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Learning Rates in Wind Energy: Cross-country Analysis and Policy Applications for Russia

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ABSTRACT

This article performs a meta-analysis of data on learning rates in wind energy, obtained from building single- and dual-factor learning curve models detailed by countries and technology development periods. It reveals a significant difference in learning rates mainly due to design and efficiency of government support programs. Multiple case studies were performed in order to interpret these results. This study proves that the maximal learning rate in wind energy can be achieved by financial support of R&D on the early stage of technological development and by attracting large manufacturers of wind turbines and other electric generation equipment on later stages. Given the fact that wind equipment manufacturing technologies are currently well developed and the global market of wind turbines is highly competitive, the tactic of obtaining technologies in exchange for access to the domestic market may prove successful even with a small domestic market capacity.

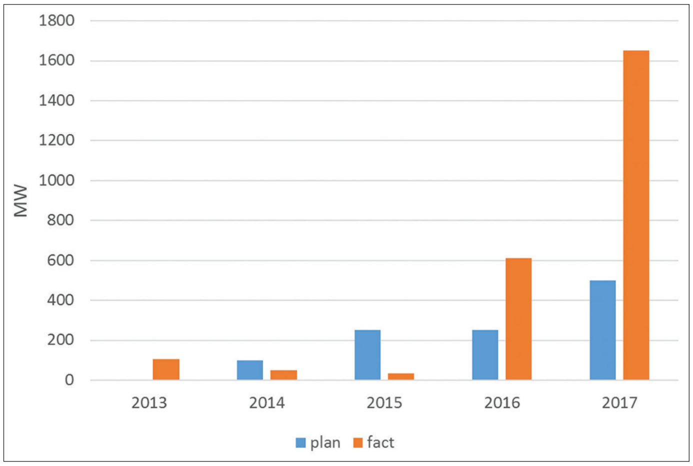
Keywords: Wind Energy, Learning Curves, Power Engineering, Economic Analysis
JEL Classifications: O33, Q42, Q47, Q48

1. INTRODUCTION

To date, Russia has one of the "greenest" fuel and electricity balances among all major industrial countries. More than half of domestic energy consumption in Russia is natural gas, the cleanest of fossil fuels, and the share of coal in the overall energy balance and power generation is significantly lower than in the EU, China or the US. In addition, over the past few years, the country has made a significant contribution to the development of renewable energy thanks to state financial incentives in the frame of Government Decree #449 "On the Mechanism of Promoting the Use of Renewable Energy in the Electric Power Wholesale Market" adopted in 2013 and lasting until 2020 (Kozlova and Mikael, 2016; Smeets, 2017). As a result of government tenders in 2013–2017 more than 180 solar and wind generation projects were selected for a subsequent support, each with a capacity of not <5 MW and total capacity more than 4,150 GW. In 2017 about 100 MW of solar power plants were built and the first large wind farm with a capacity of 35 MW was installed. The domestic technologies are developing, and the Russian production base in the field of solar and wind energy is emerging (Ratner and Nizhegorodtsev, 2017). Although the solar energy sector exhibits a stable trend of growth, in particular thanks to the creation and rapid development of Hevel Group, one of the largest PV module manufacturers in Russia, the wind energy sector still significantly lags behind the plans outlined in governmental programs for increasing the capacity of installations. Figure 1 shows the planned values for support of wind energy, as well as real values for projects that were actually supported by tenders throughout the entire period of implementation of the state program. It isn't difficult to notice the lack of quotas for wind energy project support during 2014 and 2015. The primary reason for this is Russia's inexperience in production of medium-sized and large wind turbines, as well as the difficulty of satisfying the state requirements towards the localization index. Some of the wasted opportunities for state support were caught up with in 2016-2017, but the previous unsuccessful experience with implementing wind energy projects (Figure 2) gives doubt to the possibility of projects that started in 2016-2017 being complete within the planned deadlines.

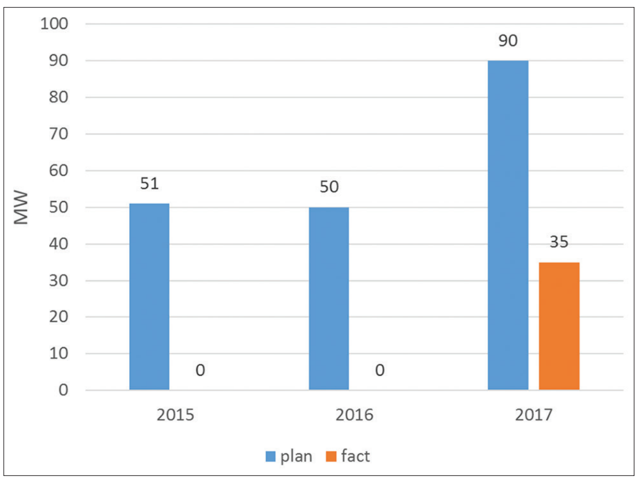
For example, the launch of the first wind farm in Russia has been delayed multiple times due to the search for a supplier

Figure 1: Plans and results of tenders for the right to receive state support for wind energy projects in Russia in 2013-2017



Source: Own calculations

Figure 2: Plans for wind installations and their actual implementation in Russia in 2015-2017



Source: Own calculations

of wind turbine components taking a long time. Finally, the Chinese company DongFung was chosen, which supplied 14 wind generators with a capacity of 2.5 MW each. Mostly Russian companies took part in the design and construction of the wind farm, many of which participated in a project like this for the first time. Despite this, the localization requirements for this project were still not fully met. The Dutch company Vestas has joined the wind farm construction as a technological partner further down the line, with the intent of having them localize their production in Russia by building a blade factory in the Ulyanovsk region.

The issue of practicality of the state support for wind energy via a guaranteed ROI over 15 years remains open. The expert opinion is split: Some believe that the program must certainly be continued to provide necessary pacing for the industry's development and create conditions for learning by doing and researching. On the other hand, some support its termination, arguing that the program gave the necessary impulse for developing renewable energy, and now market mechanisms stimulating manufacturers to decrease expenditure and increase competitiveness of their products must come into play.

The goal of this paper is to research the experience of leading countries in the field of wind energy and find best practices for decreasing the expenditure on construction and use of wind farms to further adapt them to Russian conditions. In order to project future wind technology cost trend that can be achieved in Russia we use a methodology of learning curves. The paper contributes to the literature by addressing the following questions: (1) What is the maximal possible learning rate that can be achieved in the Russian wind energy segment while executing the state support plans, (2) which learning rates are characteristic for the early stages of development of the industry and under which conditions are they attained, (3) which state-provided stimuli allow to attain the maximal learning rates in the industry and the corresponding maximal cost reduction rates.

The rest of the paper organized as follows: In Section 2 we describe the basics of learning curve methodology and its different applications for energy technologies. Section 3 is devoted to a meta-analysis of data on learning rates in wind energy, obtained from building single- and dual-factor learning curve models detailed by countries and technology development periods. It reveals a significant difference in learning rates mainly due to design and efficiency of governments support programs. Multiple case studies were performed in Section 4 in order to interpret these results. In Section 5 we estimate the learning rates that can be achieved in Russia according to data on the planned wind power generation facilities and discuss the opportunities for their improvement. Section 6 concludes the research and gives some policy applications.

2. METHODOLOGY

Understanding of the dynamics of the costs of energy produced with various technologies is an important aspect in decision-making in regards to future development of energy systems and state support of renewable energy. Throughout the last decades, the theory of learning curves has gained great popularity among economists. This theory allows one to study and forecast economic parameters of various energy technologies, both traditional and new. This approach assumes that technological development is endogenous and dependent on factors such as the size of R&D investments, intensity of stimulating measures, etc., (Romer, 1986). The cost of a unit of power is most often considered as a measure of technologic development in energy-related research.

A single-factor mathematical model of the basic learning theory in application to energy technologies can be expressed as follows (Rubin et al., 2015; Williams et al., 2017):

$$SC = a \times CC^{-b},$$

$$\log(SC) = \log(a) + (-b) \times \log(CC),$$

$$TC = \int_0^{CC} a \times CC^{-b} dCC = \frac{a}{1-b} CC^{1-b}, \qquad (1)$$

$$PR = 1 - LR = 2^{-b},$$

Where
SC – a cost for unit capacity or specific cost,
CC – a cumulative capacity installed or produced,
TC - total cumulative cost of installation or production,
PR – the progress ratio,
LR – the learning rate
a – an unit specific cost when the cumulative capacity reaches the unit value (for instance, 1 MW),
b – the coefficient of learning elasticity.

In this model, the unit cost is a function of only one argument, which is a cumulative capacity. It reflects all the experience accumulated in the process of technology development. In some studies (Rubin et al., 2015), the dependent variable in model (1) represents cumulative energy produced.

Another wide-spread model in research of energy technology cost dynamics is the two-factor learning curve model, in which the cost depends not just on the cumulative capacity, but on R&D investments as well (Rout et al., 2009; Yu et al., 2017):

$$SC = a\times(CC^{-b})\times(KS^{-c}),$$

$$PR(LBD) = 1-LR(LBD)=2^{-b}, \quad (2)$$

$$PR(LBS) = 1-LR(LBS)=2^{-C},$$

$$KS_t = KS_{t-1}(1-\delta)+R\&D_{t-lag},$$

Where,
KS – cumulative knowledge
a – cost unit (at which cumulative knowledge and capacity reach a volume divisible by 1),
b – learning by doing elasticity,
c- learning by searching elasticity,
PR(LBD) – rate of learning by doing
PR(LBS) – rate of learning by searching,
δ - rate of knowledge deprecation
lag- the time lag between the start of R&D and the start of commercial knowledge use.

Note that this form assumes cumulative capacity and knowledge to reach an integer value simultaneously. In practice, however, such a coincidence is rare (Miketa and Schrattenholzer, 2004). Data on investment into R&D of the researched technology (both from state and private sources) is most often used as a proxy variable for KS.

A large number of studies aimed at identifying the model (2) based on empirical data (for example, (Söderholm and Sundqvist, 2007; Söderholm and Klaassen, 2007; Jamasb, 2007) show that R&D investments play a significant role in reducing the cost of generating capacities on all stages of a technology's development. Quite often their influence is considered to be higher than that of learning-by-doing, besides, it's been proven that these factors aren't mutually-exclusive (Jamasb, 2007). Some research, for example, (Rubin et al., 2015), give theoretical ground for the critical importance of R&D investments in increasing productivity of technologies in the innovation phase. Throughout time and industry progress in new technologies, the importance of R&D investments to a technology's performance decreases, whereas the importance of learning by doing increases. A graphical representation of this process is shown on Figure 3.

While researching and forecasting progress for technologies that lack sufficient amounts of empirical data, the so-called "multicomponent" learning curve model (Ferioli et al., 2009) is used. This model can be represented as follows:

$$SC = \sum_{i=1}^{n} a_i \times (CC_i^{-b_i}),$$

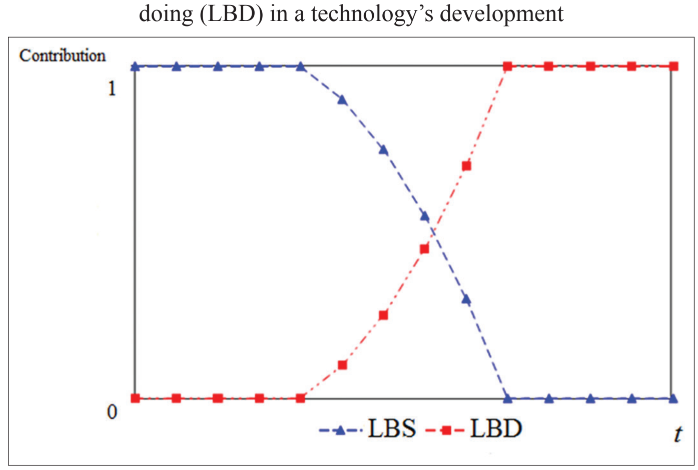
Where the index *i* specifies the number of each of *n* components of the new technologies. The rest of the variables are the same as in (1).

Use of learning curve models with three or more exogenous variables (factors) is rarely encountered in literature. This can be explained by the difficulties related to identification of the model with limited statistical data. At the same time, it is these unaccounted-for factors that represent a special interest for analyzing international differences in learning rates for the same technologies, and it is those factors that can provide an answer to the issue of effectiveness of national models for new high-tech production. The goal of this paper is, then, to build learning curve models detailed by country and sub-branches of "new energy" industries (researching ground wind generation technologies) based on a meta-analysis of statistical data. The information base for the research are the analytical materials of the International Energy Agency (IEA), the relevant reports from the Global Wind Energy Council (GWEC) as well as corporate reports from manufacturers of wind energy equipment.

3. DATA: LITERATURE REVIEW

The largest number of studies devoted to the assessment of learning rates in wind power carried out according to the data of the pioneer countries in the development of this sector of renewable energy: Denmark (Table 1) and Germany (Table 2). All

Figure 3: Importance of learning-by-searching (LBS) and learning-by-doing (LBD) in a technology's development



Source: (Rubin et al., 2015)

Table 1: Learning rates in wind energy in for Denmark

Time	Factor	Depended variable	Learning rate	Source
1981-2000	Cumulative capacity produced (MW)	Cost of wind turbine, produced in Denmark ($/kW)	8	Neij et al., 2003
1981-2000	Cumulative capacity produced (MW)	Production net cost of wind turbine in Denmark ($/kW)	14	
1981-2000	Cumulative capacity installed (MW)	Cost of wind turbine, installed in Denmark ($/kW)	9	
1984-1999	R&D investments ($)	Price of wind energy ($/kWh)	7,8	Ibenholt, 2002
1984-1988	R&D investments ($)	Price of wind energy[1] ($/kWh)	11,7	
1982-1997	Cumulative sales volume of Denmark wind turbine producers (MW)	Cost of wind turbine ($/kW)	4	IEA, 2000
1982-1997	Cumulative capacity installed (MW)	Specific investment price ($/kW)	8	McDonald and Schrattenholzer, 2001

Table 2: Learning rates in wind energy in for Germany

Time	Factor	Depended variable	Learning rate	Source
1987-2000	Cumulative capacity produced (MW)	The cost of wind turbine, produced in Germany ($/kW)	6	Neij et al., 2003
1987-2000	Cumulative capacity produced (MW)	Production net cost of wind turbine ($/kW)	12	
1987-2000	Cumulative capacity installed (MW)	The cost of wind turbine in Germany (($/KW)	6	
1990-1998	Cumulative capacity of wind turbines, sold in Germany (MW)	Specific investment price ($/kW)	8	IEA, 2000
1990-1998	Cumulative capacity installed (MW)	Specific investment price ($/kW)	8	McDonald and Schrattenholzer, 2001
1990-1999	Cumulative capacity installed (MW)	Specific investment price ($/kW)	3,1	Söderholm and Klaassen, 2007
1990-1999	Cumulative volume of R&D investments ($)	Specific investment price ($/kW)	13,2	Söderholm and Klaassen, 2007

of these studies cover the early stages of technology development (since 1981/1987-2000), as for the later periods there is no data in the literature. Limitations caused by lack of data for later periods, on the one hand, do not allow to track the entire period of wind energy development from experimental development to a commercially-successful industry throughout one country. On the other hand, the learning-rate estimates during early periods are free from the influence of technological spillover, standardization and globalization effects (Blind et al., 2017; Rainville, 2017), so it allows to more precisely identify the learning curve model in the assumption that all explaining variables are exogenous.[1]

Throughout the research period, the cumulative installed capacity for ground wind turbines in Denmark grew from 2 MW to 2.4 GW (more than a thousand times), not in the least thanks to Danish own production of wind equipment and components. Vestas, the Dutch wind turbine manufacturer launched in 1980, originally focused on the American market of California, has been on the edge of bankruptcy in 1986 thanks to a significant fall in export, however it was saved by an exponential growth of the domestic market. The stimulating state policies at the time were represented by measures such as tax credits for public cooperatives for construction and use of wind turbines (Krohn, 2002), subsidizing wind farm construction expenditures from 30% in the early 1980s to 10% in the middle of that decade, implementing bonus rates for wind energy purchases in 1993, returning a part of the wind farm construction investment through the mechanisms of the carbon market in the 1990s (Bolinger, 2001).

The learning rate estimates in Table 1 are significantly scattered and are obtained for different exogenous and endogenous variables. Nevertheless, their analysis shows some patterns in technology development:

- Higher returns from R&D investment during early stages of the technology's development, which confirms the supposition given in (Rubin et al., 2015),
- Higher elasticity of the net cost for manufacturing wind generating equipment based on the cumulative installed volume compared to the elasticity of their price, which is also affected by market factors,
- A higher learning rate for the development of the technology in its entirety, including equipment manufacture and wind farm construction, rather than for its separate parts (e.g., just wind generation equipment manufacturing).

A speedy development of the German wind industry started several years after the aforementioned Danish example. The first German wind farms that united several wind turbines and had total capacities nearing 400 kW have first appeared in the country

1 Electric energy, produced by wind turbines.

only in 1986. On the other hand, active wind energy research has started in both state-owned and private research centers back in the end of the 1970s. From 1977 to 1989, over 40 scientific companies and academic organizations have received state grants for development of both small (10 kW) and medium (200–400 kW) wind generators (Jacobsson and Lauber, 2006). Starting in 1986, wind farm demonstrations have become a part of the state science and technology program. From 1983 to 1911, 14 companies have received state financing to produce 124 wind turbines.

An important stimulus for the development of small-capacity wind generators on the domestic market was the state program supporting individual entrepreneurs and cooperatives that owned turbines in country areas. Ever since the 1980s, German farmers have had an option of taking part in wind energy project investments by providing land for their construction. The sales of electricity to the grid have become an available source of income for the population in less-developed country areas, which helped develop a positive image for the wind energy as an industry with high positive social impact. By 1989, the cumulative installed capacity in the country has reached 20 MW (Jacobsson and Lauber, 2006).

Further wind energy development in the country was mostly sustained by bonus rates for wind energy. By the end of year 2000, the cumulative installed capacity in Germany has reached a mark of over 8.7 GW.

As for wind equipment manufacturing, the first manufacturer of wind turbines in Germany, Enercon, was created and launched serial production of wind turbines with a capacity of 55 kW in 1984. By 1988, the company has mastered manufacturing turbines with capacities of 80–100 kW, and by 1993 – 500 kW. 2 years after that Enercon has released their first 1.5 MW wind turbine, which showed high effectiveness during testing. From 1996 onwards, the company has expanded abroad, purchasing production capacities in Brazil and India (McDonald and Schrattenholzer, 2001).

By the end of 1990s, the German tech giant Siemens has shown interest in wind energy, purchasing the Dutch turbine manufacturer, Bonus Energy A/S, and thus obtaining fairly developed production technologies.

Estimates of learning rates in German wind energy obtained in various researches are shown in Table 2, and are overall similar to ones exhibited in Denmark.

The only easily notable significant difference is the higher learning rate in wind power engineering (production of wind turbines) than the learning rate in the industry as a whole (installation of generating facilities). In our opinion, the revealed difference can be explained in two ways: (1) By spillover effect of wind turbine production technologies (from Denmark to Germany) and (2) by the fact that in the early stages of technology development in Germany more substantial state support for researches in this field was provided. Production technologies in Germany had a longer "incubation period" and were introduced already in a more mature state. In addition, Germany's domestic market differs from the Danish one in the period under study, in that it has a higher capacity.

Estimates of the learning rates in wind energy in Spain are similar to those for Denmark and Germany (Table 3). However, the development of the industry in this country took place in a slightly different scenario. State support programs for the development of renewable energy in the 1980s (PER'86, PER'89) were mainly aimed at creating a favorable investment climate in the industry, including foreign direct investment in wind projects. Comparatively low local component requirements of wind projects, established by the government, allowed to attract foreign manufacturers of wind power equipment and their state-of-art technologies into the country. This policy, that can be called "technology in exchange for access to the internal market," proved to be very successful, and in 1994 the Danish Vestas founded a joint venture with the Spanish machine-building corporation Gamesa. Later on Gamesa gradually developed this direction of production, making it the main one (Zhang, 2012; Bean et al., 2017). The required capacity of the domestic market in the country was ensured during this period by constant revision of the strategic goals in the field of energy. In 1991, the Spanish government approved a new National Energy Plan (PAEE 1991-2000), which included the goal of increasing the proportion of renewable energy in the country's energy balance from 4.5% to 10% by the year 2000. In 1997, the Law on Electric Power was adopted in Spain, which introduced a system of bonus tariffs for renewable energy (Jacobsson and Lauber, 2006; Bean et al., 2017).

Estimates of the learning rates in wind power in other countries (Table 3) are much more scattered and are confirmed by a smaller number of studies performed at different time intervals, which makes comparing them impossible. Nevertheless, an additional analysis of the literature on the history of technology development and measures of state support for wind energy in different countries makes it possible to verify their reliability.

4. CASE STUDIES

4.1. Case 1: Wind Energy Development Policies in Great Britain

Multiple studies about the evolution of government incentives of renewables in Great Britain demonstrate the lack of holistic policy and instability of measures of state support in 1980-2000 (Mitchell and Peter, 2004; Jordan and Matt, 2014; Lockwood, 2016). The Central Electricity Generation Board (CEGB) has started the elaboration of several demonstration projects across the UK for promoting wind energy as early as 1980. Nevertheless, the very first real opportunity for renewables' deployment was created only in 1990 due to the introduction of new Electricity Act (1989). This Act has presented the so-called Non-Fossil Fuel Obligation (NFFO) and has provided financial support to producers of nuclear and renewable energy at the expense of a significant increase in the tax on fossil fuels (Fossil Fuel Levy). Regional energy companies were now obligated to buy renewable and nuclear energy at high prices. Funds collected from the tax on fossil fuels were used to eliminate the difference between this overpriced electricity and the average price of electricity in their regions. Thanks to this model, the first British commercial wind farm was built in Cornwall in 1991.

Table 3: Learning rates in wind energy for other countries

Country	Time	Factor	Depended variable	Learning rate	Source
United Kingdom	1986-2000	Cumulative capacity installed (MW)	Specific investment price ($/kW)	5,4	Klaassen et al., 2005
	1986-2000	Cumulative volume of R&D investments ($)	Specific investment price ($/kW)	12,6	
	1991-1999	R&D investments ($)	Price of electric energy ($/kWh)	25,1	Ibenholt, 2002
Spain	1986-2000	Cumulative capacity installed (MW)	Specific investment price ($/kW)	5,4	Klaassen et al., 2005
	1986-2000	Cumulative volume of R&D investments ($)	Specific investment price ($/kW)	12,6	
	1984-2000	Cumulative capacity installed (MW)	The cost of capacity installed ($/kW)	9	Neij et al., 2003
USA	1985-1994	Cumulative volume of generated energy (kWh)	Price of electric energy ($/kWh)	32	IEA, 2000
Sweden	1994-2000	Cumulative capacity installed (MW)	The cost of capacity installed ($/kW)	4	Neij et al., 2003
Taiwan	2001-2010	Cumulative capacity installed (MW)	The cost of capacity installed ($/kW)	-5,6	Trappey et. al., 2013
China	2003-2007	Cumulative capacity installed (MW)	Price of electricity ($/kWh)	4	Qiu and Anadon, 2012
	2002-2012	Cumulative capacity installed (MW)	Levelized cost of electricity ($/kWh)	3.5-4.5	Lam et al., 2017
India	2006-2012	Cumulative capacity installed (MW)	Generation cost ($/kWh)	17.7	Partridge, 2013

The Electricity Act operated from 1990 to 1998, which explains the high values of learning rates when the price of the electricity is the dependent variable in the model (1). The process of selection of wind generation projects was focused on obtaining the lowest final price, and did not provide any penalties for companies that won the location, but never begun the construction. Contracts were also issued in the early stage of the renewable project, even before obtaining a permission for building. Many projects with realistic economic parameters did not receive a permission, and some of those that received it turned out to be unprofitable because of the underestimated final electricity price announced in the competitive selection process. In this regard, a significant part of the locations favorable for the development of wind energy remained unused.

The results of the NFFO program for wind energy development in the UK are evaluated in the literature not only in a positive way. The initial haste in the selection and construction of wind farms led to a negative attitude of the local population to wind energy, which continued throughout the decade. As a result, in 2000 only about 400 MW of wind power were put into operation in the country, which is several times less than in Denmark, Germany and Spain. This capacity of the domestic market was insufficient for the development of its own wind power production in the country, which is still represented only by VWT Power Ltd., which produces small wind turbines with a vertical axis up to 10 kW.

4.2. Case 2: Wind Energy Development Policies in USA

High estimates of learning rates in wind industry development according to the US data up to 1994 (Table 3) can be explained by introduction of Public Utility Regulatory Policies Act (PURPA), as well as by long-term implementation of the federal research program in the field of renewable energy, which has started as early as in 70s and included funding of basic and applied research, as well as demonstration projects in partnership with the private sector. The funding for R&D in renewable energy has increased from $ 1 million/year in 1970 ($2.73 million in 2011 prices) to $ 1.4 billion/year in 1980 ($3.8 billion in 2011 prices). With the introduction of PURPA in the period of 1978-1981, favorable market conditions for commercialization of developed technologies were created. Grid operators were obligated to purchase renewable energy at a price that would compensate for the costs of producers. The proposed pricing mechanism was quite complex, and its application in practice varied significantly from state to state (Mulvaney, 2013). The most attractive conditions for the development of renewable energy in the 80's were formed in the state of California, which led to a rapid increase in the volume of installations of renewable energy sources (Graves et al., 2006). By 1985, California had about 13,000 wind turbines with a total capacity of about 1 GW. Also, in the 1980s, measures of state support at the federal level, the so-called investment tax credit (ITC), were introduced in the United States, providing tax privileges in the amount which is proportional to investments in wind projects.

In the 1990s, public and private investment in the development of renewable energy technologies fell to $ 148 million/year. Totally in the period 1973-2003 USA federal government has spent about $14,6 billion. After the PURPA era, the period of stagnation (1990-1997) has started due to the decline in world oil prices and end of government support programs. The attractiveness of investments in renewable energy power has fallen. However, the time period for which the estimates of learning rates are obtained in the study (IEA, 2000), almost does not overlap with the period of stagnation and corresponds to the period of the most rapid development of RES in the US.

The history of wind power engineering in the US also begins in the 1980s. The first American developer of wind parks Zond Corp. was established in 1980, and originally engaged in the import of wind turbines from Europe, the construction and operation of wind farms. Gradually developing its own production, by the mid 90's Zond Corporation mastered the release of three new generations of wind turbines and won about 10% of the world market (Parsons, 1998). However, due to the instability of state support for wind power in the United States in the 1990s, the company's financial position became so volatile that in 1997 it was absorbed by the US energy concern Enron, which in turn was absorbed by General Electric in 2002.

4.3. Case 3: Wind Energy Development Policies in Other Countries

The estimates of the learning rates in Sweden (Table 3) are slightly lower than in Denmark, Germany and Spain, which can be explained by the insignificant capacity and low growth rates of the domestic market until the middle of the 2000s.

The estimates of the leaning rates in Taiwan and China were obtained during a period of sharp increases in prices for raw materials and materials used in wind power engineering, which led to a proportional increase in the cost of wind turbines and capital expenditures of wind projects around the world (IRENA, 2012). Nevertheless, as can be seen from Table 3, at the same time period, the learning rates in Taiwan turned out to be negative, while the learning rates in China remained in the zone of positive values and even quite comparable with the estimates of the European countries' prosperous period of development of the industry. This difference can be explained by the huge capacity of China's domestic market and its unprecedented growth rates. Whereas in the early 2000s wind energy in China was just emerging, already by 2011 the total capacity of wind generators installed in China was 62.36 GW, and the share of wind power in the country's constantly growing energy balance reached 1.5%, which led to China as a world leader. In the first half of the 2000s, China's wind power equipment market was dominated by large multinational companies such as Vestas and Gamesa, but by the end of the decade, national manufacturers (Goldwind, Sinovel, United Power, Mingyang, etc.) had reached such a production scale that they were able to impose strategy of price competition and push the international giants out of the market by offering much cheaper contracts at tenders. However, the lack of full-fledged research programs before the transition to mass production led to several dangerous incidents (explosions of operating turbines, destruction of blades, etc.), partially undermining confidence in the wind power industry in the country (China Wind Energy Outlook, 2012; Lam et al., 2017).

High assessments of learning rate in India are also obtained during the period of the most rapid growth in the volume of installation of wind generators in this country (India Wind Energy Outlook, 2012). As of March 2012, renewable energy sources accounted for 12.2% of the total energy balance of the country (25 GW from 207.8 GW of total capacity), whereas in 1995 its share was only 2%. It should be mentioned that wind energy makes up about 70% of the capacity of all renewable sources. Such a significant growth of the wind energy sector is directly related to the stimulating governmental incentives which were introduced in India in early 2010s. The commercial generation of wind energy began in India in 1986. However, prior to the appearance of the Electricity Act in 2003 (EA, 2003), there were no specific provisions in India's regulatory framework that promoted the development of renewable energy sources. Despite this shortcoming, the Ministry of New and Renewable Energy Sources of India has worked to support the sector through the development of public policy guidelines since 1994. The EA, 2003 defined the main policy directions for the promotion of renewable energy sources by the federal government as well as regional authorities and relevant institutions within their jurisdictions. According to the adopted legislation, the Regional Electricity Regulatory Authorities determine the tariffs for all renewable energy projects at the state level, and the state distribution grid companies provide connection of renewable energy sources to the grid (India Wind Energy Outlook, 2012).

The most effective measure for promoting renewable energy sources in the EA, 2003 law was the possibility of accelerated depreciation of equipment (up to 80%) in the 1st year of operation of wind farms. In addition to the possibility of accelerated depreciation in India, there are the following benefits for energy producers from alternative sources:

- Non-taxable income from the sale of energy during the first 10 years of operation of the power plant (for power plants commissioned earlier than March 31, 2013);
- A reduced rate of value added tax (VAT) (5.5% instead of 12.5%) in some states;
- Allocation and leasing of forest lands for the development of wind energy projects;
- Preferential customs duties (5%) for some of the components of wind installations;
- Development of financial institutions working in the field of renewable energy;
- The release of projects for the development of wind energy from payment of excise;
- State financing of research and development in the field of renewable energy, assistance in training specialists, product certification, testing and evaluation of renewable resources (wind, solar, geothermal).

To a certain extent, the creation of specialized domestic financial institutions, such as the Indian Renewable Energy Development Agency (IREDA), the Energy Finance Corporation and the Rural Electrification Corporation have helped projects on renewable energy to get access to financing. In addition, India has actively used the opportunities provided through the so-called Clean Development Mechanism (CDM) in a frame Kyoto Protocol. CDM provides additional assistance in financing renewable energy projects in developing countries, while being an effective tool for international due diligence for the projects under consideration of international financial funds such as IFC (International Finance Corporation). Thus, in 2012 Indian projects accounted for 18% of all projects submitted for financing under the CDM mechanism.

Table 4: Initial local component requirements for government support

Source/index of localization, %	2014	2015	2016	2017	2018	2019	2020
Solar	50	50	70	70	70	70	70
Wind	35	55	65	65	65	65	65
Small hydro	20	20	45	45	65	65	65

5. POLICY OPPORTUNITIES FOR RUSSIA

Our multiple case study of learning rates in wind energy achieved in different countries proves the hypothesis that the maximal learning rate in wind energy can be provided by financial support of R&D on the early stage of technological development and by attracting world leaders in manufacturing of wind turbines and other electric generation equipment in the country on the later stages.

Considering the fact that wind power technologies are currently sufficiently developed, the strategy of attracting large foreign wind turbine manufacturers to Russia seems most appropriate. In the original plans for the development of renewable energy, including wind energy, identified in Executive Order of the Government of the Russian Federation no. 861-r. dated May 28, 2013 indicated fairly high values of the localization index of production (local component requirements) (Table 4). But, as it was stated in Section 1, these requirements were never satisfied for wind energy projects.

In order to determine the degree of compliance of current Russian measures of government support with the optimal strategy, we will determine the planned cost decline rates according to official data of the Administrator of the Trade System of the Wholesale Power Market of the PAO Unified Energy System, selecting construction and commissioning projects of RES facilities on a competitive basis as a result of tenders in 2015-2017 (Table 5).

As one can see, the cost reduction rate in the period 2015-2017 is about 30%. The solution of equation (1) for the case when we use the average planned value of the capital expenditure per 1 kW of installed capacity of the wind-generating facility as the dependent variable, and the planned capacity of the facilities as an independent variable, allows to assess the learning rate as 22%. Such a high planned learning rate is unlikely to be achievable even in the context of a decline in the local components requirements and opening domestic market of wind turbines of Russia to foreign companies. Thus, the planed cost reduction cannot be explained only by learning and exogenous technological change, but by some other factors such as cost indices (for example, steel prices, labor prices etc.) and low ruble rate against foreign currencies.

Thereby, the current strategy of government support is fundamentally realistic, but the planned reduction in costs for the implementation of wind projects may not be achievable due to various fluctuations in market prices for primary raw materials, energy prices and currency fluctuations. A number of wind projects planned for implementation are in the risk zone according to the terms and conditions for their implementation. Considering this conclusion, it is reasonable to correct the expectations on the pace of cost reduction in the near future and increase in the process of competitive selection of projects the significance of non-price

Table 5: Official data of the Administrator of the Trade System of the Wholesale Power Market of the PAO Unified Energy System

Result of tender	2015	2016	2017
Number of wind projects selected	1	26	43
Mean of the capital expenditures per 1 kW of installed capacity (in RUB)	155,000	135,035	105,755
Total projects capacity (MW)	35	610	1651

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factors that affect the success of the project. Such factors may be the experience of the applicant company in the implementation of major projects to develop new high-tech industries, the availability and quality of the selected location of the wind park, the degree of support from regional authorities, etc.

6. CONCLUSIONS

Using a concept of learning curves as a methodology framework, we evaluated the factors influencing the cost reduction rates for wind energy technologies in different countries at early stages of wind industry development. Our results prove that the main direction of state support of wind energy in Russia corresponds to best world practices in case of mature technology, which is true for wind electricity generation technology. But the expectations on cost reduction rate are too high and may damage the implementation of selected wind projects. Considering this conclusion, it is reasonable to increase the significance of non-price factors in tender process, such as experience of the applicant company in the implementation of major projects to develop new high-tech industries, the availability and quality of the selected location of the wind park and degree of support from regional authorities.

The main limitations of our study are related to the lack of statistic data on wind projects implementation in Russia. Up to date the only one wind park has put into operation (in January, 2018). Therefore, the conclusions and recommendations obtained are relevant only in a short term and policy makers must keep track of cost changes and be ready to reconsider existing strategy of government support in order to achieve highest possible learning rates in wind energy development.

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