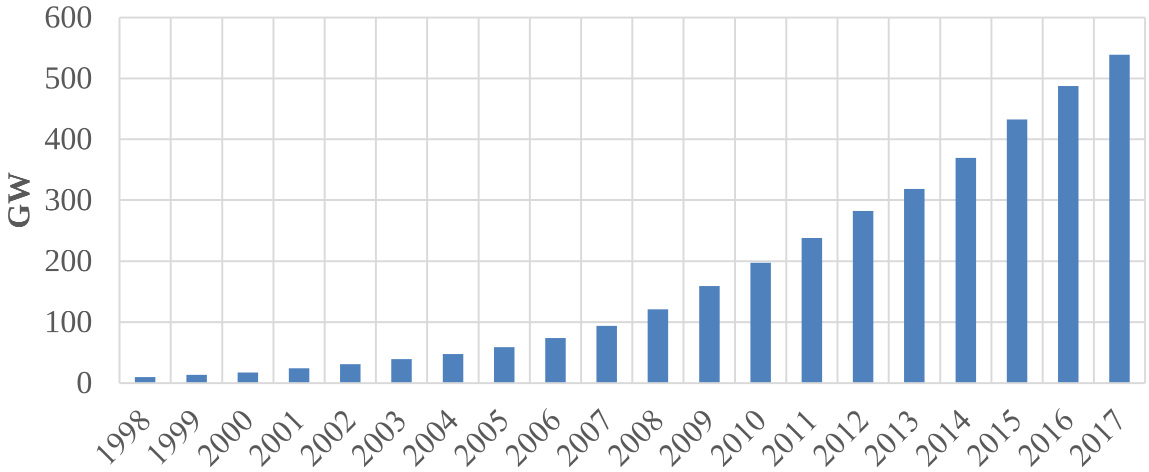

Fig. 1.3. Global wind power installed capacity (GW) [6].

It is acknowledged that the cost of “green” energy is higher in comparison to the traditional power, derived from the combustion of hydrocarbons or the splitting of atomic nuclei. However, at present, alternative energy is becoming more profitable every year According to the European Commission, the levelised cost of electricity of onshore wind ranges from 52 EUR/MWh to 110 EUR/MWh [7].

In Latvia, the first WTs TAKE TW600 with rated power of 600 kW, hub height of 50 m and a rotor diameter of 43 m were installed in 1994 in Ainaži [8]. Later, wind power parks Winergy, Vēja parks, Vides enerģija, Baltnorvent, Lenkas Energo and others with total installed capacity of 70 MW were built.

1.3. Economic risks of wind energy projects

The total project costs depend on many factors, including the cost of the turbine itself, the extent and scope of supporting environmental work for the planning application, the cost of any electrical distribution network upgrades and the cost of site works, including access roads, foundation and cabling costs.

The planning of WPP projects is usually complex, because the multitude of economic and operational risks have to be considered. After the completion of a WPP, various risks may arise during the lifetime, such as general operational and maintenance risks, business interruption due to damages or grid availability risks, natural disasters and many other factors.

Moreover, the intermittency of the flow of wind energy introduces significant uncertainty in the calculations of the predicted WPP profitability. The questions of assessing these risks and the degree of their influence on the payback period and profitability of projects have been studied by many authors [9]–[13].

The analysis of these studies allows to systematize risks and divide them in two groups depending on whether they refer to technical and structural factors or economic problems.

The risks related to the first category are associated with technical problems that are addressed at the stage of preparation of project documentation and manufacture of WT. Essentially the burden of addressing these risks rests on manufacturers that leverage on their accumulated experience by introducing new construction technologies, developing more advanced structural materials and optimising maintenance operations.

A technical failure or damage of the WT construction usually leads to a temporary shutdown of operations until the issue is addressed. Such events decrease the amount of electrical energy produced and eventually result in the deterioration of WPP economic performance.

The risks assigned to the second category are related to the management issues, site selection, park design and wind energy potential estimation, which can be directly expressed in monetary terms. However, estimating the magnitude of losses from these risk factors is not straightforward. This is due to the constant change in electricity prices and fluctuations in the flow of wind energy, which introduces uncertainty in the calculation of the economic efficiency of WPP in the short- and long-term period of operation.

In order to reduce the impact of risks attributable to the second group on the performance of WPP, analysts apply forecasting methods that aim at determining the patterns of change and relationships between the main risk drivers.

1.4. Modern methods of increasing WT efficiency

The development of renewable energy sources should not be viewed in isolation, but as part of a wider energy transition process of a long-term change in the structure of energy systems. This process is characterized by the emergence of new technologies, equipment and other important changes, many of which enhance the “green” energy, increasing its chances of success.

One of such changes is the development of energy storage technologies. The emergence of commercially attractive technologies in this field will create conditions for more intensive use of renewable energy resources that are highly dependent on weather conditions and the time of day.

Electric energy storages are the most important element of future active adaptive networks [14], [15]. Electrical energy storage (EES) is one of the key technologies in the areas covered by the IEC. EES techniques have shown unique capabilities in coping with some critical characteristics of electricity, for example hourly variations in demand and price.

The prediction of wind energy generation in terms of time frames can be considered from different perspectives, depending on the intended use. Forecasts from milliseconds to several minutes ahead can be used for turbine-active monitoring. This type of forecast is usually referred to as very short-term forecasts.

Forecasts for 24–72 hours ahead are needed for power system management and energy trading. They can serve to determine the use of plant’s standard capacity (unit commitment) and to optimize the planning of these plants (economic dispatch). The energy proposals that will be delivered per day are usually required to be ready one day in advance. These forecasts are called short-term forecasts. The numerical weather prediction (NWP) model results can be obtained for a geographical point of the wind farm or for a grid of surrounding points. In the first case the models could be characterized as “advanced power curve models”, in the second case as a “statistical downscaling” model [16], [17].

The ability to forecast wind power production volumes allows manufacturers to participate in the process of selling energy on the exchange, where the price is formed based on supply and demand considerations. At the market of commodities, participants offer quantities of energy to be provided during the next day at a given price. This allows market participants to settle the trade of electricity for various periods, depending on the various offers.

Getting a favourable price for the energy produced is a prerequisite for improving the economic efficiency of WTs. Therefore, forecasting of power production as well as the use of EES devices are promising areas for improving competitiveness enhancing methods for wind power production.

Accurate and reliable prediction of wind speed and wind power plays an important role in solving various problems, which, among others, include the design of electricity markets, planning and development of wind power system, power generation scheduling and dispatch at the main grid to fulfil the power demand, power system stability and reliability, transmission capacity upgrades, etc. [20]

Thus, the results of research in the field of improving methods for predicting the production of wind energy can serve to further improve the efficiency of WTs and promote the use of this type of RES. At the same time, work on the assessment of wind energy resources should include the study of average long-term wind speed distribution covering relevant territories at an altitude of up to 200 m.

A significant number of publications in this area indicates that an active search is being conducted to find solutions to existing problems in this field [16], [19].

2. ECONOMIC AND OPERATIONAL RISKS IN WIND ENERGY PROJECTS IN LATVIA

2.1. Risks and Uncertainty Factors in the Design of Wind Power Projects

The study considers the problem of operational and economic uncertainty in wind energy projects in the absence of state subsidies and the conditions of a liquid, integrated and free electricity market.

The goal of the research is to create a practical basis for decision-making under uncertainty in wind energy projects based on publicly available electricity price data, producer provided technical characteristics of wind generator power curves and experimental wind speed measurements. The study is based on proprietary wind measurement data gathered in the north-western coastal part of Latvia at the range of altitudes of up to 50 m and daily electricity market prices from the Latvian segment of Nord Pool power market.

This analysis starts with a brief overview of the Latvian electricity generation market with an emphasis on wind energy. As the basis for the analysis, the study also presents an overview of existing modelling options currently used in forecasting. Following designated pre-testing procedures and model calibration on historical data, the study uses stochastic differential equations (SDE) for the out-of-sample forecasting of wind speed and electricity prices.

Pre-testing procedures suggest that mean reverting Vasicek model can be used for wind speed modelling, while electricity price development is better described by a mean reverting model with jump diffusion. Time series modelling is combined with Monte Carlo simulation technique in order to come-up with the distribution of revenue projections and efficiency estimates for a hypothetical wind park.

Subsequently, the author performs a sensitivity analysis of wind generator efficiency and revenue generation potential across a range of technical factors. A broad range of project development scenarios involving several wind generator types and multiple mast height options is considered.

The results of the study provide quantitative basis for optimal decision-making process at the planning stage of wind energy projects and highlight the importance of the initial choice of wind generator models.

The development of the Latvian electricity market has been affected by several major factors over the last ten years – tighter integration into the European energy network, market deregulation and increased state support of energy production from renewable energy sources (RES) following the EU directives.

Latvia deregulated its power market and joined the Nord Pool in 2013. The deregulation of electricity market implies that prices are determined by free competition rather than by the state. According to the latest legislative initiative, wind power electricity producers could get a right to sell electricity to the grid for the price of around 120 EUR/MWh during the first 10 years of operation and for 72 EUR/MWh during the subsequent 10 years. Such approach is in line with the EU Directive promoting the use of energy from renewable sources; however, it is in stark contradiction with the ongoing market deregulation efforts. In the given situation, RES producers are not incentivized to participate in the free electricity market in Latvia, because the subsidized tariff substantially exceeds market price.

Finally, it is important to note that subsidies that are not meant to support technologies at the early stages of their development cycle can be wasteful in the long run. Therefore, it is necessary to address the problem of high project risks without eliminating the aspect of the free market discipline. Operational uncertainty can be reduced through modelling efforts, more transparent technical data availability and access to long-term wind speed measurements at high altitudes.

2.2. The Use of Stochastic Models in Wind Energy Projects

As widely acknowledged by many practitioners and academics, the penetration of wind energy will be limited without advancements in forecasting methods applicable to wind speed, due to electricity network balancing difficulties associated with the volatility of this source of energy [21]–[24]. However, in order to progress in terms of wind power management it is essential to move away from point estimations in the direction of probabilistic forecasting.

Against this background, a comprehensive review of more than 380 papers on the topic of short-term forecasting of power generated by wind turbines conducted in the course of ANEMOS.plus and SafeWind projects co-funded by the EU was timely and essential [18], [25]. In the course of the review, the authors covered approaches that were widely spread already at the time of the study, namely persistence method (naïve predictor), physical approach and a range of statistical methods such as time series analysis and artificial neural networks (ANN).

Naïve predictor method is the model most frequently used as a benchmark for the performance evaluation of other forecasting models [26], [27]. In this model, the forecast for all times ahead is set to the value it has now. Physical approach refers primarily to NWP models and is based on the use of meteorological data such as wind speed and direction, pressure, terrain structure, etc. Statistical approaches include a wide range of ARMA models [28]–[30] and machine learning techniques involving neural networks [31]–[33] and support vector machines [34], [35].

Overall, wind power output projection is an intricate task that many researchers have concerned themselves with, proposing a wide set of approaches to address it. However, the choice of forecasting methods is greatly data, aim and location specific. The benefit of reducing uncertainty in power generation is relevant not only for the owners of RES installation, but also for transmission and distribution system operators charged with maintaining system stability.

This study is based on the daily average time series of electricity prices from the Latvian segment of Nord Pool power market and a set of high frequency observations of wind speed at the heights of up to 50 m, carried out in the northwestern part of Latvia – Irbene, Ventspils region. Daily electivity prices can be highly volatile and exhibit seasonality patterns, which implies that the times series should be de-seasonalized.

It is common that long-term data on wind measurements is scarce. In the cases when historical measurement data are available, the maximum height of observation towers is limited to 50–60 m, as the construction of higher masts is not practical for small-scale projects. However, in order to assess future revenue potential of a certain geographical location, coupled with wind turbine efficiency estimates, it is necessary to possess data on wind speed at the altitudes of up to 140 m. For the purpose of the current study, power law relationship between contemporary wind speed measurements and their height was used. Parameters of the power law function were estimated for the set of wind measures every 10 min and used to extrapolate wind speed values to altitudes of 80 m, 90 m, 100 m and 110 m.

2.3. The Assessment of Economic Efficiency of Wind Energy Projects

This section covers the approach used for the pre-testing procedure and outlines the implications of the time series analysis results for SDE modelling. Prior to modelling historical time series, it is necessary to determine their general statistical properties. Time series pre-testing procedures involve checking for fat tails of the PDF, for mean reversion and seasonal patterns.

In order to test the data for normality it is transformed by taking natural logarithm and then standard tests for normality, such as Kolmogorov–Smirnov and Jarque–Bera, are applied. The results of testing log wind speed data suggest that the null hypothesis of normality for extrapolated wind speed data at 100 m altitude cannot be rejected at 5 % significance level for the log wind speed data, while for log electricity prices the null hypothesis is rejected at 5 % by Jarque–Bera test.

Apart from testing the distributional characteristics of the data it necessary to test whether mean reversion properties are present in the times series. The results of formal tests for stationarity, such as Augmented Dickey–Fuller (ADF) and Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) [36] confirm that the hypothesis of stationarity of the time series cannot be rejected for both time series.

Overall conclusion from the pre-testing procedures with respect to log wind speed and log energy prices data is that the time series can be modelled as a stochastic mean reverting process with Gaussian diffusion using an Ornstein–Uhlenbeck (O–U) type process [37], [38] such as Vasicek model [39]. However, given that the electricity price data cannot be assumed to be normally distributed, the model of this time series also has to include jump diffusion elements [40]. On top of this, electricity price time series exhibit seasonal patterns that have to be removed prior to modelling.

As suggested by the pre-testing procedures, log wind speed time series can be modelled by an O–U stochastic processes with mean reverting drift and Gaussian diffusions. The process is stationary, Gaussian, and Markovian. Over time, the process tends to drift towards its long-term mean. The O–U process can be considered as the continuous-time analogue of the discrete-time AR(1) process. It can be calibrated to historical data by performing a linear regression between the state variables and their first difference.

Wind speed data can be modelled using a standard Vasicek model:

$$\log(S_t) = x_t, \tag{2.1}$$

$$\mathrm{d}x_t = \alpha(\theta - x_t)\mathrm{d}t + \sigma \mathrm{d}W_t, \tag{2.2}$$

where S_t – wind speed;

α – mean reversion speed (the rate of mean reversion $\alpha > 0$);

θ – mean reversion level (long-run mean or level);

σ – instantaneous volatility rate ($\sigma > 0$);

t – time period; and

$\mathrm{d}W_t$ – standard Wiener process (standard Brownian motion).

In comparison to the wind speed data, electricity prices have a prominent seasonal component that has to be considered prior to modelling. As suggested by Lucia and Schwartz [40], the deterministic seasonal trend of the electricity prices is modelled using a combination of trigonometric functions (see Equation (2.5)). First, the deterministic seasonality part is calibrated using OLS. Second, after the calibration, the seasonality is removed from the logarithm of the prices:

$$\log(P_t) = f(t) + x_t, \tag{2.3}$$

$$\mathrm{d}x_t = \alpha(\theta - x_t)\mathrm{d}t + \sigma \mathrm{d}W_t + J(\mu_J, \sigma_J)\mathrm{d}\Pi(\lambda), \tag{2.4}$$

$$f(t) = s_1 \sin(2\pi t) + s_2 \cos(2\pi t) + s_3 \sin(4\pi t) + s_4 \cos(4\pi t), \tag{2.5}$$

where P_t – spot electricity price;

t – annualized time factor;

s_i – constant parameters, i = 1, 2, 3, 4;

$\mathrm{d}\Pi(\lambda)$ – Poisson process with jump intensity λ; and

J_t – jump size with normally distributed mean μ_J and variance σ_J.

The model addresses the features of electricity prices time series: fat tails, mean reversion and seasonality. The logarithm of electricity price is modelled with two components:

- deterministic seasonal part $f(t)$ is modelled by trigonometric functions;
- stochastic part x_t is modelled by mean reverting diffusion process with jumps.

Electricity price model adds jumps to a mean reverting process, assuming Poisson jumps (at most one jump per day). Overall, the process in short time instants features extreme movements beyond the Gaussian statistics, and in the long run features mean reversion.

Vasicek model of log wind speed data can be calibrated to historical data by performing a linear OLS regression between log wind speed and the first difference. In order to calibrate the SDE model with jump diffusion part, it is necessary to discretize it while assuming a Bernoulli process for the jump evets. The result of model calibration is presented in Fig. 2.1 and Fig. 2.2.

The current study helps to address the uncertainty arising from volatile weather and market conditions, incorporating modelling of stochastic processes into technical limitations of operational efficiency associated with wind generator power curves. In order to map wind speed into power, it is straightforward to use manufacturer's power curve for each wind turbine as in Brown et al. [41]. In that respect, the author chose to consider three different generator models Nordex N54/1000, Siemens SWT-2.3-101 and Nordex N131/3000 in order to compare their hypothetical performance at the chosen location.

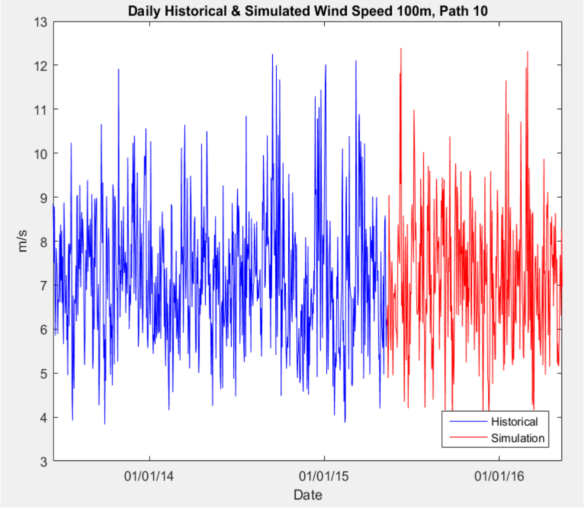

Fig. 2.1. Actual and simulated wind speed at 100 m altitude.

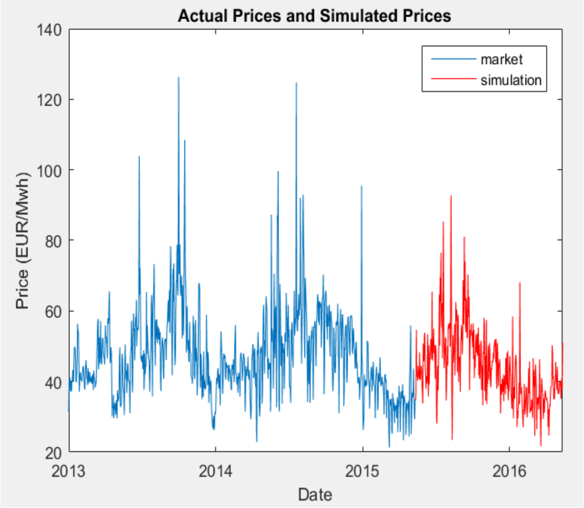

Fig. 2.2. Actual and simulated electricity prices.

The current study helps to address the uncertainty arising from volatile weather and market conditions, incorporating modelling of stochastic processes into technical limitations of operational efficiency associated with wind generator power curves. In order to map wind speed into power, it is straightforward to use manufacturer’s power curve for each wind turbine as in Brown et al. [41]. In that respect, the author chose to consider three different generator models Nordex N54/1000, Siemens SWT-2.3-101 and Nordex N131/3000 in order to compare their hypothetical performance at the chosen location.

The results of the modelling exercise and Monte Carlo simulation show that the operational efficiency is highly dependent on the type of generators chosen for the project and very sensitive to the height at which the generator is going to operate. The summary of the results for all three generator types is presented in Table 2.1.

Table 2.1

Out of Sample Forecasting Results for Three Types of Wind Generators

Height, m	**Type, WT**	**Revenue, EUR (mean)**	**Revenue, EUR (SD)**	**Efficiency, %**
80	Nordex N54/1000	47 445	3 085	12.5
90	Nordex N54/1000	62 050	3 727	16.0
	Siemens SWT-2.3-101	264 680	13 535	29.7
	Nordex N131/3000	432 010	21 071	37.2
100	Nordex N54/1000	78 868	4 486	20.4
	Siemens SWT-2.3-101	324 610	15 504	36.4
	Nordex N131/3000	514 580	22 547	44.3
110	Siemens SWT-2.3-101	387 210	17 456	43.5
	Nordex N131/3000	603 020	24 536	51.9

2.3. Conclusions

The study used historical daily data on electricity prices in the Latvian segment of the Nord Pool power market for the period of 2013−2015 in combination with long term wind speed measurements performed in Irbene, Latvia, at the altitude of up to 50 m. Extrapolation approach based on power law functional relationship between the wind speed and altitude was used to obtain the estimates of wind speed at higher altitudes.

In the course of the study, several SDE models were calibrated to historical data and used to forecast operational efficiency of three wind generator types, along with the resulting revenue distribution. The revenue forecast takes into consideration seasonal patterns and stochastic jumps in electricity prices.

Overall, the results of the study show that forecasted efficiency and revenue potential are highly dependent on the initial choices of the generator model and can range from 12 % for old, but still operational in Latvia, wind generators Nordex N54/1000 to 52 % for new Nordex N131/3000 model at high altitudes of operation.

The study showed that 2.3 MW Siemens generators SWT-2.3-101 installed at the largest Latvian wind farm, accounting for one third of wind energy capacity installed in Latvia, might not be optimal generator type for the Latvian conditions. The study suggests that a rigid and multifaceted sensitivity analysis based on physical wind measures and historical electricity market data should be conducted prior to project implementation.

3. REDUCING THE COSTS AND UNCERTAINTY OF WIND SPEED MEASUREMENTS

3.1. The Modelling of Wind Flow Interaction With a Triangular Lattice Mast

The starting point of any decision regarding the construction of a wind power generator is the evaluation of wind energy potential at the selected construction site. Therefore, at the start of any WPP project, a set of estimations is carried out in order to assess its future efficiency. The analysis is primarily based on the technical characteristics of wind turbines and average annual measurements of wind speed collected at the foreseen construction location of the WPP. The main tools for evaluating the potential performance of a future WPP are wind measurement complexes.

The stage of project planning plays an important role in ensuring that the construction site, height of the hub, and turbine type are chosen correctly. Altogether, the precision of wind speed measurements is the main factor determining the reliability of the economic feasibility studies and the precision of the break-even period estimation.

An important aspect of wind speed measurement implementation in wind projects is that the obtained results should refer to the height of WT axis. In order to satisfy this requirement it is necessary to place anemometers at the corresponding height and take measurements for the period of at least a year. In order to save time and resources in the deployment of new wind speed measurement masts it would be justified to use the existing network of cellular communication masts, as it minimizes the installation and assembly costs of the measurement equipment.

In order to avoid the measurement distorting effect of the surface, mast height should exceed 30 m [42]. At the same time, wind speed measurements have to be carried out in compliance with the requirements set by an international standard IEC [43].

In practice, efforts and costs associated with the task of wind speed measurement can be greatly reduced if existing communication masts are used to place the measuring sensors instead of erecting new masts dedicated solely to the purpose of wind measurements [45].

However, in that case it is necessary to consider the impact of the mast design elements on the distribution of airflow and confirm the possibility of using the existing mast for obtaining reliable wind speed data [46], [47].

This study investigates the relationship between the speed of wind flow and the size of the area in which the deviation of wind speed measurements from the actual values is greater than 1.0 %. Specifically, the author investigates how wind flow distribution around a cellular communication mast (CCM) depends on its sizes and design.

The results of the analysis obtained using CFD simulations and reported in [44] suggest that the boundary of the domain where the distortion of airflow speed does not exceed ±1.0 % is at a distance of 3.5 m, covering 320° area around the mast. At the same time, in the 40° sector the boundary of this domain is at a distance of up to 9.0 m. Overall, it means that in cases when CCMs are used for placing measurement sensors, compliance with the recommendations of the IEC standard for determining distance *R* does not guarantee that the measurements are performed with required precision.

In order to estimate the extent to which the structure of a lattice CCM affects the speed distribution of wind flow around it, we first consider the interaction of wind flow with a metrological mast with the side width 0.74 m. Fig. 3.1 shows a contour map of wind flow speed distribution around a lattice mast for wind speed $U = 10.0$ m/s and the angle of wind direction $\alpha = 0°$ relative to the triangular lattice mast.

The position of sensor S is fixed on the mast by a boom at a distance of 3.0 m relative to the triangular mast centre, to which one-metre-step concentric octagons are attached.

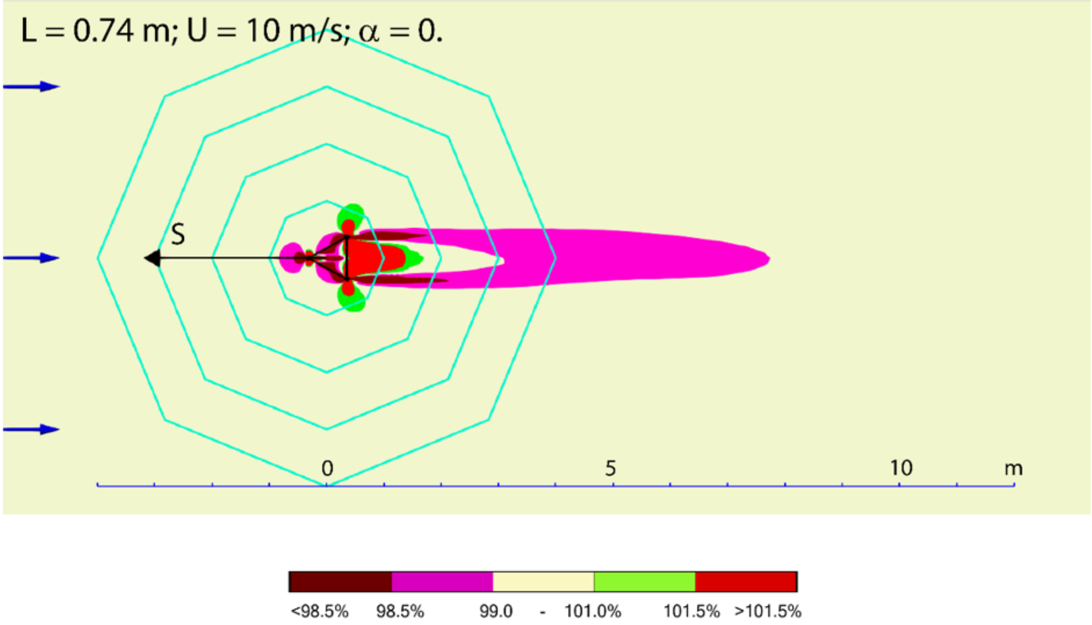

Fig. 3.1. CFD model of the wind flow interaction with a triangular lattice metrological mast, side width $L = 0.74$ m, at the wind speed $U = 10.0$ m/s and angle $\alpha = 0°$ relative to the position of a boom with sensor S.

In turn, Fig. 3.2 demonstrates the speed distribution of a wind flow around a lattice CCM with side width 0.74 m for wind speeds $U = 5.0$ m/s and $U = 10.0$ m/s and the angles of wind direction $\alpha = 0°$ and $\alpha = 180°$ relative to the position of a boom with sensor S.

Grey area in Fig. 3.1 andFig. 3.2 corresponds to 100 % ± 1 % of the undisturbed wind flow speed values. Green area corresponds to 101−101.5 %, red area to more than 101.5 %, while violet area corresponds to 98.5−99.0 % and brown area to less than 98.5 % of the undisturbed wind flow speed values. The contour maps show the wind flow speed that would satisfy the IEC standard requirements in grey, green and violet areas, while in the red and brown regions the deviations would exceed the allowed error margin.

The use of CFD models shows that the presence of cable lines inside a triangular lattice cellular communication mast slows down wind flow speed by more than 1.5 % and causes the appearance of a narrow tail with the length of 7.0–9.0 m and angular dimensions of less than

10°. Within the boundaries of the remaining 350° sector, the length of the region with wind speed distortions beyond ±1.5 % does not exceed 1.5–2.0 m from the mast centre.

CFD modelling results indicate that in order to perform wind measurements using a mast with side width $L = 0.74$ m and solidity $t = 0.35$ (i.e. complying with IEC standard [43]), it suffices to use a 2.0 m long boom. In this case, within the limits of 350° sector wind speed will be measured with deviation not greater than ±1.5 %.

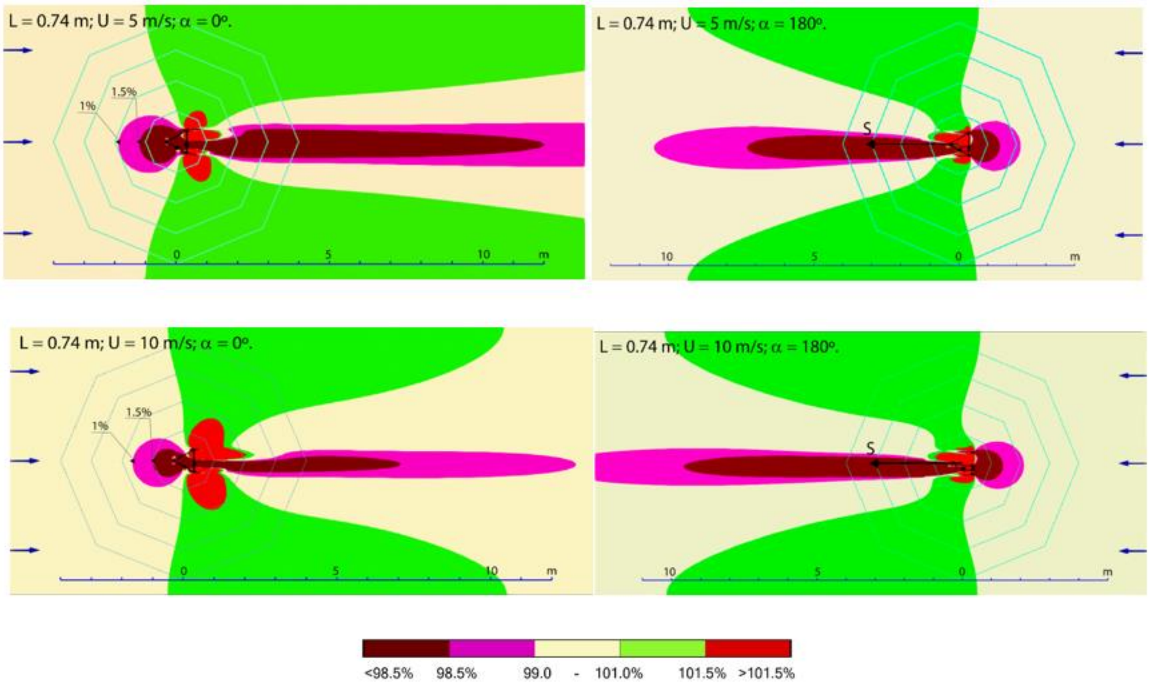

Fig. 3.2. CFD modelling results of the wind flow field around a triangular lattice CCM, side width $L = 0.74$ m, for wind speeds $U = 5$ m/s and $U = 10$ m/s and angles $\alpha = 0°$ and $\alpha = 180°$ relative to the position of a boom with sensor S.

However, within the sector of less than 10° for measurements with the same accuracy the sensor should be placed at a distance of 9.0 m from the mast centre. It would require considerable additional resource related to boom fastening at a longer distance from the centre in order to ensure that the IEC standard is followed also in the problematic 10° region. It is noteworthy to mention that in the considered case, the share of observations obtained from this sector amounts to 2.5 % of the total amount of measurements. The performed calculations make it possible to refine the results of other authors' studies indicating that the requirements of the IEC standard [43] regarding the length of the boom are overestimated. At the same time, the simulation results allow to conclude that the standard does not guarantee the measurement accuracy of 100.0 % ± 1.0 % in the shadow area of the mast ($\alpha = 180°$).

Such method of wind speed measurements would allow considerably lowering the requirement with respect to the minimum boom length. The relaxation of the requirements would result in much easier sensor installation process of sensors on measurement masts.

It is noteworthy, that the use of paired sensors for wind measurements creates an opportunity to employ the existing network of triangular lattice CCM. That considerably lowers the costs of data collection necessary for performing the assessment of wind energy resource potential.

3.2. The Use of Lattice CCM for Wind Shear Assessment

For wind energy resource assessment on the shores of the Baltic Sea, a program of physical experimental studies was developed, which involves the use of three 100 m CCMs to carry the measuring sensors of the Symphonie PLUS3 wind measuring complex.

The experimental site locations of the three masts were selected on the shore of the Baltic Sea in Ventspils, Pāvilosta and Ainaži regions. The location of the masts are at Site 1 – Staļdzene, Ventspils, Site 2 – Tebra, Pāvilosta, and Site 3 – Rozēni, Ainaži. For the estimation of influence of a lattice mast structure on the airflow, a method of physical measurement of wind speed using cup anemometers installed around the mast at an angle of 120° at four levels was used.

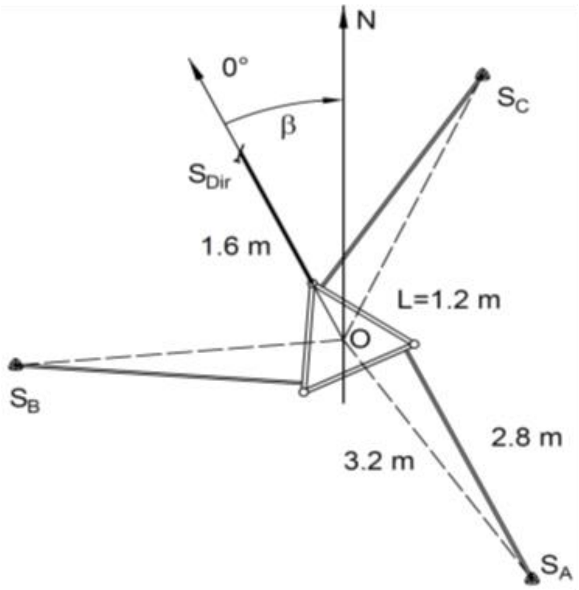

Fig. 3.3. The vector diagram of the arrangement of a wind direction sensor S_{Dir} on a 1.6 m boom with an angle of offset β with respect to the northward vector N and anemometers S_A, S_B, S_C on 2.8 m long booms that are located at a 3.2 m distance from the centre O of the triangular CCM with a side length $L = 1.2$ m.

The layout of cup anemometers and wind direction sensors installation at the height of 40 m is shown in Fig. 3.3. On this vector diagram the arrangement of a wind direction sensor S_{Dir} on a 1.6 m boom with an angle of offset β with respect to the northward vector N and anemometers S_A, S_B, S_C on 2.8 m long booms are displayed. Given that an anemometer is installed on a 2.8 m long boom, its distance from the mast centre O with a mast side width $L = 1.2$ m is 3.2 m.

3.3. The Analysis of Measurement Results

The practical implementation of the project related to the wind speed measurements using CCM made it possible to assess the technical and economic issues that should be solved in order to implement such type of studies. Summarizing the financial costs of the conducted experiments allows concluding that in specific cases for each site the cost of performing wind speed measurements at four levels during the year may be by an order of magnitude lower than the costs needed for erecting and decommissioning a generic 100 m metrological mast.

In a related study [48], where the results of airflow modelling around a triangular lattice mast are discussed, it can be seen that when measuring wind speed using two or three sensors with offset by 120° from each other, at each moment only one sensor can be in the shadow of the mast. Therefore, if the calculations of average wind speed from the database excluded measurements made by the sensor located in the shadow of the mast, it would be possible to increase the reliability of the result of calculations.

According to the analysis of the results of 10 min measurements for two sensors located at the same height, it can be assumed that the ratio of their values should characterize the deviation of the airflow velocity in the corresponding sector around the mast. Therefore, the results of wind speed measurements of all sensors were grouped by time of measurement and in the direction from 0° to 360° with the steps of 1°.

The results of simultaneous wind speed measurements by two anemometers installed at the same height with 120° displacement makes it possible to estimate the degree of wind flow distortion caused by the mast structure. For the quantitative evaluation of the average value of wind flow distortion indicator, the equation of relative wind speed can be used:

$$V_{w\_\mathrm{avg}} = \frac{1}{n} \sum_{k=0}^{n} \left({V_{\mathrm{A}_k}}/{V_{\mathrm{B}_k}} \right) = \frac{1}{n} \sum_{k=0}^{n} V_{w_k}, \qquad (3.1)$$

where V_{A_k} and V_{B_k} are simultaneous 10-min wind speed measurements, for sensors S_A and S_B, at the same height; and $k = 1, 2, ..., n$ is the number of wind measurement step, where n is the total size of the sample.

The ratios calculated using Equation (3.1) for sensors S_A and S_B and sensors S_A and S_C in relationship to the angle of wind direction, averaged in steps of one degree for Staļdzene site at the Levels 1−4, corresponding to the heights 12.4 m, 40.4 m, 61.4 m and 83.9 m above the ground, in relationship to the angle of wind direction are shown in Fig. 3.4.

A characteristic feature of these curves are peaks corresponding to the wind direction angles 105° and 225° with respect to the angle 0° of the direction sensor S_{Dir}. The results of long-term wind speed measurements, performed simultaneously by three anemometers S_A, S_B, and S_C, at the height of 40.4 m at site 1 for 24 hours period, are shown in Fig. 3.5.

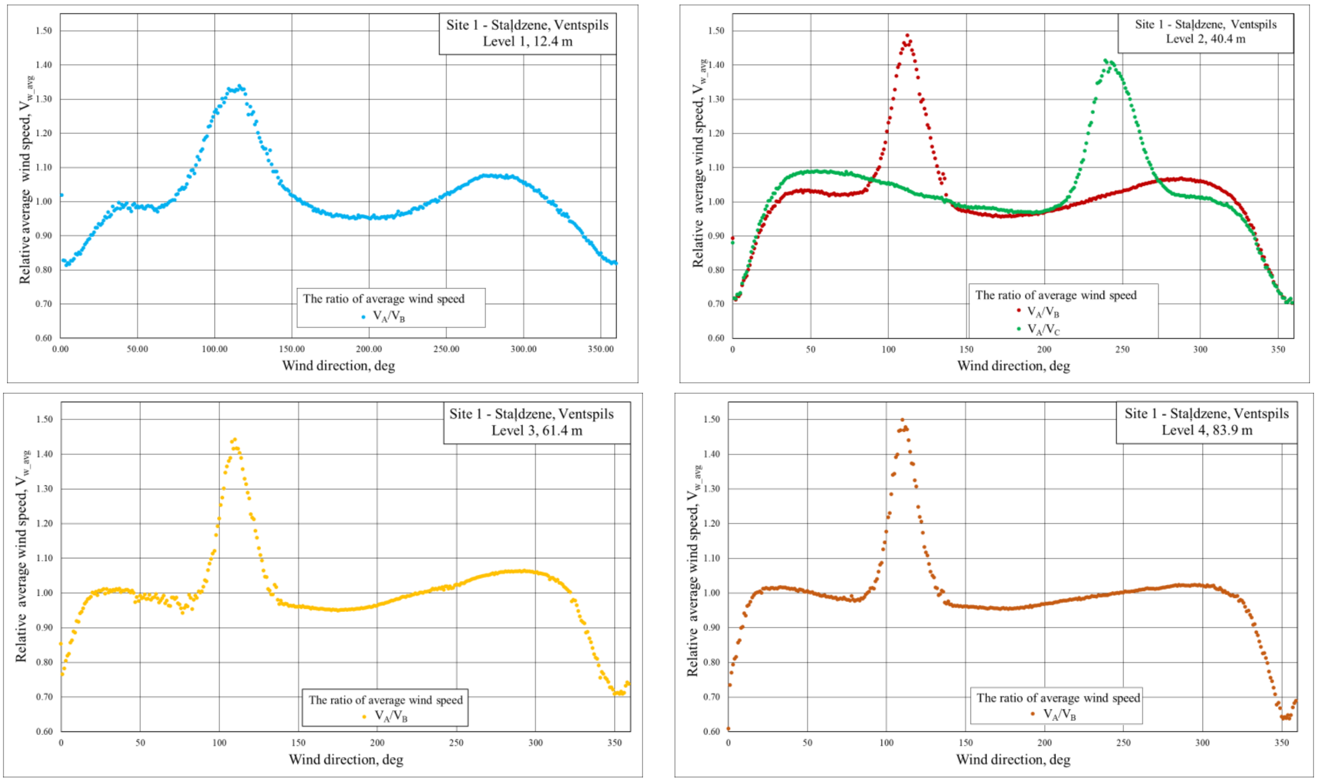

Fig. 3.4. Relative average wind speed V_{w_avg} from sensors S_A, S_B and S_C installed on the CCM with side length 1.2 m in Ventspils site at Levels 1–4 in relationship to the angle of wind direction.

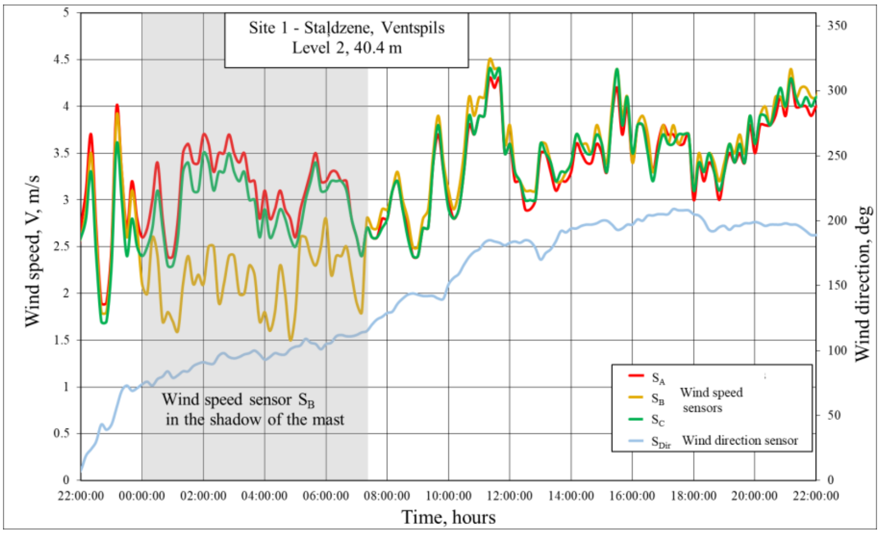

Fig. 3.5. Average wind speed data with 10 min increments from anemometers S_A, S_B, S_C and wind direction from sensor S_{Dir}. The grey area indicates the period when sensor S_B was in the shadow, which corresponds to the wind direction 75–115°.

In Fig. 3.5., the time period highlighted in grey corresponds to the weather conditions when sensors S_A, and S_C, were open to the flow of wind, while sensor S_B, was located in the shadow area created by the mast structure. It is noteworthy that the figure also illustrates that the results of wind speed measurements during this period differ by ~2.0 times.

Comparing the wind speed and wind direction sensor curves, it can be seen that the shadow area corresponds to the direction of 75–115°. Thus, the extent of the effect of the mast on the measuring sensors can be represented as a vector diagram in Fig. 3.6, which shows the wind flows with directions 106°, –14° and –124°, as well as the respective shadow areas behind the mast of sensors S_A, S_B, S_C.

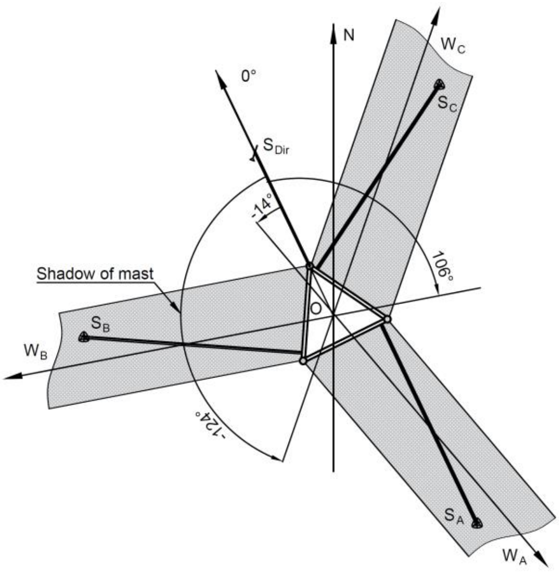

Fig. 3.6. The vector diagram of wind flows W_A, W_B, W_C and their shadows of sensors S_A, S_B, S_C.

It means that in order to measure wind speed in accordance with the requirements of the standard, two sensors offset by an angle of at least 120° must be used and the results of measurements should be related to the direction of the wind flow. In this case, the measured values of wind speed, which are obtained in the area shaded from the wind, must be excluded from calculations.

The comparison of the wind speed measurement results shows that, as a result of the correction, the average speed at all heights increased by ~1.9–3.9 %. Since distorted values were excluded from the calculations, this means that the reliability of the measurement results has increased by a similar amount.

Based on the wind speed measurements for the measurement period from 01.2018 to 01.2019, wind shear models for Ventspils, Pāvilosta and Ainaži sites, which are shown in Fig. 3.7 were calculated. In order to extrapolate the measured wind speed values, the power law function is used, which approximates the mean wind speed values with a sufficiently high index of R^2 [63]. Obtained wind speed values are well approximated by Equation (3.2).

$$V_{\text{avg}} = V_{\text{avg\_}H}\left(\frac{h}{H}\right)^{\alpha} = \frac{V_{\text{avg\_}H}}{H^{\alpha}}h^{\alpha} = \gamma h^{\alpha}, \text{ m/s,} \tag{3.2}$$

where V_{avg} – average wind speed at height h, m;

H – the height of wind speed measurement, m;

h – the estimation height, m;

$V_{\text{avg\_}H}$ – the average wind speed, measured at height H, m/s;

γ equal to: 0.638, 0.561 – for Sites 1, 2, and 1.05 – for Site 3; and

α – app. coefficient equal to: 0.52; 0.513; 0.364, corresponding to Sites 1, 2 and 3.

The diagram shows the models of average wind speed V_{avg} with relationship to the height calculated from raw measurements and corrected data. In this case, the wind shear model does not take into account the roughness of the terrain, the properties of which can be seen in Fig. 3.7.

It is worth comparing the wind share curves obtained as a result of the simultaneous measurements of wind speed at three sites on the shores of the Baltic Sea. It can be seen that the parameters γ and α in Equation (3.2) of power law function for Sites 1 and 2 have similar values and the curves have similar shape. However, for Site 3, the curve of the wind shear differs in the nature of the slope and has an intersection with the curves for Sites 1, 2, reflecting different wind conditions in northern Latvian coast compared to southwestern Latvian coast.

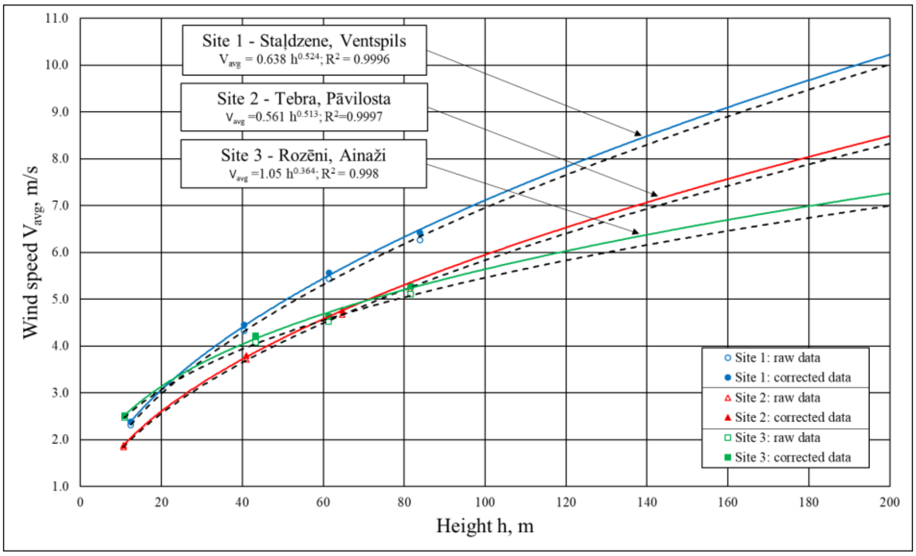

Fig. 3.7. Wind shear models for average wind speed V_{avg} for Ventspils, Pāvilosta and Ainaži sites, calculated using raw measurements (dashed lines) and corrected data (solid lines), for the period 01.2018–01.2019.

3.4. Conclusions

The implementation of IEC standards [53] for calculating the boom length does not guarantee the accuracy of the wind speed measurement 100 % ± 1 % in the shadow area of the mast, whereas in all other directions the boom length is overestimated.

Based on the analysis of the contour maps of wind flux interaction with a triangular lattice CCM obtained using CFD modelling, it can be concluded that these masts can be used to measure the wind speed with the accuracy that meets the requirements of IEC regulations in case two sensors placed in anti-phase are used for that purpose.

In order to make wind speed measurements compliant with the requirements of IEC standards, using typical lattice CCM with side width of 1.2 m and 1.4 m and a height up to

100 m, anemometers should be located at a distance of at least 3.2 m from the centre of the mast.

The use of measurement results from two anemometers, located with offset angle at least 120°, allows identifying the wind speed measurements made in the mast shadow area. Furthermore, the data comparison method provides objective grounds for excluding these values from calculations, thus improving the accuracy of wind speed measurements.

The reliability of the estimations of average wind speed increases after the exclusion of distorted measurements from the calculations. Subject to such correction, the speed values at all heights increased by ~1.9–3.9 % on average.

4. THE ASSESSMENT OF WIND ENERGY POTENTIAL IN LATVIA

4.1. Wind Energy Resource Spatial Distribution Modelling

This research is based on data obtained using certified measuring sensors installed at meteorological observation stations belonging to LEGMC. The results of physical measurements are recorded as discrete values of wind speed with 1 min increments from 22 observation stations at 10 m height above the ground, over a period from 01.01.2015. to 31.12.2016.

For the analysis of wind speed distribution the most often used approximation is Weibull probability density function. This function is considered to be a good approximation of the wind speed frequency distribution and is described by the following equation:

$$F(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \quad \text{for } V > 0, \tag{4.1}$$

where c is scale factor;

k is shape factor; and

V is wind speed, m/s.

Parameters c and k of the Weibull wind speed frequency distribution functions [49] for 22 stations were estimated using the maximum likelihood method. The maximum likelihood estimator was derived by maximizing the likelihood function [44] and was estimated using functions from the R package MASS [50].

The uniform distribution of observation stations on the territory of the country and a long measurement period allow us to present the results as a visual model in Fig. 4.1. The colour palette used in the model allows identifying areas in the territory of Latvia with the same level of wind speed. In this case, the spatial distribution of the average value of the wind speed V_{avg} is depicted in steps of 0.5 m/s. The value of the average wind speed for the measurement period at the measurement points was calculated as follows:

$$V_{\text{avg}} = \frac{1}{n}\sum_{i=1}^{n} V_i, \tag{4.2}$$

where V_i is the average wind speed with 1 min increments, m/s;

n is the number of measurements for the observation period from 01.01.2015 to 31.12.2016; and

i is observation 1, 2, 3, …, n.

In order to estimate the value of the meteorological parameter between the observation stations, a spatial interpolation of measured data was used and a geostatistical method – universal kriging – was applied [51], [52].

Apart from the observed values from the nearest stations, this method also uses additional spatial factors that influence meteorological parameters. The most relevant factors for average wind speed interpolation are geographical coordinates in metric system LKS-92, elevation above the sea level and distance from the Baltic Sea or the Gulf of Riga. Spatial interpolation is performed on a grid with a resolution of 1 km × 1 km.

Modern weather modelling techniques allow predicting the magnitude of wind speed above the surface of land and sea. For example, climatological reanalysis dataset ERA5, created by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides information for a variety of meteorological parameters. ERA5 covers the Earth with a 31 km grid and stratifies the atmosphere into 137 levels from the surface up to the height of 80 km. The first 7-year segment of the ERA5 dataset is now available for public use [53].

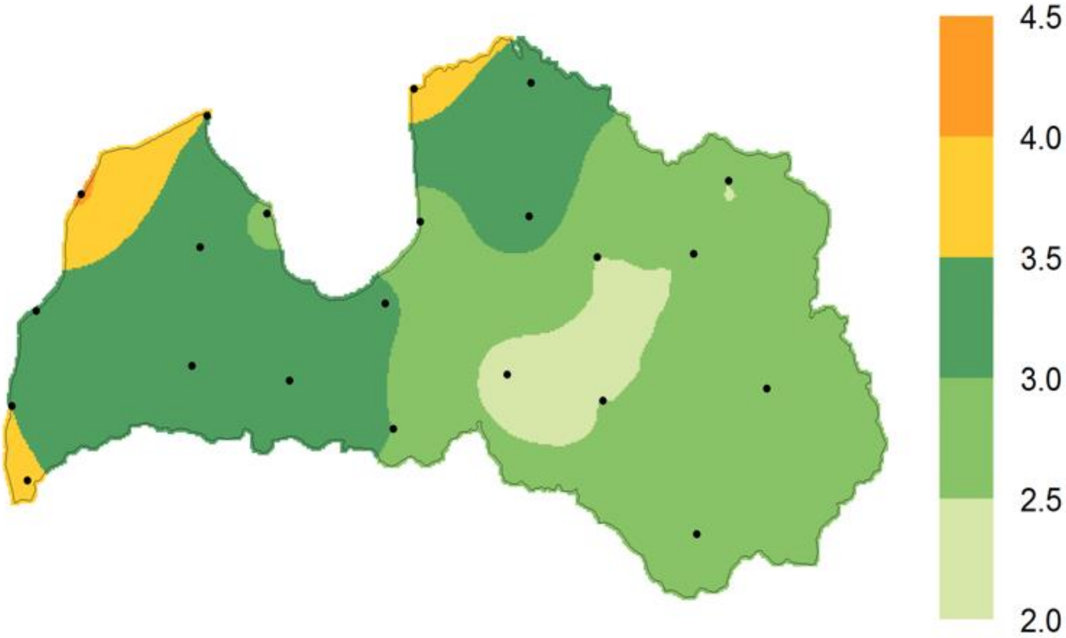

Fig. 4.1. Model of the spatial distribution of average values of wind speed V_{avg} m/s at an altitude of 10 m above the ground on the territory of Latvia.

Comparative analysis shows that the results of ERA5 simulation consistently exceed the measured historical values in all regions by ~20–50 %. It is likely that ERA5 modelling results are strongly influenced by the structure of the terrain.

4.2. Wind Energy Assessment Methods

In Latvia, systematic long-term measurements of the wind speed that also take into account its height distribution are being carried out since 2007 at two sites on the northwestern shore of the Baltic Sea in Ventspils region and on the north of the country in Matīš village, near the Burtnieku lake (35 km from the seashore) [54], [55].

At the Matīš site, the on-site measurements of wind speed were carried out using certified sensors for wind speed and sensors indicating the direction of air streams. In order to collect the wind data, measurement sensors were mounted at several levels on a 60 m high metallic mast [56].

The distribution of Weibull parameters (k – shape factor and c – scale factor) as a function of height is well approximated by the power law curves [57]. The expressions for c and k based on the wind speed measurement results at the Matīš site using power law approximation are as follows:

$$\mathrm{c} = c_H \left(\frac{h}{H}\right)^{\alpha_c}, \tag{4.3}$$

$$k = k_H \left(\frac{h}{H}\right)^{\alpha_k}, \tag{4.4}$$

where c_H, k_H are the values of the Weibull's distribution coefficients calculated for the reference height H;

h is the rotor hub height, m; and

α_c, α_k are the values of approximation coefficients.

The modelling of c and k parameters of Weibull distribution as a function of height h using Equations (4.5) and (4.6) allows the extrapolation of their values to the heights up to 150 m, where the mentioned relationship is expected to hold. The results of wind speed measurements allow to calibrate parameters c and k in Equations (4.3) and (4.4) for the Matīši site:

$$c = c_H \left(\frac{h}{H}\right)^{0.359} = \frac{c_H}{H^{0.359}} \cdot h^{0.359} = 1.205h^{0.359}\,, \tag{4.5}$$

$$k = k_H \left(\frac{h}{\mathrm{H}}\right)^{0.226} = \frac{k_H}{H^{0.226}} \cdot h^{0.226} = 0.937h^{0.226}. \tag{4.6}$$

The proposed approach proved information on the wind speed frequency distribution at any point in the country and enables the calculation of the AEP by generators, making it possible to estimate the efficiency of WT.

4.3. Wind Energy Potential Assessment Models

The scale parameter values (see Fig. 4.2), which stretch or shrink the distribution, are decreasing with the distance from the sea, indicating that coastal stations have wider probability density functions. The spatial distribution of the shape parameter values (see Fig. 4.3) is influenced by topography as the lowest values are observed in the highlands. Overall, the shape parameter values vary from 1.6 to 2.1, indicating that the density function has a positively skewed bell shape.

The estimates of parameters c and k presented in the form of contour maps allows estimating the frequency characteristics of the wind speed distribution for any point on the territory of Latvia at the height of 10 m above the ground using Equation (4.1). This greatly simplifies the assessment of the amount of wind energy that can be produced when choosing the location for a small wind turbine generator (SWTG) installation.

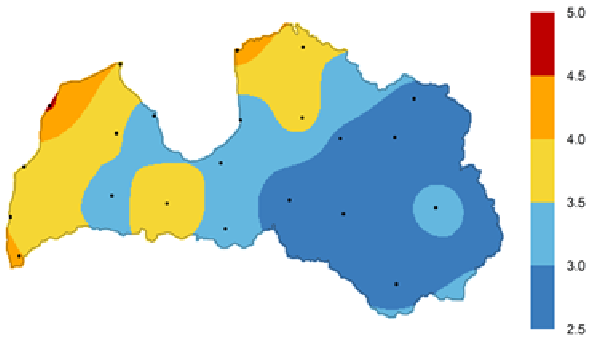

Fig. 4.2. Model of the spatial distribution of the scale parameter *c* of Weibull wind speed probability density at the height of 10 m above the ground.

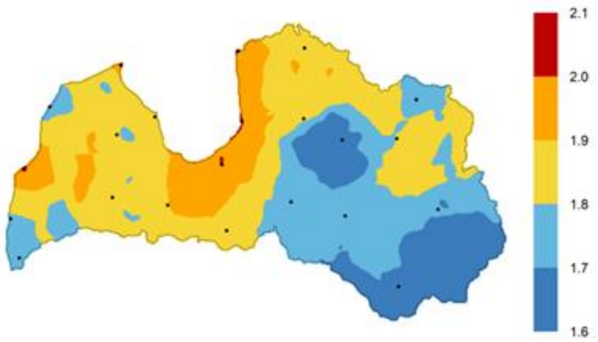

Fig. 4.3. Model of the spatial distribution of the shape parameter *k* of Weibull wind speed probability density at the height of 10 m above the ground.

Due to the cyclical nature of the wind and nonlinear relationship between wind speed and energy it carries, it is not possible to perform an assessment of the wind energy potential based on Equation (4.2). In order to perform a more accurate assessment, it is necessary to take into account the frequency distribution function from Equation (4.1). In this case, the value of the average energy density that the airflow carries over an area of 1 m^2 is calculated from [47]:

$$P_{\text{avg}} = \frac{1}{2}\rho V_{\text{avg.cub}}^3, \tag{4.7}$$

where ρ is air density (1.23 kg/m^3 for standard condition at the sea level and temperature 15 °C); and

$V_{\text{avg.cub}}$ is average cubic wind speed, m/s.

Average cubic wind speed can be calculated either based on actual wind speed measurements according to Equation (4.8) or using the frequency of wind speed occurrence obtained in accordance with Weibull distribution function following Equation (4.9).

$$V_{\text{avg.cub}} = \sqrt[3]{\frac{1}{n}\sum_{i=1}^{n} V_i^3}, \tag{4.8}$$

where V_i is average wind speed for 1 min measurement interval, m/s;

n is the number of measurements for the entire measurement period; and

i is the number of a measurement interval 1, 2, 3, …, *n*.

$$V_{\text{avg.cub}} = \sqrt[3]{\frac{1}{100}\sum_{i=1}^{n} V_i^3 F(V_i)}, \tag{4.9}$$

where V_i is wind speed in bin *i*, m/s;

$F(V_i)$ is Weibull cumulative distribution function for wind speed V_i, %; and

i is the number of bins with 1 m/s interval, 1, 2, 3, …, *n*.

As can be seen from Equation (4.7), the amount of energy that the wind carries is proportional to the value of the average cubic wind speed (Equations (4.8) and (4.9)). At the same time, the division of the territory of Latvia into five regions according to the level of the average cubic wind speed makes it possible to make an estimate of the resource of wind energy that these regions have.

Assuming that the maximum value of the average energy density, which the wind carries on the shore of the Baltic Sea, is taken as 1.0, then the values of the average energy density in relative units for each station will be determined by Equation (4.10):

$$P^{*}{}_{\mathrm{avg}.i} = {V^{3}_{\mathrm{avg.cub}.i}}\Big/{V^{3}_{\mathrm{avg.cub.max}}}, \tag{4.10}$$

where $V_{\mathrm{avg.cub.max}}$ is average cubic wind speed at Ventspils station;

$V_{\mathrm{avg.cub}.i}$ is average cubic velocity at each of the 22 stations; and

i is observation station 1, 2, 3, …, 22.

By interpolating the obtained values, it is possible to create a map of the spatial distribution of the average density of wind energy $P^{*}{}_{\mathrm{avg}.i}$ on the territory of Latvia in relative units, which is shown in Fig. 4.4.

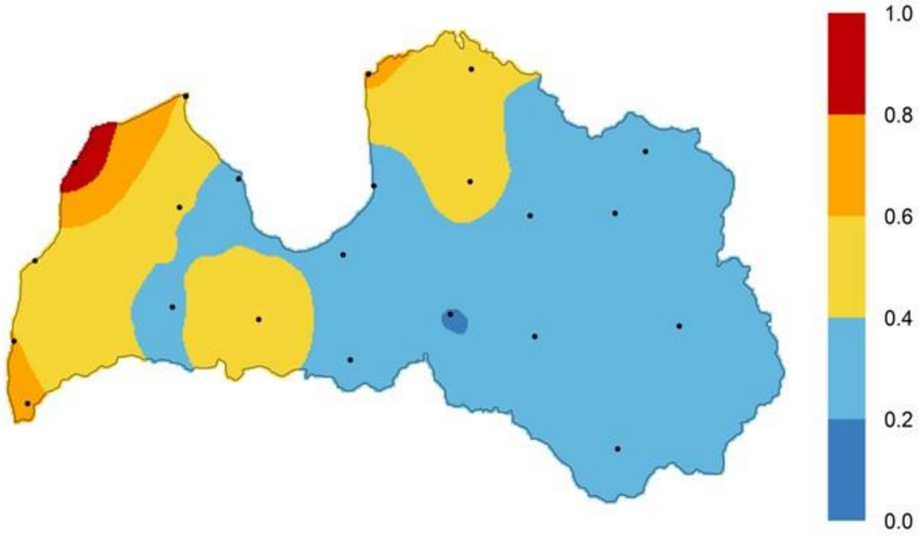

Fig. 4.4. Model of the spatial distribution of the average wind energy density in relative units $P^{*}{}_{\mathrm{avg}}$ at the height of 10 m above the ground in the territory of Latvia.

The values obtained using Equations (4.2), (4.7), and (4.10) and the values of the parameters of the Weibull wind speed frequency distribution function, calculated on the basis of measurements at the meteorological observation station in Ainaži, Daugavpils, Priekuļi, Saldus and Ventspils for the measurement period from 01.01.2015. to 31.12.2016.

4.4. Forecasting the Efficiency of SWTG

The study presents the results of the analysis of the efficiency of using low-power wind generators. A distinctive feature of these generators is that they are designed to transform the energy that wind carries at an altitude of 10–25 m above the ground. In most cases, SWTGs are used to power an autonomous load or serve as a backup power source in a private farm, the operation of which does not depend on the power grid.

The author proposes to use historical records of long-term measurements of wind speeds that are available in the archives of the National Meteorological Observation Service for forecasting the efficiency of low-power wind generators. The study of the SWTG performance was carried out using the power curves of two types of SWTG: Horizontal Axis WTs (HAWT) with rated power 0.75 kW, 2.5 kW, 5.0 kW, 20.0 kW and Vertical Axis WTs (VAWT) 0.75 kW, 2.5 kW, 6.0 kW.

The main technical and design characteristics of the SWTG wind power converters is in line with the models presented in the Catalogue of European Urban Wind Turbine Manufacturers [56].

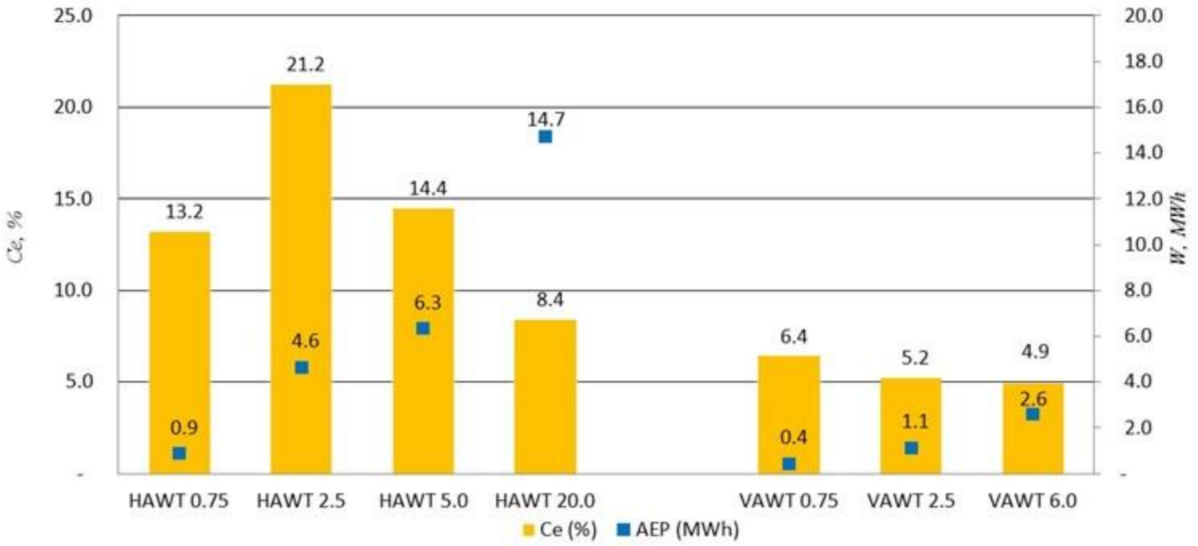

Fig. 4.5. Forecasted values of capacity factor C_e and AEP for HAWT converters with rated power 0.75 kW, 2.5 kW, 5.0 kW, 20.0 kW and VAWT Darrieus H-type 0.75 kW, 2.5 kW, 6.0 kW for Ventspils site.

The efficiency of a wind converter depends on the aerodynamic properties of the wind turbine and the wind type prevailing in the region. Therefore, it is of interest to evaluate the advantages of using both convector types in the specific conditions of the Latvian landscape.

The summary of the estimates of capacity factor C_e for wind converters of HAWT and VAWT type in Ventspils region are presented in Fig. 4.5. The comparison shows that regardless of the type, the efficiency of the wind turbine operation decreases with increasing converter rated power.

The results of the study suggest that the SWTG wind power converters of HAWT type, mounted on a mast with the height of at least 10 m above the ground, are more suitable for operating in the conditions of Latvia compared to VAWT type generators.

The efficiency of wind energy converters in the territory of Latvia can be represented as a model of the spatial distribution of the capacity factor C_e in relative units. Taking the maximum value of the capacity factor $C_{\text{e\_max}}$ to serve as the basis, relative capacity factor $C^*_{\text{e\_}i}$ for each meteorological observation station can be determined from Equation (4.11):

$$C^*_{\text{e\_}i} = {C_{\text{e\_}i}}/{C_{\text{e\_max}}}, \tag{4.11}$$

where $C_{\text{e\_max}}$ is value of the capacity factor corresponding to the performance of HAWT 2.5 kW wind power converter for the type of wind observed at the Ventspils station; and

$C_{\text{e\_}i}$ is value of the capacity factor corresponding to the efficiency of the HAWT 2.5 kW wind type converter for the wind type at each of the 22 stations.

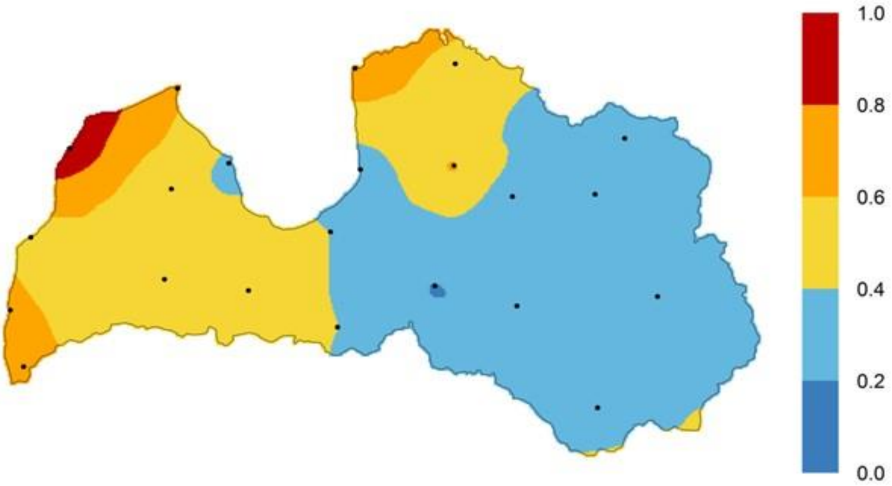

Fig. 4.6. Model of the spatial distribution of relative capacity factor C^*_{e} for HAWT type generator with rated power 2.5 kW at the height of 10 m above the ground.

The developed model of the spatial distribution of factor $C^*{}_{\text{e}}$ in relative units is presented in the form of a colour contour map in Fig. 4.6. The figure identifies areas within which HAWT 2.5 kW is expected to work with the certain level of efficiency relative to the one projected for the Ventspils region. Thus, the results of the presented study can serve as a tool for estimating and forecasting the feasibility of the commercial use of small wind energy converters at an altitude of 10 m in the territory of Latvia. In this case, the maximum value of the capacity factor corresponds to the SWTG of HAWT type with rated power 2.5 kW operating in the meteorological conditions observed at the Ventspils observation station.

4.5. The Assessment of WT Efficiency in Latvia Under Low-Wind Conditions

Depending on the wind speed and the magnitude of the turbulence, an international standard defines three wind classes [57], [58]. However, turbine wind class is just one of the factors that needs to be considered during the complex process of the WPP design. Wind classes determine which turbine is suitable for the typical wind conditions of a particular site.

They are mainly defined by the average annual wind speed (measured at the turbine's hub height), the speed of extreme gusts that could occur over 50 years, and how much turbulence there is at the wind site.

The results of the wind shear studies show that Latvia is characterized by low wind speed streams. In order to estimate the AEP of a set of chosen WT types, the author uses wind speed frequency distribution function $F(V)$ for the heights corresponding to the rotor hubs approximated by power law models in combination with power curves $P(V)$ of the generators.

In order to compare the performance of WT in terms of the AEP at different heights under Latvian conditions, five WT generators from the leading European turbine designers were chosen. These turbines are designed to operate in wind class conditions II and III.

The theoretical maximum power output is assumed to be the amount of energy that can be obtained from a generator during 8760 hours of its uninterrupted operation with the rated power P_{R} (*kW)*. The efficiency % of a particular WT can be expressed as:

$$C_{\mathrm{e}} = \frac{W}{P_{\mathrm{R}} \cdot 8760} 100, \qquad (4.12)$$

where W is the amount of energy (kW/h) produced in 1 year period.

The calculation results of forecasted efficiency C_{e}, % for the considered WTs are summarized in Fig. 4.7.

The analysis of the results shows that Vestas V136-3.45 and Nordex N131/3000, whose power curves correspond to wind class III, have the highest estimated efficiency among the considered WT types. Vestas V136-3.45 with hub height 132 m could achieve maximum efficiency equal to 39 %. The efficiency of Nordex N131/3000 with height 131 m could reach 37 %. For the Enercon E101 and Siemens SWT-3.2-113, SWT-2.3-108 WTs, which are designed for wind class II, values of efficiency coefficient would not exceed 32 % for hub height 142 m and only 23 % for 90 m.

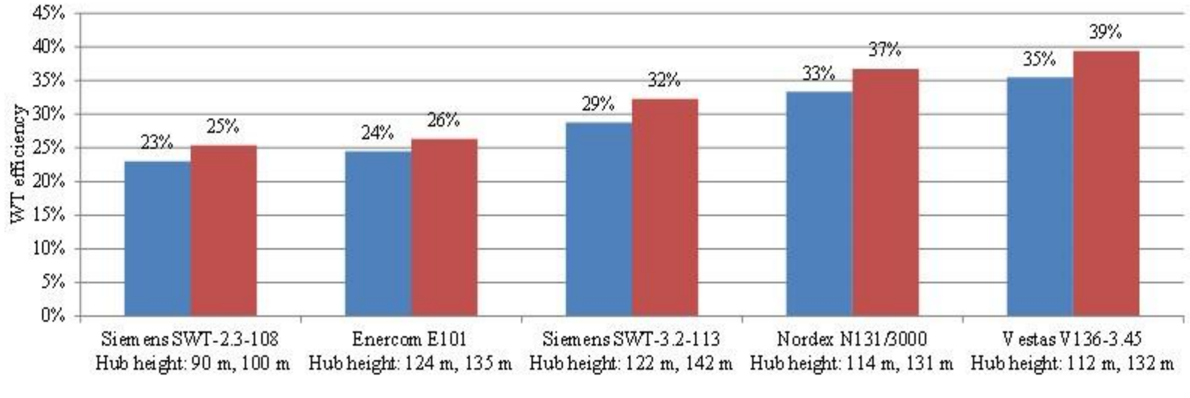

Fig. 4.7. Forecasted efficiency C_{e}, %, for Nordex N131/3000, Enercon E101, Vestas V136-3.45 and Siemens SWT-3.2-113, SWT-2.3-108 WTs for different heights of rotor hubs (height in meters) performing under the low-wind conditions in Latvia.

The study results suggest that in Latvia WT of wind class III should be used for wind power parks as their power curve is specially tailored to operate in low-wind conditions.

4.6. Conclusions

The study presented the spatial distribution models of average wind speed, parameters of Weibull wind speed distribution, relative wind energy density and operational efficiency of SWTG at the height of 10 m above the ground. The spatial models were presented in the form of colour contour maps. The visual representation of the distribution of wind energy resource makes it possible to estimate the efficiency of wind generators on the entire territory of Latvia. Thus, the developed models of the spatial distribution of wind speed and wind energy can serve as a practical tool and reference material for analysing the prospects of using wind generators in various regions of Latvia and assessing the possibility of commercial use of wind energy at a height of 10 m.

The results of the comparison suggest that HAWT type generators with rated power 2.5 kW tend to perform better than other considered wind energy converters under Latvian meteorological conditions in terms of efficiency. The results of the study can serve as a tool for forecasting AEP and estimating the feasibility of the commercial use of wind energy at the height of 10 m in the territory of Latvia.

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