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ELECTRICAL ENGINEERING, MINING ENGINEERING D73

Technical-Economic Analysis of Distributed Generation Units in Power Systems

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Victor Astapov ....

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ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D73

Elektri hajatootjate tehnilis-majanduslik analüüs energiasüsteemis

VICTOR ASTAPOV

TTÜ KIRJASTUS

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List of abbreviations

AC	Alternating Current
ACSA	Ant Colony Search Algorithm
CO_2	Carbon dioxide
DC	Direct Current
DG	Distributed Generation
EELD	Economical Environmental Load Dispatch
ELD	Economical Load Dispatch
EPC	Engineering, Procurement, Construction
EU	European Union
GA	Genetic Algorithm
IEEE30	IEEE 30-bus test system
LP	Linear Programming
LPP	Large Power Plant
LTC	Load Tap Changing
MOEA	Multi-Objective Evolutionary Algorithm
NP	Nonlinear Programming
O&M	Operational and Maintenance
PSO	Particle Swarm Optimization
SO	System Operator
SPP	Small Power Plant
QP	Quadratic Programming
UPS	Uninterruptible Power Supplies

Symbol index

A	frontal area of the vehicle
B	fuel cost
$B(P)$	fuel cost characteristic of power unit
E	emissions
$E(P)$	emission cost characteristic of power unit
I	current
P	active power
P_G	active power generated by unit
P_D	active power demands
P_L	active power losses
Q	reactive power
R	resistance
S	full power
Sk	capacity of transmission line
V	voltage
Y	admittance
Z	impedance
ΔB	difference in fuel costs
a,b,c,e,f	fuel cost coefficients
$b(P)$	marginal characteristics of power unit
$\alpha, \beta,\gamma,\lambda,\xi$	emission cost coefficients
η (P)	efficiency characteristic of power unit

1. INTRODUCTION

1.1. Motivation and Background

Power system is a very complicated structure with a lot of equipment which have different and unique parameters and characteristics. Generation, transmission, distribution, consumption processes, etc. are intensively studied and developed. Each direction has its own subtasks, problems to be solved, and methods. Nowadays a lot of technologies have been invented and researchers have proposed new technical decisions aiming to improve system performance, and increase profit. Many of them lead to huge investments which can not always pay for itself.

Another issue is a climate problem and influence of greenhouse gases on nature. Energy sector produces a huge amount of carbon dioxide (CO_2) emissions, up to 41%. The world-wide situation with CO_2 emissions by sector is shown in Figure 1.1.

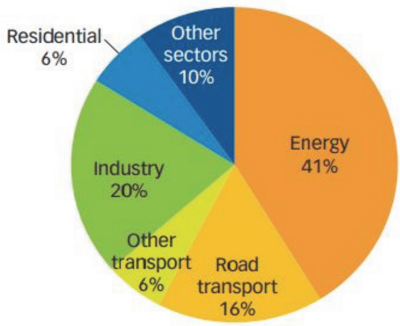

Figure 1.1. CO_2 emissions by sector [1]

To protect the nature and environment, several organizations and regulations were created to cut pollutions. The priority of economical fuel consumption was pushed by new environmentally-friendly strategy of development. It is especially important nowadays due to the open electricity market and Kyoto protocol [2]. According to this document, member countries took commitments to reduce greenhouse gas like CO_2 and other emissions, in particular, SO_x and NO_x. Emissions above standard limit lead to additional penalties and consequently increase the cost of the energy produced.

That is why starting from the date of its signing in 1997, strategies of many energy companies have changed. Thereafter, plenty of different solutions have been proposed, such as extra filters, switching to other types of fuel, having better characteristics of emissions. The Kyoto Protocol served as a mighty impulse for the development of alternative energy sources like wind and solar generation, fuel cells, etc.

Under the Kyoto Protocol, European Union (EU) members in 2008-2012 reduced their collective emissions to 8% compared to 1990 level. For 2020, the EU declared the target of cutting its emissions to 20% below 1990 levels [1].

According to [2], in 2014, 7.2 GW of coal capacity, 2.9 GW of gas, and 1.1 GW of fuel oil was decommissioned in EU. At the same time almost 26.9 GW of capacity was installed (20 GW of green energy and 6.9 GW of fossil fuel), see Figure 1.2.

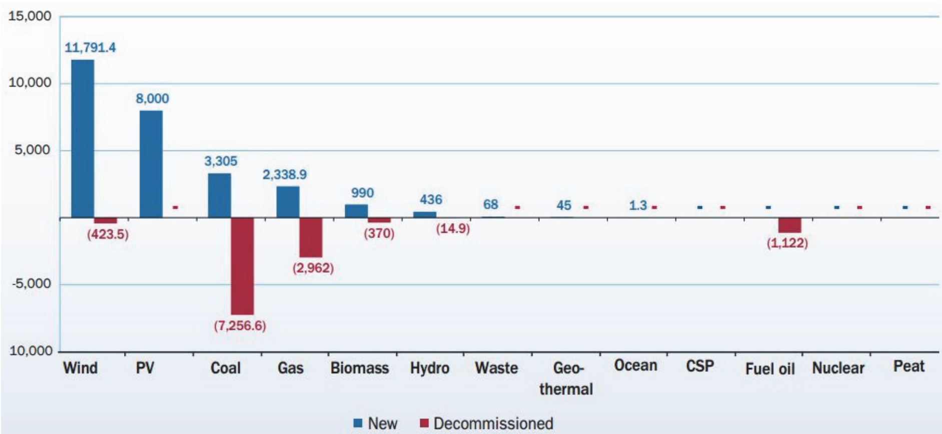

Figure 1.2. New installed and old deinstalled capacities in MW[2]

However, all of these methods require significant investment, in some cases, upgrading equipment, training of personnel, etc. At the same time, in reality the energy generation sector established large quantities of power plants using fossil fuel, 44.9% of all energy resources of which are still mined [2]. The EU power mix is shown in Figure 1.3.

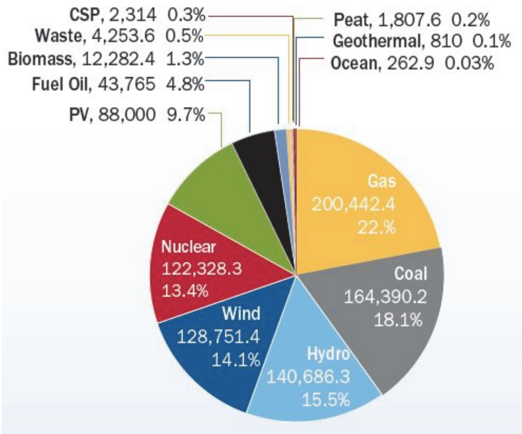

Figure 1.3. EU power mix in 2014 in MW[2]

In Estonia, the power system is mostly based on fossil fuel. In the first quarter of 2015 17,3% of total generated electricity was produced from the renewable sources [3].

That is why in the Estonian case less expensive option of reducing costs is the optimization of the network operation through searching for the optimal regime of power system. In other words, optimization is a compromise between economical fuel consumption and harmful emissions into the atmosphere made by generating units. In case of power generation, it is the reduction of fuel consumption and emissions; in case of transmission and distribution of electricity, it is the optimization of power flow and deduction of power losses; finally, in case of consumption, it is the prediction of the electricity market, strict management, and scheduling.

1.2. Objectives and Contributions of the Thesis

Main Objectives and Tasks of the Thesis

The first aim of this thesis is to show the opportunities for economical benefits, reducing emissions, and generally improving power system operation. The second aim is to take a look at the existing successful decisions in energy sector depending on its different aspects (which sometimes can exclude each other) and clarify their influence on the price of electricity.

This research focuses on the efficiency problem of power systems. It takes into account different aspects which appear during system operation and affect the costs of electricity generation. This work considers fuel-cost and emissions characteristics. The research focuses on optimal power flow dispatch as well as the costs spent on operating and maintaining the equipment. Comparison of centralized and decentralized generation is made.

The results were obtained mostly using standard IEEE 30-bus test system which will be described further. Computations were made with the help of MATLAB Simulink and Power World Simulator.

Theoretical and practical originality of the doctoral thesis

The theoretical originality of the thesis includes:

- new methodology for technical-economical comparison of centralized and decentralized generation systems;
- new topology for technical-economic analysis of thermal generation units based on IEEE 30-bus test system;
- new approach for adaptation of different data type to test systems.

The practical novelty of the thesis includes:

- identification of factors such as fuel, emissions and equipment costs, the optimal choice of generator, it's placement and power flow, and their impact on the price of electricity;
- technical-economic comparison of centralized and decentralized generation, efficiency of systems;
- solutions of making generation process more efficient and environmentally-friendly with fewer investments.

The relevance of the thesis

The relevance of the thesis is based on the potential implementation of the described methods to different systems, in particular, with bigger amount of energy sources when determined factors are more weighable. This research summarizes modern directions and its solutions are oriented to solve the optimization process problem and show system efficiency dependence on its parameters. It creates a basement for the future investigations in this field and can be also used in educational purposes.

Dissemination of the Results

The results of the doctoral thesis have been presented by the author at 6 international conferences. The author has published four international scientific papers, all of them are directly associated with the thesis. Three of them are available in the IEEE database.

1.3. Development of the Study

Chapter 2 presents the main definitions and technologies. It describes processes taking place during generation, transmission and distribution of electric energy step by step. The main objective of the chapter is to make an overview of technologies, create clear picture of the issues and explain methods to apply for the solution of these problems. Attention is paid to the pieces of research in optimization field, variety of methods and results achieved. The main aim is to show how methods described in Chapter 2 have been implemented.

Chapter 3 consists of several investigations made by author. The overview of optimization field was made for the case of a condensing power plant. Different parameters of power system such as power losses, voltage drop, optimal placement, volume of generators, etc. were considered. The analysis of their impact on generation process was conducted. Fuel consumption dependence on changing of one or another parameter of the system was presented. The investigation of distributed generation with its benefits and drawbacks was shown. Attention is paid not only to fuel and emission characteristics, but to capital, operational, and maintenance costs too. System efficiency had been studied for the case of changing of power demands. The scenario with wind generation and its impact on the system operation, changing in fuel consumption and emissions, were considered. Cost components of the price for 1MWh are calculated.

In addition to the main part, conclusion and possible future work are described in Chapter 4. The conclusive list of references consists of 77 external and 4 author's publications, an abstract and curriculum vitae are attached.

2. MATERIAL AND METHODS

2.1. Power Systems

Electricity Generation

Electricity generation is the process of generating electric power from other sources of primary energy. This is only a short definition which shows the main purpose and energy transformation. A wider description includes type of fuel or sources and technological process of generating.

There are plenty of generation technologies developed in accordance with the type of used fuel. Turbines, reciprocating engines, photovoltaic panels, fuel cells and other approaches produce electrical energy via transformation of thermal, mechanical, chemical and other types of energy. It should be mentioned that different generation technologies, however, may use the same type of fuel, and vice versa: different type of fuel may be used with the same technology. For example solar energy can be collected with mirror and used for heating the boiler (thermal generation). Another application of solar energy is photovoltaic generation panel.

This work focuses on the thermal power plants to be further described in details. This equipment uses energy of steam or burning gas which spin turbine. Thermal power plants can be divided into several groups taking into the account the various properties. According to the output, they fall into two groups [4]:

- power plants generating only electric power;
- co-generation power plants, producing both heat and electric power.

Combined cycle power plant represents a hybrid of two technologies described above and shown in Figure 2.1. The solution is that from gas turbine flue gases follow to the steam generator, used like a boiler in condensing power plant. Another difference is that water goes from condenser to steam generator, making a cycle this way. This type of power plant has relatively high efficiency of more than 50%.

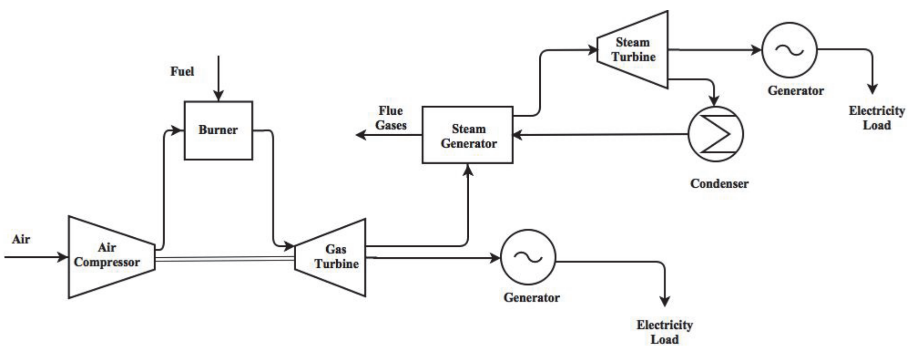

Figure 2.1. Typical scheme of thermal condensing power plant [4]

Electricity transmission and power flow

The generated electricity passes through several stages of transformation and is delivered to consumers via electrical – transmission and distribution – lines. They can use direct current (DC) or alternating current (AC) technologies. The main differences between transmission and distribution lines are the voltage class, as well as the scheme of their connection. Transmission lines, as a rule, have 110 kV and upper voltage and are connected as a closed loop. The voltage of distribution lines is usually less than 110 kV and the system has its own normal loop brakes. In this research, both types of AC lines have been considered.

Complex electrical network is characterized not only by a large number of nodes and branches; its main features the presence of closed loops with common branches. Unlike the simple closed network where the power flow goes along a branch with the same direction, or simple closed network, where power arrives from two sides only and calculation can be performed by elemental substitution pattern, a node of the complex closed network can have more than two directions of power flow.

Another problem in the calculation of steady-state regimes is a case with non-linear elements. A variety of methods can be used for this calculation, however, the most widely used is the node voltage method. Power flow problem with linear elements can be solved using direct Gauss elimination, iteration Jacobi, or Gauss–Seidel methods. For the nonlinear equations these methods also could be applied, but the most preferred to use is Newton-Raphson method [5], [6]. During every iteration, the system of non-linear equations is replaced by the linear system with the implementation of differential equations, with respect to the desired variables. The solution of this system gives the values of the variables that are closer to the desired solution than the initial approximation. The computational process continues until solution equals the desired value within the specified tolerance accuracy [7].

Power balance and transmission losses in power systems

Power losses are important to consider in power system. According to different sources, losses can reach up to 30% of transmitted power. The calculations of transmission losses depend on several parameters, such as voltage and type of the line, configuration of the network, etc. In this subsection, some approaches are considered.

The situation is the same as power flow calculations: open circuits have less parameters and are easier to calculate. One of the simplest and, as a result, less accurate formula to calculate active power losses PL in transmission line is [8]:

$$P_L = 50(P \times 10^{-3})^2 , \tag{2.1}$$

where P is power in the beginning of the line. In this case there is no necessity to know parameters of transmission line. This formula can be used in initial stage or general cases.

For the simple systems with normal loop brakes or systems where one node has no more than two branches, it is possible to calculate power losses P_L and Q_L in transmission line with voltage V, current I, and resistance R [9]:

$$P_L = I^2 R = \frac{P^2}{V^2 \cos^2(\varphi)} R , \tag{2.2}$$

or

$$P_L = \frac{P^2 + Q^2}{V^2} R . \tag{2.3}$$

In case of a series connection, calculation start from the last line and power losses in the first line can be found step by step. In case of a simple loop connection, it is possible to transform it into a series connection by making a break in the one of the node. After this, actions are the same as in (2.3).

For the complex loop systems, the methods are more complicated and the most typical approach of B-matrix can be implemented. Power losses in the system consisting of n busses can be calculated according to the Kron's formula [10]:

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j , \tag{2.4}$$

where B_{ij} – are the coefficients of B-matrix.

Another kind of calculations were presented by Dopazo et al. in [11] during investigation of active and reactive power allocation.

Interconnected power systems

The connection of several generating stations in parallel is known as *interconnected grid system* [12].

In the era of globalization and countless associations, the energy sector is moving in the same direction of cooperation too. Power systems of neighbouring countries or network operators (in some countries, such as Germany or the United States more than one system operators) are integrated with each other to reduce costs and increase system reliability.

SO is a grid company responsible for pure power transmission, its quality and conformance standard, named Grid Code. SO must support established parameters of the grid, such as voltage and frequency. Denmark and Germany were the first countries to adapt their grid codes for wind power integration in high voltage networks. Eltra and Elkraf, the Danish System Operators, have developed specific grid codes for voltage networks under 110 kV as well in 2004. In many researches E.On system operator in Germany is mentioned as the first adapted the grid code for voltage ride through wind farms, it was actually Denmark where the first specific grid code for wind farms was implemented [13].

The idea of interconnection and its technical, economical, environmental, social, and political benefits are quite obvious. Through the connection, each system provides backup reserve for the neighbouring systems members. It leads to increase in overall capacity of interconnected systems and reduction of the amount of power reserve in particular country. From economical point of view, it cuts expenses for the equipment; from the technical side, it lets old equipment to be used only to cover peak loads. The interconnection gives the possibility to use renewable power sources from neighbouring systems, avoiding local pollution. Cooperation increases investments into the relatively poor countries, creates new working places, and develops business between countries.

The example of cooperation of interconnected power grids is the interaction on September 10, 2014, when two DC cables, lines EstLink 2 and later EstLink 1, were switched off due to faults [14]. Belarusian energy system provided emergency assistance to Estonia. At the request of Eesti Energia, Estonian energy system was granted statutory emergency reserve capacity of 100 MW; while the volume of electricity transmitted to Estonia amounted to 1400 MWh. Energy transfer was carried out on September 10 from 10:00 to 24:00. The corresponding request to the dispatcher RUA "ODU" (Belarus) came at 09:55 [15]. Before, in 2008, Estonia has helped Belarus during one of the biggest failures at BelGRES Power Plant.

Nevertheless, there are several negative drawbacks of interconnection. First of all, a less modern system must be upgraded according to the requirements or grid. For the same reason, personnel must have more up-to-date professional knowledge. Synchronizing with the help of convertor power stations is very expensive. Political relationships between countries can be changed and all of the work and investments may be spent in vain.

At the moment, the largest organization in Europe, representing the interests of the international system operators is ENTSO-E. Its objectives are marked in the slogan: “Reliable. Sustainable. Connected. Cooperating for reliable operation, optimal management and sound technical evolution of the European electricity transmission system”[16]. This organization consists of 41 members from 34 countries, including Estonia. Technically, at this point, Estonia is in BRELL. This is the synchronized power systems interconnection represented by cooperation of Belarus, Russia, Estonia, and Lithuania. In the near future Estonia and other Baltic Countries are planning to switch completely to the ENTSO-E. For this reason, Estonia already laid two cable DC lines between itself and Finland: EstLink 1 and EstLink 2. At the same time, to increase the capacity of transmission lines between Latvia and Estonia, the line “Riga - Kilingi-Nõmme” project is running [17]. In turn, Lithuania plans to complete the installation of transmission lines with Poland and Sweden by 2022 [18]. After the construction is finished, it will be possible to fully enter ENTSO-E.

2.2. Energy Market. Main Costs

Modern energy sector is currently a complex multi-level structure with a lot of interaction between the participants. Until the late 20th century, all power equipment, ranging from generators to insulators on customers’ houses, used to be managed and controlled by one owner, mostly, the state structure. The cost of electricity has been fixed with the division into different consumer groups.

Some states, such as Belarus, still hold a monopoly in the energy sector, while most of European countries follow the liberalization of the market, adding new investors and participants.

It should be noted that with the development of different types of technologies, each country or each producer of electricity in particular, is able to choose its own vector of development, based not only on the economic component, but also on climatic and environmental conditions. This is especially significant in case of renewable energy, as different geographic position allows for availability of different resources, e.g. wind, sun, or water. If earlier the question of what to do with the generated electricity arose, nowadays the market conditions and interconnected power system let the surplus to be sold.

In addition, during long period of operation of the equipment things may change. Fluctuation of the fuel prices is the most obvious scenario, while there are a number of other unforeseen circumstances too. These circumstances may be technical (the accident at the Fukushima nuclear power plant), political (the closure of the Ignalina nuclear power plant in Lithuania after the accession to the EU), or systemic (exclusion of Nurekskaya hydro power plant in Tajikistan from synchronization zone, consequent functioning in part-load regime and dumping the excess water through tunnels).

Nevertheless, in spite of the different technologies, the costs of electricity production can be classified as follows:

- capital costs;
- fixed operational and maintenance costs;
- variable operational and maintenance costs;
- fuel costs;
- emission costs.

Capital costs are determined per kW and include several subcategories such as equipment and installation investment, project lead costs, and demolition costs. Capital costs of power plants are very much differing depending on capacity, lasting of equipment, and type of labour in the country where it is to be constructed. In running power plants, there are other costs associated with the repair or maintenance of equipment and personnel payments. Certain costs are directly associated with the generation process and are called operational and maintenance costs (O&M costs). O&M costs can be of two types: variable and fixed [19].

Fixed O&M costs are those expenses which do not depend on generation process, i.e. from the volume of produced energy. They consist of all kinds of payments for personnel, including monthly fees and bonuses, bills for post, phones, etc. Maintenance of structures and grounds, predictive maintenance, and plant support of equipment are part of fixed O&M costs too.

Variable O&M costs are production-related expenses varying according to the amount of energy generated. Depending on technology, variable O&M can include the following categories: raw water, waste and wastewater disposal expenses; chemicals, catalysts and gases, ammonia for selective catalytic reduction; lubricants and other consumable materials and supplies.

Power plants operating on fuel have additional costs associated with primary energy sources. Fuel costs vary according to the type and the price for unit of fuel, delivery and storage fees, etc. Generally, the better fuel consumption efficiency of thermal power stations is, the more loaded generating unit becomes. Modular units, working in parallels are exceptions.

Every thermal generation unit operating on fuel is unique and has its own parameters, including fuel consumption. Generally fuel consumption which depend on power output and described by input cost characteristics as following [4], [20]:

– *input cost characteristics*

$$B(P) = a + bP + cP^2 . \tag{2.5}$$

In some publications on this topic it is possible to find more complicated formulae which includes valve point loading [21]:

$$B(P) = a + bP + cP^2 + e(\sin f(P_{\min} - P)) , \tag{2.6}$$

where *a, b, c, d, e* – are coefficients of input cost characteristics, P – power output of generation unit, P_{min} – minimal amount of power which can be produced by generation unit. The fuel costs characteristics of generating unit can be represented as a table, based on experimental measurements as well, but function-type is more wide-spread. Measurement units are MWh/h or \$/h.

There are several important expressions to describe fuel consumption of generating unit [4]:

– *input incremental or marginal characteristics*

$$b(P) = \frac{\partial B(P)}{\partial P} , \tag{2.7}$$

– *efficiency characteristics*

$$\eta(P) = \frac{P}{B(P)} . \tag{2.8}$$

In some sources cost coefficients are more detailed and presented in dual form for different generator output, see Table 2.1

Table 2.1. Example of fuel-cost characteristics for different generator capacities [22]

Generator	From MW	To MW	Cost Coefficients		
			a	***b***	***c***
G1	50	140	55.0	0.7	0.005
	140	200	82.5	1.05	0.0075
G2	20	55	44.0	0.3	0.001
	55	80	80.0	0.6	0.002

In some pieces of research, the characteristics found are presented in a general form, regardless of the block type or types of fuel. For example, in [23] authors distinguish blocks only by power capacity, assigning each factor range of power output. There is a case of ten different ranges increments 25-50-100 MW. This form is of favourable versatility in case of the lack of generators' data, but, on the other hand, it losses accuracy of the calculations. After all, blocks with a difference in 10-20 MW of installed capacity and even in some cases with the same output may have different characteristics that can significantly change the modes of generation and therefore operational costs. Besides, it is obvious that each type of fuel has its own fuel efficiency and emissions of harmful gases.

Emissions costs can be described the same way as fuel costs, with different nuances though. Each generation unit operating on fuel has own emission characteristics. Technically this is an amount of emitting greenhouse gases such as carbon dioxide, oxides of sulphur, and oxides of nitrogen. While CO_2 emissions lead to global warming, SO_2 and NO_x are amenable to acid rain. The emission characteristic can be expressed by formulae [24]:

$$E(P) = \alpha + \beta P + \gamma P^2 . \tag{2.9}$$

In some sources pollutions such as NO_x and SO_2 also considered and emission characteristic takes the following form [25]:

$$E(P) = 10^{-2}(\alpha + \beta P + \gamma P^2) + \xi \exp(\lambda P), \tag{2.10}$$

where are $\alpha, \beta, \gamma, \lambda$, and ξ are coefficients of input emissions characteristics, P – is output power of generation unit. Usually emission characteristic is measured in t/h or t/MWh. In the same way as a ton of fuel has its price, a ton of emission has its own price too. Transformation mechanism of emissions into the value of money has different manner and is determined by two conventional methods – carbon taxes and cap-and-trade mechanisms [26].

The first method is a traditional regulation, when regulatory authorities are responsible for strategy of how much emissions will be limited, how to achieve it and to control it. The cap-and-trade is a market approach which was first represented in the USA. The idea is that the regulator determines the total amount of emissions that must be reduced or may not be exceeded – the cap. Each company also has own prescription for reducing emissions or allowance to produce some exact amount. Nevertheless, for each manufacturer the emission abatement costs vary. Meanwhile, for the environment, it is important, how much of greenhouse gases went out, not their source though. Thus, companies with higher costs can reduce these by buying allowances from companies with lower costs for modification. This trading approach gives more flexibility and is less expensive for reducing pollutions, i.e. makes the ultimate goal real [27].

To summarize this chapter, it should be mentioned that each technology has its own proportional share of costs. This ratio is not strict. For example, price for emissions could be changed, as well as prices for fuel [28].

2.3. Centralized and Decentralized (distributed) Generation

Distributed Generation

Distributed generation (DG) is quite new and a very popular trend nowadays, while it is still not easy to find proper definition for it. In 2000

Acherman et al. examines existing DG descriptions [29]. They made an analysis of the relevant literature, singling out the most important criteria and cited different definitions and even names of DG from well-known researchers on the topic or state documents. Among other names for DG are “decentralized”, “embedded”, “dispersed” generation. One of its main attributes is that the unit generates only active power and has relatively small installed capacity. The volume of generation may start from few kilowatts up to 300 MW. The second property is a location with respect to the consumption point or connection point. DG unit should be placed close to loads and connected to the distributed system or consumers’ network. There are many more issues that can be added to the definition (not necessarily though): purpose, power delivery area, mode of operation, and technology.

The main grounds of DG’s expansion are the following:

- renewable sources become the main type of fuel. Small and medium power plants operating by bio fuel, wind, and solar energy replace big plants firing fossil fuel with huge emissions;
- the structure in which generation, transmission, and distribution have only one owner is splitting up nowadays, and electricity market of generation is open. It stimulates the elaboration of DG technologies. As a result, many investments and new electricity suppliers appear in this field. Small DG units can be installed in short time with low-key budget in comparison with large power plants. The possibilities of connecting DG units to the distributed system appear. Installation of DG units reduces losses in transmission lines;
- DG let medium companies construct their own small cogeneration heat and power units next to plants, facilities, or equipment; customers generate their own electricity using rooftop solar panels.

Yet, looking back, it is possible to find some similarities between first steps of electricity and present decentralisation tendencies. In the beginning of electricity era, when power systems did not exist, electric grids structure was like the DG. Generators had small capacities and were placed near the power consumers. Further, with growing demands, science development and progress of technologies, electric grids started growing up. They were united in power system at long last. Since then it was possible to transfer huge amount of electric power over long distances, power plants capacities increased, types of generation became more varied. Different types of power plants allow the flexibility of the system, satisfy the quality requirements and support the power balance.

Applications of DG

Each system has its own power demands which change over the time of the day. However, the amount of consuming power each day repeats itself during the season. That is why maximum load (peak) time and minimum load time occur. The objective of power balance is the regulation of electricity generation in compliance with the demand. In case of power balance voltages and frequency at the consumer buses should be fine. Thus, reliability and power quality is one of the purposes of using DG. These issues are very important for the System Operator. The main technical issues in DG connection to the grid are voltage and reactive power control, frequency control, fault ride-through capabilities. According to these, any DG unit connected to the main grid should be tested and checked to satisfy safety, stability and other requirements. Only in this case, the DG can be used.

The second task of DG is the emergency backup. Many customers need energy all the time for different reasons, e.g. technological process, security, or steady indispensable functioning in hospitals or dispatching centres of system operator. Certainly, in case of damage of the main grid these consumers have a second connection point and automatic reserve. Nonetheless, if serious accidents happen in the power system, DG can prevent work stoppage. As a rule, emergency reserve does not have very big capacity of power and is brought about with diesel or petrol engine generator in cooperation with Uninterruptible Power Supplies (UPS). Another solution is to use hydrogen fuel cells, which nowadays have become cheaper and compete with batteries reserve. At the same time, this technology is more environmentally-friendly than generators [30].

DG units with bigger capacities have another function. Frequently power plants in the power system or generation units do not work at optimal regime. They generate less power than their installed capacity, sometimes they are 60-70% loaded and, as a result, generation process is less economic. If a unit suddenly switches off by the mistake of the personnel or due to some damage, the system should immediately increase generation volume to support the frequency. It is impossible to do it with thermal generation unit or nuclear power block. As mentioned above, this equipment should be already started and operated. As an alternative solution, DG can be used. The solution to avoid a blackout is to reduce total load of the system means, that some consumers must be disconnected. It leads to huge economical losses and is, of course, unacceptable, but nonetheless it happens [31].

Another option to preserve the system's stability is taking a necessary amount of power from a neighbouring power system. Today it is easier, because of the interconnected power systems. Nevertheless, it conducts to the expenses in terms of electricity market. The price for the one MWh during this period can be much higher than usually.

One more objective of DG is generating power directly for the consumer. It could be *base load application*, when the owner use 100% of produced power for own needs and buy necessary amount of power from external grid. In case of rural and remote areas, DG helps to avoid high costs of connection to the main grid. This is called *stand alone application*.

Drawbacks of DG

One of the most obvious problems of renewable energy is the unpredictability of its generation. Photovoltaic panels and wind turbines are very dependent on weather conditions. In this regard, for system reliability, the power system must have a backup capacity, i.e. power plant operating on fuel or interconnection with neighbouring power systems. This requires additional costs.

Another difficulty takes place when consumers have their own generation. The question of management, coordination, and control of power quality on the equipment arises. In this case, some problems with bi-directional power flow occur. First of all, this is the difficulty of tuning power system protection. Voltage fluctuations and complicate reactive power flow can affect the system stability. Bi-directional power flow has is dangerous of the repairing personnel during network damages [32].

In case of radial distribution systems, DG can create harmonics because of inverter and has impact on short circuit levels. Installation of DG in wrong places leads to abnormal operation process. For example, short distance between DG unit and voltage regulator or LTC transformer can create hindrance for voltage regulation [33].

The contentious issue is the cost associated with installing the equipment. In the beginning, many sources mentioned have noted the high costs of DG calculating $ per MW installed capacity and big gap inside DG group. For example difference between combustion turbines and fuel cells was 1000 €/kW and 20000 €/kW respectively. According to the report [34] in 2014 installation costs (€/kW) for big power plants and DG unites became almost equal.

Comparison of decentralized and centralized power systems, based on fuel-cost and emissions characteristics and cooperation of wind power with thermal power plants will be presented in Chapter 3.

2.4. Multi-Criteria Optimization

Optimization of the fuel consumption

One of the first objectives of the optimization is to reduce fuel consumption. With power demands P_D and n generators units, the optimization problem can be presented [4], [35] as:

$$\text{minimize } B_T = \sum_{i=1}^{n} B(P_i) = a_i + b_i P_i + c_i P_i^2 . \tag{2.11}$$

$$\text{with respect } P_D + P_L = \sum_{i=1}^{n} P_i . \tag{2.12}$$

Here any kind of losses are defined as P_L. From (2.11) and (2.12) the La Granje function is:

$$L = B_T + \lambda (P_D + P_L - \sum_{i=1}^{n} P_i) . \tag{2.13}$$

The minimum of B_T is possible to obtain when:

$$\partial L / \partial P_i = 0 \text{ and } \partial L / \partial \lambda = 0. \quad (2.14)$$

In other words:

$$\partial B_i / \partial P_i + \lambda(\partial P_L / \partial P_i - 1) = 0 \text{ and } P_D + P_L - \sum_{i=1}^{N} P_i = 0. \quad (2.15)$$

From (2.15) and (2.7)

$$b_i(P) = \lambda\left(1 - \partial P_L / \partial P_i\right). \quad (2.16)$$

In case the losses are neglected, (2.16) takes following form:

$$b_i(P) = \lambda. \quad (2.17)$$

The generation regime of several units has optimal fuel consumption when their marginal costs are equal.

Formulation of the problem

As noted above, after signing the Kyoto Protocol, one of the main objectives now is to reduce the amount of green house gases. Of course, the development of wind energy, fuel cells and solar panels diminishes emissions, but at the moment a complete rejection of burning fuel technology is impossible.

One of the options for thermal power plants is the transition to a more environmentally-friendly type of fuel or green energy. The second option is the installation of equipment for the collection of emissions from its subsequent disposal. All of this leads to additional investment costs, training of staff, etc.

The alternative lies in the correct regime of generation output and the whole system power flow. As noted above, during generating, unit consumes fuel and releases an amount of substances. Due to the unique characteristics of the units, modes of maximum efficiency are different too. One block may have a better performance on combustion mode at 80% load, while the other – at 90%. Indicators on emissions from these modes are also different.

The number of emissions and the amount of fuel consumed is not directly proportional to the amount of generated energy, and, most importantly, their functions are opposite to each other. The search for optimal solution (compromise) for these functions is the task for multi-criteria optimization.

In general case, the formulation of the problem is possible to describe with following expressions [36]:

$$\text{optimize}\, F(x) = \left[f_1(x), f_2(x), \ldots, f_k(x)\right], \quad (2.18)$$

where x = (x^1; x^2; ... ; x^n)T ∈ X is a solution vector and X is the feasible domain. An optimization problem can be a model where the main task is to minimize some characteristics (e.g. costs, energy losses, errors, etc.) or increase some outputs (e.g. profit, efficiency, etc.), taking into the account constraints of the system.

A solution vector x* is Pareto optimal if:

$$\neg\exists x \in X : f_i(x) \le f_i(x^*) \wedge f(x) \ne f(x^*). \quad (2.19)$$

A solution x^1 dominates x^2 ($x^1 < x^2$) if:

$$f_i(x^1) \le f_i(x^2) \wedge \exists j : f_j(x^1) < f_j(x^2). \tag{2.20}$$

If there are no solutions which dominate x1, then x1 is non-dominated. A set of non-dominated solutions is a Pareto set or Pareto front. In other words, a feasible solution is called Pareto optimal if there is no other possible solution, which has equal results in all of the optimizing functions, but, at the same time, has much better performance at least in one of them. Function values corresponding to the set of Pareto optimal solutions, and represent the best compromise between the function results, called the Pareto front [37].

The task to minimise the cost of generation, with satisfaction of power system constraints and keeping pollution within limits is known in research literature as Environmental Economic Load Dispatch (EELD) problem [25], [38]. Solving EELD problem by varying the amount of energy generated at each individual stations or units, it is possible to save considerably fuel consumption and reduce emissions. EELD without constraints can be presented as:

$$\text{optimize}\, O(P) = \left[B(P); E(P)\right]. \tag{2.21}$$

The fuel characteristics and emissions characteristics can be represented as t/h, or t/MWh. Thus, the calculations must take into account the cost per unit of fuel and emissions. These data are constantly changing. For example, at the moment, due to the low level of prices for emissions (an average cost of one ton is 6.5 € [39]), the priority shifted toward fuel economy. On the other hand, with an increase in the price of emission, the pattern may change. From this point, one of the possibilities is to create a value factor ω, present (2.31) with the following formula, and find the optimal allocation between emissions and fuel consumption [40], [41]:

$$\text{optimize}\, O(P) = \omega B(P) + (1-\omega)E(P), \tag{2.22}$$

where ω is in the range from 0 to 1 and indicates the ratio between costs for 1 ton of fuel and 1 ton of emissions. For example, when $\omega = 0$ only the environmental objective is taken into account, and when $\omega = 1$ only fuel consumption is considered.

Optimization of the whole complex system is a very complicated process, because power losses function has various arguments, described before and needs the calculations of power flow.

During the optimization, the following constraints must be taken into account: generation capacity constraints (2.23 – 2.27), where N_g – number of generators, N_b – number of busses, N_l – number of lines in the system, P_{Gi} – active power generated by unit i, Q_{Gi} – reactive power generated by unit i, V_{Bj} – voltage at the bus B_j, P_D – system demands of power, S_{Lk} – power capacity of the line L_k.

Minimum and maximum power output constraints:

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}, i = 1, \ldots, N_g, \tag{2.23}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i = 1, \ldots, N_g. \tag{2.24}$$

Voltage constraints:

$$V_{Bj}^{\min} \le V_{Bj} \le V_{Bj}^{\max}, j = 1,...,N_b. \quad (2.25)$$

Power balance constraints:

$$\sum_{i=1}^{N} P_{Gi} + P_D + P_L = 0. \quad (2.26)$$

Capacity of transmission line:

$$S_{Lk} \le S_{Lk}^{\max}, k = 1,...,N_l. \quad (2.27)$$

Modern techniques

To solve the problem of multi-criterion optimization, various mathematical programming techniques are used:

- *Linear Programming* (LP) or Quadratic Programming (QP), when the objective function is linear or quadratic, while the constraints are linear;
- *Non-linear Programming* (NP), in which the objective function or the constraints are non-linear. NP and LP techniques were widely used in the pieces of research about power systems optimal power flow, active and reactive power dispatch;
- *Integer and Mixed-Integer Programming*, when independent variables can take only integer values. This approach is usually applied for power systems planning, unit commitment, and generation scheduling;
- *Dynamic Programming* (DP) is very useful in case of complex problems, for example, to find an optimal solution for n generators and s possible outputs. This approach is the most suitable technique especially with particular class of search algorithms known as multi-objective evolutionary algorithms (MOEAs). [42].

Along with the main goal to reduce the consumption and emissions, there are many other areas in power engineering, where multi-criteria optimization approach helps to solve complex problems. For example, in [43] author used PSO to solve ELD problem with optimal placement of DG unites. The article shows possibilities of reducing fuel consumption and emission costs. This problem is also considered in [44], where GA and Generalized Reduced Gradient optimization technique is used during the search of new DG optimal location in case of IEEE 14-bus and IEEE 30-bus system. The optimal expansion of a power transmission network by adding new connection with the GA help is studied in [45]. Generator scheduling also can be solved using multi-criteria optimization. Comparison of proposed method and both evolutionary algorithm and simulated annealing algorithm is made in case of 10-unit system. Then, the approach was applied for IEEE 118-bus system [46]. Inverse problem of loads dispatching was solved [5].

Solutions for grids are also obtained in different pieces of research. Optimal power flow problem is solved in [47] and [48]. There are many articles dedicated to reactive power control problem [49]; a very detailed overview considering different types of optimization approaches and methods is made in [50].

About 95% articles focused on optimization problem through DP are based on *Genetic Algorithm* (GA) [51]. GAs are a part of a larger group of methods, called evolutionary computation, which combine various uses of evolutionary principles to achieve the final goal. The basement of the method is more biological than physical, copying annealing [40]. The first reference point for GA is Darwin's "On the Origin of the Species" (1859) [52], and after more than 100 years only, biological research led to the creation of the concept of GA, which was first mentioned by J. H. Holland in 1975 [53]. The author of thesis mostly used this type of algorithm in his research.

Natural phenomena also give other ideas to create algorithms aimed at solving optimization problems in the conditions of uncertainty. Command structure and algorithms replicate the behaviour of insects, cells – all those whose behaviour is not seen clearly, because of a number of components and conditions. The *immune algorithm* is also based on behaviour of cells. The distinction from GA lies in pattern recognition and memorization capabilities [54]. On a closer inspection, it can be logically traced, optimized and validated by the nature. For example, *Ant Colony Search Algorithm* (ACSA) [55], is based on how ants find a path [56].

Another idea based on a natural phenomenon, is a *Particle Swarm Optimization Algorithm* (PSO), which appeared due to flocks of birds. In 1987, Craig Reynolds recreated the algorithm that simulates the behaviour of the birds in the air [57]. The idea was based on the general rules: birds do not collide, a bird flies in the same direction with the neighbouring birds, and birds try to be on the same distance from each other. As a result, optimum distance and trajectory were obtained. Later, this method was developed and eventually PSO algorithm was presented [58], [59].

There are other methods designed to solve optimization problems, which copy natural phenomena. For example, the *Bee Algorithm* [60] which is a modification of PSO, *Firefly Algorithm,* which was introduced in 2009 by Xin-She Yang [61], *Bacterial Foraging Algorithm* [62], or even *Shuffle Frog Leaping Algorithm* [63].

However, scientists take the idea of creating algorithms by copying the behaviour of not only animals or microorganisms, but also social and political aspects in the life of the human being and development of society. For example, *Imperialist Competitive Algorithm* takes as a basis the development of empires and their colonies [64]. Changing the strategy of algorithms, it is possible to improve the results obtained earlier. There are so many changes that sometimes modifications have their own modifications. For example, *Multi-hive Multi-objective Bee Algorithm* [65] or *Tribe-Modified Differential Evolution Algorithm* [66]. Some algorithms are the result of the integration of several approaches together, such as *Chaotic Swarm Optimization*, [67] which combines the chaotic behaviour of individual ant with the intelligent foraging actions.

3. RESULTS

3.1. Decentralized and Centralized Generation. Comparison of Efficiency

The main aspect of decentralized generation is that electricity must be produced locally, next to consumption points, without transmission over long distances, in such a way reducing transmission and distribution losses. Nowadays there is a variety of DG forms and applications and the spread of this trend goes fast in many countries all over the world. However, even though DG is not a new trend, a comprehensive study of DG's pros and cons is still problematic, because of the variety of its forms and applications. It depends on power plant construction, type of fuel, locality and application area, ownership, etc. The main grounds for DG's popularity are obvious in renewable sources case. Nevertheless, the reasons for using a number of thermal power plants with small capacity instead of plant with big generation possibilities are not so clear.

Study Case 1

Some investigations about the suitability of condensing power plants to power distribution system are presented in [PAPER-I] on example of two different models. The first one consists of 6 nodes with 191MW power demands each. The second model includes 12 nodes with load equal 47.75 MW each. Models are presented on Figure 3.1 and Figure 3.2

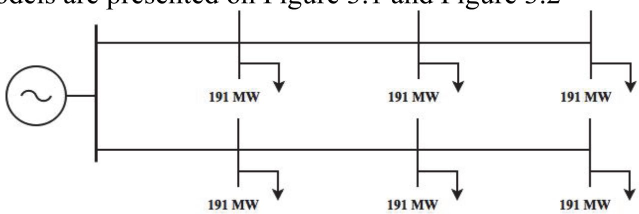

Figure 3.1. Model 1 with 6 nodes

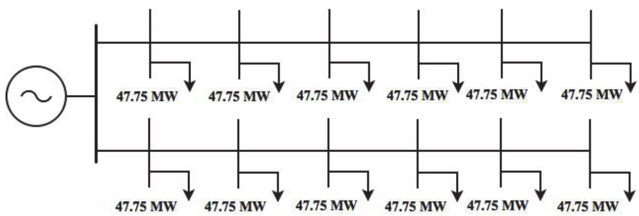

Figure 3.2. Model II with 12 nodes

The total power demands are 1200 and 600 MW correspondingly. There are several types of generators with cost characteristics for different type of fuel presented in the Table 3.1 used in calculations. The coefficients were taken from [68] with consideration that 1 MWh = 3,6 GJ

Table 3.1. Input cost characteristics coefficients [68]

Type of fuel	P_{max}, MW	Cost Coefficients		
		a	***b***	***c***
Coal	50	13.8667	2.7944	0.0029
Oil	50	14.6861	2.9083	0.0032
Gas	50	14.8944	2.9611	0.0033
Coal	200	48.2250	2.4083	0.0006
Oil	200	50.1889	2.5108	0.0007
Gas	200	50.7278	2.5528	0.0007
Coal	600	128.4111	2.3000	0.0001
Oil	600	134.2889	2.4028	0.0002
Gas	600	136.1167	2.4250	0.0002
Coal	1200	314.1111	2.0750	0.0002
Oil	1200	331.8333	2.1444	0.0002
Gas	1200	344.5333	2.1444	0.0002

For each model there are four cases to be considered. The first case of the Model I is made up from one large power plant (further – LPP) which generates electricity for the whole power system and presented in Figure 3.1. LPP and loads are connected with the means of two electric lines. In the second case, six small power plants (further – SPP) are installed in the nodes.

For Model II with 12 nodes, the comparison between one LPP with installed 600 MW capacity and SPP of 50 MW capacities will be made.

It is very important to perform reservation of power capacity in case of equipment rehabilitation or an accident. There are several ways to perform it: through the interconnection with another grid or organizing reserve. That is why the third and forth cases are added to previous: one additional LPP and one SPP for an emergency reserve will be installed into the system. Table 3.2 provides cases and models which will be considered below.

Table 3.2. Quantity and capacities of generation units

CASE / MODEL	1	2	3	4
	LPP, MW	***SPP, MW***	***LPP, MW***	***SPP, MW***
I	1x1200	6x200	2x1200	7x200
II	1x600	12x50	2x600	13x50

At the first stage of this research, distribution and transmission losses are not taken into account. According to the data from Table 3.1, Table 3.2 and (2.2) the following results for three types of fuel were obtained for the range of the load from 40 till 100%. Table 3.3 and Figure 3.3 demonstrate the results for the coal type of fuel. The similar results are obtained for other two types of fuel.

It can be seen that one large plant is much more profitable than 6 SPPs. Consumption of fuel in the first case is less, then about 8 % in comparison with SPPs' case. When the reserve is organized, the configuration with SPPs is more efficient in range of 40-76.8% of power demands. At the same time, organizing of reserve with the help of one additional SPP insignificantly enlarges fuel consumption.

Table 3.3. Fuel consumption without calculations of power losses. Model I. Fuel:coal.

Load,%	**P_{gen}, MW**	**Cases 1-2 without reserve**			**Cases 3-4 with reserve**		
		***B_1*, MWh/h**	***B_2*, MWh/h**	***$\Delta B_{1\text{-}2}$*, %**	***B_3*, MWh/h**	***B_4*, MWh/h**	***$\Delta B_{3\text{-}4}$*, %**
40	458.4	1304.4	1415.7	7.86	1598.9	1460.7	-9.46
50	573	1564.2	1704.3	8.22	1847.8	1747.5	-5.74
60	687.6	1828.9	1995.7	8.36	2099.0	2036.7	-3.06
70	802.2	2098.4	2289.8	8.36	2352.7	2328.3	-1.05
80	916.8	2372.9	2586.8	8.27	2608.8	2622.3	0.51
90	1031.4	2652.3	2886.6	8.12	2867.4	2918.6	1.76
100	1146	2936.5	3189.1	7.92	3128.3	3217.4	2.77

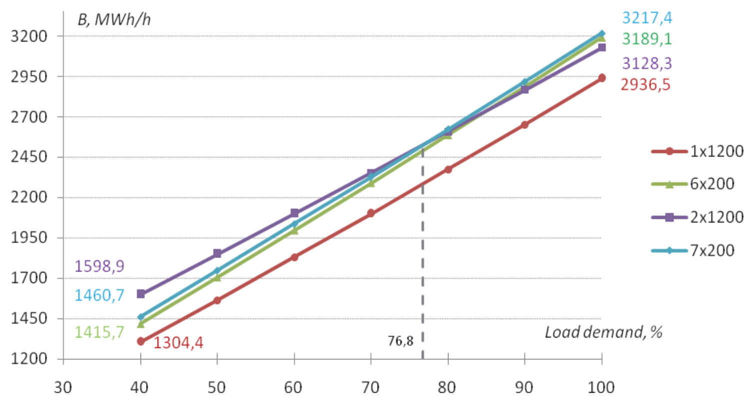

Figure 3.3. Fuel consumption without calculations of power losses. Model I. Fuel: coal.

For the approximate estimation, the transmission losses P_L (2.1) can be used for the calculations. It does not take into account the specific network parameters such as resistance, voltage, etc. Losses for each section of line, branch, and total are presented in Table 3.4.

Table 3.4. Active power losses in Model I.

		Load demands, %						
		100	***90***	***80***	***70***	***60***	***50***	***40***
P_L, MW	section 3	16.95	15.25	13.56	11.86	10.17	8.47	6.78
	section 2	7.37	6.63	5.89	5.16	4.42	3.68	2.95
	section 1	1.82	1.64	1.46	1.28	1.09	0.91	0.73
	In branch	26.14	23.52	20.91	18.30	15.68	13.07	10.45
	Total	52.27	47.05	41.82	36.59	31.36	26.14	20.91

To count these losses, all cases and regimes of generators for each type of fuel were calculated again. Fuel consumption for type of fuel coal is presented in Table 3.5 and on the diagram in Figure 3.4. Difference in fuel consumption between cases is shown in Table 3.6.

Table 3.5. Fuel consumption considering power losses. Model I. Fuel: coal.

Load, %	Cases 1-2 without reserve				Cases 3-4 with reserve			
	P_1, MW	B_1, MWh/h	P_2, MW	B_2, MWh/h	P_3, MW	B_3, MWh/h	P_4, MW	B_4, MWh/h
40	479.3	1351.4	458.4	1415.7	479.3	1644.2	458.4	1460.7
50	599.1	1624.1	573	1704.3	599.1	1904.8	573.0	1747.5
60	719.0	1902.2	687.6	1995.7	719.0	2168.2	687.6	2036.7
70	838.8	2185.5	802.2	2289.8	838.8	2434.2	802.2	2328.3
80	958.6	2474.3	916.8	2586.8	958.6	2702.9	916.8	2622.2
90	1078.4	2768.3	1031.4	2886.6	1078.4	2974.2	1031.4	2918.6
100	1198.3	3067.8	1146	3189.1	1198.3	3248.3	1146.0	3217.4

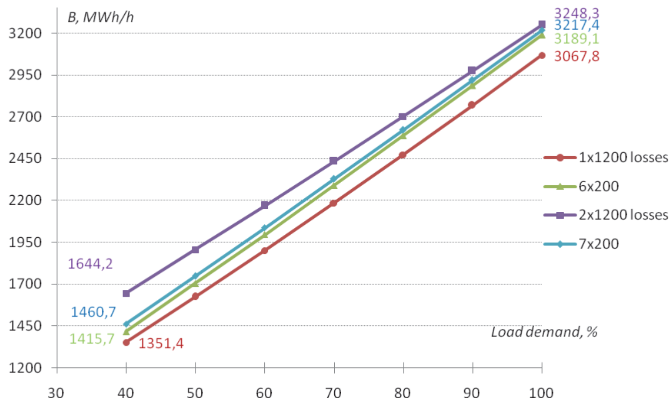

Figure 3.4. Fuel consumption considering power losses. Model I. Fuel: coal.

Table 3.6. Difference in fuel consumption considering power losses. Model I. Fuel:coal.

Load, %	$\Delta B_{2\text{-}1}$, % (6x200 vs 1x1200)	$\Delta B_{4\text{-}3}$, % (7x200 vs 2x1200)	$\Delta B_{3\text{-}1}$, % (2x1200 vs 1x1200)	$\Delta B_{4\text{-}2}$, % (7x200 vs 6x200)
40	4.54	-12.56	17.80	3.08
50	4.70	-9.00	14.74	2.47
60	4.69	-6.46	12.27	2.01
70	4.55	-4.55	10.21	1.65
80	4.35	-3.07	8.46	1.35
90	4.10	-1.91	6.92	1.10
100	3.81	-0.96	5.56	0.88

From the tables it could be seen that even considering losses case 1 with one LPP has more economical consumption of fuel if compared to others cases.

However, with installation of additional unit for power reserve, the situation changes. Case 3 with SPP's has better results, especially in the range of low load demands, comparing to Case 4.

At the same time, difference between cases 1 and 3 is very large when load demands are low, and achieve 17.8%. Close to the maximum, load demands delta reduces, but is still high and equal to 5.56%. It means that systems consisting of two LPPs for reserve reasons are not economically good solutions. In such a case, it is better to organize power reserve through the interconnection to neighbouring power systems. Summarizing diagram for type of fuel coal is presented in Figure 3.4. The results for other types of fuel are similar.

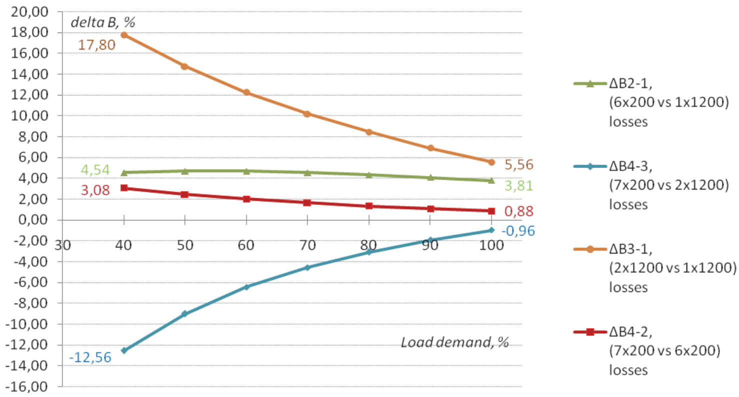

Figure 3.5. Difference in fuel consumption considering power losses. Model I. Fuel: coal

The same calculations, but only considering losses were performed for Model II with 12 nodes. Table 3.7 presents power losses in the system,

Table 3.8 and Table 3.9 present fuel consumption results for coal type of fuel, diagram of fuel consumption is presented in Figure 3.6.

Table 3.7. Active power losses in Model II.

		Load demands, %						
		100	***90***	***80***	***70***	***60***	***50***	***40***
P_L, MW	section 6	4.29	3.86	3.43	3.00	2.57	2.14	1.72
	section 5	2.93	2.64	2.35	2.05	1.76	1.47	1.17
	section 4	1.85	1.67	1.48	1.30	1.11	0.93	0.74
	section 3	1.03	0.93	0.83	0.72	0.62	0.52	0.41
	section 2	0.46	0.41	0.37	0.32	0.27	0.23	0.18
	section 1	0.11	0.10	0.09	0.08	0.07	0.06	0.05
	in branch	10.68	9.61	8.55	7.48	6.41	5.34	4.27
	Total	21.37	19.23	17.09	14.96	12.82	10.68	8.55

Table 3.8. Fuel consumption considering power losses. Model II. Fuel: coal.

Load, %	Cases 1-2 without reserve				Cases 3-4 with reserve			
	***P_1*, MW**	***B_1*, MWh/h**	***P_2*, MW**	***B_2*, MWh/h**	***P_3*, MW**	***B_3*, MWh/h**	***P_4*, MW**	***B_4*, MWh/h**
40	229.2	683.5	237.7	819.4	229.2	807.8	237.7	832.3
50	286.5	824.9	297.2	986.6	286.5	946.8	297.2	998.9
60	343.8	967.4	356.6	1155.3	343.8	1086.4	356.6	1167.0
70	401.1	1110.8	416.1	1325.6	401.1	1226.5	416.1	1336.5
80	458.4	1255.3	475.5	1497.5	458.4	1367.1	475.5	1507.5
90	515.7	1400.9	534.9	1670.9	515.7	1508.2	534.9	1679.9
100	573	1547.5	594.4	1845.9	573	1649.9	594.4	1853.7

Table 3.9. Difference in fuel consumption considering power losses. Model II. Fuel: coal.

Load, %	ΔB_{2-1}. % (12x50 vs 1x600)	ΔB_{4-3}. % (13x50 vs 2x600)	ΔB_{3-1}. % (2x600 vs 1x600)	ΔB_{4-2}. % (13x50 vs 12x50)
40	16.58	2.95	15.38	1.55
50	16.38	5.22	12.88	1.24
60	16.27	6.91	10.96	1.00
70	16.20	8.23	9.43	0.82
80	16.17	9.31	8.18	0.66
90	16.16	10.22	7.12	0.54
100	16.17	11.00	6.21	0.42

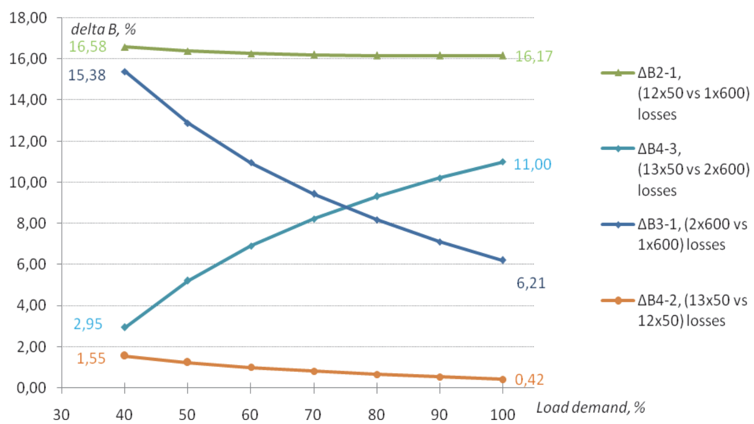

Figure 3.6. Difference in fuel consumption considering power losses. Model II. Fuel: coal

Compared to Model I, the efficiency of LPP systems is more significant than SPPs, even considering the reserve. As in Model I, fuel consumption of system consisting of two LPPs for the reserve reasons increases up to 15%; in case with SPPs, the difference is considerable.

Resume

Fuel consumption of different power generating units operating on fossil fuels was calculated in this part of the research. Different regimes and types of system configurations were considered.

Calculations show that the construction of energy system, which consists of small power stations, is not always advantageous compared to the generation of electricity in large power plant, even taking into account power losses in transmission lines. In case of small loads, the system, which consists of big amount of generators with small capacities, is less profitable than the system with one or two LPP. In case of medium generation units, reducing the losses have some benefits, especially in low ranges of the load. When LPP works close to the maximum, output difference in fuel consumption is not so significant, around 1%. From another point of view, on the assumption of having the reserve from outside, the case with one LPP is the best to achieve.

The results show that in case of DG it is less expensive to ensure the reserve through installation of additional equipment. However, the effectiveness of the system is reduced to about 4%. In case with LPP, this difference is much more significant, up to 18% depending on total load. Therefore, it is more logical to organize the reserve through the interconnection system.

As a rule, emission costs are higher in SPP case than in LPP case. The situation with capital costs is the same. Usually, the installation costs of 1 MW capacity are lower for big unit than for a small one. These factors are very important and considered in next chapter.

Study 2

More accurate analysis needs more accurate calculations of losses. For this reason in [PAPER-II] IEEE 30-bus test system (further – IEEE30) was used as a model. This is the test case which represents a simple approximation of the part of American Electric Power system. The IEEE30 consists of 30 buses, 6 generators, 41 lines, 4 transformers and 21 loads with total demand of 283.4 MW, presented in Figure 3.7. All the data for calculations except cost characteristics of generation units were taken from [69]. For fuel expenses, comparison of power units with other cost characteristics was taken from [68] with consideration that 1 MWh = 3,6 GJ. Generators' data is presented in Table 3.10.

Table 3.10. Fuel cost coefficients for generators [68]

Type of fuel	**Pmax, MW**	**Cost Coefficients**		
		a	***b***	***c***
Oil	50	14.6861	2.9083	0.0032
Oil	200	50.1889	2.5108	0.0007

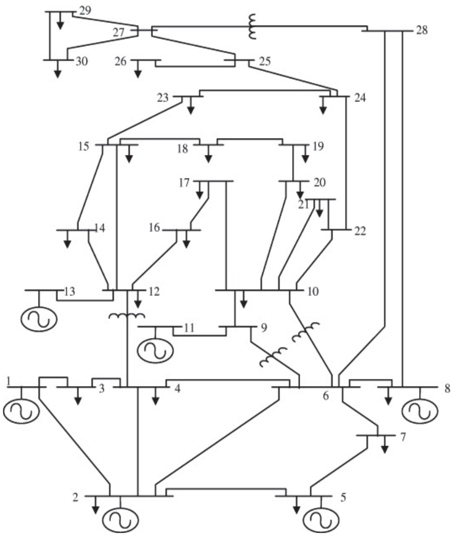

Figure 3.7. IEEE 30-bus test system[69]

Two models which are modifications of IEEE 30 will be considered further. The first model consists of one generator of 200 MW capacity at bus number 1 and five smaller generators of 50 MW connected to buses number 2, 5, 8, 11, 13. This configuration was chosen because in original IEEE30, generator with capacity 200 MW is also located at bus number 1. The second model consists of 2 generators of 200 MW allocated on buses number 1 and 5, because in this point the biggest load is 94.2 MW.

Both models include at least one generator of 200 MW capacity, and total generation output is very close to the original IEEE30 with 435MW capacity. This means that the reliability of the systems is more or less similar. In case of accident with 200 MW capacity unit, generated power will not be enough to cover demands in both cases.

For both models power flow was calculated through the simulations in PWS. The fuel consumption was calculated as well using (2.5). Generators output P_g, with fuel B_g and marginal b_g costs, total losses P_L and total fuel consumption are presented in Table 3.11 and Table 3.12.

Table 3.11. Results of the calculations for Model I

Bus number	**P_g, MW**	**B, MWh/h**	**b_g, MW/MW**	**P_L, MW**
1	181.1	527.77	2.76	
2	28	98.63	3.09	
5	25.82	91.91	3.07	
8	21	77.17	3.04	10.49
11	20	74.13	3.04	
13	18	68.07	3.02	
Total	293.89	937.96		

Table 3.12.Results of the calculations for Model II

Bus number	P_g, MW	B, MWh/h	b_g, MW/MW	P_L, MW
1	151.75	447.32	2.72	
5	146.26	432.39	2.72	14.61
Total	298.01	879.72		

From Table 3.11 and Table 3.12 it can be seen that fuel consumption in Model II is better compared to the Model I. At the same time, generators in Model I are not loaded so much. For this reason, for Model I several cases were considered. The number of generators was reduced to 5, i.e. one generator of 50 MW capacity excluded from busses number 2, 5, 8, 11, or 13. Total system capacity in this case is equal to 400 MW. For each possible generator, allocation power flow simulations were made and fuel consumption calculated. The results are shown in Table 3.13.

Table 3.13. Results of the calculations for Model II with 5 generators

Bus number	P_g, MW	P_L, MW	B, MWh/h
1,5,8,11,13	292.77	9.37	921
1,2,8,11,13	295.22	11.83	929
1,2,5,11,13	294.16	10.76	933
1,2,5,8,13	294.40	11,00	926
1,2,5,8,11	293.99	10.59	924

As shown, the power losses in case when generator at bus 2 is switched off are reduced as along with the total fuel consumption. In other cases, losses grow up, but efficiency of the system is still better. That is why, similarly, the fuel consumption for system consisting of 4 generators was found. The best result is presented in Table 3.14. Fuel consumption is again reduced. This is because all generators are loaded close to the nominal capacity, where fuel cost characteristics are better. In case of 3 generators, the power flow cannot be calculated because of capacity limits of the lines.

Table 3.14.The best result for Model II with 4 generators

Bus number	P_g, MW	P_L, MW	B, MWh/h
1,5,8,11	293.23	9.83	895

Resume

Burning fuel in small power stations is not always advantageous compared to the generation of electricity in a large power plant, even with the consideration of power losses in transmission lines. In case of 5 generation units with small capacities, the effectiveness of the system is reduced. Calculations show that decreasing the amount of small plants, the efficiency of the system is increasing. The best model is in case of two generators of 200 MW capacity.

Difference in fuel consumption is about 6 %, depending from the number of units. It should be noted that sometimes the cut-off of one generator improves parameters of the system. In this particular case, switching generator at bus number 2 leads to reduction of losses and fuel consumption.

3.2. System Optimization Considering Power Flow, Fuel Consumption, and Emissions Costs

In previous chapter, several models were considered and centralized and decentralized generations were compared. According to the calculations, the benefits of DG are not so obvious as it can be imagined. The fuel cost characteristics of generation units with big capacities are much better than small. This fact lets centralized systems cover power losses in most cases. Nevertheless, the price for electricity is created by several components, not only by fuel.

In this chapter, based on [PAPER-III], the analysis of power system with different capacity of generation units, including fuel consumption, emissions, capital, and operating costs is made.

A system with 200 MW load demands was considered. For simplicity, the system has 20 nodes with a load of 10 MW each. To satisfy the demand for electricity, power units of 200, 50 and 10 MW were taken.

The fuel-costs and emission characteristics are presented in Table 3.15 [70]. Under the terms of reliability, it is very important to perform reservation of power capacity in case of equipment rehabilitation or an accident. The system should provide backup unit which will cover missing power in case of the accident. Thus, the following cases are considered in Figure 3.8.

Table 3.15. Generators data[70]

Parameter	**Generators**		
	G1	***G2***	***G3***
Pmin, MW	50	15	5
Pmax, MW	200	50	10
a,$/h	0	0	0
b,$/MWh	2	1	3.25
c,$/MW^{2}h	0.00375	0.0625	0.00834
α,t/h	4.091	4.258	6.131
β,t/MWh	-0.05554	-0.05094	-0.05555
γ,t/MW^{2}h	0.00065	0.00046	0.0005151
λ,t/MWh	0.0002	0.000001	0.00001
ξ,t/h	0.02857	0.0008	0.0006667

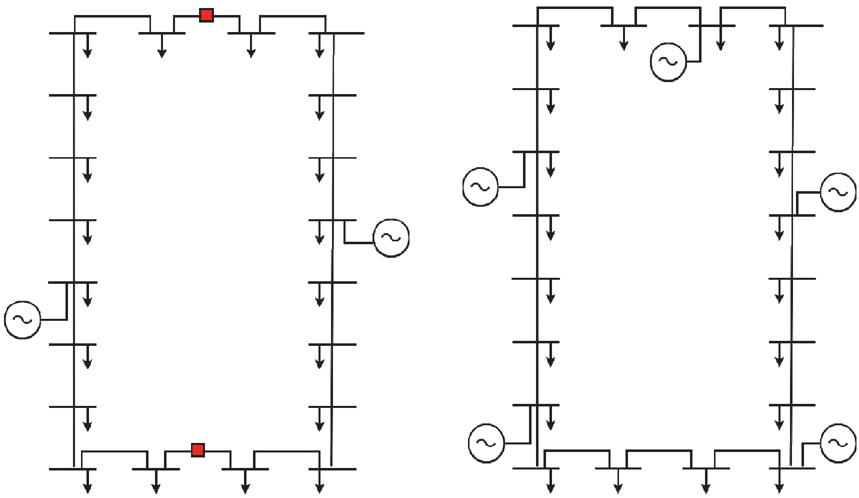

Figure 3.8. Models with 2x200 MW and 5x50 MW generators

The first model consists of two units of 200 MW. To reduce the losses in terms of optimal control, the network is normally open in two points with the reserve-switching device condition. The second model consists of 5 generation units, 50 MW each. The third model includes 21 units of 10 MW capacities.

Here, the general case was considered. To simplify the calculation of losses, the assumption is made that the system is a loop network with 20 nodes located at the same distance to the adjacent. In this case, it is possible to calculate power losses according to the (2.1). In the first case the losses ΔP_1 = 0.853 MW, i.e. each generator must produce P_1 =100.426 MW. Thus, using (2.5) and (2.10) and taking into the account number of generators, i.e. multiplying results by two, fuel costs B_1 and emissions E_1 were found. B_1 =477.35 $/h and E_1=3.2528 t/h. Taking into the account power demands these, B_1=2.387$/MWh and E_1=0.016 t/MWh correspondingly.

The same calculation is made for the power demand of 160, 120 and 80 MW with the aim to compare costs in different regimes of the system. The results of the calculations are presented in Table 3.16.

Table 3.16. Fuel and emissions costs. Model I

Costs	**Power demands, %**			
	100	***80***	***60***	***40***
ΔP_L, MW	0.85	0.55	0.31	0.14
P_G, MW	200.853	160.546	120.307	80.138
B_1(P),$/h	477.35	369.42	267.75	172.31
E_1(P), t/h	3.252	2.411	1.9282	1.7832
B_1(P), $/MWh	2.387	2.309	2.231	2.154
E_1(P), t/MWh	0.016	0.015	0.016	0.022
E_1(P), $/MWh	0.557	0.516	0.550	0.763

At the same time, according to the European directive 209/29/CE, since 2013 the CO_2 producers should pay for every ton of carbon dioxide polluted. An average cost is 6.5 € per ton [39]. Assuming that 1€=1.37 $ (currency rate at the period this research was made), emissions costs are equal to 0.5547 $/MWh for two generators G1 in case of 100.426 MW production. Same calculations are made for 160, 80, and 40 MW. The results of calculations are added to Table 3.17.

The calculations for Model II are similar to calculations made above. The results of calculations are given in Table 3.18.

Table 3.17. Fuel and emissions costs. Model II

Costs	**Power demands, %**			
	100	***80***	***60***	***40***
ΔP_2, MW	0.15	0.1	0.05	0.02
P_2, MW	200.150	160.096	120.054	80.024
$B_2(P)$,$/h	700.90	480.48	300.22	160.07
$E_2(P)$, t/h	4.430	4.646	4.949	5.340
$B_2(P)$, $/MWh	3.505	3.003	2.502	2.001
$E_2(P)$, t/MWh	0.022	0.029	0.041	0.067
$E_2(P)$, $/MWh	0.759	0.995	1.413	2.286

The third model consists of 21 generators. As each generator is installed near loads, it is possible to neglect losses in transmission lines, thus, they are not counted in this calculation. In this case, each generator produces 9.254 MW. Using (2.5) and (2.10), fuel costs B_3 and emissions E_3 were found. The results of calculations for the third pattern are shown in Table 3.18.

Capital and operating costs are taken from [71] and [72]. For convenience, the data were transferred to the same measurement units, and pounds were converted into dollars at the rate of 1 £ = 1.67 $ (currency rate at the period this research was made) and presented in Table 3.19.

Table 3.18. Fuel and emissions costs. Model III

Costs	**Power demands, %**			
	100	***80***	***60***	***40***
P_{L2}, MW	0	0	0	0
P_2, MW	40	32	24	16
$B_2(P)$,$/h	665.89	530.17	395.72	262.54
$E_2(P)$, t/h	35.593	36.154	36.738	37.3455
$B_2(P)$, $/MWh	3.329	3.314	3.298	3.282
$E_2(P)$, t/MWh	0.178	0.181	0.184	0.187
$E_2(P)$, $/MWh	6.095	6.191	6.291	6.395

Table 3.19. Equipment costs

Parameter	Generators		
	G1	***G2***	***G3***
P, MW	200	50	10
Lifetime period, y	30	20	20
Capital costs, $/KW	621	1194.551	1407.81
V O&M, $/MWh	3.37	0.334	0.334
F O&M, $/KW	11.32	3.26	5.01

There are three different types of equipment costs with different meaning and measurement units. To make the calculation of additional component to the price for 1 MWh transformation of capital and fixed O&M costs was made. The additional part of the price calculated for each type of generator and output regime, taking into account the life period of equipment and operational hours 8760. The results are shown in Table 3.20.

Table 3.20. Capital and Fixed O&M costs for the different regimes

Parameter	Generators		
	G1	***G2***	***G3***
P, MW	200	50	10
Lifetime period, y	30	20	20
Power demands, %	100		
Capital costs, $/MWh	2.363	6.818	8.035
F O&M, $/MWh	0.043	0.372	0.572
Power demands, %	80		
Capital costs, $/MWh	2.954	8.523	10.044
F O&M, $/MWh	0.054	0.465	0.715
Power demands, %	60		
Capital costs, $/MWh	3.938	11.364	13.392
F O&M, $/MWh	0.072	0.620	0.953
Power demands, %	40		
Capital costs, $/MWh	5.908	17.046	20.089
F O&M, $/MWh	0.108	0.929	1.430

Resume

The comparison of three models of power system has been made, taking into account the cost of fuel, emissions taxes, capital, and operating costs. It can be concluded that producing electricity through the overall installation of very small generators near loads is not profitable. Reducing losses in transmission lines is not enough to cover fuel and emissions costs. The situation can be changed when losses in lines are higher, i.e., an amount of transferring power will increase, as well as loads. In the considered case, the losses are very low.

The situation with capital and maintains expenses is the worst. The price gap between small and big units is considerable enough to make Model III very expensive, especially with the loads decreasing. If the life period of equipment becomes longer, difference between the models is reduced.

From the stability point of view, Model I has a number of drawbacks. For example, in case one generation unit fails or is under repair, all power should be transmitted along one line. It leads to high losses, worse quality of electricity, and the reduction of stability. The transmission lines cross section must be increased, that leads to more expensive costs of the system which are not included here.

Final comparison of three models for four regimes is presented in Table 3.21.

Table 3.21. Comparison of the Models

Parameter	**Model**		
	I	***II***	***III***
P_{max}, MW	200	50	10
Number of generators	2	5	21
Power demands, %	*100*		
B(P), $/MW	2.387	3.505	3.329
E(P), $/MWh	0.145	0.197	1.585
Equipment, $/MWh	5.776	7.524	8.941
Total, $ /MWh	8.308	11.226	13.856
Delta,%		25.995	40.041
Power demands, %	*80*		
B(P), $/MW	2.309	3.003	3.314
E(P), $/MWh	0.134	0.259	1.610
Equipment, $/MWh	6.378	9.321	11.093
Total, $ /MWh	8.821	12.583	16.016
Delta,%		29.900	44.927
Power demands, %	*60*		
B(P), $/MW	2.231	2.502	3.298
E(P), $/MWh	0.143	0.367	1.636
Equipment, $/MWh	7.380	12.317	14.680
Total, $ /MWh	9.755	15.186	19.613
Delta,%		35.768	50.265
Power demands, %	*40*		
B(P), $/MW	2.154	2.001	3.282
E(P), $/MWh	0.198	0.594	1.663
Equipment, $/MWh	9.385	18.309	21.852
Total, $ /MWh	11.738	20.904	26.797
Delta,%		43.850	56.198

3.3. Factors Influencing Multi-Criteria Optimization Process

In the previous part, the simple system was considered with calculations of fuel, emission, and equipment costs. Nevertheless, calculations of losses were very simplified. Thus, in [PAPER-IV] all of these factors were studied again, but using IEEE30, which was presented in Figure 3.7, because this system has line parameters and allows for more accurate computation.

According to (2.5) and (2.10) multi-objective function (2.11) is determined. During the calculations, all of the constraints (2.23) - (2.27) were taken into account.

In this part of the research, three modifications of IEEE30 were taken. The aim of the calculations is to show different dependences and aspects, which appear during the system's operation, and their impact on the final fuel consumption and atmospheric emissions.

The first is absolutely similar to IEEE 30 which consists of 30 buses, 6 generators (at the buses number 1, 2, 5, 8, 11, 13), 41 lines, 4 transformers, and 21 loads with the total demand of 283.4 MW [70]. Generators data is presented in Table 3.22. Line parameters are taken from [22].

Table 3.22. Generators data [70]. *Model I*

Parameter	**Generators**					
	G1	***G2***	***G3***	***G4***	***G5***	***G6***
Pmin, MW	50	20	15	10	10	12
Pmax, MW	200	80	50	35	30	40
a, $/h	0	0	0	0	0	0
b, $/MWh	2	1.75	1	3.25	3	3
c, $/MW2h	0.00375	0.0175	0.0625	0.00834	0.025	0.025
α, t/h	4.091	2.543	4.258	5.326	4.258	6.131
β, t/MWh	-0.05554	-0.06047	-0.05094	-0.0355	-0.05094	-0.05555
γ, t/MW^2h	0.00065	0.00056	0.00046	0.00033	0.00046	0.00052
λ, t/MWh	0.0002	0.0005	0.000001	0.002	0.000001	0.00001
ξ, t/h	0.02857	0.00033	0.0008	0.0002	0.0008	0.00067

The second and third model consist of two and three generators with bigger capacity of 300 MW each. One of the ideas of the research is to show dependences and factors influencing the generation process, when the system has some similarities and distinctions. That is why models II and III have the same capacities. In case of three generators, it is more reasonable to use the capacity of 200 MW, which will be considered later. Fuel cost and emissions characteristics are also provided in Table 3.23. The generators data was taken from [73].

Table 3.23. Generators data [73]. *Models II and III*

Parameter	**Generators**		
	G1	***G2***	***G3***
Pmin, MW	30	30	30
Pmax, MW	300	300	300
a,$/h	150	200	115
b,$/MWh	1.89	1.3	2
c,$/MW2h	0.00005	0.000045	0.000055
α, t/h	0.0023333	0.0024313	0.0021022
β, t/MWh	-0.015	-0.0181	-0.0182
γ, t/MW^{2}h	0.016	0.018	0.031

The first aspect is an optimal placement of the generators. Because of three different types of generators with own unique characteristics, there are 91 possibilities to install 2 generators at 10 high voltage buses (№№ 1, 2, 3, 4, 5, 6, 7, 8, 11, 13, 28).

In the beginning, the most obvious operation is the minimization of losses. In case 2, it is assumed that each generator produces 95 MW. For every of 91 set, power flow and transmission losses in high voltage level lines had been found with the help of Power World Simulator. The best results were obtained and presented in Table 3.24.

The same procedure was implemented for case 3. There are 42 possibilities to install 2 generators which produce 150 MW of power each. The results are presented in Table 3.24.

Table 3.24. Generators placements for Models II and III

№№Buses	**P_L 110 (35kV), MW**
5,6	3.14 (4.65)
4,5	4.22 (5.88)
4,5,6	1.07 (2.42)
4,5,8	1.37 (2.7)

The optimal regime for Model I was found by using (2.5) and (2.10) with the help of MATLAB. According to the calculation, fuel costs amount to 799.599 $/h, emissions – 0.3384 ton/h. Pareto front is presented in Figure 3.9. Power generation in this case equals to 289.525 MW, losses – to 6.125 MW.

According to the European directive 209/29/CE, since 2013 the CO_2 producers should pay for every ton of carbon dioxide produced. An average cost of one ton is 6.5 € [39].

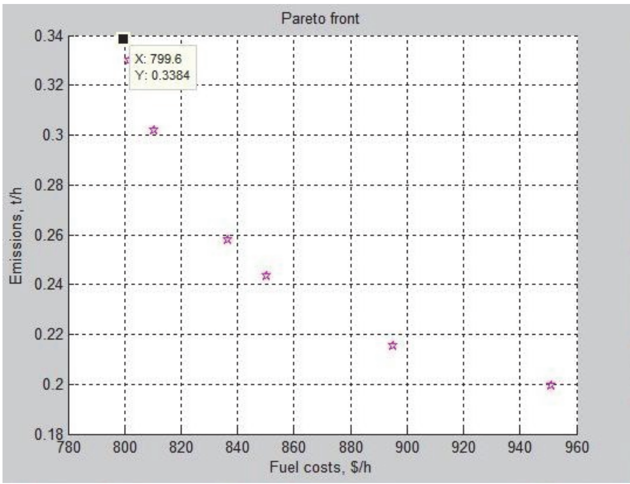

Figure 3.9. Results of multi-criteria optimization for model I

Assuming 1€=1.37 $ (currency rate at the period this research was made), it means that emissions cost is 8.905 $ per ton. It is possible to calculate the price of one MWh, taking into account that system demands is 283.4 MW. The results are presented in Table 3.25.

Table 3.25. Fuel consumption and emissions. Model I

Generator	**Fuel consumption priority**			**Transmissions losses priority**		
	P, MW	***B, $/h***	***E, t/h***	***P, MW***	***B, $/h***	***E, t/h***
G1	168.65	443.95	0.1557	80.00	184.00	0.0398
G2	46.92	120.62	0.0100	52.40	139.75	0.0097
G3	29.79	85.25	0.0315	50.00	206.25	0.0286
G4	14.97	50.54	0.0507	35.00	123.97	0.0469
G5	10.16	33.06	0.0379	30.00	112.50	0.0314
G6	19.04	66.18	0.0526	40.00	160.00	0.0473
Total	289.52	799.6	0.3384	287.4	926.47	0.2038
P_L, MW	6.125			3.99		
Price $/h	802.640			928.285		
Price, $/MWh	2.832			3.276		

Another calculation was made with the priority to reduce transmission losses. In this case, the losses are estimated to be 3.99 MW. The results are filled in Table 3.25 too.

It is seen that the reduction of losses in this case is not an optimal solution. Difference in losses is 2.135 MW, but generation is more expensive during decreasing losses. The difference is 125.645 $/h or 0.444 $/MWh.

The same situation can be seen when power demand increased up to 110% and total 311.74 MW. In this case, difference in losses is more essential and estimated as 7.23 MW, fuel costs are 124.184 $/h higher during the reduction of losses, difference in price is 0.734 $/MWh. The results of calculations are shown in Table 3.26.

Table 3.26. Fuel consumption and emissions. 110% demand. Model I

Generator	**Fuel consumption priority**			**Transmissions priority**		
	P, MW	***B, $/h***	***E, t/h***	***P, MW***	***B, $/h***	***E, t/h***
Total	324.85	919.70	0.395	317.62	1045.55	0.2092
P_L, MW	13.11			5.88		
Price $/h	923.229			1047.413		
Price, $/MWh	2.962			3.696		

Calculations of fuel costs and emissions were made for 120% and 130% of the load. The results are presented in Table 3.27.

Table 3.27. Fuel consumption and emissions. 120% and 130% demand. Model I

Generator	**120% Demands**			**130% Demands**		
	P, MW	***B, $/h***	***E, t/h***	***P, MW***	***B, $/h***	***E, t/h***
Total	354.02	1032.95	0.427	382.73	1155.89	0.416
P_L, MW	13.94			14.308		
Price $/h	1036.754			1159.617		
Price, $/MWh	3.049			3.148		

The conclusion is that reducing the transmission losses is not the first important factor during the optimization process. The price per MW increases with the growing of the load. The rate of emissions per MW also increases. It means that to obtain a more economic regime, the system should not be overloaded.

The second factor is a choice of particular generator. For Model II, numbers of buses where generators should be connected were already found and presented in Table 3.24. However, another possibility to cut fuel costs is an optimal choice between generators. To determine the location of generators with different characteristics on the buses, preliminary analysis was made. In Figure 3.10 fuel consumptions of generators are presented.

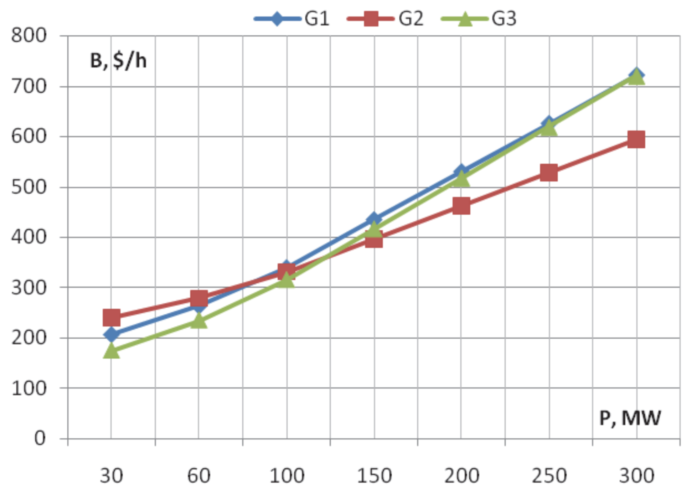

Figure 3.10. Model II. Fuel-cost characteristics of generators

The generator G2 is more efficient with loads close to the maximum. Fuel consumption of generators G1 and G3 is more or less equal when they work with minimum and medium loads. Taking into account this fact and considering the maximum load of 94.2 MW connected to bus number 5 it is more logical to assume that the generator G1 might be placed to bus number 4, G2 to bus 5, G3 to bus 6. For the verification of this presupposition, computation was made for 3 possibilities of generators placement. Generating power, fuel costs, and emissions level are presented in Table 3.28.

Table 3.28. Generators placement verification. Model II

Generator/Bus number	P, MW	B, $/h	E, t/h	E, $/h	Price, $/h
G1/5, G2/4, G3/6 (G1/6, G2/4, G3/5)	289.2	882.12	1.266	11.27	893.40
G1/4, G2/5, G3/6 (G1/6, G2/5, G3/4)	290.7	884.10	1.283	11.43	895.53
G1/4, G2/6, G3/5 (G1/5, G2/6, G3/4)	287.46	879.82	1.247	11.10	890.93
G1/5, G2/4, G3/8 (G1/8, G2/4, G3/5)	288.99	881.84	1.264	11.26	893.01
G1/4, G2/5, G3/8 (G1/8, G2/5, G3/4)	290.41	883.72	1.280	11.40	895.11
G1/4, G2/8, G3/5 (G1/5, G2/6, G3/4)	291.34	884.95	1.290	11.49	896.43

It can be also seen that during generators' arrangement, it is not always a better solution to install generator with the best characteristics at a maximum load close to the biggest load demand. The same calculations were made for the case when generators are placed at buses number 4, 5 and 8. The results were filled in Table 3.28.

The best result was obtained in the case when G2 placed was at bus 6. The price for the fuel and emissions in this case is 890.93 $/h. This placement had been taken for further computations. Optimal regime was calculated for the unstable system with growing load demands equal to 110%, 120% and 130%. To save the space, the results of calculations are presented in chart form in Figure 3.11.

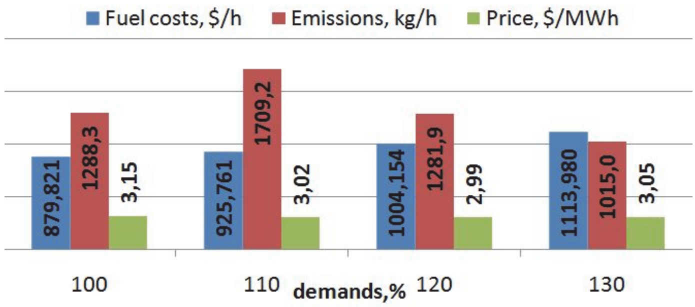

Figure 3.11. Model II. Fuel and emissions costs

At the diagram, the price was converted to $/MWh and emissions to kilo/h to make results more visible. We can see that the price is decreasing when the generation rises. The results are different from those obtained before, because in case with 3 generators of 300 MW most of the time two of them (G1 and G3) operate close to the minimal limits. The system is very far from the overload regime.

From this point of view, it is more reasonable to use only two generators. The examination of this possibility would be considered in case with Model III. On the basis of Figure 3.10, in this kind of model, generators G2 and G3 will be used. The same preliminary analysis was made for 4 possibilities of the arrangement of generators at the buses. The results are presented in Table 3.29.

Table 3.29. Generators' placement verification. Model III

Generator/ Bus number	P, MW	B, $/h	E, t/h	E, $/h	Price, $/h
G2/4, G3/5	293.65	720.92	1.6563	14.75	735.67
G2/5, G3/4	290.33	716.53	1.6146	14.38	730.91
G2/5, G3/6	293.42	720.62	1.6534	14.72	735.34
G2/6, G3/5	287.81	713.19	1.5833	14.1	727.29

As shown, it is better to install generator G2 on bus number 6, not bus 5 which looks more obvious because here the main load concentrates. It demonstrates the importance of power flow calculations in correct placement of the generator. The price in this case is 727.29 $/h. Optimal regime was calculated for the unstable system with growing load demands equal to 110%, 120%, and 130%. The results of the computations are presented in Figure 3.12.

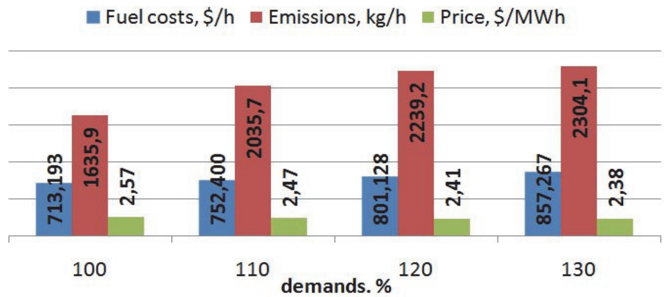

Figure 3.12. Model III. Fuel and emissions costs

For the complete analysis, the cost of maintaining equipment and capital expenditures costs should be taken into account. Equipment costs data such as EPC (engineering, procurement, construction), variable and fixed O&M costs are presented in Table 3.30.

Depending on load of the unit, the price for 1 MWh will be changing. For this reason the calculations of different regimes were made. Additional equipment as part of the price was found for each model. The results of calculations are presented in Table 3.31. Assuming 1€=1.37 $ (currency rate at the period this research was made), summary Table 3.32 was created.

Table 3.30. Equipment costs [34]

Power Plant capacity, MW	EPC, €/kW	Variable O&M costs, €/MWh	Fixed O&M costs, €/kW per year
Less than 30	2000	4	40
30<P≤200	1500	4	40
More than 200	1000	4	40

Table 3.31. Equipment costs (€/MWh) depending on load demands

Model, generators	100%	110 %	120%	130 %
I, 6 generators	7.01	6.37	5.84	5.39
II. 3x300 MW	14.50	13.18	12.08	11.15
III. 2x300 MW	7.25	6.59	6.04	5.58

Table 3.32 shows that nowadays, with low price for emissions, this part of costs does not have a proper influence on the price. The fuel consumption of Model III is much preferable comparing to Model I. Yet, as equipment in Model III is very far from optimal regime, the equipment costs are significantly higher than in Model I. Model II has small power losses, but total price is much higher

than in other cases. Based on this, it is possible to conclude that generation units must be loaded as much as it is possible.

Table 3.32. Generation costs of the systems

Parameters	**Model I, 6 generators**	**Model II, 3x300 MW**	**Model III, 2x300 MW**
Load demands, %		100	
Fuel costs $/MWh	2.821	3.105	2.517
Emissions costs $/MWh	0.011	0.040	0.051
Equipment costs, $/MWh	22.863	35.280	25.364
Total costs, $/MWh	25.695	38.425	27.914
Load demands, %		110	
Fuel costs $/MWh	2.950	3.262	2.414
Emissions costs $/MWh	0.011	0.021	0.058
Equipment costs, $/MWh	21.283	32.571	23.540
Total costs, $/MWh	24.244	35.853	26.012
Load demands, %		120	
Fuel costs $/MWh	3.037	2.953	2.356
Emissions costs $/MWh	0.011	0.034	0.059
Equipment costs, $/MWh	19.966	30.313	22.035
Total costs, $/MWh	23.014	33.299	24.450
Load demands, %		130	
Fuel costs $/MWh	3.137	3.024	2.327
Emissions costs $/MWh	0.010	0.025	0.056
Equipment costs, $/MWh	18.562	28.403	20.762
Total costs, $/MWh	21.999	31.451	23.144

For this reason, other generators were selected for Models II and III. Model II now has three generators with 200 MW each, Model III consists of generator G1 with nominal output 200 MW, and generator G2 with capacity of 300 MW. The results were updated and presented in Table 3.33.

Another aspect for system comparison is the reliability as additional factor. From the results obtained above, it is clear that reducing number of generators and simultaneously increasing their capacity makes the power system more efficient. Along with profitability, the system should operate at any time and be stable: the shutdown process leads to serious consequences and great losses of money. That is why reliability factor is very important during preliminary estimation. There are two most serious accidents in power system considered: the line or the generator/transformer switching off. For the Models I, II, III, different values of loads modelling were made in Power World Simulator. In Table 3.34 it is possible to find information about the system stability.

Table 3.33. Generation costs of the systems. Updated results

Parameters	**Model I, 6 generators**	**Model II, 3x200 MW**	**Model III, 1x300 and 1x200 MW**
Load demands, %		100	
Fuel costs $/MWh	2.821	2.375	2.154
Emissions costs $/MWh	0.011	0.005	0.055
Equipment costs, $/MWh	22.863	28.657	23.139
Total costs, $/MWh	***25.695***	***31.037***	***25.347***
Deference, $/MWh	*0.348*	*5.690*	-
Load demands, %		110	
Fuel costs $/MWh	2.950	2.256	2.011
Emissions costs $/MWh	0.011	0.005	0.054
Equipment costs, $/MWh	21.283	28.811	21.534
Total costs, $/MWh	***24.244***	***28.811***	***23.599***
Deference, $/MWh	*0.645*	*5.211*	-
Load demands, %		120	
Fuel costs $/MWh	3.037	2.157	1.894
Emissions costs $/MWh	0.011	0.004	0.005
Equipment costs, $/MWh	19.966	24.795	20.196
Total costs, $/MWh	***23.014***	***26.956***	***22.144***
Deference, $/MWh	*0.870*	*4.811*	-
Load demands, %		130	
Fuel costs $/MWh	3.137	2.080	1.800
Emissions costs $/MWh	0.010	0.004	0.054
Equipment costs, $/MWh	18.852	23.309	19.064
Total costs, $/MWh	***21.999***	***25.393***	***20.918***
Deference, $/MWh	*1.081*	*4.475*	-

Table 3.34. System stability

Load. %	**Mode l**	**Lines (possible to switch off)**	**Transformers/generators (possible to switch off)**
100	I	any line	up to three generators. except G1
	II	any line	any one generator
	III	any line	G1 with following reducing of the load
110	I	any line	up to two generators except G1
	II	any line	any one generator, in some cases two with following reducing of the load
	III	any line	none
120	I	any line	one of the G3, G4, G4, or G6
	II	any line	any one generator
	III	any line, except 4-12, 28-27	none
130	I	any line	one of the G4, G4, or G6
	II	any line	any one generator
	III	any line, except 4-12, 28-27	none

Resume

In this part, three different models of power system were analyzed. Fuel costs, emissions, transmission losses, equipment expenses and their interactions during generation process were considered. It was shown how such factor as reducing losses, changing capacity, and correct placement of generators and choosing their capacities influence the generation process and the price of electricity.

Calculations for possible changes of loads in case of projected growth of loads or abnormal regime were made as well. Various combinations of the number of generators and their capacity are considered in order to identify the main issues and patterns in this direction. Capacity limitations of electric lines, transmission losses, and voltage drop on the bus section were taken into account to avoid a formal approach to the calculation of the optimum mode.

According to the calculations, the best is model with two generators. The difference from Model I is 0.348 $/MWh, from Model II is 5.69 $/MWh at 100% of power demands. The Model III has better fuel consumption as well.

At the same time, Model III has worse results if compared to emissions in other models: almost 5 times more compared to Model I and 10 times to Model II. However, because of low price for ton of emissions this aspect does not make Model II more expensive. Furthermore, system reliability is worse than any model, regardless of the load, but acceptable in case when the system is stable and power demands is no more than 100 %.

Model II with three generators of 200 MW is the less efficient, but the most reliable. It is possible to temporarily transform Model III to Model II in normal regime through switching generator G1 to non-spinning reserve with the aim to make a system more profitable.

When power demands of the system grow, the difference in price between Model I and III grows too, while the price between Model II and III, on the contrary, it is then reduced.

The first conclusion is that for choosing an optimal regime it is better to focus on fuel consumption and emissions than on power losses. One of the parameters which may be changed during generation process is fuel consumption. Calculations for Model I show that the regime with 6.125 MW of losses is more efficient than regime with losses 3.99 MW. Prices for fuel in case of 100% load are 2.832 and 3.276 $/MWh correspondingly.

The second factor is the number of generators and their capacity. Model III with two generators of 200MW and 300 MW has better results compared to Model I consisting of one generator with 200 MW and five small generators.

The third issue is the placement and choice of generators. Calculations for Models II and III show that the installation of generator with the best characteristics at a maximum load close to the biggest load demand point does not always have a better result.

Nowadays, the price for the emissions polluted is not very high, and this aspect does not have considerable influence on the price. Nevertheless, electricity producers can be limited by restrictions. In this case, generation units must operate in non-optimal fuel consumption regime.

The analysis shows that equipment costs constitute the main part of the price for the electricity. That is why, the capacity of generation units should be carefully calculated. On the examples of Models II and III, it is shown how unused capacity increases expenses. This is a precondition for interconnected power systems, which has fast power reserve, for instance, hydropower plant or hydropower storage. Interconnection also helps to solve the problem of reliability and flexibility of the system. In case of small number of generators with big capacity, the system has less possibility for organizing maintenance works, including in case of an accident.

3.4. The Impact of Green Energy on Efficiency of Thermal Power Plants

In the previous sections, centralized and decentralized systems consisting of only thermal power plants (further – TPP) were considered. In this section, the model with the wind park is studied. The objective of the research is to focus on changing the fuel consumption of TPP and polluting emissions in case with cooperation on green energy. With the connection of wind park into the system, the question about efficiency of power plants appears. As known, the efficiency of TPP reduces with the decreased loads. On the contrary, green energy has no emissions and fuel costs. To make the analysis deeper, the costs for the equipment (EPC, variable, and fixed O&M) were taken into the account, and comparison of load shifting was also made. Calculations are based on data from IEEE 30-bus test system. The data of green generation during March 2015 was taken from Estonian SO "Elering" web-page [74]. Form the same archive the power demands data were taken for the same period. The diagram is presented in Figure 3.13.

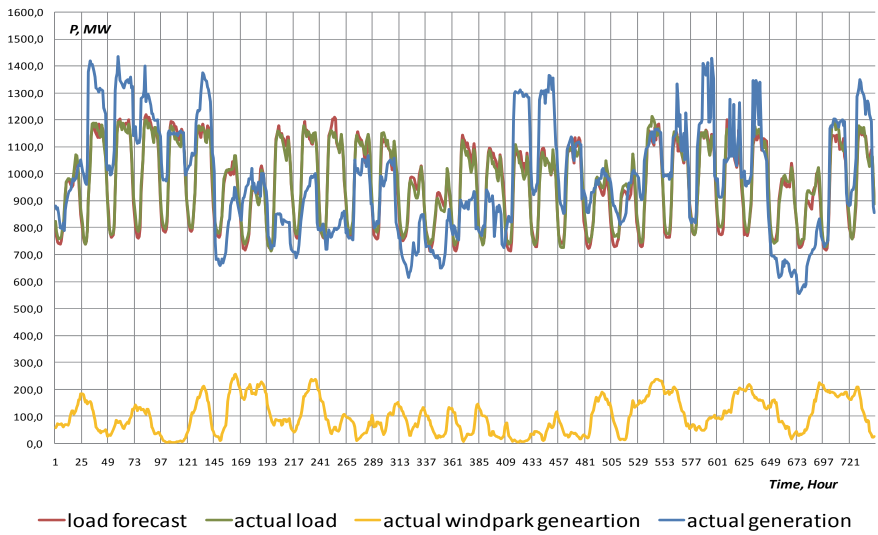

Figure 3.13. Loads and generation of power in Estonia in March 2015

The maximum load during the period is 1214.7 MW. IEEE30 has predetermined demands equal to 283.4 MW. To make studying case relevant, all of the data from Elering archive were divided by 1214.7/283.4=4.3. In this case, system demands, wind and power plants generation are presented in Figure 3.14.

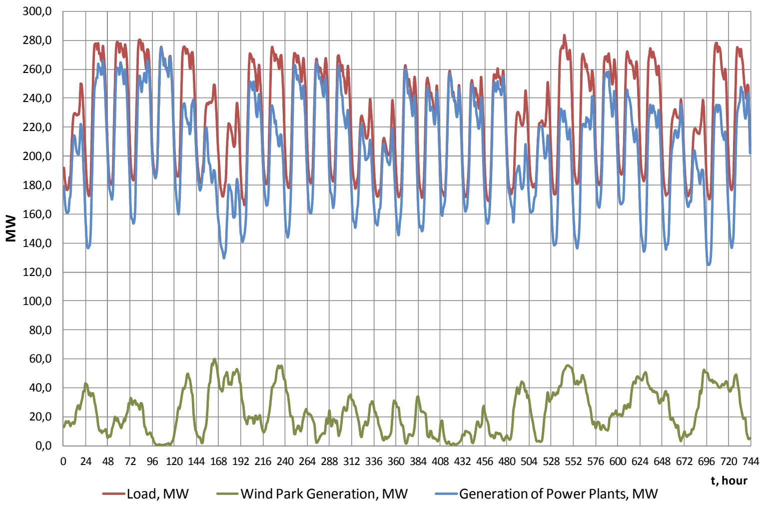

Figure 3.14. Loads and generation of power in case of study

The maximum load in case of the study is 283.4 MW; the minimum load is 166.4 MW. Wind generation range is from 0 to 59.7 MW. The maximum participation factor is 29% of total demands. The fuel consumption and emissions data for IEEE30 generators were taken from [70] and are presented in the Table 3.35.

Table 3.35. Fuel and emission characteristics

Parameter	**Generators**					
	G1	***G2***	***G3***	***G4***	***G5***	***G6***
Pmin, MW	50	20	15	10	10	12
Pmax, MW	200	80	50	35	30	40
a, $/h	0	0	0	0	0	0
b, $/MWh	2	1.75	1	3.25	3	3
c, $/MW2h	0.00375	0.0175	0.0625	0.00834	0.025	0.025
α, t/h	4.091	2.543	4.258	5.326	4.258	6.131
β, t/MWh	-0.05554	-0.06047	-0.05094	-0.0355	-0.05094	-0.05555
γ, t/MW^{2}h	0.00065	0.00056	0.00046	0.00033	0.00046	0.00052
λ, t/MWh	0.0002	0.0005	0.000001	0.002	0.000001	0.00001
ξ, t/h	0.02857	0.00033	0.0008	0.0002	0.0008	0.00067

As in previous research, the comparison of several models was made. The first model is equal to classical IEEE30 and consists of six generators, which are presented in Table 3.35. The second model consists of two medium size generators with 200 MW each.

The equipment costs and plant lifetime were taken from [34], converted into \$ assuming 1€ = 1.12\$ (currency rate at the period this research was made), and presented Table 3.36.

Table 3.36. Equipment costs

Power Plant type, capacity, MW	Life time, year	EPC, \$/kW	Variable O&M costs, \$/MWh	Fixed O&M costs, \$/kW per year
Oil fired, P less than 30	50	1792	3.92	44.8
Oil fired, 30<P≤200	50	2240	3.92	44.8
Wind on-shore, 30<P≤200	20	1792	0	56

Model with 6 generators

There are few scenarios considered. The first scenario is when the new wind park is connected to the system without any changes. It means that wind generation and amount of energy produced by 6 TPPs are defined according to the diagram in Figure 3.14. In MATLAB the code which determines the optimal regime between six generators for each period (one hour) is written. The result of the simulations is presented at the diagram in Figure 3.15.

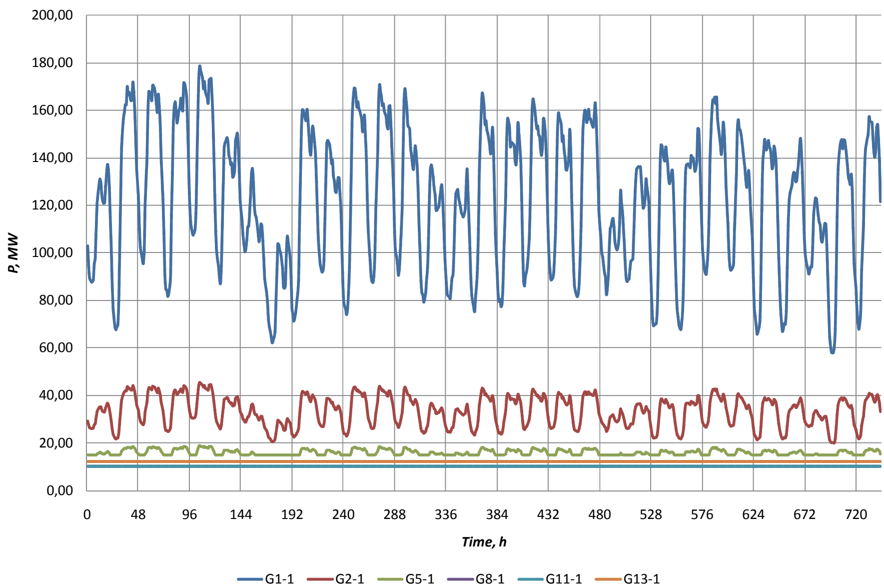

Figure 3.15. Optimal generation regime. 1-st scenario

After this, for each hour fuel costs are calculated, than summarized for one month. The level of pollutions in tons is found the same way, and, considering the price 7.06$ for tone, final emissions costs are obtained. From the data in Table 3.36, it is possible to find ECP and Fixed O&M costs of the equipment for one month. The results of the calculations for one month are presented in Table 3.37.

Table 3.37. Calculation of the price for 1MWh. 1-st scenario

Parameter	**Technology**	
	Wind power	***Thermal power plants***
Generation, MWh per month	17 322.86	151 076.22
Fuel costs, $ per month	-	385 589.54
Emissions, t per month	-	1.458
ECP costs, $ per month	448 000	1 321 600
Fixed O&M costs, $ per month	280 000	1 624 000
Fuel costs, $/MWh	2.29	
Emissions costs, $/MWh	0.01	
ECP costs, $/MWh	10.51	
Variable O&M costs, $/MWh	3.47	
Fixed O&M costs, $/MWh	11.31	
Total, $/MWh	27.58	

The second scenario is the case of the new wind park launched instead of the existing TPP. In contrast to the previous case, generator G6 is excluded because it has the worst fuel costs characteristics. The fuel consumptions of all generators are presented in Figure 3.16. At the same time, the capacity 40 MW of the G6 is very close to the total amount generated by the wind park.

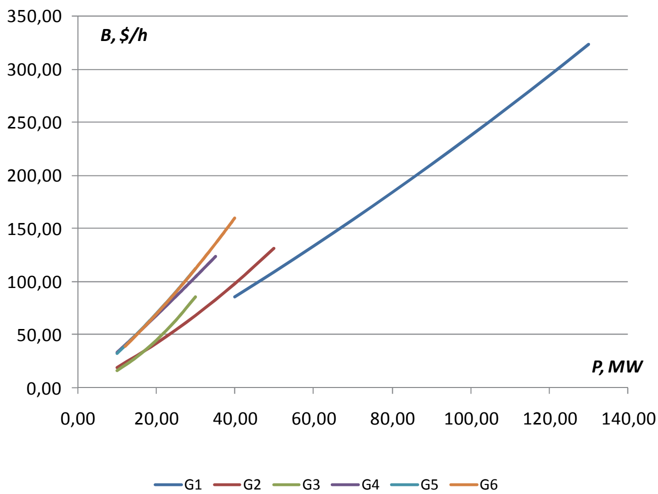

Figure 3.16. Fuel costs characteristics of generation units

Determination of the optimal regime and calculations of the price are repeated for this scenario and presented in Figure 3.17 and Table 3.38.

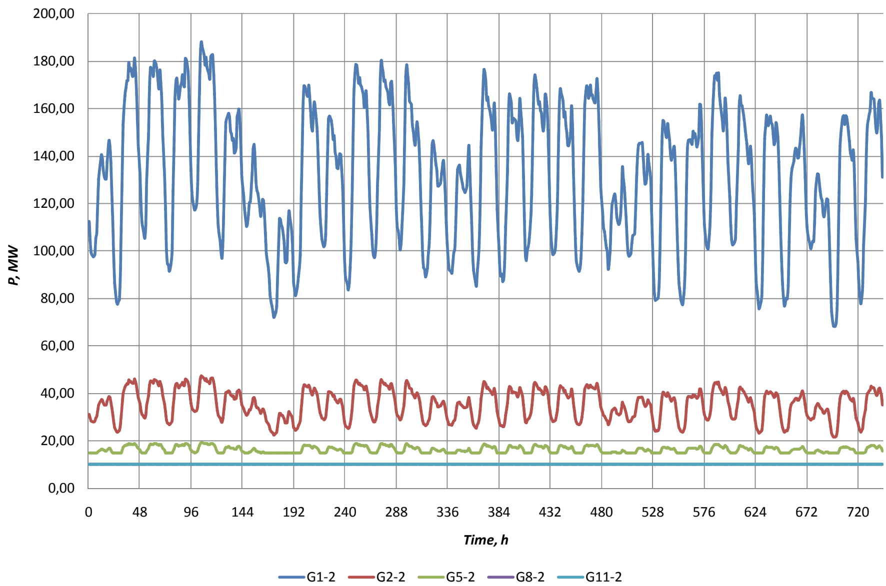

Figure 3.17. Optimal generation regime. 2-nd scenario

Table 3.38. Calculation of the price for 1MWh. 2-nd scenario

Parameter	Technology	
	Wind power	***Thermal power plants***
Generation, MWh per month	17 322.86	151 076.22
Fuel costs, $ per month	-	382 484.09
Emissions, t per month	-	1.233
ECP costs, $ per month	448 000	1 172 266
Fixed O&M costs, $ per month	280 000	1 437 333
Fuel costs, $/MWh	2.27	
Emissions costs, $/MWh	0.01	
ECP costs, $/MWh	9.62	
Variable O&M costs, $/MWh	3.47	
Fixed O&M costs, $/MWh	10.20	
Total, $/MWh	25.57	

Finally, calculations for the existing system are made. There are 6 power plants which cover power demands according to the load diagram presented in Figure 3.18. The results of the calculations with comparison to both scenarios are presented in Table 3.39.

Table 3.39. The comparison of the prices for Model with 6 generators

Parameter	Scenario		
	Initial conditions	***1-st Scenario***	***2-nd Scenario***
Fuel costs, $/MWh	2.59	2.29	2.27
Emissions costs, $/MWh	0.01	0.01	0.01
ECP costs, $/MWh	7.85	10.51	9.62
Variable O&M costs, $/MWh	3.92	3.47	3.47
Fixed O&M costs, $/MWh	9.64	11.31	10.20
Total, $/MWh	24.02	27.58	25.57

In the real generation process, shifting of loads is very important because it leads to over-expenditure of fuel, and incremental fuel costs grow. As wind power is unpredictable and fluctuant, the comparison of generators output shifting for all scenarios is made. The biggest changes are observed in case with G1. The diagram of shifting for initial model and Scenario 2 is presented in Figure 3.18. The maximum shifting of output in system with the wind park is 28.4 MW, without – 25.5 MW. The average changing in the first case is 6.89 MW/h in the second – 6.69 MW/h.

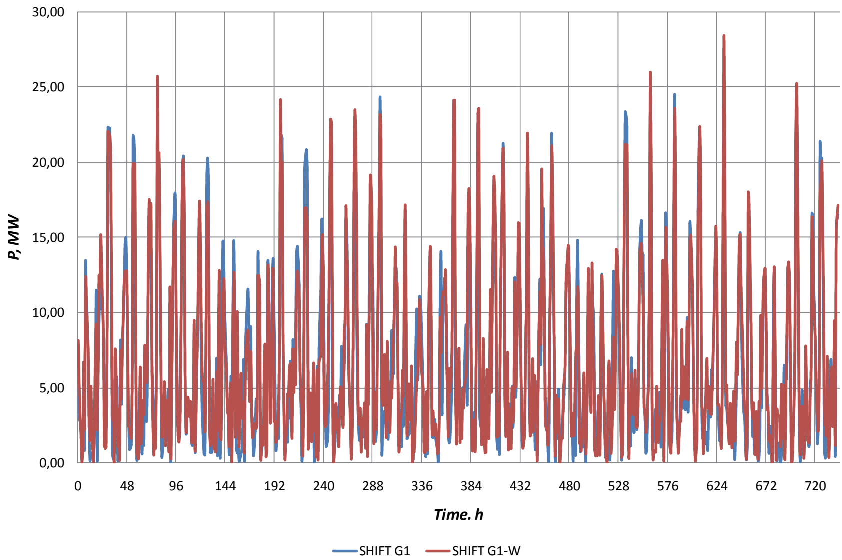

Figure 3.18. Output power shifting for G-1 in Model with 6 generators, 2-nd scenario

Model with 2 generators

The second model consists of two generators of 200 MW. Here there is no possibility to launch the wind park instead of one of the generators. The generators have the same fuel cost characteristics, and, according to (2.17), it means that the optimal regime will be reached in case when power outputs of both generators are equal. This simplifies the calculations of optimal regime. The load, which should be covered by TPPs, is just divided by 2. For the obtained results, on the analogy, the prices for 1 MW/h for cases with the wind park and initial system, are found and presented in Table 3.40. Moreover, the diagram of shifting for initial model and the case with the wind park is found. The maximum shifting of output in system with the wind park is 17.2 MW, without – 16.2 MW. The average changing in the first case is 4.17 MW/h, in the second – 4.32 MW/h.

Table 3.40. The comparison of the prices for Model with 2 generators

Parameter	**Scenario**	
	Initial conditions	***With wind park***
Fuel costs, $/MWh	2.43	2.15
Emissions costs, $/MWh	0.009	0.009
ECP costs, $/MWh	7.09	9.75
Variable O&M costs, $/MWh	3.92	3.47
Fixed O&M costs, $/MWh	8.87	10.53
Total, $/MWh	22.32	25.91

Resume

In this part of research, the impact of wind generation on the existing system is studied. Changing of fuel consumption and emissions are considered. The main parts of fuel price are calculated. Calculations are made for several scenarios and two system models. The final comparison of 5 cases is presented in Figure 3.19.

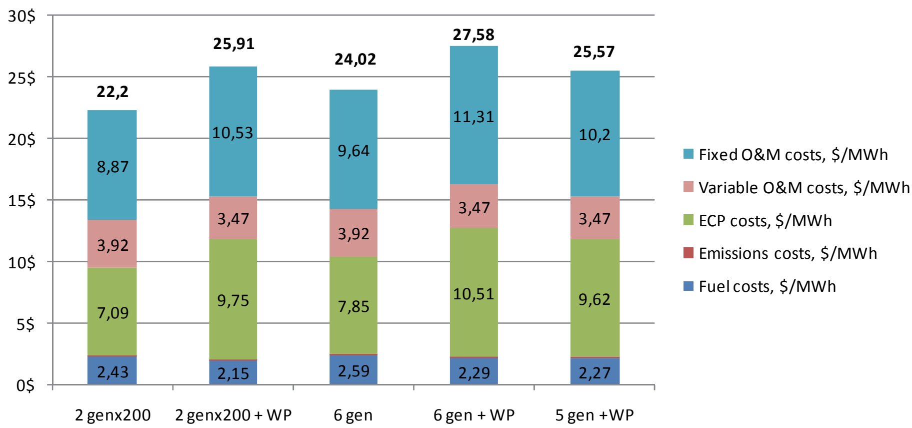

Figure 3.19. The final comparison of models

From the diagram above it, can be concluded that the price for 1 MWh becomes higher with the launching of the wind park. ECP and fixed O&M costs are higher; fuel, emissions, and variable O&M costs are lower. In case with two medium generators, there is no possibility to stop existing power plant and price grows up to 3.7 $/MWh (14%). However, fuel consumption decreased and 16 ton/month (16%) of emissions reduction is obtained. When the system consists of one medium and several small generators, the situation is similar: the difference in price is 3.56$/MWh. However, when the wind park replaces one of the old TPP or there is a choice of what kind of power plant to install, the model with 5 generators and the wind park does not look so unprofitable. The difference in price is 1.55 $/MWh (6%), but the level of emissions is less than 22%, and fuel consumption is reduced too. If the price for emissions becomes higher, the difference in price for 1MW/h becomes more considerable. As connected to shifting output of generators, cases with 2 and 5 generators are almost equal: the amplitude of G1 rises for 1.5-3 MW.

4. CONCLUSION AND FUTURE WORK

During the research, the technical-economic comparison of centralized and decentralized power system is made based on different models with a variety of data. Distributed generation models include wind and common sources. The main components of electricity price are distinguished. The analysis, based on generation and equipment costs, considers power flow and an organizing of emergency reserve. Calculations for optimal regime of generation units are made with the help of optimization techniques; power flow is found with the help of simulation software according to transmission lines and voltage drop limitations. Factors such as reduction of losses, capacity and placement of the units, and their influence on the optimal generation are considered.

The results show that costs are generally higher in case of decentralized power systems. The reduction of transmission losses and, correspondingly, the output amount of power through the local placement of generation units, is not enough to cover difference in fuel consumption. The difference becomes especially significant in case with big amount of small loads and generation units. Moreover, the calculations show that very often during generation process it is better to prioritize fuel consumption instead of power losses in the system. Thermal power plants with bigger capacity have better fuel consumption efficiency. At the same time equipment costs are the main expenses. That is why generation units should be loaded as closer to the maximum as it possible. Emissions costs nowadays play a small role in creating the price. It means that reduction of emissions through wind power does not give valuable profit. At the same time, fluctuating power injection into the power system results in non-optimal loads of the units in the same way as ramping causes fuel overrun. Even though the reduction of emissions does not influence the final electricity price a lot nowadays, it should not be excluded from the optimization. First of all, the price for emissions changes from time to time. Secondly, in some cases producers are limited to the allowed amount of emissions and generation units operate in non-optimal regime.

The reliability of distributed generation is higher and equipment costs for power reserve are lower. However, in case of interconnection centralized model with neighbouring power systems, the difference in costs is considerable.

In this research, some factors were not taken into the account and could be explored in the future. The first of these factors is the power balance. With the opening of the energy market and the implementation of the transmission of electricity to neighbouring countries, the issue of finding the optimal mode of generation became considerably more complicated. On the one hand, the production efficiency can be improved through loading generation blocks close to the optimum, while selling the surplus of electric power. On the other hand, it is necessary to take into account constant changes in the price per unit of electricity and the market situation.

Ramp time of generators is the second factor, which also could be studied more thoroughly. This parameter affects the fuel consumption when the load changes, and, with the transition to wind and solar energy it is currently even more significant than before. Optimal planning of generating units in power system considering uncertainty of information [75] also should be studied.

Due to the changing of fuel, emissions and technologies prices, additional areas for analysis could be extended with programs which define the prospects for energy development, such as LEAP [76] or Energy Fundamentals Platform [77].

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List of Author's Publications

The present doctoral thesis is based on the following publications that are referred to in the text by Roman numbers.

[PAPER-I] **Astapov, V.;** Shuvalova, J. (2013). About suitability of condensing power plants to power distribution system. 4th International Youth Conference on Energy (IYCE 2013), Siofok (Hungary), IEEE, pp. 1–5.

[PAPER-II] **Astapov, V.;** Shuvalova, J. (2013). The Comparative Analysis of Fuel Costs for Generation Process (based on the Example of IEEE 30-bus Test System). 14th International Scientific Conference on Electric Power Engineering (EPE2013), Kouty nad Desnou (Czech Republic), IEEE, pp. 187 - 189.

[PAPER-III] **Astapov, V.;** Shuvalova, J. (2014). Comparison of reducing losses and reducing generation costs during electricity production. 15th International Scientific Conference on Electric Power Engineering (EPE 2014), Brno (Czech Republic), IEEE, pp. 49–52.

[PAPER-IV] **Astapov, V.;** Shuvalova, J. (2015). Factors Influencing Multicriteria Optimization Process. 16th International Scientific Conference on Electric Power Engineering (EPE 2015), Kouty nad Desnou (Czech Republic), pp. 192-197.

Author's Own Contribution

This section describes the author's contribution to the papers listed in the thesis as author's publications.

[PAPER-I] Victor Astapov is the main author of the paper, responsible for the data collection, calculations and modelling. He had a major role in writing. He presented the paper at 4th International Youth Conference on Energy (IYCE 2013), Siofok, Hungary.

[PAPER-II] Victor Astapov is the main author of the paper, responsible for the literature review, data collection, calculations and modelling. He had a major role in writing. He presented the paper at 14th International Scientific Conference on Electric Power Engineering (EPE2013), Kouty nad Desnou, Czech Republic.

[PAPER-III] Victor Astapov is the main author of the paper, responsible for the literature review and data collection. He had a major role in writing. He presented the paper at 15th International Scientific Conference on Electric Power Engineering (EPE 2014), Brno, Czech Republic.

[PAPER-IV] Victor Astapov is the main author of the paper, responsible for the literature overview, data collection and calculations. He had a major role in writing. He presented the paper at 16th International Scientific Conference on Electric Power Engineering (EPE2015), Kouty nad Desnou, Czech Republic.

Abstract

Technical-Economical Analysis of Distributed Generation Units in Power Systems

One of the options to improve the efficiency of the power system is the modernization of equipment or generation process. Another solution is in the optimization field. The latter needs less investment and also gives a lot of possibilities, because the structure, laws, and technologies in energy sector are now under the transformation. Kyoto protocol created limitations for pollutions and pushed electricity producers to change their strategies considering emission costs during generation process. Green energy, distributed generation and other trends are the results of new energy sector demands and conditions. Interconnection of power systems and open energy market allow for organizing the reserve of power and selling surplus of generated electricity. This thesis includes the overview of modern technologies with the references to the examples of their implementation.

In the main part, different models are studied and with a variety of parameters and conditions of power system considered. The technical-economic approach for system analysis is undertaken. Fuel, emission, operational, and maintenance costs are taken into account. System parameters, such as power flow, reliability, and their significance for the final price of electricity is presented.

The main difference from this state of things current thesis presents is looking on modern trends, such us decentralized power system, wind energy, and emission reduction in a wider way. 'For example, the statement "decentralized power system has fewer losses, than centralized system" is correct. However, not so many researchers pay attention to the efficiency of equipment with different capacities, their fuel consumption, and own costs. The results of the research show that efficiency of decentralized power system is lower compared to the centralized one. The difference depends on number of generators, loads, and power reserve organization.

Wind turbines is a very popular trend nowadays, but looking on their output power fluctuation and remembering that power plants have low efficiency when they half loaded, it becomes obvious, that wind power increases the cost of electricity generated in the system. In this case, interconnection with other power systems and open electricity market should be employed. Another drawback of wind energy is increasing power ramping of generators, which leads to over-expenditure of fuel. Some of these questions are also considered in the thesis.

Kokkuvõte

Elektri hajatootjate tehnilis-majanduslik analüüs energiasüsteemis

Energiasüsteemide efektiivsuse tõstmise üheks võimaluseks on seadmete moderniseerimine või tootmisprotsesside muutmine. Teiseks lahenduseks on optimeerimine. Viimane nõuab vähem kulutusi ning pakub palju võimalusi efektiivsuse tõstmiseks. Kyoto protokoll piiras emissioonide hulka ja sundis tootjaid arendama uusi tehnoloogiaid ja elektri tootmise strateegiaid läbi vaatama. Roheline energeetika, hajutatudtootmine ja teised suunad on uute nõuete ja tingimuste tulemused energiasektoris. Naaberenergiasüsteemide koostöö ja avatud elektriturg lubavad võimsuse reservi juhtida ja energia ülejäägi müüa. Väitekiri sisaldab kaasaegsete tehnoloogiate ülevaadet ja nende rakenduste näiteid.

Väitekirja põhiosas on uuritud erinevad mudelid koos energiasüsteemi erinevate parameetritega ja talitluse tingimustega. Esitatud on tehnilis-majanduslik lähenemisviis süsteemi analüüsiks, kütusekulude, emissioonide, kapitali- ja tegevuskulude arvestamisega. Käsitletud on järgmisi süsteemi-parameetreid: koormuste jaotus ja töökindlus, nende mõju elektrienergia lõpphinnale.

Peamine erinevus eelmisest uuringutest on see, et autor vaatleb uusi trende (hajutatud energiatootmine, roheline energia ja emissioonide vähendamine) laiemalt. Näiteks, üldine arvamus, et hajutatud elektritootmine vähendab elektri kadusid võrreldes tsentraliseeritud tootmisega, on enamikul juhtudel tõsi. Paljudel uuringutel ei arvestata erinevate võimsustega seadmete efektiivsust, nende kütusekulusid, kapitaal- ja tegevuskulusid. Uuringu tulemused näitasid väiksemat efektiivsust detsentraliseeritud mudelite puhul. Erinevus sõltub paljudest faktoritest, generaatorite arvust, koormuste suurustest ja võimsuse reservi vajadusest.

Kiirel tuuleenergeetika arengul on ka rida puudusi. Ebastabiilne toodang, fakt, et soojuselektrijaamade efektiivsus halvendab koormuste vähendamisel ja see suurendab elektri tootmise kulusid. Lisaks tuleb meeles pidada, et koormuste reguleerimise talitluses soojuselektrijaamade kütusekulu suureneb. Samal ajal tuuleenergeetika kasutamine suurendab soojuselektrijaamade talitluse muutmist püsitalitluselt reguleerimistalitlusele. Mõned nendest küsimustest on ka käsitletud antud väitekirjas.

Curriculum Vitae

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2. Education

Educational institution	Graduation year	Education (field of study/degree)
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Gomel State Technical University	2007	Power engineering/M.A.

3. Language competence/skills (fluent; average, basic skills)

Language	Level
Belorussian	Native language
Russian	Native language
English	Fluent
Estonian	Basic

4. Professional Employment

Period	Organisation	Position
2015 – ...	Tallinn University of Technology	Engineer
2014 – 2015	Tallinn University of Technology	Junior researcher
2010 – 2011	"Saint-Petersburg Cable TV"	Vice-head of Power engineering department
2009 – 2010	"Saint-Petersburg Cable TV"	Power engineer
2006 – 2009	"Vitebskenergo", branch of Vitebsk Electricity Network	Dispatcher of district electricity network
2004 – 2006	"Vitebskenergo", branch of Vitebsk Electricity Network	Electrician of district electricity network

Elulookirjeldus

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2. Hariduskäik

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Vitebski Riiklik Ülikool	2001	Matemaatika ja füüsika õpetaja/magister
Homieli Riiklik Tehnika-ülikool	2007	Insener-energeetik/magister

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Valgevene	Kõrgtase
Vene	Kõrgtase
Inglise	Kõrgtase
Eesti	Algtase

4. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2015 – ...	Tallinna Tehnikaülikool, Energeetikateaduskond	Insener
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2010 – 2011	Sankt-Peterburi kaabel TV	Peaenergeetiku asetäitja
2009 – 2010	Sankt-Peterburi kaabel TV	Insener-energeetik
2006 – 2009	Jaotusvõrk Vitebskenergo (Vitebsk, Valgevene)	Dispetšer
2004 – 2006	Jaotusvõrk Vitebskenergo (Vitebsk, Valgevene)	Elektrimonteerija

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *POWER ENGINEERING, ELECTRICAL ENGINEERING, MINING ENGINEERING*

1. **Jaan Tehver**. Boiling on Porous Surface. 1992.
2. **Aleksandrs Cars**. Woodhips Combustion Technology. 1992.
3. **Endel Risthein**. Electricity Supply of Industrial Plants. 1993.
4. **Tõnu Trump**. Some New Aspects of Digital Filtering. 1993.
5. **Vello Sarv.** Synthesis and Design of Power Converters with Reduced Distortions Using Optimal Energy Exchange Control. 1994.
6. **Ivan Klevtsov**. Strained Condition Diagnosis and Fatigue Life Prediction for Metals under Cyclic Temperature Oscillations. 1994.
7. **Ants Meister**. Some Phase-Sensitive and Spectral Methods in Biomedical Engineering. 1994.
8. **Mati Meldorf**. Steady-State Monitoring of Power System. 1995.
9. **Jüri-Rivaldo Pastarus**. Large Cavern Stability in the Maardu Granite Deposit. 1996.
10. **Enn Velmre**. Modeling and Simulation of Bipolar Semiconductor Devices. 1996.
11. **Kalju Meigas**. Coherent Photodetection with a Laser. 1997.
12. **Andres Udal**. Development of Numerical Semiconductor Device Models and Their Application in Device Theory and Design. 1998.
13. **Kuno Janson**. Paralleel- ja järjestikresonantsi parameetrilise vaheldumisega võrgusageduslik resonantsmuundur ja tema rakendamine. 2001.
14. **Jüri Joller**. Research and Development of Energy Saving Traction Drives for Trams. 2001.
15. **Ingo Valgma**. Geographical Information System for Oil Shale Mining – MGIS. 2002.
16. **Raik Jansikene**. Research, Design and Application of Magnetohydrodynamical (MHD) Devices for Automation of Casting Industry. 2003.
17. **Oleg Nikitin**. Optimization of the Room-and-Pillar Mining Technology for Oil-Shale Mines. 2003.
18. **Viktor Bolgov**. Load Current Stabilization and Suppression of Flicker in AC Arc Furnace Power Supply by Series-Connected Saturable Reactor. 2004.
19. **Raine Pajo**. Power System Stability Monitoring – an Approach of Electrical Load Modelling. 2004.

20. **Jelena Shuvalova**. Optimal Approximation of Input-Output Characteristics of Power Units and Plants. 2004.

21. **Nikolai Dorovatovski**. Thermographic Diagnostics of Electrical Equipment of Eesti Energia Ltd. 2004.

22. **Katrin Erg**. Groundwater Sulphate Content Changes in Estonian Underground Oil Shale Mines. 2005.

23. **Argo Rosin**. Control, Supervision and Operation Diagnostics of Light Rail Electric Transport. 2005.

24. **Dmitri Vinnikov**. Research, Design and Implementation of Auxiliary Power Supplies for the Light Rail Vehicles. 2005.

25. **Madis Lehtla**. Microprocessor Control Systems of Light Rail Vehicle Traction Drives. 2006.

26. **Jevgeni Šklovski**. LC Circuit with Parallel and Series Resonance Alternation in Switch-Mode Converters. 2007.

27. **Sten Suuroja**. Comparative Morphological Analysis of the Early Paleozoic Marine Impact Structures Kärdla and Neugrund, Estonia. 2007.

28. **Sergei Sabanov**. Risk Assessment Methods in Estonian Oil Shale Mining Industry. 2008.

29. **Vitali Boiko**. Development and Research of the Traction Asynchronous Multimotor Drive. 2008.

30. **Tauno Tammeoja**. Economic Model of Oil Shale Flows and Cost. 2008.

31. **Jelena Armas**. Quality Criterion of road Lighting Measurement and Exploring. 2008.

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