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MASTER THESIS

COST OF ELECTRICAL ENERGY IN COMPLEX ENERGY SYSTEM

DOROSHENKO ALEXANDR

Prague 2016

Declaration:

“I hereby declare that this master’s thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – “On maintaining ethical principles when working on a university final project, CTU in Prague“.

Date Signature

ABSTRACT

Wind power is the most developing area in the Kazakhstan renewable energy market, but there are a lot of limitations on its integration into power system, including balancing activities. The main idea is to locally balance wind power by conventional generators. Steam turbines could quickly response to load changes and therefore suitable for balancing activities. The research was carried out with energyPRO software. The essence of this work is calculation of cost of energy before and after wind power introducing.

KEYWORDS

Combined heat and power plant, wind power, replacement, energyPRO software, cost of energy.

ABBREVIATIONS

BCR	Benefit-to-Cost Ratio
CCA	Competitive Capacity Auction
DPB	Discounted Payback
FOR	Forced Outage Rate
IEA	International Energy Agency
IRR	Internal Rate of Return
LEGC	Levelized Electricity Generation Cost
LCOE	Levelized Cost of Electricity
LOLP	Loss Of Load Probability
LUCE	Levelized Unit Cost of Electricity
NPC	Net Present Cost
NPV	Net Present Value
O&M cost	Operation and Maintenance Cost
RES	Renewable Energy Sources
RR	Required Revenues
SPB	Simple Payback
TLCC	Total Life-Cycle Cost
UN	United Nations
UPAC	Unitary Present Average Cost
WACC	Weighted Average Cost of Capital
WECS	Wind Energy Conversion System

CONTENTS

1 INTRODUCTION

Nowadays numerous opportunities to use renewable power sources exist. More and more electricity is generated from renewable sources worldwide because of the government incentives, environmental problems, and improvement of green energy producing technology.

Kazakhstan has extremely big renewable energy sources potential with estimated output of one trillion kWh/year, this amount is ten times higher than overall energy demand. Wind energy is the most perspective and cost – effective renewable energy source in Kazakhstan due to this country has favorable geographical position with an abundance of strong winds exceeding 6 m/s. Opportunities for wind power development are very significant. The National Programme of Wind Power Sector Development was developed in Kazakhstan by the year 2015, this program has now been prolonged until 2024. The main goal of this program is to enhance using of Kazakhstan wind power potential and to generate 900 million kWh of energy per year by 2015 and 5 billion kWh of energy per year by the year 2024 [1].

As a member of the UN Framework Convention on Climate Change, Kazakhstan signed up to the Kyoto Protocol in 2009 and obliged to reduce greenhouse gas emissions. Embedding of wind power into Unified Energy System is one of the most important measures to fulfill Kyoto Protocol obligations [1].

In this work problem of replacement conventional generators by wind farm was investigated. Wind power energy gradually penetrating electrical grids, therefore part of power system load, which is covered by wind energy increases. These technologies are permanently improving to ensure grid code requirements and safe operation under normal, fault, post fault conditions. Wind turbines may replace some part of conventional generators in case of low load modes with powerful wind. Every project concerning replacing conventional power turbines with wind turbines have to be analyzed economically and technically. From technical point of view the most important thing is the appropriate work of power station equipment. Wind power in conventional power plants makes influence on system balancing, voltage, frequency control, system static and dynamic stability. In order to replace conventional generators with wind turbines it is necessary to ensure reliable and safe operation of such power system. From economic point of view it is necessary to recover project costs in order to achieve necessary profit level. If cost of energy produced by power system with wind generators is higher compared to classical source, it will lead to higher cost of energy for final consumers. [2].

The main goal of this work is cost of energy optimizing of complex energy system comprising of thermal power station and wind farm. The emphasis has been on technical, economic, financial, environmental assessments of renewable energy project.

2 LITERATURE OVERVIEW

2.1 Wind power integration issues

A lot of researches were made to analyze wind power behavior in power systems. The major part of these works dedicated to voltage and frequency stability and control, system balancing, dynamic stability.

According to Kling and Slootweg (2010) research replacement of conventional generators by wind turbines without decreasing system reliability will be possible if all functions of conventional generators will be taken over by wind generators. In this paper it was investigated if all conventional power plant functions could be carried out by wind turbines [5].

Elrich et al. (2006) study about impact of wind power on frequency stability focuses on impact of large wind power (50% of all power) on power system frequency stability. The paper dwells on frequency control measures which could be implemented in wind power plants to ensure reliable work during sudden generation loss or load increase [6].

Ackerman (2005) analyzed existing wind turbine concepts and described classical and new generator types. Detail classification of wind turbines by speed control and power control was given. Author also provided comprehensive research about generator concepts which can be used in wind turbines and devoted special attention to doubly-fed induction generator as an interesting option in a growing market [7].

Gudimentla et al. (2010) provided research of wind power capacity credit. This research includes calculation of wind power capacity credit for power system consisting of conventional and wind generators and permanent load. Investigation about dependencies of different factors on capacity credit was also included [8]. Another attempt of capacity credit calculation was made by Patil (2010). This work comprises renewable sources review, wind power perspectives overview, wind power reliability assessment. Simple approach to calculate the capacity credit of wind power under different load was presented [9].

A lot of attempts to analyze combined heat and power plants behavior in case of wind power presence were made. Troy (2011) provided comprehensive research related to conventional generators operation with high penetration of wind power. Different types of damages because of variable operation and their consequences to conventional generators were analyzed in this research [10]. Doherty et al. (2003) developed a methodology to quantify reserves to ensure system security. This methodology takes into account such uncertainties as conventional generator forced outage rate, load forecast error, wind power production error [11].

Ummels et al. (2007) proposed a new modelling method that allows estimate all impacts of wind power on system operation. Special attention was devoted to thermal generation system [12].

Another attempt to analyze behavior of combined heat and power units balancing wind power were performed by Kuhi–Thalfeldt. Numerical example of thermal power units balancing wind power were presented and technical and economic aspects of this problem were analyzed [13].

2.2 Wind power investment project evaluation

According to El-Kordy et al. (2002) research there are four key cost factors of evaluation of the energy systems economics: initial capital investment, maintenance cost, fuel cost, external cost. Fuel and external costs strongly depend on efficiency and type of the system. Such economic parameters as discount and inflation makes influence on evaluation. Future amounts of money always should be discounted. In order to compare the various alternative variants present value approach can be applied [2].

The IEA (1991) elaborated a guideline for the renewable energy technology projects, which could be seen in the Figure 1. The IEA's presented methodology represents general approach which is suitable for energy projects feasibility [2].

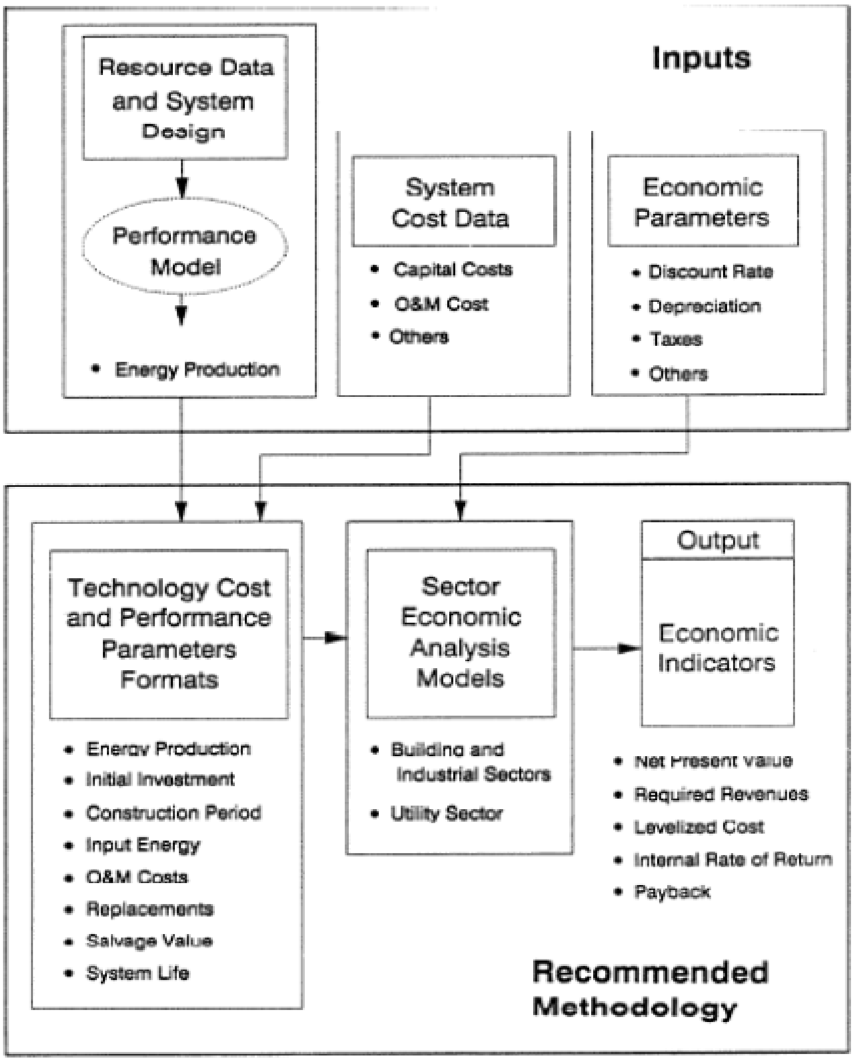

Figure 1–Recommended economic analysis approach [2]

For Gökçek and Genç (2009), to calculate electrical energy generation costs, all installation payments including land, construction, fuel, O&M costs are required. Cost per unit energy can be defined by dividing the produced energy amount to the total expenditures during certain time spat. One of the most vital criteria for estimating operation of power supply systems is levelized cost of electricity. LCOE is special approach to calculate the kWh cost throughout lifetime of the project. The levelized cost of electricity for wind energy conversion systems can be obtained as the value of the total annualized cost of the wind energy conversion to the annual electricity generated by the system [2].

Nouni et al. (2007) proposed the levelized unit cost of electricity. The LUCE is frequently used as economic indicator for financial evaluation of decentralized power systems based on renewable power sources. Total annualized cost was calculated as a sum of capital costs and annual operation and maintenance costs [2].

Arslan (2010) made a techno-economic analysis of wind energy electricity generation, claimed that lifetime costs for wind farm comprises two major components, which are investment and O&M costs. The investment costs implies turbines, foundation, grid connection, civil work costs. According to this research the costs of damages to nature and human health should be added [2].

Zhang et al. (2010) presented a new method for wind farms economic evaluation. It is based on cost of energy optimization. It shows that profitability is strongly depends on changes in capital investment, capacity factor, electricity escalation rate. Profitability is slightly less volatile to changes in O&M costs, also there is a limited impact of the inflation and turbine rated power [2].

The National renewable energy laboratory (1995) issued a *Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies* that can be a guidance on economic measures and economic evaluation methods. It focuses on standard assumptions, primary economic measures and finance fundamentals. This guidance is also comprises special consideration in the renewable energy projects economic evaluation [2].

Oliveira (2010) made a comprehensive overview regarding indicators of effectiveness such as simple payback, discounted payback, net present value, internal rate of return, benefit-to-cost ratio, required revenues. Levelized cost of energy, total life-cycle, net present cost, levelized electricity generation cost, utinary present average cost was also discussed. A simulation carried out with these indicators identified that they have to be used as a tool kit for wind energy project economic evaluation. These indicators are not supposed to be used independently, they should be combined in function of the evaluation objective [2].

Many authors such Kobos et al. (2006), Ibenholt (2002), Lund (2006), Neij (1999, 2008), Pan and Köhler (2007) and Sorensen (1997) wrote about importance of cumulative production, research, development aspects. Technological aspect and its improvements significantly impacts on wind energy project cost reduction analysis. That aspect is important and has to be considered [2].

As you can see there is a massive list of authors, institutions concerning economic evaluation methodologies and approaches applied to energy projects. Each approach and method has its own objective, but they usually show only economic value, in energy project engineering variables are also important [2].

3 RESEARCH QUESTION STATEMENT

3.1 Thermal power plant equipment analysis

The main object of my research is thermal power station with total available capacity 556 MW, which is located in Kazakhstan and supplies local industrial and domestic consumers with heat and electrical energy. On this power station six boilers BKZ-420-140 with 420 t/h steam productivity are installed. Boilers and turbines parameters were taken from [15]. Turbines and generators data are given below in Table 1 and Table 2. This thermal power station produces heat and electricity for local consumers and transfers excesses of energy to the grid. Structural circuit of this thermal power station is given below in Figure 2.

Table 1 – Thermal power plant turbines parameters [14]

No	Type	S_{nom}, MW	S_{max}, MW	Steam expenditure, t/h	Maximum steam expenditure, t/h
1	PT-65/75-130	65	75	415	430
2	PT-65/75-130	65	75	415	430
3	P-50-130	50	60	415	450
4	T-120/130-130	120	140	515	520
5	T-120/130-130	120	140	515	520
6	T-100/120-130	110	120	400	415

Table 2 – Thermal power plant generators parameters [14]

No	Type	U_{nom}, kV	S_{nom}, MVA	P_{nom}, MW	P_{max}, MW	$\cos\varphi_{nom}$
1	TF-63-2Y3	6	78,75	63	69,3	0,8
2	TF-80-2Y3	6	100	80	85	0,8
3	TF-63-2Y3	6	78,75	63	69,3	0,8
4	TF-125-2Y3	10	156,25	125	140	0,8
5	TF-125-2Y3	10	156,25	125	140	0,8
6	TF-120-2Y3	10	125	100	120	0,8

Table 3 – Thermal power plant transformers parameters [14]

No	Type	S_{nom}, kVA	U_{hv}, kV	U_{mv}, kV	U_{lv}, kV	ΔP_{os}, kW	ΔP_{sc}, kW	I_{os}, %	U_{sc}, %
1,2	TDTN-80000/110	80000	110	35	6	28,5	140	0,7	10,5 17,5 6,5
3,4	TDTN-80000/110	80000	110	35	10	28,5	140	0,7	10,5 17,5 6,5
5	TDC-160000/110	160000	110	–	10	65	450	0,5	10,5
6	TDC-125000/110	125000	110	–	10	120	400	0,55	10,5

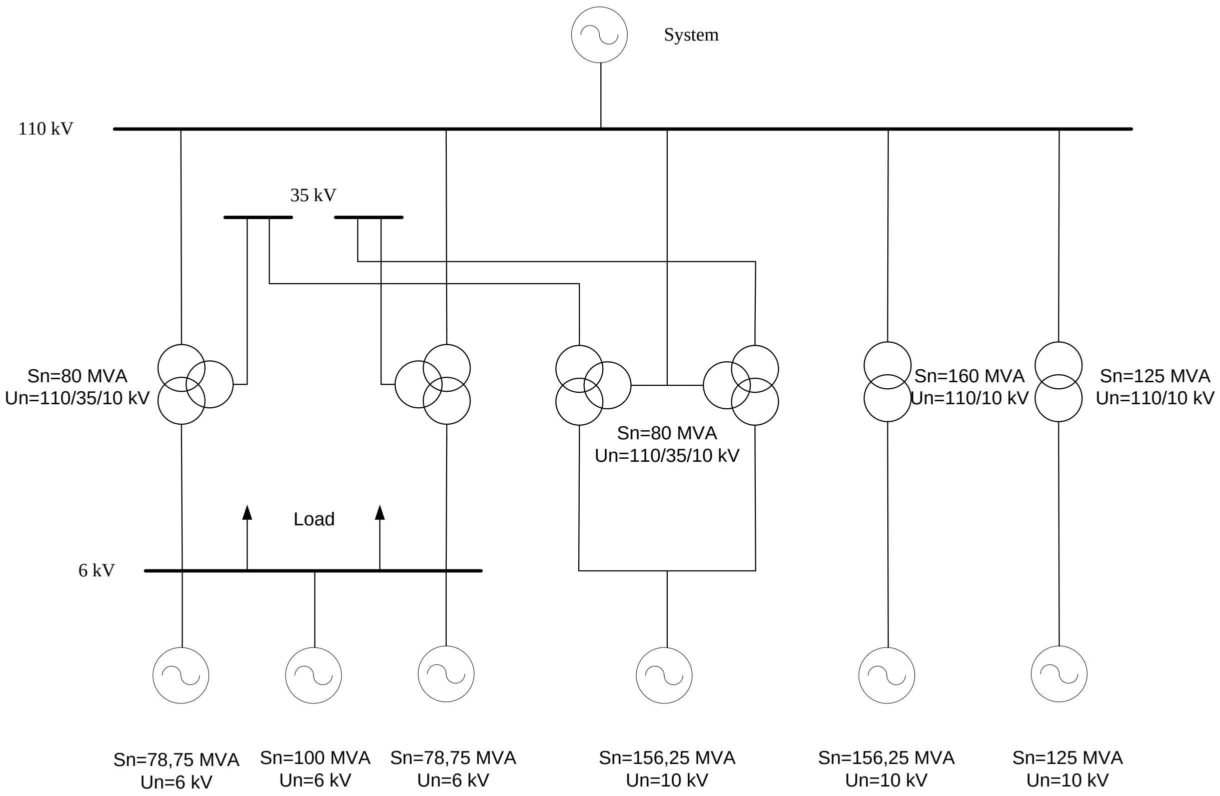

Figure 2–Structural circuit of thermal power station

Forecast for thermal and electrical energy production in 2016 given by Kazakhstan Electricity Grid Operating Company presented in Table 4.

Table 4 – Unit commitment analysis

Parameters	Units	Months											
		01	02	03	04	05	06	07	08	09	10	11	12
Electrical energy production	ths. kWh	301320	281880	286440	205200	256680	216000	256680	256680	252000	286440	276904	300576
Electrical load	MW	405	405	385	285	345	300	345	345	350	385	384,6	404
Auxiliary electricity requirements	%	13,5	14,1	13,8	15,8	11,3	12,1	11,3	11,4	11	11,3	14	13,3
Heat energy production	Ths. Gcal	299,0525	304,881	265,043	238,195	91,407	85,771	86,228	94,313	55,289	180,964	295,545	345,797
	Gcal/h	402	438	356	331	123	119	116	127	77	243	410	465
Quantity of working boilers		5	5	5	5	5	5	5	5	5	5	5	5
Average boilers load	t/h	405	405	393	324	357	388	357	357	363	413	417	409
Turbine No1	MW	60	60	70	70	70	70	70	70	70	70	70	65
	h	744	696	530	720	744	720	744	744	720	744	720	744
Turbine No2	MW	60	60	70	70	70	60	70	70	70	70	70	65
	h	744	696	744	720	744	240	744	744	720	744	720	744
Turbine No3	MW			20	25		20				25	25	
	h			744	720		360				446	536	
Turbine No4	MW	100	100	100	120	100	100	105	105	105	115	104	100
	h	744	696	744	480	744	720	744	744	720	744	720	744
Turbine No5	MW	100	100	100	120	105	100	100	100	105	115	113	100
	h	744	696	744	240	744	720	744	744	720	744	720	744
Turbine No6	MW	85	85	100									70
	h	744	696	336									744

3.2 Power plant operation optimization problem

As thermal load wasn't divided by turbines I made modelling of this thermal power station in EnergyPro software. This software can be applied for creating, analysis and improvement of energy projects. Based on user–defined inputs EnergyPRO optimizes power plant operation [16]. I created an EnergyPRO model of thermal power station which is shown in Figure 3.

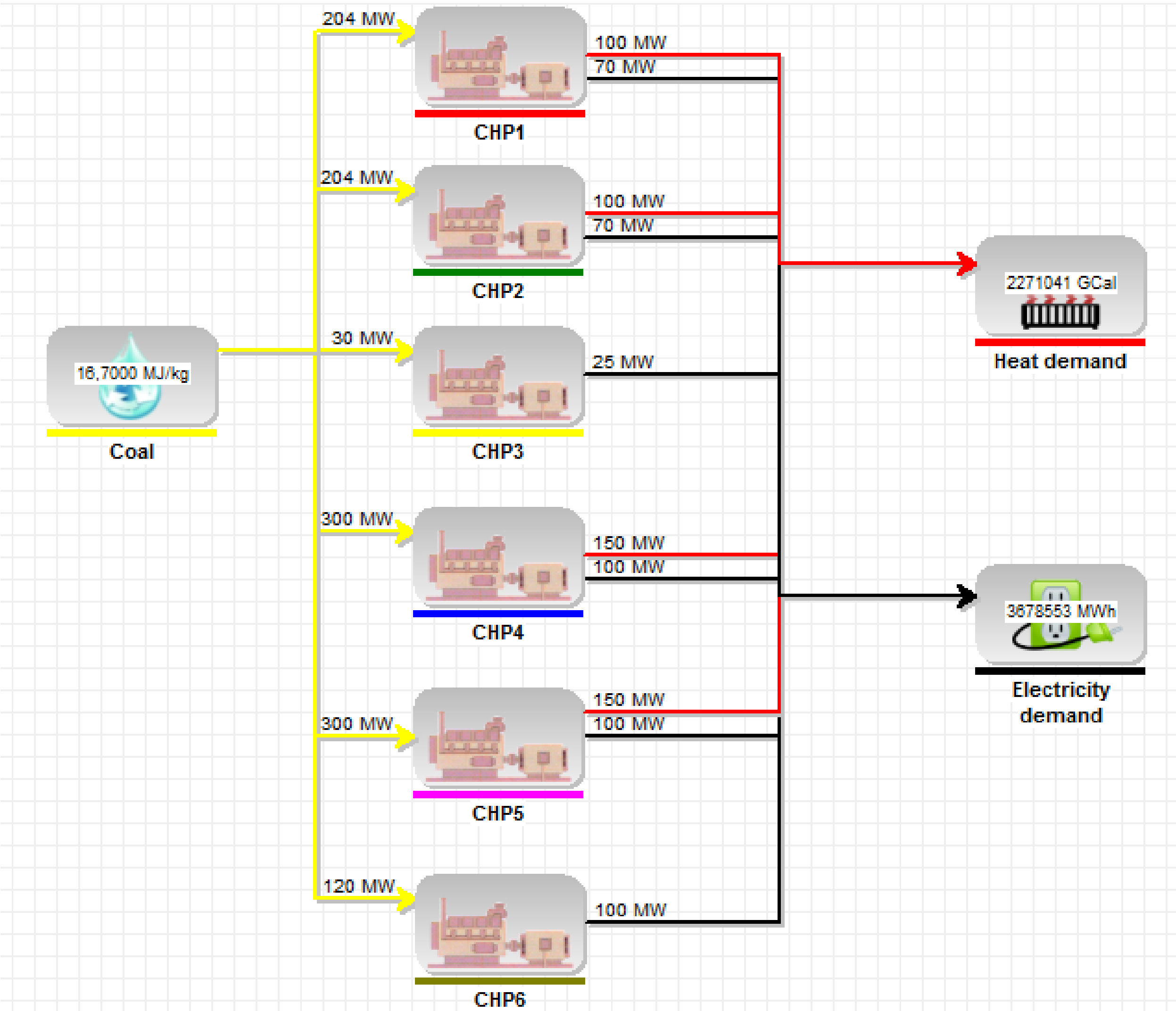

Figure 3 – Thermal power plant 1 model

In this model the inputs are as follows: CHP parameters and fuel data, electricity and heat demand curves. All necessary data concerning CHP can be found in Tables 15–17. The fuel of thermal power station is coal, heat value of this coal is 16,7 MJ/kg. As a result I derived thermal power plant electricity and heat production data for each turbine according system operator plant for year 2016 which is illustrated in Figure 4.

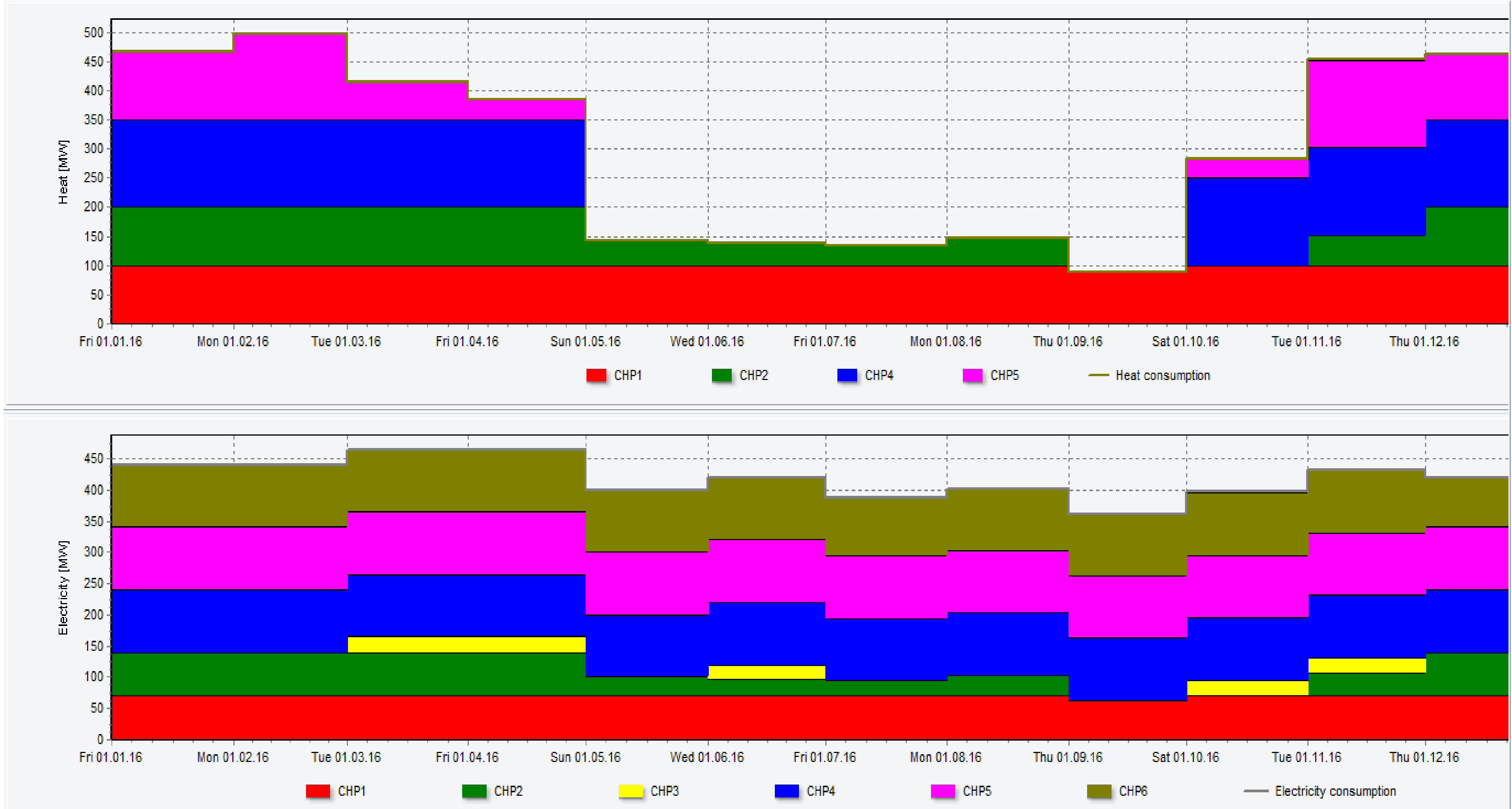

Figure 4 – Thermal power station 1electrical energy and heat production

I made the following assumptions during system operator plan modelling:

- All generators generate rated power, partial electrical load wasn't used
- Generator No 6 reconstruction period wasn't taken into consideration

As it can be seen from Figure 5 four turbines is enough to cover all heat load of thermal power station . It means that Turbine 6 will work in condensing mode. After modelling EnergyPRO also generates annual energy conversion report which is listed below.

Calculated period: 01.2016 – 12. 2016.

Heat demands: 2 271 041,0 GCal.

Maximum heat demanded: 498 MW.

Heat production by CHP units can be found in Table 5.

Table 5 – Heat production

CHP unit	Heat amount, MWh/year	%
CHP 1	870 689,5	33,2
CHP 2	507 667,7	19,4
CHP 3	0	0
CHP 4	776800	29,2
CHP 5	479 488,4	18,2
CHP 6	0	0
Total	2 271 041	100

Electricity demands: 3 678 553 MWh.

Maximum electricity demanded: 465 MW.

Electricity production by wind farm and CHP units can be found in Table 6.

Table 6 – Electricity production

Unit	Electricity amount, MWh/year	%
CHP 1	609 482,7	16,6
CHP 2	365 997,6	10
CHP 3	89 786,4	2,3
CHP 4	878 400	23,9
CHP 5	878 400	23,9
CHP 6	855 336	23,3
Total	3 587 353	100

Table 7 – Hours of operation

Unit	Time, h/year	%
CHP 1	8 784	100
CHP 2	7 320	83,3
CHP 3	3 648	41,5
CHP 4	8 784	100
CHP 5	8 784	100
CHP 6	8 784	100
Total	8784	100

After evaluation of turbines annual production, I devoted attention to long-term perspectives of thermal power plant production ability. Generators year of production, input into exploitation year and average lifetime are summarized in Table 8.

Table 8 – Thermal power plant generators data [15]

Generator	No1	No2	No3	No4	No5	No6
Type	TF-63-2Y3	TF-80-2Y3	TVF-63-2Y3	TF-125-2Y3	TF-125-2Y3	TVF-1202Y3
Year of production	2010	2012	1973	2014	2013	2008
Input into exploitation year	2012	2015	1973	2015	2014	2010
Lifetime, years	40	40	40	40	40	40

As it can be seen from Table 8, reconstruction process on this thermal power plant started in 2010. In order to make this thermal power plant more cost-effective and to finish reconstruction process replacement of generator No3 (63 MW) due to ending of lifetime period is required. The purpose of this work is offering thermal power station improvement project. This project implies replacement of one conventional generator (total capacity 63 MW) by wind generators.

4 METHODOLOGICAL DESIGN

4.1 Technical analysis

4.1.1 Wind energy replacement segment

Basically, the daily load duration curve of power system with different types of conventional generators can be divided into three categories: base load, intermediate load, peak load. Base load is usually covered by nuclear power plants, large hydropower plants, coal power plants. Intermediate load can be covered by coal power plants, oil-fired power plants, combined cycle gas turbine plants. Peak load can be covered by pumped-storage hydropower plants, open cycle gas turbine plants [17].

Wind power cannot replace all segments of load duration curve due to production variability. To be more precise, wind energy cannot replace nuclear or large hydropower plant because both of them operate in base load segment. Pump hydro power plants also cannot be replaced by wind generators due to production variability. The last possibility to replacement is conventional generators working on fossil fuels (coal, oil, gas). However, it is important to take into account that coal power station operates in base load segment as well [17].

Thermal power plants can be divided into base-load, mid-merit and peaking. Mid–merit units operate at daily demand and switched off during night, peaking units are used to cover load peaks. Base-load thermal units run at continuous operation mode with maximum efficiency and have minimal operation flexibility. Using these generators as wind power back–up will lead to more frequent failures, operational costs rising, reduced power unit lifetime [10].

To replace conventional generators by wind power large amount of wind turbines and land area are required. Total output power of such system changes smoothly, zero output power is not a credible event. As a result, wind farm can be as reliable as coal power plant and ensure base–load if small back-up power will be added. In practice there is no difference whether power plant install back-up generators or back-up energy will be taken from central grid [18].

4.1.2 Reliability assessment of power system with wind generation

Traditional power system operates with one type of uncertainty – load uncertainty. Wind power brings another uncertainty into power system because of unpredictable nature of wind. However, power system with significant penetration of wind power always must ensure reliability requirements. Loss of load probability (LOLP) is a common measure which can be applied for power system reliability evaluation. If wind power penetration level into conventional power system increases LOLP will be increased either, because the robustness of WECS is lower than conventional units [9].

Forced outage rate (FOR) is one of the important parameters for power system reliability evaluation. FOR is always presented in p.u. and shows the percentage of generating unit out of operation time. The FOR value for conventional power plant is much lower compared to wind power units, because wind deficiency will lead to zero output power just as a wind generator failure [9].

Capacity credit is another important parameter for power system reliability calculation. Wind power capacity credit is the fraction of installed capacity that can replace conventional generation without power system reliability decreasing. For instance, 100 MW of wind power with assigned capacity credit 0,5 will operate with the same reliability as 50 MW of conventional generators. It means that 100 MW of wind power with capacity credit 0,5 can safely replace 50 MW of conventional generators [9].

One of the methods for WECS capacity credit calculation is weighted capacity credit method. This approach based on calculation of capacity credit for each load step. Weighted average of capacity credit values with using probability of each load occurrence as weighting factor can be obtained for each level of wind penetration and different wind regimes [9].

In case of my thermal power station main purpose of weighted capacity calculation is to define necessary amount of wind power to safely replace 63 MW of conventional generation. Step–by–step weighted capacity credit calculation is presented below.

Load analysis

In order to make capacity credit calculation annual load duration curve is required. Annual load duration curve is a plot with loads in descending order and quantity of hours. This load representation type is commonly used on planning stages of generation systems [9].

Thermal power station load was taken from Table 4, results are presented in Table 9.

Table 9–Monthly load representation

Month	Duration, h	Load, MW
January	744	405
February	672	405
March	744	385
April	720	285
May	744	345
June	720	300
July	744	345
August	744	345
September	720	350
October	744	385
November	720	384,6
December	744	404

Annual load duration curve for power station is given below in Figure 5.

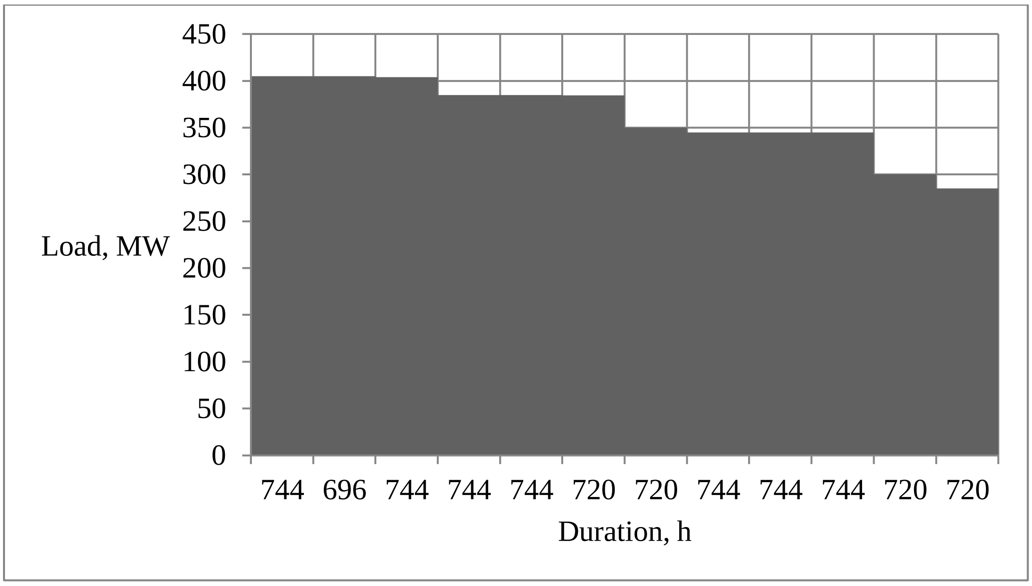

Figure 5 – Annual duration curve

I aggregated some similar load steps to simplify calculations, as a result I obtained annual load duration curve with four load steps. It can be seen below in Figure 6.

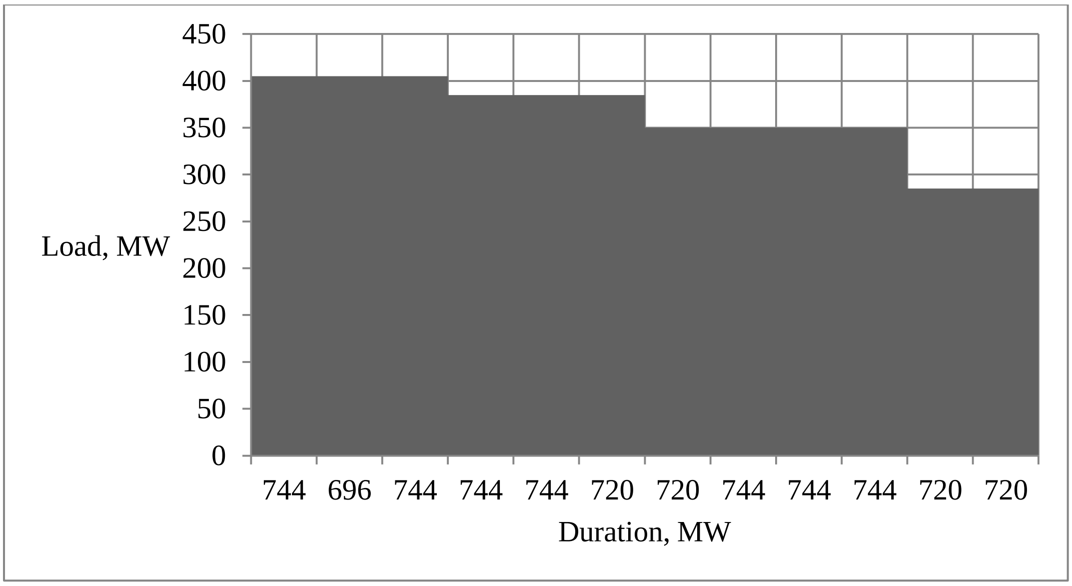

Figure 6 – Simplified annual duration curve

Table 10 lists different load steps with every step probability and duration.

Table 10 – Step by step load representation

Load level, MW	Duration, h	Usage
405	2184	0,25
385	2208	0,25
350	2952	0,34
285	1440	0,16
	8784	1,00

System consists of six conventional generators, total capacity is 556 MW. The purpose of my calculation is to define wind power capacity, which can replace generator No3 with a capacity 63 MW.

FOR value for conventional generators equals to 0,02, FOR value for the wind generator equals to 0,7; 0,41; 0,21 (low, moderate, high wind regime) [9].

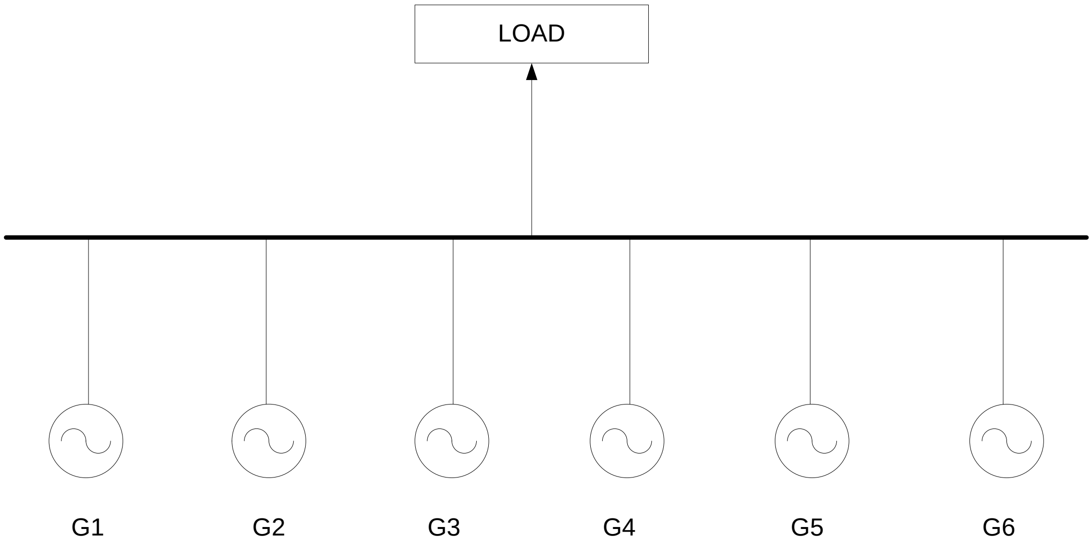

Figure 7 – System with six conventional generators

After loss of load probability calculation generator No3 is replaced by wind generator of variable capacity. Capacity of wind generator is changed until the same loss of load probability value is obtained [9].

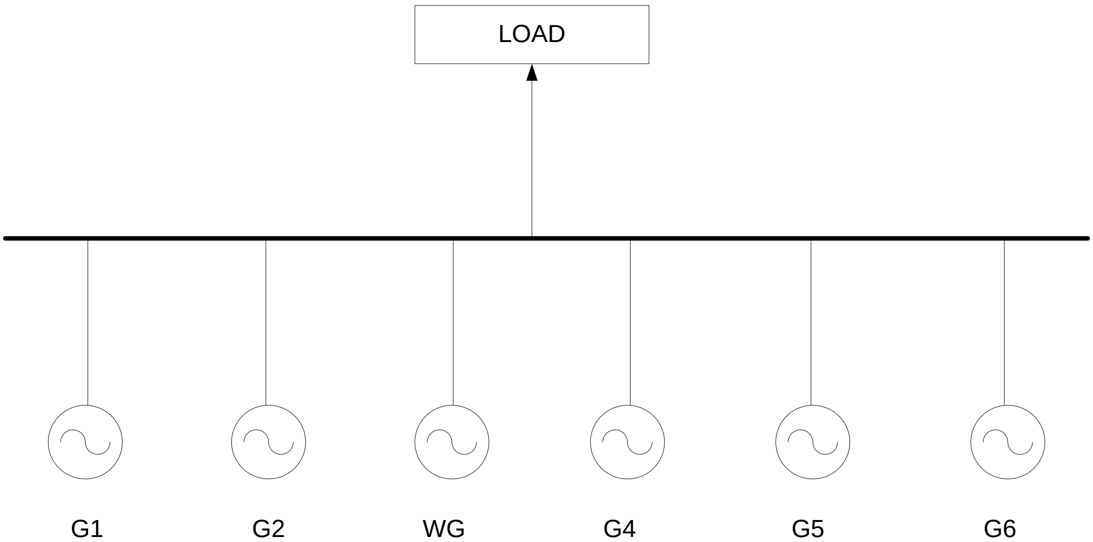

Figure 8 – System with five conventional generators and one wind generator

Capacity of G3 divided by calculated capacity of WG is the capacity credit that can be assigned for this load. This calculation is repeated for each of four load steps and every wind regime. After that capacity credit values for all load steps multiplied by their probability of occurrence, the sum of these products is weighted capacity credit of this system [9].

Results of weighted capacity credit calculation for moderate wind regime are presented in Table 11.

Table 11 – Weighted capacity credit calculation for moderate wind regime

Load level, MW	Probability of occurrence (P_i)	Capacity credit (C_i)	P_i×C_i	Σ P_i×C_i
405	0,25	0,6	0,15	0,6
385	0,25	0,6	0,15	
350	0,34	0,6	0,2	
285	0,16	0,6	0,1	

To demonstrate wind regime influence weighted capacity credit for high wind regime was calculated. Results are presented in Table 12.

Table 12 – Weighted capacity credit calculation for high wind regime

Load level, MW	Probability of occurrence (P_i)	Capacity credit (C_i)	P_i×C_i	Σ P_i×C_i
405	0,25	0,8	0,2	0,8
385	0,25	0,8	0,2	
350	0,34	0,8	0,27	
285	0,16	0,8	0,13	

Calculations of weighted capacity credit show that to replace conventional generator No3 with 63 MW capacity without reliability decreasing 108,62 MW or 79,74 MW of wind power under moderate and high wind regime respectively is required. This approach has the following drawbacks:

- Conventional generators work on full power or completely switched off, in other words, generators malfunctioning when operation with decreased output power is allowed was not taken into account, generators overloading capability also wasn’t investigated
- Output power of wind is assumed to be 63 MW or zero, however zero output power of large wind power plant is not credible event
- Heat energy production change was not included in this research

It is necessary to define certain amount of wind power that can be balanced by conventional generators. Power generator's balancing ability depends on electrical and heat load and will be discussed in the next part.

4.1.3 Combined heat and power plant balancing wind power

Situation when wind power is integrated in traditional power system inevitably leads to more variable operation of conventional generators. Base–load coal power plants operate on permanent basis with maximum efficiency and have small operational flexibility. Before introducing of large amounts of wind power uncertainty in power system were represented by load uncertainty and equipment failure possibility. To ensure reliable operation proper levels of spinning and non–spinning reserves were assigned to cover all possible errors. Deployment of wind generation brings one more source of uncertainty related to volatile nature of renewables. In case of low level of wind power higher amount of reserve is required; with higher level of penetration using higher level of reserves is not efficient and sometimes is not possible [18].

Total system demand always has to be covered by sufficient generation level (conventional generation or wind power generation). System should always carry some level of reserves in case of conventional generators failures, wind power deviations, unforecasted load increase. Reserve level depends on system reliability requirements [11].

Typical constraints which can be faced during CHP and WP balancing are as follows [11]:

1) electricity demand

2) heat demand

3) ramping capabilities of generation units

4) minimum up-time and down-time

All generating unit of thermal power station is combined heat and power producing units which has additional operation constraints. Typical operation area for CHP can be seen on Figure 9.

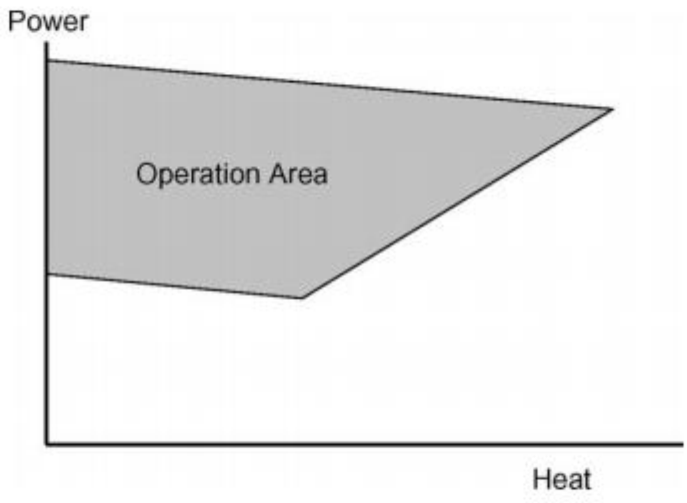

Figure 9 – Operation area of CHP generator [11]

Figure 9 shows that in case of high heat demand power output flexibility decreases. CHP are usually meet district or industrial heat demand, according to their heat demand curves [11].

At hours of good WP productivity electrical load of CHP units will be decreased, during low WP productivity all electrical and heat load will be covered by CHP generators.

The main purpose of this study is to define certain amount of WP that CHP plant could back-up and how it would affect CHP operation.

The main idea of local CHP-balancing wind power is to reduce additional costs related to building new power lines and balancing generators. WP will be balanced by CHP and therefore there will be no need transfer electrical energy excesses to the grid and overload transmission lines. This idea illustrated in Figure 10 [13].

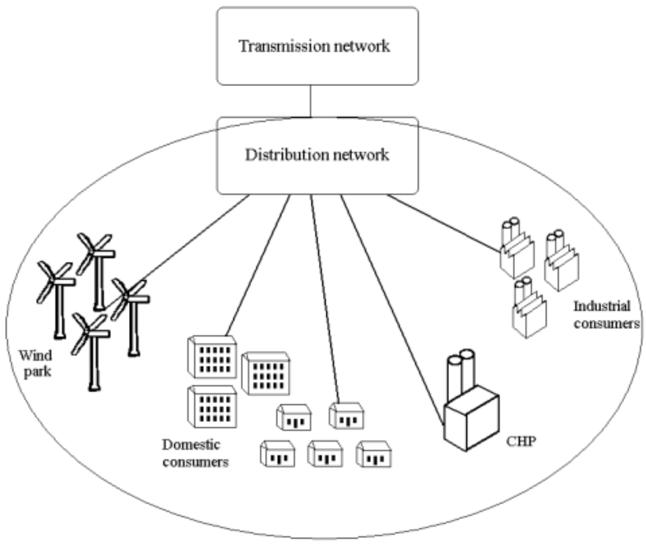

Figure 10 – Power system model [13]

It can be seen from Figure 10 that CHP with wind generation will produce electricity to meet electrical and heat energy demand of industrial and domestic consumers. The important thing is to avoid import of energy from outside area and minimize energy which cannot be consumed by local consumers to prevent overloading of interconnection lines. The following expression describes power balance of such system [13]:

$$P_{cons} + P_{eks} = P_{WT} + P_{CHP} + P_{imp} \tag{1}$$

where P_{cons} – consumed energy

P_{exs} – exported energy

P_{WT} – wind power generation

P_{CHP} – CHP generation

P_{imp} – imported energy

The purpose is to reduce P_{eks}, P_{imp}. The following expression describes heat balance of such system [13]:

$$Q_{cons} = Q_{CHP} \tag{2}$$

where Q_{cons} – consumed heat

Q_{CHP} – CHP produced heat

Because of unpredictable nature of wind power all balancing functions will be carried out by CHP. In case of proper balancing there will be no need to transfer electricity from the grid to feed local load, also in ideal case there would be no electricity excesses to be transferred to the grid. From system point of view it will not bring any negative effect on system operation, due to wind power deviations will not reach power system and therefore no regulation from the grid side and no investments to increase system flexibility would be required [13].

CHP will be operated to satisfy electricity and heat demand and to balance WP production. Electricity and heat demand can be evaluated according system operator forecast presented in Table 17. WP production will have priority which means that WP will produce maximum possible amount of power, remaining electricity demand will be covered by CHP generators. CHP plant will also cover all demanded heat. In order to evaluate remaining CHP balancing functions overloading capability existing unit commitment should be carefully investigated.

For simulation of CHP operation balancing WP I used EnergyPRO software package. This software can be applied for creating, analysis and improvement of energy projects. Based on user-defined inputs EnergyPRO optimizes power plant operation. As electricity yield of wind power wasn’t known I included wind farm with total capacity 60 MW in previous model. As a result I obtained new model of thermal power station. New EnergyPRO model of thermal power station is shown in Figure 11.

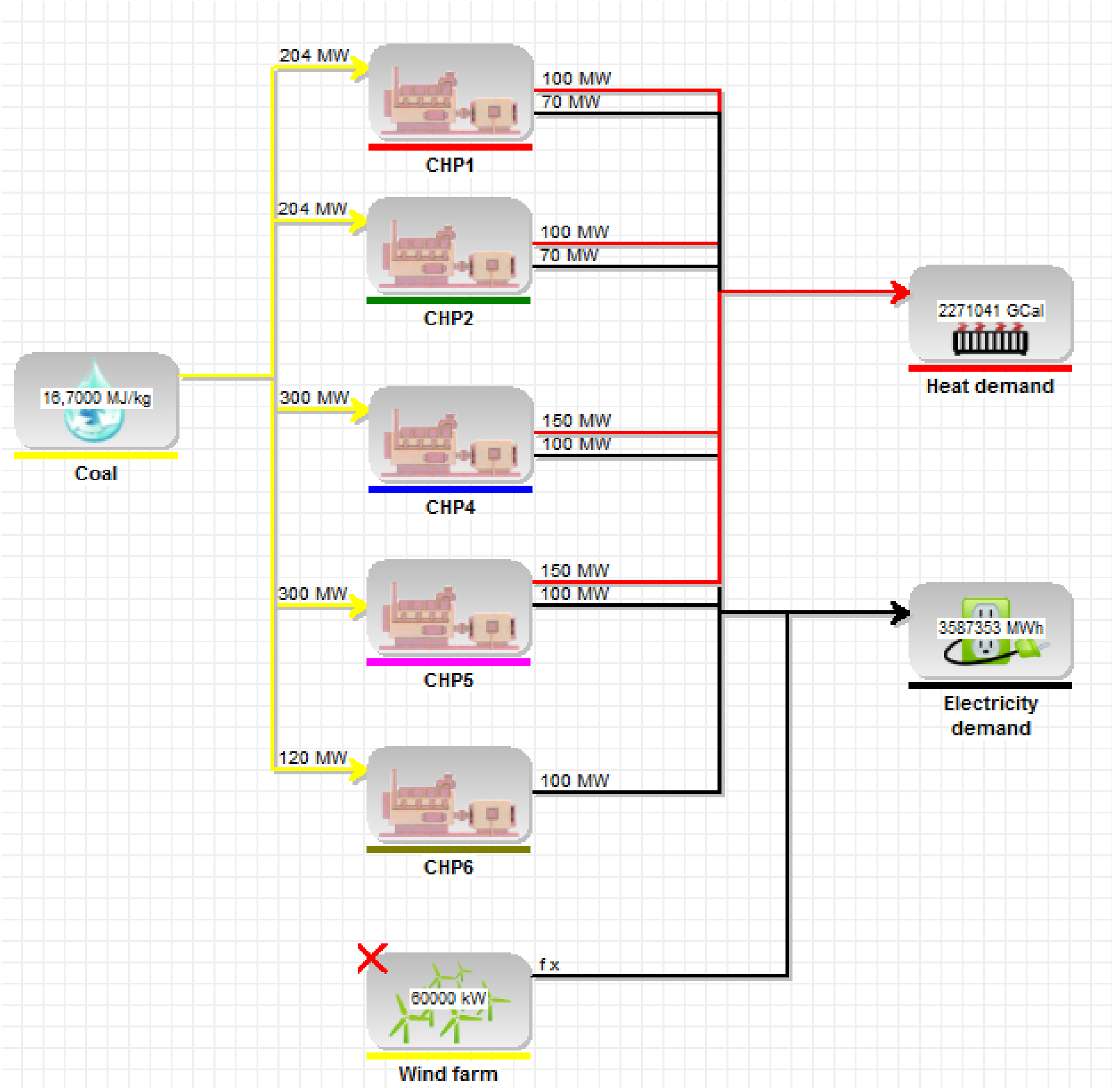

Figure 11 – Thermal power station model

In this model the inputs are as follows: CHP parameters and fuel data, wind turbines parameters and wind speed data parameters, electricity and heat demand curves. All necessary data concerning CHP, fuel, electricity and heat demand curves remains the same as in the first model. The fuel for thermal power station is coal, heat value of this coal is 16,7 MJ/kg. Wind speed hourly deviations throughout year 2016 which were taken from meteorological records for year 2015 are shown in Figure 12.

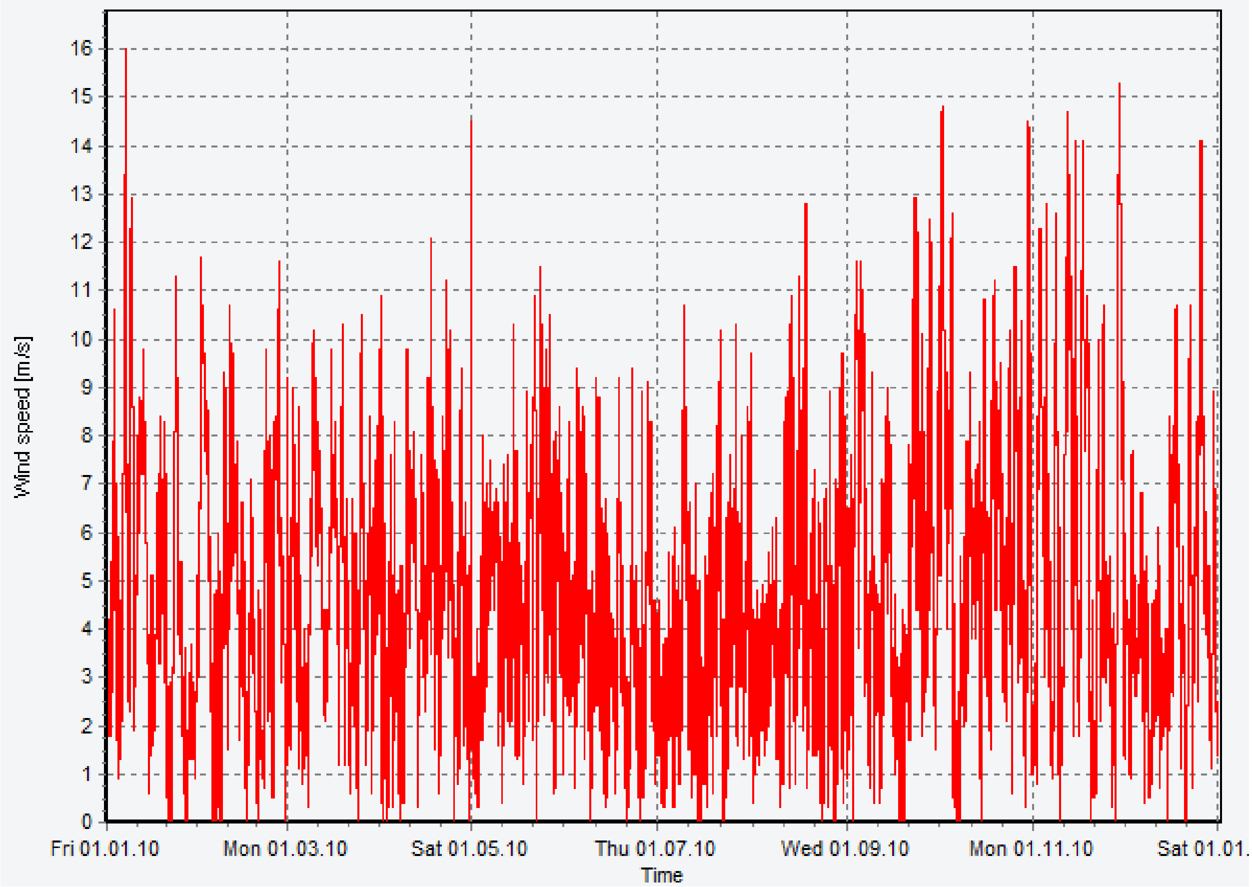

Figure 12 – Wind speed profile [19]

Wind farm will consist of thirty wind turbines Vestas V80 with 2 MW rated power. Power curve for Vestas V80 wind turbine is given below in Figure 13. In the current project hourly wind power production was calculated.

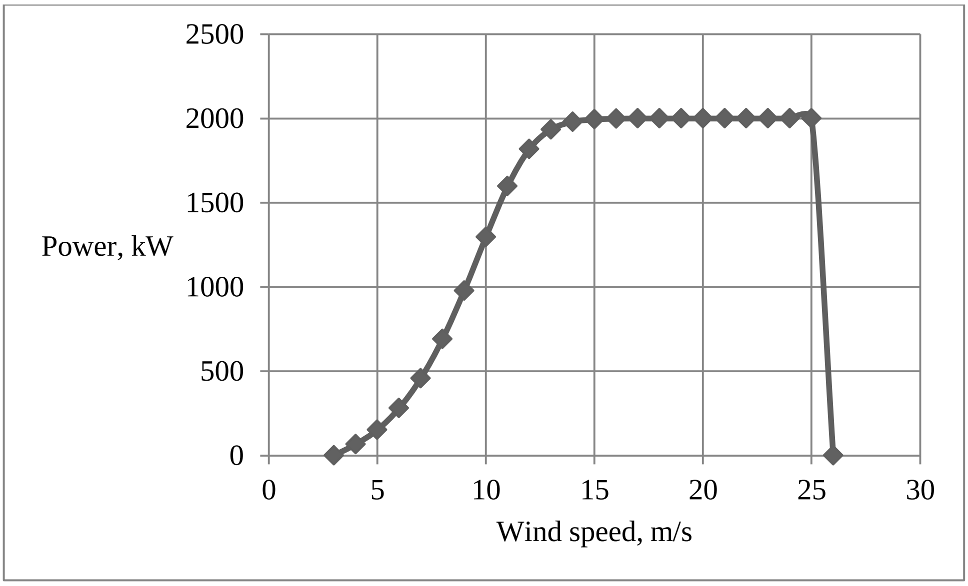

Figure 13 – Vestas V80 power curve [20]

EnergyPRO optimization strategies are based on power plant operation strategy. Operation strategy consist of power units generating priorities. Model creates power plant operation strategy in accordance with electricity and heat demand taking into account power units generating priorities defined by user. WP is prioritized; electricity demand which wasn't covered by wind power will be covered by CHP generators [16]. All heat demand will be covered by CHP generators. As a result I derived electricity and heat production data for each power turbine and wind farm electricity production data. Graphical results of thermal power plant electricity and heat production are presented in Figure 14.

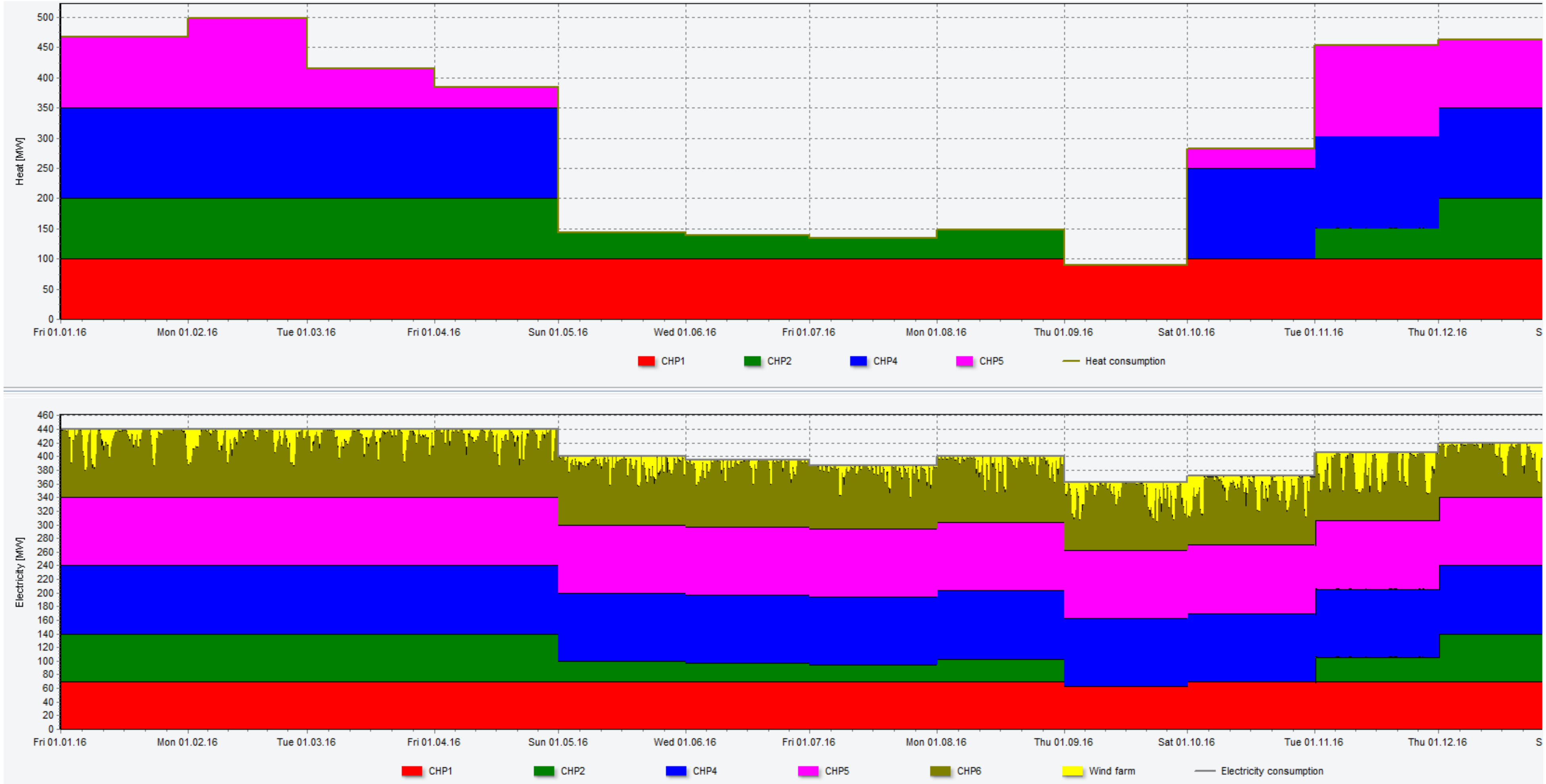

Figure 14 – Thermal power plant electricity and heat production

It can be seen that CHP 1, CHP2, CHP 4 and CHP5 can cover all demanded heat. It will allow to use CHP 6 for wind power balancing activities. CHP 6 can perform balancing activities until its load is higher than 40 %. When CHP 6 load less than 40 % it is better to curtail wind power production than switch off CHP 6 and increase CHP 5 load. More precise data can be taken from EnergyPRO annual energy conversion report which is automatically generated after modelling.

Calculated period: 01.2016 – 12. 2016.

Heat demands: 2 271 041,0 GCal.

Maximum heat demanded: 498 MW.

Heat production by CHP units can be found in Table 13.

Table 13 – Heat production

CHP unit	Heat amount, MWh/year	%
CHP 1	870 689,5	33,2
CHP 2	507 667,7	19,4
CHP 4	776800	29,2
CHP 5	479 488,4	18,2
CHP 6	0	0
Total	2 271 041	100

Electricity demands: 3 587 353 MWh.

Maximum electricity demanded: 440 MW.

Electricity production by wind farm and CHP units can be found in Table 14.

Table 14 – Electricity production

Unit	Electricity amount, MWh/year	%
CHP 1	609 482,7	17,0
CHP 2	355 367,4	9,9
CHP 4	878 400	24,5
CHP 5	878 400	24,5
CHP 6	780 020,2	21,7
Wind farm	85 422	2,4
Total	3 587 353	100

Table 15 – Hours of operation

Unit	Time, h/year	%
CHP 1	8 784	100
CHP 2	7 153	83,3
CHP 4	8 784	100
CHP 5	8 784	100
CHP 6	8 784	100
Wind farm	6 247	73,2
Total	8784	100

The conclusion has been that thermal power station has sufficient level of flexibility reserves to back up large wind farm with total power 60 MW. Wind farm will cover part of CHP 6 load. CHP 6 rated power is 100 MW, maximum admissible power 120 MW. Minimal active power is 40 MW. Without wind power CHP 6 generates 855 336 MWh of energy per year. Wind power will generate approximately 10 % of CHP 6 load. In order to motivate CHP plant to balance wind power economical aspects of this activity have to be carefully investigated.

4.2 Economical analysis

As was pointed in the previous chapters, two opportunities of thermal power plant operation optimization exist. The first one is put out of operation generator No3 since its operation period has expired and continue operation with five remaining generators. The load of thermal power plant will be decreased. The second opportunity is to put out of operation generator No3 and deploy wind farm with total capacity 60 MW. The first project costs will contain operation and maintenance costs of thermal power station, the second project will incorporate thermal power station operation and maintenance costs and establishing wind power investment project. In the following part I summarized basic economic approaches which can be applied to investment project attractiveness evaluation. Special attention will be devoted to wind power projects evaluation approaches.

4.2.1 Power project evaluation methods overview

Projects evaluation basics

The main purpose of investments economic evaluations is to analyze project robustness and attractiveness. Power projects are typically extremely capital–intensive and consequences of wrong investment decision can be dangerous for investor. Those kinds of investment decisions require careful analysis of potential attractiveness and risks of the project. In this section will be discussed evaluation methods which can applied to estimation of thermal power plant operation and establishment of wind power investment case.

Simple payback method

The simple payback (SPB) can be defined as period of time during which project's cash inflows will recover initial investments. SPB can be a measure of risk; with higher return time risk for investors will be also higher. Negative cash flows (initial investments) are usually followed by positive cash flows (revenues) in later periods. SPB can be expressed as minimum period of time t, which satisfies the following condition:

$$(C_I - C_O)_1 + (C_I - C_O)_2 + ... + (C_I - C_O)_t = \sum_{t=1}^{t}(C_I - C_O)_t \geq C_{II}, \quad (3)$$

where C_I – cash inflows,

C_O – cash outflows,

C_{II} – initial investment,

t – number of periods.

For renewable energy investment projects revenues or cash inflows should be assumed to be constant during the project lifetime. SPB can be calculated by this expression:

$$SPB = \frac{ICC}{AAR}, \quad (4)$$

where ICC – initial capital cost,

AAR – average annual revenue.

It is important to underline that this model presumes equal amount of electricity production per year with the same energy prices during all project lifetime. This method has some drawbacks which are listed below [4]:

1. SPB ignores time value of money which will inevitably lead to too optimistic results.
2. SPB doesn't take into consideration cash flows that will occur after payback period.

Taking into account all SPB disadvantages decision about investment opportunity cannot be made only on the basis of this method, however SPB method can be useful for understanding discounted payback method.

Discounted payback method

Discounted payback (DPB) approach takes into consideration time value of money by discounting cash flows and comparing them with the initial investment. DPB can be expressed by the following equation:

$$\frac{(C_I - C_O)_1}{(1+i)^1} + \frac{(C_I - C_O)_2}{(1+i)^2} + ... + \frac{(C_I - C_O)_t}{(1+i)^t} = \sum_{t=1}^{t} \frac{(C_I - C_O)_t}{(1+i)^t} \geq C_{II} \quad (5)$$

where C_I – cash inflows,

C_O – cash outflows,

C_{II} – initial investment,

t – number of periods,

i – discount rate.

For wind power projects DPB can be expressed by the following formula:

$$DPB = \frac{ICC}{[AAR - (O\,\&\,M + LLC)]}, \quad (6)$$

where ICC – initial capital cost,

AAR – average annual revenue,

O&M – Operation and Maintenance cost

LLC – Land lease cost.

DPB takes longer periods of time than SPB because of discounting future cash flows to a present moment. The main weaknesses of this method are [4]:

1. DPB doesn't take into consideration cash flows that will occur after payback period.
2. Payback period can be wrong because of deviation of discount rate

Net present value

Net present value (NPV) is the difference between discounted cash inflows and outflows, in other words, NPV is the sum of all discounted cash flows related to the project. Equation for NPV calculation:

$$NPV = (C_I - C_O) + \frac{(C_I - C_O)_1}{(1+i)^1} + \frac{(C_I - C_O)_2}{(1+i)^2} + ... + \frac{(C_I - C_O)_T}{(1+i)^T} = \sum_{t=1}^{t} \frac{(C_I - C_O)_t}{(1+i)^t}, \quad (7)$$

where C_I – cash inflows,

C_O – cash outflows,

t – number of periods,

i – discount rate.

It is assumed that annual revenue will be the same, but these cash flows should be discounted, since it will be earned in the future. The uniform cash flows NPV can be calculated by the following expression:

$$NPV = AAR\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] - ICC, \quad (8)$$

where AAR – average annual revenue,

ICC – initial capital cost,

i – discount rate,

N – wind farm lifetime.

This method has some drawbacks which are listed below [4]:

1. The task of defining real value of capital cost cannot be easily done, because interest rate that measures capital costs should include risks of the project.
2. The discount rate presumed to be constant, although it cannot be fixed due to market behavior and risks are permanently changing.
3. NPV value is always in monetary units, whereas it would be easier to compare if it would be in percentage units.

Internal rate of return

Internal rate of return (IRR) is the rate that makes NPV equal to zero. Investments will be attractive if IRR equals or greater than IRR expected by the investor. The project with higher level of IRR is preferable.

IRR can be calculated according to the expression:

$$NPV = \sum_{t=1}^{t} \frac{(C_I - C_O)_t}{(1+i)^t} = 0 \Rightarrow i = ? = IRR \tag{9}$$

where NPV – net present value,

C_I – cash inflows,
C_O – cash outflows,
t – number of periods,
i – discount rate.

The IRR represents the maximum rate of discount rate I that can still create zero NPV project. Zero NPV means that project covers capital costs and interest payments. The IRR of a wind energy project with uniform annual revenues can be found by the following expression:

$$NPV = AAR\left[\frac{(1+IRR)^N - 1}{IRR(1+IRR)^N}\right] - ICC = 0, \tag{10}$$

where IRR – internal rate of return,

AAR – average annual revenue,

ICC – initial capital cost,

N – wind farm lifetime.

This method has some drawbacks which are listed below [4]:

1. Investment project can have more than one IRR, depending cash flows structure; clear decision cannot be made.

2. The IRR ignores investments sizes, an alternative project can have smaller IRR but higher return. Absolute value of return can be more important for the investor; NPV approach doesn't have this drawback.

Cost of energy approach

Cost of energy calculation is one of the methods for evaluation and comparing power projects. Energy cost is cost paid by wind farm owner to produce one kWh of energy. Cost of energy from wind power projects represents the total sum of all costs over project lifetime. Important components wind power energy cost calculation is described in Figure 15.

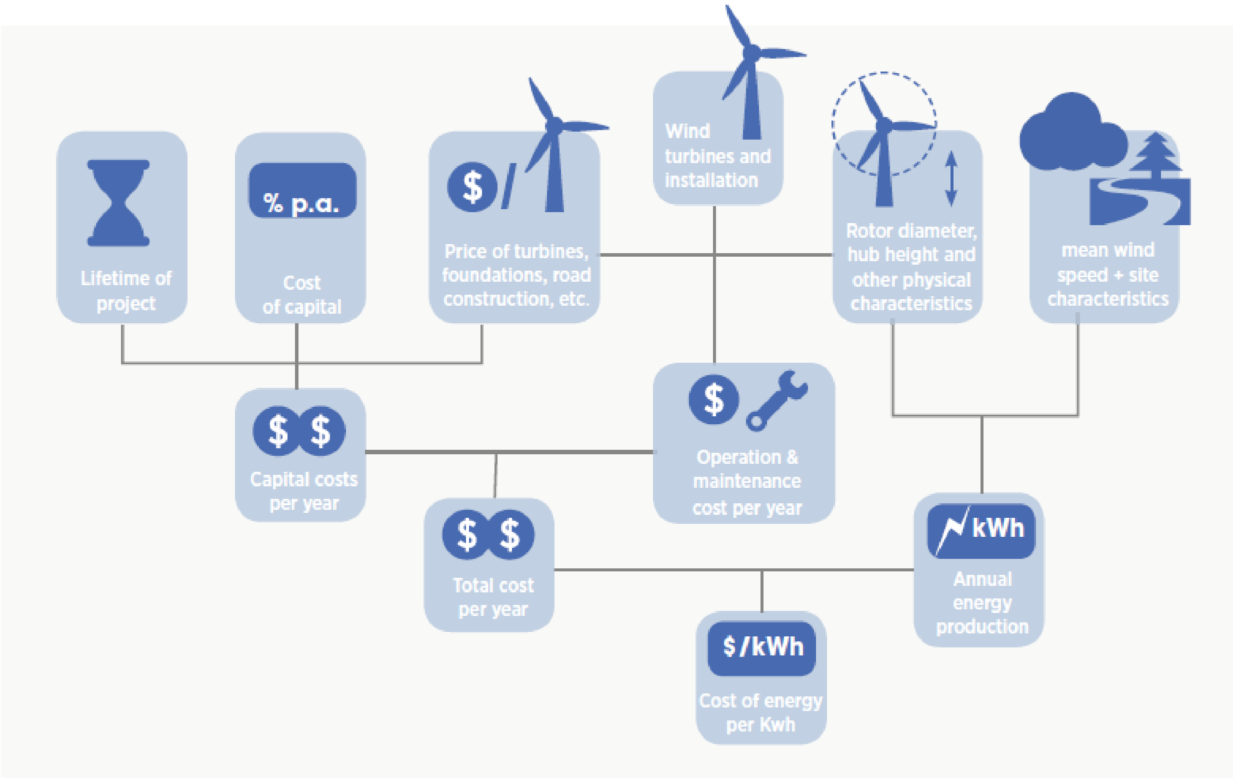

Figure 15 – Wind power energy cost calculation scheme [21]

Estimation of the cost of producing one unit of energy is important to the energy producer, due to investment project has to ensure necessary return for the investor [4].

In my case wind farm cost of energy will be calculated according to NPV=0 equation. After that wind power cost will be compared to thermal power plant electricity cost.

4.2.2 The first scenario analysis

In order to economically evaluate the first project attractiveness the following initial conditions and assumptions should be made:

- Generators lifetime is 40 years
- All generators were commissioned in the first year of the project
- Power plant is depreciated equally for the whole power plant lifetime
- Thermal power plant owner won't use loaned capital for operation of thermal power plant

The next step of the first scenario analysis is calculation of thermal power plant annual operation and maintenance costs.

Thermal power plant costs

The main idea of this chapter is to determine thermal power plant production costs and costs of energy. After that all production costs will be divided into electrical and heat energy production costs.

Planning thermal power plant electrical and heat energy production cost in case of absence of wind power will be made first. In order to define production costs all expenditures should be calculated. Production costs contain the following elements [19]:

- Fuel for technologic purposes – C_F,
- Maintenance costs – C_M,
- Depreciation costs – C_D,
- Salary payment – C_S,
- Payments for social needs – C_{SN},
- Other expenditures – C_O,
- Atmosphere emissions costs – $C_{EM.}$

Required heat amount produced by boiler can be derived by summing up quantity of heat demanded for electricity and heat production and auxiliary heat needs on different stages of thermal power plant production cycle [22]. Heat balance is presented in Table 16.

Table 16 – Heat balance

Purpose		Amount, GJ
Heat expenditure on electricity generation	Q_E	35 455 646,19
Heat supply	Q_T	9 689 949,60
Industrial needs	Q_{Ind}	5 434 485,60
Heating needs	Q_{Heat}	4 255 464,00
Heat expenditure on turbine workshop auxiliary needs	Q_{Auxt}	1 772 782,31
Heat losses	Q_{Loss}	484 497,48
Heat distribution losses	Q_{Distl}	474 028,76
Boiler net heat	Q_{net}	47 881 692,51
Heat expenditure on boiler workshop auxiliary needs	Q_{Auxb}	1 480 877,09
Boiler gross heat	Q_{Gross}	49 362 569,59

Standard coal quantity with specific calorific value 29,31 GJ/t required for boiler gross heat amount production, t

$$B_{St} = k_{St} \cdot \frac{Q_{Gross}}{\eta_B} = 0,0342 \cdot \frac{49362569,59}{0,895} = 1886256,85 \qquad (11)$$

where k_{st} – coefficient to transfer one GJ of heat into one ton of standard fuel;

η_B – boiler room gross efficiency;

Natural coal quantity with specific calorific value 16,7 GJ/t required for boiler gross heat amount production, t

$$B_{Nat} = B_{St} \frac{q_{st}}{q_{nat}} = 1886256,85 \cdot \frac{29,7}{16,7} = 3300949,49 \qquad (12)$$

Fuel costs for technologic purposes, ths.€/year

$$C_F = B_{Nat} \cdot \left(C_E + C_{TR}\right) \cdot \left(1 + p\right), \qquad (13)$$

where C_E = 18,75 – coal extraction cost, €/t;

C_{TR} = 0,1 – coal transportation cost, €/(t*km);

p = 1,21 – fuel storage losses, %;

$$C_F = 3300949,49 \cdot \left(18,75 \cdot 10^{-3} + 150 \cdot 0,1 \cdot 10^{-3}\right) \cdot \left(1 + 0,0121\right) = 112755, \text{ [22].}$$

Salary payment costs include main production staff wage payment, bonuses payment and so on [22]. Thermal power plant staff is 1066 people, annual average salary is 4500 € [15]. Annual salary payment expenditures, ths.€/year:

$$C_S = 4500 \cdot 12 \cdot 1066 \cdot 0,001 = 4797.$$

Social needs payments reflect social insurance, pension fund, health insurance payments [22]. Social tax contains 11 % of salary payments, ths.€/year:

$$C_{SN} = 4797 \cdot 0,11 = 528.$$

Maintenance costs can be defined by thermal power plant repair payment standards. Repair staff payment can be taken as 35 % of total repair work costs, 65 % are material costs, repair parts costs and so on[22]. According to unified energy system standards repair staff quantity for coal thermal power plant with six boilers and six generators with total boiler steam productivity 2520 t/h will contain 25% of all staff [23].

$$C_M = 0,25 \cdot (C_S + C_{SN}) / 0,35 = 3803 ths.€ / year \quad (14)$$

Depreciation costs depends on power generators expected lifetime and depreciation method. Generators lifetime is 40 years, linear depreciation method (equal payments every year) [22].

$$C_D = \frac{c_{sp} \cdot P}{N} = \frac{0,065 \cdot 556000}{40} = 904 ths.€ / year \quad (15)$$

where c_{sp} – specific investment costs, ths.€/kW;

P – thermal power plant rated power , kW;

N – generators lifetime, years.

Other payments in production cost calculation comprise equipment insurance payment, short–term interests payment, rent payment, security payment and so on [22]. Other payments amount can be approximately estimated as 10% of fixed costs, ths.€/year.

$$C_O = 0,1 \cdot (0,75 \cdot C_S + 0,75 \cdot C_{SN} + C_D + C_M) = \quad (16)$$
$$= 0,1 \cdot (0,75 \cdot 4797 + 0,75 \cdot 528 + 904 + 3803) = 870.$$

The next category of thermal power plant annual costs is atmosphere emission costs. The main sources of emissions are six thermal power plant boilers. Fuel for thermal power plant boilers is coal; parameters of this coal are given in Table 17.

Table 17 – Thermal power plant fuel parameters [15]

Fuel type	Calorific value, q_{nat}, GJ/t	Annual average fuel structure						
		A^P, %	S^P, %	N^P, %	O^P, %	H^P, %	C^P, %	W^P, %
Coal	16,7	40,57	0,38	0,81	7,72	2,7	42,64	5,18

Atmosphere emissions can be divided by five elements:

- Nitrogen dioxide, NO_2,
- Nitrogen oxide, NO,
- Sulphur dioxide, SO_2,
- Carbon oxide, CO

- Inorganic dust, SiO_2

Total annual amount of all above mentioned emissions for the year 2013 is presented in Table 18 [15]:

Table 18 – Emissions amount [15]

Substance	Emission, t/y
Nitrogen dioxide, NO_2,	12258,62
Nitrogen oxide, NO,	1991,95
Sulphur dioxide, SO_2,	19287,4
Carbon oxide, CO	1943,1
Inorganic dust, SiO_2	6904,42

Those measurements were made for the year 2013, in 2013 thermal power plant output power was 505 MW, electrical energy production was 2 862 286,88 MWh, heat energy production was 8 485 534,1 GJ, annual coal expenditure was 2 404 071 tons [15], in 2015 thermal power plant output power was increased to 556 MW and, according to my calculations, electrical energy production will be 3 929 760 MWh, heat energy production will be 9 689 949,6 GJ, annual coal expenditure will be 3 300 949,5 tons. These data differs a lot, therefore emissions data need to be adjusted to the new parameters. Dependency between emissions amount and burnt coal amount is linear [15]; emissions amounts will be recalculated proportionally. Emission costs for thermal power plant were taken from [24]; cost decreasing coefficient 0,3 is applied to all thermal power station emissions, price of atmosphere emissions exceeding declared value is ten times higher [24]. Total emission costs for the first case scenario are presented in Table 19.

Table 19 – Emissions cost for the first scenario

Substance	Emission, t/y	Cost, ths.€/y
Nitrogen dioxide, NO_2,	16831,9	571,21
Nitrogen oxide, NO,	2735,08	92,82
Sulphur dioxide, SO_2,	26482,88	898,72
Carbon oxide, CO	2668	90,54
Inorganic dust, SiO_2	9480,23	321,72

Total annual atmosphere emission costs for the first case scenario:

$$C_{EM} = 1975 \text{ths.€} / \text{year}$$

After calculation of all expenditures I divided them by workshops. There are three groups of workshops in aggregated calculations: I – boiler and turbine workshop, II – electrical workshop, III – common expenditures [22]. Cost division of power station costs is shown in Table 20.

Table 20 – Cost division by power plant main workshops, ths.€/year

Cost	Workshop		
	I	II	III
C_F	112 755	0	0
C_S	1 400	1 698	1 699
C_{SN}	154	187	187
C_D	420	430	54
C_M	1900	2100	454
C_O	0	0	1 003
C_{EM}	1975	0	0
C	C^{I}=118604	C^{II}=4415	C^{III}=3264

All thermal power plant costs should be divided by electrical and heat energy. The first group costs are divided proportionally to the fuel cost, so fuel costs should be divided between electrical energy and heat production first [22].

Fuel expenditure on heat energy production, t

$$B_H^{/} = \frac{Q_T}{\eta_K^H * Q_P^H}, \quad (17)$$

$$B_H^{/} = \frac{9689950}{0,86 * 29,31} = 384546,21.$$

where Q_T – total amount of heat calculated from Table 16, GJ;

η_k^H – boiler room efficiency coefficient;

Q_{sp}^{st} – standard fuel specific calorific value, GJ/t;

Fuel expenditure on electrical energy production, t (losses of heat)

$$B_E^{/} = B_{St} - B_H^{/}, \quad (18)$$

$$B_E^{/} = 1886256,85 - 384546,21 = 1476516,71.$$

Heat losses were omitted during this fuel division; however this approach also doesn’t take into consideration electrical energy losses on heat energy production, which cannot be neglected, due to it will inevitably lead to the underestimation of heat quantity needed for heat production [22]. Fuel expenditure on heat energy production should be recalculated using following expression:

$$B_H = B_H^{/} + b_e \cdot E_{HP}, \quad (19)$$

where $b_e = \frac{B_E^{/}}{E - E_{HP}}$ – specific fuel expenditure, t/kWh;

E_{HP} – electrical energy expenditure on heat energy production

$$B_H = 384546,21 + 0,00038 \cdot 20279,68 = 384571,4,$$
$$B_E = B_{St} - B_H = 1886256,85 - 384571,4 = 1501685,45.$$

Proportion between B_E and B_H is 79,6% and 20,4% respectively, thus all first workshop group costs will be divided in that way. Cost division for the first group is shown in Table 21.

Table 21 – Cost division for the first workshops group

Type of costs	Cost			
	Electrical energy		Heat energy	
	ths.€	%	ths.€	%
C_F	89 766,49	0,951	22 988,58	0,951
C_S	1 115	0,012	285	0,012
C_{SN}	123	0,001	31	0,001
C_D	334,37	0,004	85,63	0,004
C_M	1512,63	0,016	387,37	0,016
C_O	0	0	0	0
C_{EM}	1572,33	0,02	402,66	0,02
C^I	$C_E^I = 94423$	100	$C_H^I = 24181,08$	100

First group costs C^I were divided into electricity production costs $C_E^I = 94423 \text{ths.€}$ and heat production costs $C_H^I = 24181,08 \text{ths.€}$. The second group cost dedicated entirely to the electrical energy production. It means that $C^{II} = C_E^{II} = 4415 \text{ths.€}$ and $C_H^{II} = 0$. The second group expenditures are summarized in Table 22.

Table 22 –The second group of workshops expenditures

Type of costs	Cost			
	Electrical energy		Heat energy	
	ths.€	%	ths.€	%
C_F	–	0	–	–
C_S	1 698	38,5	–	–
C_{SN}	187	4,2	–	–
C_D	430	9,7	–	–
C_M	2100	47,6	–	–
C_O	–	0	–	–
C_{II}	$C_E^{II} = 4415$	100	$C_H^{II} = 0$	–

Cost division for the third group will be made according to the cost proportion of the first and the second group.

$$C_E^{III} = C^{III} \cdot \frac{C_E^I + C_E^{II}}{C^I + C^{II}}, \tag{20}$$

$$C_E^{III} = 3264 \cdot \frac{94423+4415}{118604+4415} = 2623,2$$

$$C_H^{III} = C^{III} \cdot \frac{C_H^I}{C^I + C^{II}}, \quad (21)$$

$$C_H^{III} = 3264 \cdot \frac{24181,1}{118604+4415} = 641,57$$

The third group costs will be divided by electrical $C_E^{III} = 2623,2$ths.€ and heat energy $C_H^{III} = 641,57$ths.€ in proportion 80% and 20% respectively. Cost division for the second group is shown in Table 23.

Table 23 – Cost division for the third workshops group

Type of costs	Cost			
	Electrical energy		Heat energy	
	ths.€	%	ths.€	%
C_F	–	0	–	0
C_S	1365,04	52	334	52
C_{SN}	150,15	6	36,71	6
C_D	43,39	2	10,61	2
C_M	364,76	14	89,24	14
C_O	699,02	27	171,02	27
C_{III}	$C_E^{III} = 2623,2$	100	$C_H^{III} = 641,57$	100

Annual electrical energy production costs, ths.€

$$C_E = C^I{}_E + C^{II}{}_E + C^{III}{}_E, \quad (22)$$

$$C_E = 94423+4415+2623,2 = 101461,2.$$

Annual heat energy production costs, ths.€

$$C_H = C^I{}_H + C^{III}{}_H, \quad (23)$$

$$C_H = 24181,08+641,57 = 24822,65.$$

Cash flow model for the first scenario

After calculation of annual thermal power plant operation and maintenance costs, these expenditures will be incorporated in forty–year long cash flow stream. Electric and heat energy production costs need to be adjusted to the prices escalation rate within the whole project lifetime. In my opinion, thermal power plant fuel costs, salary costs, social needs expenditures and consequently thermal power plant revenue will grow following Kazakhstan inflation rate.

After National Bank of Kazakhstan gave up the control of the national currency exchange rate on August 20th, 2015, national currency lost half of its value against US dollar in five months. As a consequence, inflation rate is growing rapidly. Inflation rate changes during last 12 months are reflected in Figure 16.

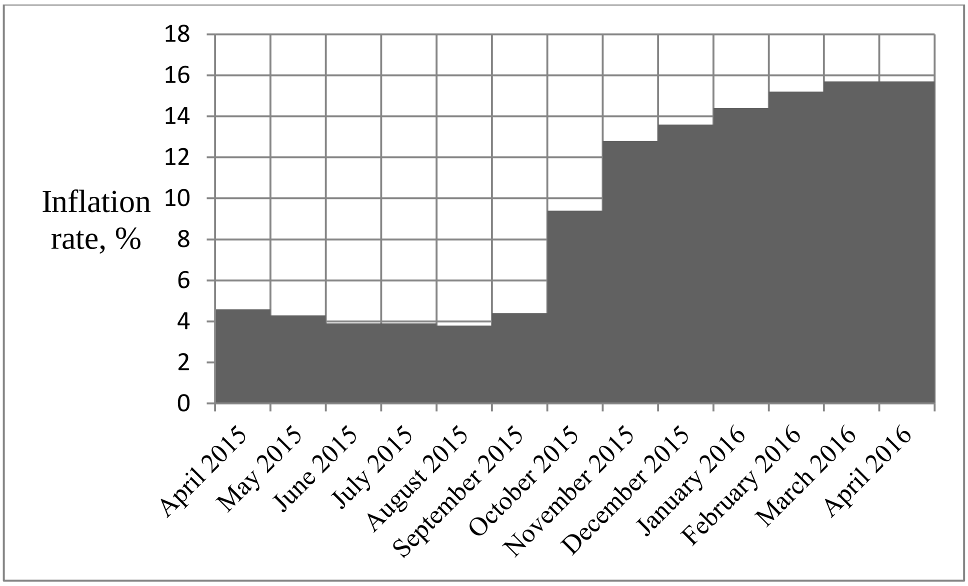

Figure 16 – Kazakhstan inflation rate [25]

Country–specific escalation rate forecast according to Trading Economics global macro models and analysts expectations is given in Table 24.

Table 24 – Inflation rate forecast [25]

	Actual	Q2/16	Q3/16	Q4/16	Q1/17	2020
Inflation rate, %	15,7	12,03	7,3	9,3	9,3	6,56

According to these data annual inflation rate for 2015 and 2016 year will contain 9,2% and 9,7% respectively. I assumed that after year 2020 inflation rate will remain on the same level and will contain 6,5 % annually. Discount rate (or opportunity cost of capital) should always cover inflation and should be set at the point of another low–risk investment, such as bank saving account.

National Bank Governor increased maximum interest rate from 10 percent up to 14 percent on newly accepted bank deposits in national currency. This decision was made pursuing the goal of compensating the increased level of inflation and increasing of deposits in the national currency. Under increasing inflation rate conditions this decision was the only logical [26]. I presume that after year 2020 maximum interest rate will be returned back to the 10% value to follow inflation rate curve.

The other important factor which makes significant influence on thermal power plant operation is taxation system. According to Kazakhstan taxation system [27], the thermal power plants are imposed by the following taxes [1]:

- Corporate income tax. Income tax is applied to all companies and equals to 15% of revenue
- Value added tax. This tax should be applied to the value added by thermal power station and set at 12% rate.
- Social tax. Social tax contains 11% of salary and paid by producers.

Taking into account all previous assumptions and calculations, cash flow model for the first thermal power plant operation scenario was built. Cash flows for heat and electrical energy were calculated separately, total NPV of the project is the sum of these two cash flows net present values.

To calculate minimum price of electrical and heat energy I found prices which satisfied NPV=0 condition using What–If analysis in Excel.

Minimum price of electrical energy $P_{el.min1}$ = 0,026 ths.€/MWh.

Minimum price of heat energy $P_{h.min1}$ = 0,00255 ths.€/GJ.

Total NPV sensitivity analysis to the electrical and heat energy costs is given in Table 25.

Table 25 –The first scenario total NPV analysis

		Cost of electrical energy, ths.€/MWh					
NPV Total, ths. €		0,025	0,026	0,027	0,028	0,029	0,03
Cost of heat energy, ths.€/GJ	0,0025	-76300,06	-10472,33	55355,40	121183,13	187010,86	252838,59
	0,0026	-59792,84	6034,89	71862,62	137690,35	203518,08	269345,81
	0,0027	-43285,61	22542,12	88369,85	154197,58	220025,31	285853,04
	0,0028	-26778,39	39049,34	104877,07	170704,80	236532,53	302360,26
	0,0029	-10271,17	55556,56	121384,29	187212,02	253039,75	318867,48
	0,003	6236,05	72063,79	137891,52	203719,25	269546,98	335374,71

During first scenario cash flow analysis cost of electrical and heat energy was calculated. Cost of energy for the first scenario will be used during the second scenario analysis and for energy costs comparison.

4.2.3 The second scenario analysis

In order to economically evaluate the second project attractiveness the following initial conditions and assumptions were made:

- Conventional generators lifetime is 40 years
- Conventional generators were commissioned in the first year of the project
- Power plant is depreciated equally for the whole power plant lifetime
- Wind farm development process will take 3 years

- Wind farm total lifetime is 20 years

The first step of the second scenario analysis is calculation of thermal power plant annual operation and maintenance costs in case of wind power presence.

Thermal power plant costs

In this chapter I calculated thermal power plant production costs in case of presence of wind power. The cost structure will remain the same; the major differences will be in fuel costs.

Heat balance for the second case is presented in Table 26.

Table 26 – Heat balance

Purpose		Amount, GJ
Heat expenditure on electricity generation	Q_E	33 374 761,63
Heat supply	Q_T	9 689 949,60
Industrial needs	Q_{Ind}	5 434 485,60
Heating needs	Q_{Heat}	4 255 464,00
Heat expenditure on turbine workshop auxiliary needs	Q_{Auxt}	1 668 738,08
Heat losses	Q_{Loss}	484 497,48
Heat distribution losses	Q_{Distl}	452 179,47
Boiler net heat	Q_{net}	45 674 693,73
Heat expenditure on boiler workshop auxiliary needs	Q_{Auxb}	1 412 619,39
Boiler gross heat	Q_{Gross}	47 087 313,12

Standard coal quantity with specific calorific value 29,31 GJ/t required for boiler gross heat amount production was calculated from equation (11):

$$B_{St} = k_{St} \cdot \frac{Q_{Gross}}{\eta_B} = 0,0342 \cdot \frac{47087313,12}{0,895} = 1799314,09t,$$

where k_{st} – coefficient to transfer one GJ of heat into one ton of standard fuel;

η_B – boiler room gross efficiency;

Natural coal quantity with specific calorific value 16,7 GJ/t required for boiler gross heat amount production was calculated from equation (12):

$$B_{Nat} = B_{St} \frac{q_{st}}{q_{nat}} = 1799314,09 \cdot \frac{29,7}{16,7} = 3148799,65t.$$

Fuel costs for technologic purposes were calculated from equation (13):

$$C_F = B_{Nat} \cdot \left(C_E + C_{TR}\right) \cdot \left(1 + p\right),$$

where C_E = 18,75 – coal extraction cost, €/t;

C_{TR} = 0,1 – coal transportation cost, €/(t*km);

p = 1,21 – fuel storage losses, %;

$$C_F = 3148799,65 \cdot \left(18,75 \cdot 10^{-3} + 150 \cdot 0,1 \cdot 10^{-3}\right) \cdot \left(1 + 0,0121\right) = 107558 \text{ths.€} / \text{year}, [22].$$

Annual salary payment and social needs expenditures will remain on the same level since thermal power plant staff quantity won't be changed. Annual salary payment expenditures, ths.€/year:

$$C_S = 4500 \cdot 12 \cdot 1066 \cdot 0,001 = 4797.$$

$$C_{SN} = 4797 \cdot 0,11 = 528.$$

Maintenance costs will be decreased approximately by 15%, due to one of six turbines will be out of operation; calculated from equation (14):

$$C_M = 0,85 \cdot 0,25 \cdot (C_S + C_{SN}) / 0,35 = 3157 ths.€ / year.$$

Depreciation costs will be also decreased because thermal power plant rated power will be decreased by 63 MW; calculated from equation (15):

$$C_D = \frac{c_{sp} \cdot P}{N} = \frac{0,065 \cdot 493000}{40} = 801 ths.€ / year.$$

where c_{sp} – specific investment costs, ths.€/kW;

P – thermal power plant rated power , kW;

N – generators lifetime, years;

Other payments amount was calculated from equation (16):

$$C_O = 0,1 \cdot (0,75 \cdot C_S + 0,75 \cdot C_{SN} + C_D + C_M) =$$
$$= 0,1 \cdot (0,75 \cdot 4797 + 0,75 \cdot 528 + 801 + 3157) = 795 \text{ths.€} / \text{year}.$$

Atmosphere emissions costs were calculated with the same approach as for the first case scenario. Total annual atmosphere emission costs for the first case scenario:

$$C_{EM} = 1884 \text{ths.€} / \text{year}$$

Cost division by thermal power station workshops and cost division by heat and electrical energy were made in the same way.

Electrical energy production costs were calculated from equation (22):

$$C_E = C^I_E + C^{II}_E + C^{III}_E,$$

$$C_E = 88852,34 + 3887,78 + 2520,78 = 95260,9 \text{ ths.€}.$$

Heat energy production costs were calculated from equation (23):

$$C_H=C^I_H+C^{III}_H,$$

$$C_H=24143{,}54+656{,}04= 24800 \text{ ths.€}.$$

The conclusion has been that if part of thermal power station electrical load will be taken by wind farm thermal power plant electrical energy production costs will be decreased by 6% or 6200 ths.€ annually, heat energy production costs will approximately remain on the same level.

The next step of the second scenario analysis is calculation of wind farm construction and annual operation costs.

Establishing the wind power investment case

The purpose is development of wind farm with total capacity 60 MW. Development of wind power project usually starts from various feasibility studies such as geological study, wind potential study, environmental impact, project rights and preliminary economic evaluation. The purpose of each investment case analysis is to evaluate investment project profitability and uncertainty before final investment decision. Wind power project development process typically takes five years, wind farm operation last from twenty years up to thirty years. In order to properly evaluate wind power investment project eight elements should be taken into account [28]:

- Project costs
- Energy production
- Energy prices and subsidies
- Operating costs
- Project–end options
- Financing
- Taxation system
- Risks and uncertainties

These elements will be enumerated separately and incorporated into financial model to economically evaluate wind power investment project.

Project costs

Wind farm costs consist of two major parts [4]:

- Investment costs
- Operation and maintenance costs

It is important to take into account differentiation of wind farm costs on costs per installed MW and costs per kWh of produced wind power. The major fundamental difference between electricity generated by wind power and conventional power plant is the absence of fuel costs. On the other hand, initial investment costs can easily reach 80% of wind farm overall costs during all project lifetime [4].

Investment costs

This type of costs can be also called “capital costs” or “initial investments”. These expenditures occurs only once in the beginning of the project. Investment costs include purchasing and installation of wind turbines and other equipment, land preparation, obligatory licenses obtainment, grid connection development [4].

Investment costs of wind power project can be divided into four main parts [28]:

- Wind turbines cost
- Civil works cost
- Grid connection cost
- Other capital costs

Investment costs breakdown for a typical onshore wind power project illustrated in Figure 17.

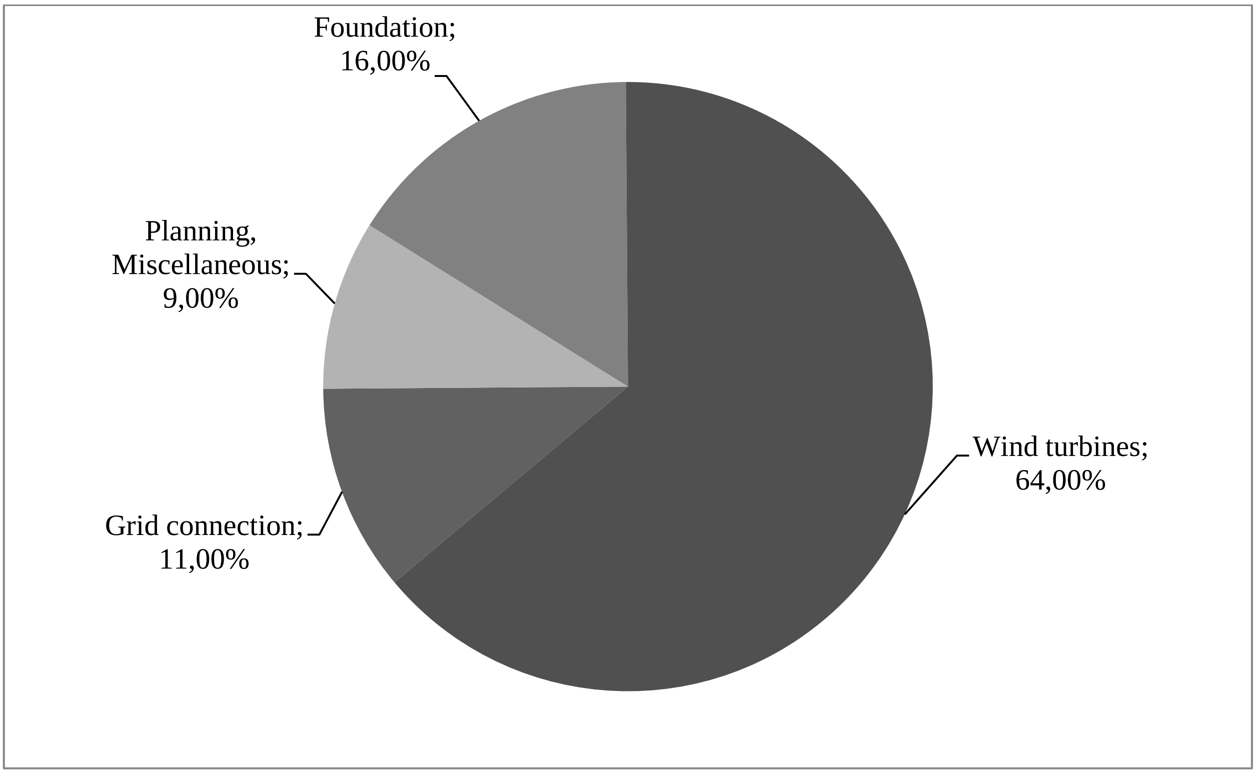

Figure 17 – Wind power investment costs division [21]

Wind turbines costs

As illustrated in Figure 17 wind turbines costs are the most substantial part of wind farm investment costs. Wind turbines costs depend on the country, wind industry development and other factors. The most expensive parts of wind turbine are tower and rotor blades, comprising almost half of overall wind turbine cost. Tower and rotor blades costs strongly depend on steel prices, however increased competition and implementation of light–weight materials can reduce these costs. Blades weight minimization is another cost reduction potential. Improving blades design and using more carbon materials will lead to weight and cost reduction, however high costs of carbon materials can become a serious issue. Using gearless drive generators can be another cost reduction potential [28].

Grid connection costs

It is possible to connect wind farm to electricity grids via transmission or distribution network with step–up transformers, which will increase project cost. There is also a possibility to use high voltage direct current link in case of long–distance connection, however energy losses in converting alternating current into direct current should be kept in mind. Responsibility for grid connection can be taken by system operator or wind farm owner. Typical grid connection costs include step–up transformers cost, power lines cost, electrical work, and connection point costs [28].

Civil work costs

Wind turbines transportation and installation costs, wind turbine foundation and access roads construction costs are incorporated in civil work costs. Wind turbine foundation is capital–intensive, due to it is typically made by concrete and requires a lot of steel. Efficient foundation design and materials substitution can reduce wind turbines foundation costs. The second major component of civil work is wind turbine installation and transportation costs [28].

Wind turbines costs ranging from less than 770 €/kW in China up to 1650 €/kW in developed countries. The total capital costs including all above mentioned cost factors are as little as 1375 €/kW in China and between 2035 and 2420 €/kW in USA, Germany and Spain [21]. I decided to purchase wind turbines in China, due to lowest market prices and close location which will reduce wind turbines transportation costs. Total costs for onshore wind farms in China for the year 2015 were ranged from 1045 €/kW up to 1375 €/kW [21]. The 1200 €/kW value will be taken as a base cost of capital.

Total capital costs of wind farm, ths.€:

$$C_{Tot} = 1,2 \cdot 60000 = 72000.$$

According to capital costs division in Figure 17 all wind farm capital costs components were calculated.

Table 27 – Wind farm capital cost components

Component	Cost, ths.€
Wind turbines costs	46080
Construction works costs	11520
Planning and other costs	6480
Grid connection costs	7920

Wind energy production

Expected power production of wind farm is the paramount importance input factor. Wind speed is the main factor of wind farm energy production and wind farm revenues. Therefore wind speed profile has to be carefully measured and forecasted. Wind speed study implies 2–5 years of wind speed measurements in 10–minute intervals; direction, temperature, humidity and wind density also has to be taken into account. All these data will be used to predict expected annual energy production of wind farm. Wind speed profiles of nearby wind parks and wind maps data can be used as an alternative [28].

In my case annual energy production data were simulated by EnergyPRO software. Wind speed profile can be seen in Figure 12, wind farm annual energy production 85422 MWh. Wind farm monthly production data presented in Table 28.

Table 28 – Wind farm monthly production data

Month	Production, MWh
January	7318,7
February	7496,3
March	6662,5
April	5405,6
May	6235,3
June	3634,4
July	3978,6
August	5346,4
September	9201,2
October	10918,3
November	13056,1
December	6169,5

Wind farm annual energy production is assumed to be constant during the whole project lifetime. Distribution of wind speed will remain on the constant level from year to year, resulting in uniform amount of electricity produced by wind farm.

Renewable energy prices and subsidies

The State Program for Accelerated Industrial and Innovative Development of the Republic of Kazakhstan defines renewable energy sector development as one of the key steps of future economic growth. There are a lot of existing plans for support and promotion of building and operating clean energy power plants. A lot of efforts are being made to develop mechanism of integration of renewable energy into unified power system. The government commitment of renewable sources of energy support and promotion was officially justified in the republic of Kazakhstan law on Support to the use of renewable energy sources, 2009. This law includes combination of renewable energy incentives. According to this law regional power grid companies ensure that clean energy producing power plants will access the grid and all generated energy will be purchased. Also companies generating clean energy won’t pay power transmission fees. Other incentives are feed–in–tariffs and governmental guaranteeing that planned renewable energy facilities will be constructed and connected to the power grids [1].

In base case scenario of the second project energy generated by wind farm will be bought by power system with the same price as electricity generated by conventional generators of thermal power plant. Different price of wind power will be also investigated during the second project sensitivity analysis.

Operation and maintenance costs

This type of costs incorporates all expenditures that will occur after commission and ensures regular operation of wind farm.

Operation and maintenance of wind power project can be divided into six parts [28]:

- Maintenance and repair
- Land rent payment
- Management
- Insurance costs
- Equipment decommission costs
- Other operating costs

Operation and maintenance costs breakdown for a typical onshore wind power project illustrated in Figure 18.

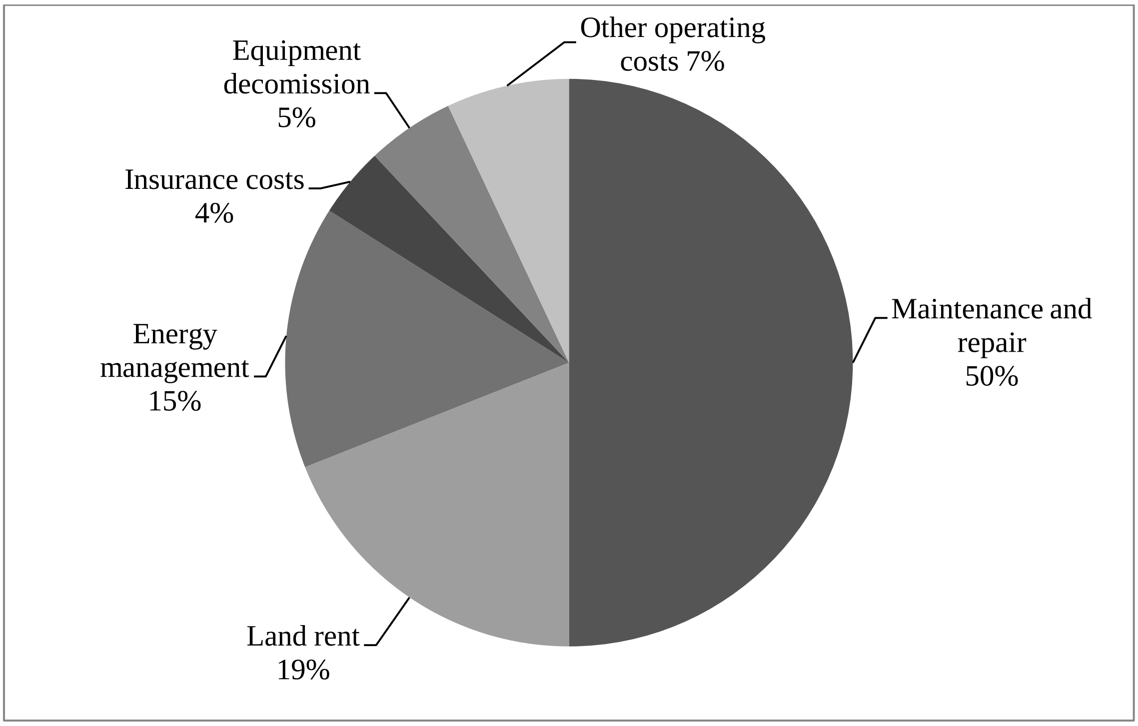

Figure 18 – Wind power operation and maintenance costs division [21]

Annual operating costs such as land rent, equipment insurance, energy management costs, O&M costs can be assumed as fixed; however, some of these costs depend on wind turbine production. Some of O&M costs can be covered by wind turbine supplier company throughout all wind turbines lifetime period. Although wind turbines total lifetime is 20 – 25 years, significant repair can be required after first 10 years of the wind farm operation [4]. Also, wind turbines can require more often repairs in the end of lifetime period, which can cause additional wind turbines repair and maintenance costs.

The lowest level of O&M costs which can be seen in China is 0,011 €/kWh. Average European O&M costs are around 0,022 €/kWh.

Annual operation and maintenance costs of wind farm, ths.€:

$$\mathrm{C_{Tot}} = 0,011 \cdot 85422 = 939,64.$$

According to O&M costs division in Figure 18 wind farm O&M costs components were calculated.

Table 29 – Wind farm capital cost components

Component	Cost, ths.€
Maintenance and repair costs	469,82
Land rent payment	178,53
Energy management costs	140,95
Insurance costs	37,58
Equipment decommission costs	47
Other operating costs	65,77

Wind farm operation and maintenance costs also include salary payments, social needs payments, wind turbines depreciation costs. 60 MW wind farm will require permanent presence of 5–6 qualified engineers, annual average salary is 4500 €. Annual salary payment expenditures, ths.€/year:

$$C_S = 4500 \cdot 12 \cdot 6 \cdot 0,001 = 324.$$

Social tax contains 11 % of salary payments, ths.€/year:

$$C_{SN} = 324 \cdot 0,11 = 35,64.$$

Depreciation costs depends on wind generators expected lifetime and depreciation method. Generators lifetime is assumed to be 20 years, linear depreciation method was chosen, calculated from equation (15).

$$C_D = \frac{c_{sp} \cdot P}{N} = \frac{46080}{20} = 2304 ths.€ / year$$

where c_{sp} – specific investment costs, ths.€/kW;

P – wind farm rated power , kW;

N – generators lifetime, years.

Project–end opportunities

Basically, in the end of the wind power project two options exist: wind turbines decommission or wind park repowering with new wind turbines. If it is possible to extend land lease contract then repowering of the wind park is more credible event. It is also important to define wind power project lifetime, which can be set to 20–30 years [28].

Wind power project financing

A decision of wind power project financing (capital need and capital structure) should be made on early stage of project development. Project can be financed by external investors (banks or investors) or thermal power plant owner's equity. During evaluation of wind power investment project different combinations of debt and equity have to be tested and the best capital structure has to be defined. [28].

Weighted average cost of capital (WACC) allows calculating weighted average costs of different funding sources (debt and equity). Debt weight can be defined as the ratio:

$$W_D = \frac{\text{Debt}}{\text{Debt} + \text{Equity}} \tag{24}$$

WACC is calculated using the following expression:

$$r_{WACC} = (1 - W_D) \cdot r_E + W_D \cdot r_D \cdot (1 - t), \tag{25}$$

where r_{WACC} – weighted average cost of capital; W_D – debt weight, r_E – return on equity, r_D – cost of debt before tax, t – taxes [4].

Cost of debt, return on equity, debt–to–equity ratio varies between different projects and countries. Typically, onshore wind power projects have 50% debt financing [28]. Cost of the debt is always known (it is adjusted with project creditors requirements), whereas cost of equity is less obvious [4].

Taxation system

Indispensable factor which makes substantial impact on wind power project investment case attractiveness is taxation system. According to Kazakhstan taxation system wind farm will be imposed by the following taxes:

- Corporate income tax. Income tax is applied to all companies and equals to 15% of revenue

- Value added tax. This tax should be applied to the value added by thermal power station and set at 12% rate.
- Social tax. Social tax contains 11% of salary and paid by producers.

As a part of wind power incentives system it is possible to take into consideration tax–free period for wind farm.

Risks and uncertainties

Wind power investment project stage–specific risks and risks related to the all stages of the project illustrated below in Figure 19.

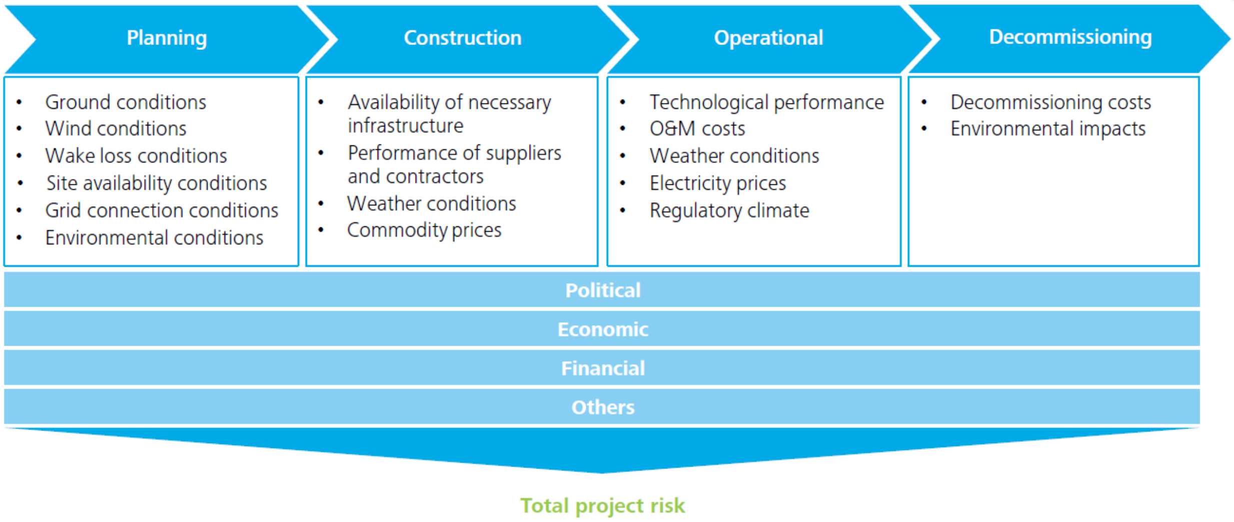

Figure 19 – Wind power project risks overview [28]

Stage–specific risks overview

Planning stage risks

- All planning stage studies must be performed properly in order to successfully develop the project
- Site feasibility studies are capital intensive (3 – 7 % of capital costs) and may result in site rejection
- Cautious investors won't invest under uncertain conditions during planning stage
- To operate renewable energy power plant companies must obtain the permission from the Agency of the Republic of Kazakhstan for the Regulation of Natural monopolies [1]
- Land required for new power plant construction have to be obtained from the lands intended for this purposes in accordance with Land Code [1]
- Project feasibility studies and governmental permission must be adjusted with state's architectural and engineering supervisory bodies [1]

However, in Kazakhstan wind farm construction requirements are no more onerous than the same procedures for the conventional power plants construction.

Construction stage risks

- Unfavorable weather conditions during construction period can postpone wind farm commission into operation
- Infrastructure and supply chains need to be improve significantly to avoid procrastination of time

Operational risks

- Possible wind turbines faults and malfunctioning will affect wind farm energy production
- Immaturity of energy markets can be a barrier to receive profit
- Interrelation between production and financial risks
- Possible environmental impacts

Decommission stage risks

- Lack of experience can cause environmental impact such as soil and bird migration damage
- Lack of experience with the process and costs of decommissioning
- Potential changes in decommission responsivities

Entire project life risks overview

Political risks

Basically, political risk implies confiscation, expropriation or nationalization of power project assets. Several problems which can be caused by changing governmental policy are listed below:

- New taxes, tariffs, restrictions
- Currency devaluation
- Imposition of new environmental regulations etc.

Power projects are extremely sensitive to political risks, the main political risk mitigation measure is insurance. Governmental support and incentives system is also significantly affect project feasibility and profitability.

Economic risks

- Energy prices and demand can be changed in wide range
- Prices of the components can grow and increase overall project costs

- High inflation rate can change investment project cash flows

Financial risks

Financial risk involves changing in national currency exchange rate, increase of interest rates, world commodity prices, inflation growth above forecasted values. Financial risks aversion implies including hedging facilities against currency exchange rate and interest rate growth, using currency and interest rate swaps, interest rate caps and other financing techniques.

Other risks

- Environmental risks – all power projects, including renewable energy projects, require environmental impact overview that identifies all environmental risks and standards regarding these risks.
- Force majeure is a risk of natural disasters such as fires, floods, earthquakes. This kind of risk can be mitigated through commercial insurance.
- Deficiency of qualified workforce may affect the wind farm development, construction and operation.
- Deficiency of qualified staff can affect the wind farm construction and operation.
- Unpredictable weather conditions during construction and operation stage.

The key tool for wind power project risk assessment is a risk matrix, which summarizes in matrix form classification, reasons, mitigation measures, consequences for the lender and investor of all risks related to the project. The main purpose of risk matrix construction is to identify and analyze each risk and its possible impact. Risk matrix distributes identified risks according to potential impact and probability of occurrence. This matrix can be helpful for further risk prioritizing and defining risk–mitigating actions on the most indispensable risks.

The main structure of risk matrix for wind power investment project is given in Figure 20.

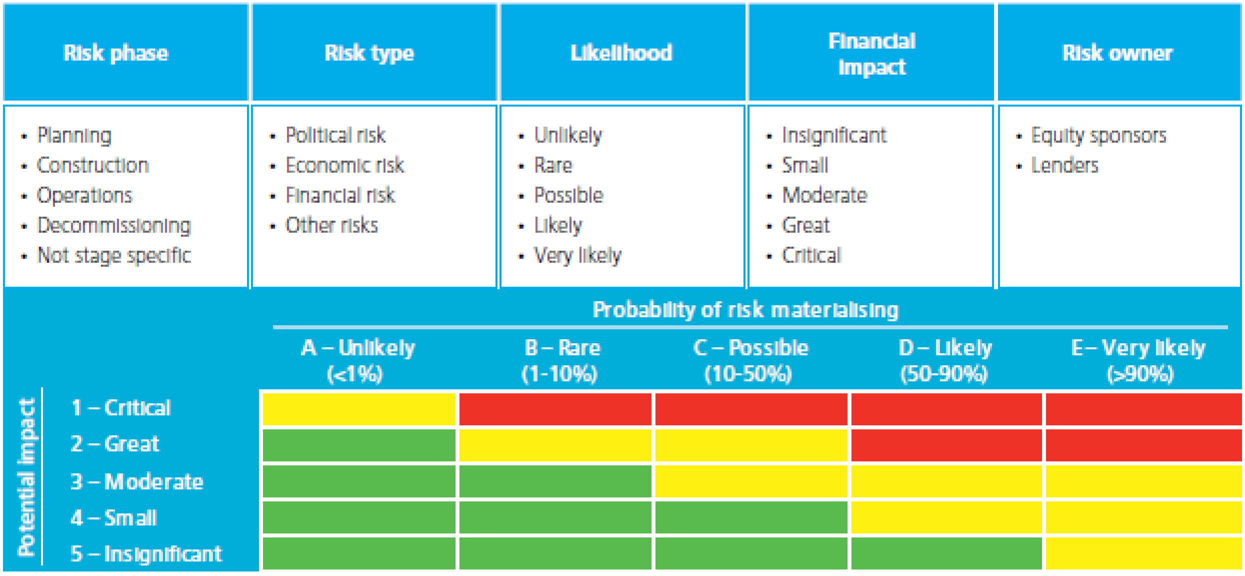

Figure 20 – Risk matrix for wind power project [28]

Combination of risk matrix and cash flow model will give detailed information for understanding the relation between risk and return. Risk and return are two key elements when deciding whether to invest or not.

Cash flow model for the second scenario

After calculation of annual thermal power plant operation and maintenance costs and wind power investment project these expenditures will be incorporated in forty–year long cash flow stream.

I will use all assumptions and calculations from the first scenario cash flow model; the only difference is the presence of loaned capital for wind power part.

Interest rate in Kazakhstan is estimated to be 15% by the end of the first quarter of 2016 according to Trading Economics global macro models and analysts' expectations. In the next two years interest rate will stand at 12% level. In the long term Kazakhstan interest rate will follow inflation and expected to be around 7,5% by the year 2020. Interest rate forecast is presented in Table 30.

Table 30 – Interest rate forecast [29]

	Actual	Q2/16	Q3/16	Q4/16	Q1/17	2020
Interest rate, %	15	15	15	12	12	7,5

12 % interest rate will be taken as base value for wind farm loaned capital, other values of interest rates will be analyzed during the second scenario sensitivity analysis. Debt maturity will match wind power project length.

Capital structure analysis is on paramount importance during wind power project robustness evaluation. 50 – 70 % of debt financing is typical for wind power project. Large debt ratio means higher equity capital requirements [28]. Capital structure with 70 % of debt will be considered as base case scenario.

Taking into account all previous assumptions and calculations, cash flow model for the second operation scenario was built. Cash flows for thermal power plant heat and electrical energy and wind farm electrical energy were calculated separately, total NPV of the project is the sum of these three cash flows net present values.

Wind farm capital structure analysis is given in Table 31.

Table 31 – Wind farm capital structure analysis, 12% interest rate

Own money, %	0	30	50	70	100
Wind farm NPV, ths. €	-26661,70	-26289,83	-26046,52	-25806,82	-25453,84

Table 32 – Wind farm capital structure analysis, 11% interest rate

Own money, %	0	30	50	70	100
Wind farm NPV, ths. €	-24049,10	-24559,66	-24855,06	-25117,38	-25453,84

At first I assumed that thermal power plant and wind farm will have the same price of electricity. I incorporated thermal power plant electrical energy production cash flow NPV and wind farm production cash flow NPV and calculated minimum price of electrical energy for the second scenario.

Minimum price of electrical energy $P_{el.min2}$ = 0,0262 ths.€/MWh.

NPV sensitivity analysis to the electrical energy costs is given in Table 33.

Table 33 – The second scenario NPV analysis

	Cost of electrical energy, ths.€/MWh				
	0,025	0,026	0,027	0,028	0,029
NPV, ths. €	-78307,57	-14051,27	50205,03	114461,33	178717,63

After that minimum price of heat energy for the second scenario was calculated.

Minimum price of heat energy $P_{h.min2}$ = 0,0025 ths.€/MWh.

NPV sensitivity analysis to the heat energy costs is given in Table 34.

Table 34 – The second scenario NPV analysis

	Cost of heat energy, ths.€/GJ				
	0,025	0,026	0,027	0,028	0,029
NPV, ths. €	-41,10	16466,13	32973,35	49480,57	65987,80

Total NPV sensitivity analysis to the electrical and heat energy costs is given in Table 35.

Table 35 –The second scenario total NPV analysis

		Cost of electrical energy, ths.€/MWh					
NPV Total, ths. €		0,025	0,026	0,027	0,028	0,029	0,03
Cost of heat energy, ths.€/GJ	0,0025	-78348,66	-14092,37	50163,93	114420,23	178676,53	242932,83
	0,0026	-61841,44	2414,86	66671,16	130927,46	195183,75	259440,05
	0,0027	-45334,22	18922,08	83178,38	147434,68	211690,98	275947,28
	0,0028	-28826,99	35429,30	99685,60	163941,90	228198,20	292454,50
	0,0029	-12319,77	51936,53	116192,83	180449,13	244705,42	308961,72

I transferred the costs of heat and electrical energy from the first scenario to the second scenario and obtained positive NPV for thermal power plant heat and electrical energy, but total NPV of the second scenario is negative because of high wind power production costs. I considered NPV of heat and electricity production separately to avoid overestimation of heat prices to compensate losses of expensive energy from wind power.

The second approach to the second scenario cost definition process implies using price of electrical and heat energy from the first scenario for thermal power plant and calculate minimum cost of wind energy which will satisfy total NPV = 0 condition.

Minimum wind power cost $P_{WP} = 0{,}03$ ths.€/MWh.

Table 36 – Dependence of total NPV on wind farm energy cost

Cost of WP energy, ths. €/MWh	0,026	0,027	0,028	0,029	0,03	0,031
Total NPV, ths. €	-5673,68	-4309,83	-2945,98	-1582,13	-218,28	1145,57

As a result I obtained price of electrical energy 0,026 ths.€/MWh and price of heat 0,00255 ths. €/GJ which won't depend on presence or absence of wind power in the power system. Price of electricity generated by wind farm is 0,03 ths.€/MWh, this price is higher than thermal power plant electricity price. Price difference can be compensated by government and embedding of wind power won't make any influence to the price of electricity for final consumers. It means that power system will buy amount of electricity equal to amount produced by wind farm with the price 0,03 ths.€/MWh, remaining electricity will be bought with the price 0,026 ths.€/MWh.

The third approach of the second scenario cost definition is calculation of wind power costs separately. Wind power investment case will be considered as separated project without thermal power plant.

Minimum wind power cost P_{WP} = 0,0453 ths.€/MWh.

Table 37 – Dependence of wind farm NPV on wind farm energy cost

Cost of WP energy, ths. €/MWh	0,025	0,03	0,035	0,04	0,045	0,05
WP NPV, ths. €	-27653,68	-20834,43	-14015,18	-7195,93	-376,67	6442,58

Cost of electricity from both scenarios are equal to the real cost of electricity tariffs of this thermal power station. Heat tariff of this thermal power station is significantly higher than minimum cost of production. It can be caused by heat costs underestimation or governmental support to heat energy producers.

The high cost of energy becomes another major obstacle for wind power projects in Kazakhstan. Typically cost of wind energy in Kazakhstan is in 0,066 – 0,079 €/kWh range, opposed to 0,016 €/kWh from more traditional power sources. This problem poses serious difficulties in wind power sector development [1]

5 CONCLUSIONS

In accordance with goal of the work cost of energy analysis of complex energy system consisting of combined heat and power plant and wind farm was performed. This task was broken down into several parts.

On the first stage I chose existing thermal power station located in Kazakhstan. I analyzed power station equipment and unit’s commitment and offered power station improvement project which implies replacement of one conventional generator with total capacity 63 MW by wind farm.

On the second stage I calculated power station reliability and amount of wind power which will ensure the same reliability level as was before power station reconstruction.

During the third stage I proved that power station has sufficient level of flexibility reserves to back up wind farm with total power 60 MW. According to my results wind farm will generate 85 422 MWh annually.

In economical part I analyzed two existing opportunities of thermal power plant operation. The first one is put out of operation generator No3 and to continue operation with five remaining generators. The second opportunity is to put out of operation generator No3 and deploy wind farm with total capacity 60 MW. Cost of energy calculation for both variants was the key objective of this work. Minimum prices of electrical and heat energy according to the first scenario are 0,026 ths.€/MWh and 0,00255 ths.€/GJ respectively. Minimum prices of electrical and heat energy according to the second scenario are 0,0262 ths.€/MWh and 0,0025 ths.€/GJ respectively. It can be concluded that thermal power plant energy price won’t be affected significantly by embedding 60 MW wind farm.

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