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DAY-AHEAD ECONOMIC LOAD DISPATCH FOR OIL SHALE POWER PLANTS IN DEREGULATED ELECTRICITY MARKET

Master's thesis

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ABSTRACT

The Estonian electricity sector development has been very rapid during the last years - from the domination of the power monopolies in the regulated market to the electricity trading over the borders in the deregulated market. The deregulated market brings new challenges for power producers that are facing the economic power dispatch problem in the competitive conditions. The traditional economic power dispatch problem considers the minimizing of total thermal cost rate, where only the electric constraints are satisfied in the electric power system. Moreover, the traditional economic power dispatch problem and unit commitment is based on the conditions of regulated electricity market, where the electricity prices are relatively stable and under the control of the government. Deregulation of the electricity market makes it necessary to perform the changes in classical algorithm and develop the new model for finding a good solution in a reasonable period of time.

The objectives of this paper is to elaborate day-ahead economic dispatch model for existing oil-shale-based power plants; implement the proposed algorithm by using different optimization techniques, and estimate the effectiveness of the used optimization techniques for solving the economic dispatch problem.

The day-ahead economic dispatch optimization is formulated as a mixed-integer linear programming problem. The proposed algorithm has been implemented in the modeling language GAMS using Cplex mathematical programming solver. The test cases with different properties were carried out for existing generating units using by primal simplex, dual simplex and interior-point optimization techniques.

The results of using optimization techniques have marginal difference; the optimization techniques could be useful for day-ahead economic dispatch problem solving for power plant's precise performance evaluation. The proposed algorithm may serve as a basis for more accurate economic dispatch model of power plants. The data presented in this work will be helpful for the power plant management, energy planners, researchers and analysts.

Keywords: economic dispatch, unit commitment, primal simplex, dual simplex, interior-point, GAMS, Cplex, day-ahead market.

INTRODUCTION

The Estonian electricity sector has been going through major changes during the last years. Until recent time, the sector was characterized by vertically integrated monopolies, where Eesti Energia AS controlled the generation, distribution and retail sales. However, at present the electricity sector has been fully reformed to meet the requirements of the European Union Directives regarding liberalization of the electricity markets.

The day-ahead market trading is driven by the members' planning, and the system price is determined by supply and demand curves. In competitive conditions of the deregulated electricity market, the power producers face a problem: how to operate power plants in order to fulfil the power contracts, meet the emissions limit and maximize profits by producing electricity as much as possible during high-priced peak hours and reducing the electrical load during off-peak hours.

Optimal power generation or economic load dispatch is an important task in power plant planning and operation. The solution of traditional economic power dispatch problem consideres the determination of real power outputs by minimizing the total thermal cost rate and satisfying the electric constraints in the electric power system. Moreover, the traditional economic power dispatch problem and unit commitment is based on the conditions of the regulated electricity market. Deregulation of the electricity market makes it necessary to perform the changes in classical algorithms and develop a new model for finding a good solution, taking into account changes in the Estonian energy market related to the European Union's strict technological and environmental requirements, and this should occur in a reasonable period of time.

Today, there are several factors that have decisive influence on the economic dispatch problem solution in the condition of deregulated market. The most significant among them are environmental policies, fast emerging difference between demand and supply, and competition amongst power generating companies. On the other hand, only a limited number of energy companies have an economic dispatch solution and outcomes of optimal operation evaluations. The main reason is the complexity of the evaluations and the lack of tool that has a systematic approach capable of integrating together the multiple economic dispatch problem aspects.

The largest Estonian producer of electricity and heat energy is the Narva Power Plants, owned by Eesti Energia, which provide over 80% of the electricity produced in Estonia. The Estonian and Baltic Power Plants, the production plants in Narva, are the world's largest power plants using oil shale as the main fuel. However, the day-ahead economic dispatch problem has not been solved yet for these power plants mainly due to the absence of input data and lack of efficient calculation algorithm and tool.

The objectives of the thesis are:

- the elaboration of day-ahead economic load dispatch algorithm for existing oil-shale-based power plants in the conditions of the deregulated market;
- implementation of the proposed algorithm using different optimization techniques;
- the effectiveness estimation of the used optimization techniques.

The problem of economic dispatch requires the following tasks:

- oil-shale-based power units input characteristics and determination of optimality conditions for day-ahead economic load dispatch model;
- comparison of economic load dispatch and unit commitment;
- analysis and evaluation of the existing optimization techniques;
- practical testing of the economic load dispatch algorithm by using optimization techniques;
- evaluation and summing up the research results.

The scientific novelty and originality of the thesis lies in the adaptation of oil-shale-based energy production constraints and deregulated market conditions to the economic dispatch problem for precise performance evaluation of the power plant operation demonstrated for the first time in Estonia.

The practical value of the thesis is the creation of real day-ahead optimization model for Narva Power Plants operation evaluation by using mathematical programming solver GAMS/Cplex in Eesti Energia Energy Trading Department to prove the possibility for minimization of generation costs in the power plant.

All this makes the thesis to be significant and valuable.

The thesis is composed of three interlinked chapters. The first chapter is devoted to the theoretical part of the economic load dispatch problem. The modeling of power generating units in the deregulated market and its peculiar properties are introduced. Input-output characteristics of the existing oil shale generating units, such as heat and electrical power curves, manufacturing fixed costs, electrical and heat efficiency, emission limitations and taxes, start-up costs are determined. The optimality conditions of the operation of each generating unit are defined. Both the economic dispatch and the unit commitment problems are essential to be solved, so the main difference between them is discussed in the first chapter.

The second chapter introduces optimization techniques used for solving the economic dispatch problem for oil-shale-based power units in the conditions of Estonian deregulated electricity market. For a complete understanding of how optimization problems are carried out, the algorithm of economic dispatch for existing power generating units is provided.

The third part focuses on the implementation of the proposed algorithm using three different optimization techniques. The optimal solution of power units' electrical power output for a typical winter and summer week is provided. The effectiveness estimation of the used optimization techniques is presented.

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I would like to thank my family and friends for constant support and encouragement at different stages of the present work. I dedicate this work to my children Jegor and Darja.

1. ECONOMIC LOAD DISPATCH PROBLEM

1.1. Modeling of power generating units in deregulated market

The development of the electricity market in Estonia has been in the focus ever since the country reached independence. In recent years, important steps to establish common and joint electricity markets have been taken. The development is very rapid - from the separate market dominated by the national power monopolies to an open market allowing for trade with electricity over the borders (Swedish Energy Agency, 2002). Deregulation of the electricity market in Estonia has brought favorable possibilities to encourage competition among power producres by improving the efficiency and operational management. However, at the same time, it has also created new challenges and uncertainties in this sector (Carraretto, 2006).

The Directive 96/92/EC covers the common rules of the internal market in electricity. The Directive was adopted by the Council of Ministers on December 19, 1996 and two months later it entered into force. The Directive's main goal is "to increase efficiency in the production, transmission and distribution of electricity, while reinforcing security of supply and the competitiveness of the European economy and respecting environmental protection". The Directive provides free competition in generation, where eligable consumers will be the first to benefit from an open market and smaller consumers will follow, free access to the transmission network via Third Party Access or Single Buyer, an unbundling of accounts between generation, transmission, and distribution (Directive 96/92/EC, 1997).

In 2003, when Estonia's treaty of accession to the European Union (EU) was signed, it was agreed that Estonia would open its electricity market partially in 2009, and completely in 2013. The partial opening of the electricity market in Estonia took place in April 2010 for large-scale consumers, who consumed more than 2 GWh of electricity per year. At the beginning of 2013, Estonian electricity market was opened for small and household consumers (Elering, 2012). Estonia is a member of NordPoolSpot (NPS) power market and mainly operates in Elspot and Elbas power markets.

Estonia’s two large oil-shale-fired electric power plants, Estonian Power Plant and Baltic Power Plant, belong to the state-owned enterprise Eesti Energia, which controlled the generation, distribution and sales in almost all over the country till 2010. Currently, these two power stations, which are located in the city of Narva and together, make up Narva Power Plants, supply more than 80% of Estonia's electricity (Figure 1) (Eesti Energia AS Annual Report, 2013).

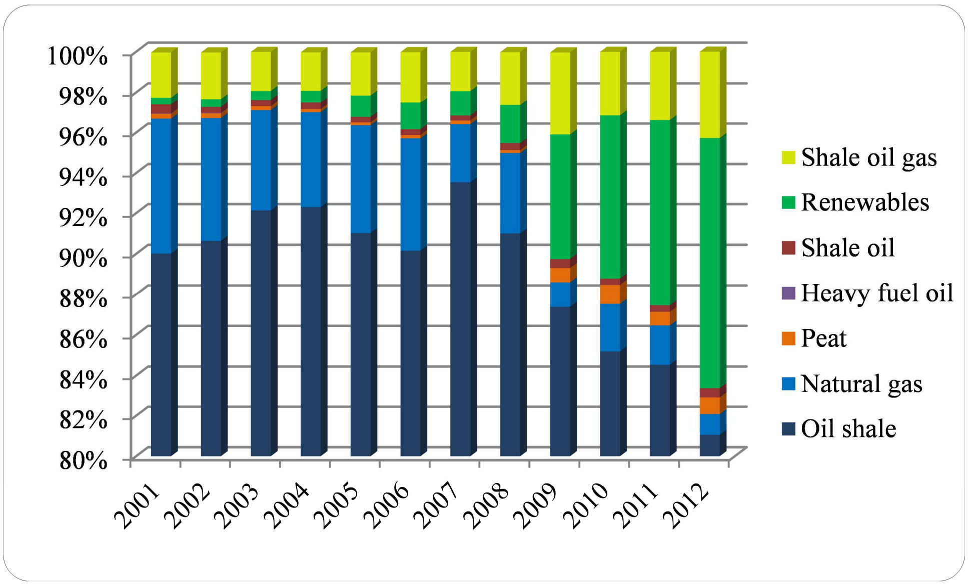

Figure 1. Estonian gross production by fuel type in 2001-2012

Source: Statistics Estonia

Nord Pool, the Nordic Power Exchange, is the world's first international commodity exchange for electrical power. 357 members are trading on the Elspot market and 123 members are trading on the Elbas (NordPoolSpot, 2012). The primary role of the market price is to establish equilibrium between supply and demand. This task is especially important in the power markets because of the inability to store electricity and high costs associated with any supply failure. The spot market at Nord Pool Spot is an auction based exchange for the trading of prompt physically delivered electricity (Bajpai, Singh, 2004). At the moment there are 12 licensed electricity-sellers in Estonia (Elering, 2012).

Elspot is the day-ahead market in the Nordic region, where daily trading is driven by the members' planning, and system price is determined by supply and demand curves. Elbas is an intraday market for trading power operated by Nord Pool Spot (NordPoolSpot, 2012).

According to Eesti Energia AS Annual Report 2013, electricity prices increased in all Nord Pool price areas as compared to year 2012. The average Nord Pool system price increased by 22% (+6,9 €/MWh) in 2013. The significant increase in the Nord Pool system price is attributable to the extraordinarily low price level from last year (average system price is 31,2 €/MWh) arising from historically high hydro reservoir levels in the second half of 2012. The significant price increase in June-July period up to 103,9 €/MWh was attributed to the electricity deficit in Latvia and Lithuania and limitations in cross-border transmission capacities (Figure 2).

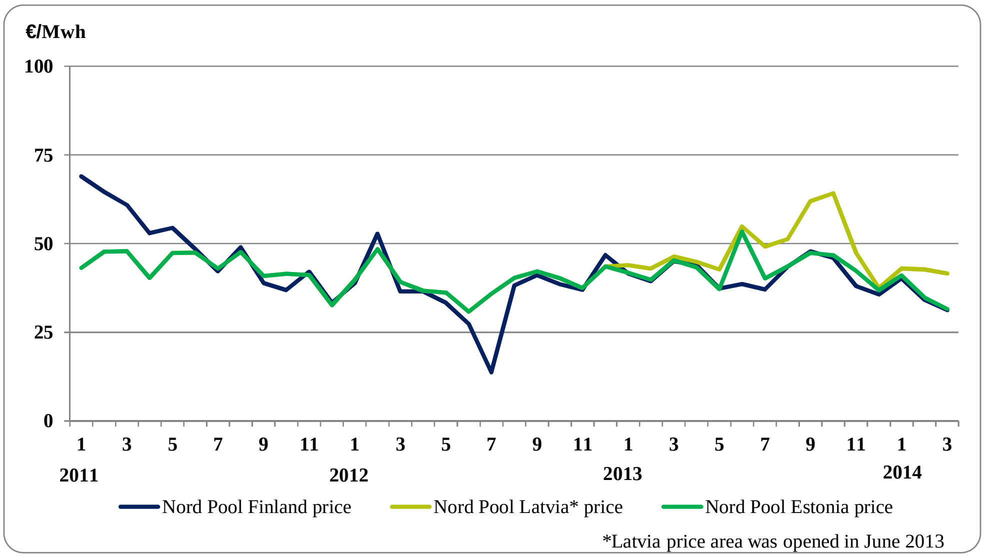

Figure 2. Monthly average prices of electricity in 2011-2014
Source: NordPoolSpot

Narva Power Plants consist of 8 power generation units in Estonian Power Plant and 4 units in Baltic Power Plant. The main fuel is oil shale and the auxiliary fuels are shale oil and retort gas. Narva Power Plants used also biomass for the electricity generation in the Baltic Power Plant, but from the beginning of the year 2013, electricity production from biomass is no longer supported.

Narva Power Plants generate revenues depending on electricity prices and traded volumes in deregulated market. In the competitive conditions of the deregulated electricity market the power plant faces the problem of finding effective supply offers. Moreover, when hourly prices are announced to the market and trades are settled, another problem arises: how to operate power plants in order to fulfil the power contracts, meet the emissions limit and maximize profits by producing the electricity as much as possible during high-priced peak hours and reducing the electrical load during off-peak hours.

The definition of economic dispatch provided in Energy Policy Act 2005 section 1234 is as follows: “The operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities”.

There are two fundamental components to economic load dispatch (ELD): day-ahead and intraday economic dispatch. This paper focuses on the day-ahead market and economic dispatch. The benefits of day-ahead economic dispatch are as follows (US Department of Energy, 2005):

- reduction in total electricity generation costs;
- better fuel utilization and air emission reduction by using more efficient generation units;
- increasing operational reliability without increasing costs.

Profit deriving from plant operation can be determined by correctly evaluating the input characteristics of the power plant units that are presented in the second chapter. The main problem in modeling the power generating units is the lack of detailed and reliable data for plant performance evaluation. Another important problem is the accuracy of the measured data, which could be helpful to analyze effects of operating characteristics on the power plant management. The deregulating market has its effects on the electricity pricing, fast emerging difference between demand and supply and competition amongst power generating companies.

1.2. Input-output characteristics and optimality conditions of operation

Input-output characteristics are the most important initial data for solving the economic dispatch task. Input-output characteristics would be defined from the following parts:

- input and output characteristics from deregulated market;
- input and output characteristics from power plant units;
- limitations related to technological and environmental requirements;
- optimality conditions of power units operation.

Input and output characteristics from deregulated market

Input and output characteristics from deregulated market are electricity prices and volumes. The electricity price for each hour is determined by intersection of the aggregate supply and demand curves, which represent all bids and offers from the participants of the market. A volume corresponding to the trading capacity on the constrained connection is added as a price independent purchase in the surplus area and a price independent sale in the deficit area. In the deficit area the sale will give a parallel shift of the supply curve while in the surplus area the additional purchase will give a parallel shift of the demand curve. The area price in the surplus area and the deficit area is found in the new equilibrium points given after the addition of the flow between the areas as purchase and sale respectively. The price is relatively lower in the surplus area and relatively higher in the deficit area (Figure 3).

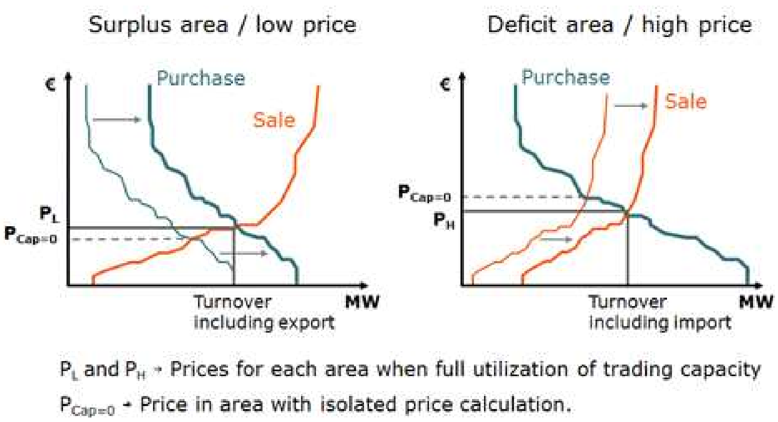

Figure 3. Market price and market balance principle

Source: NordPoolSpot

The example of Elspot market overview with electricity prices and volumes in different areas for 18th December 2013 is provided in the Figure 4.

Nord Pool Spot publishes a spot price to the market at 12:42 CET (Central European Time) for each hour of the coming day in order to synthetically balance supply and demand. Once the market prices have been calculated and trades have been settled, the scheduling of generating units for each hour of the next day should be calculated. From 00:00 CET the next day, power contracts are physically delivered hour by hour according to the contracts agreed (NordPoolSpot, 2014).

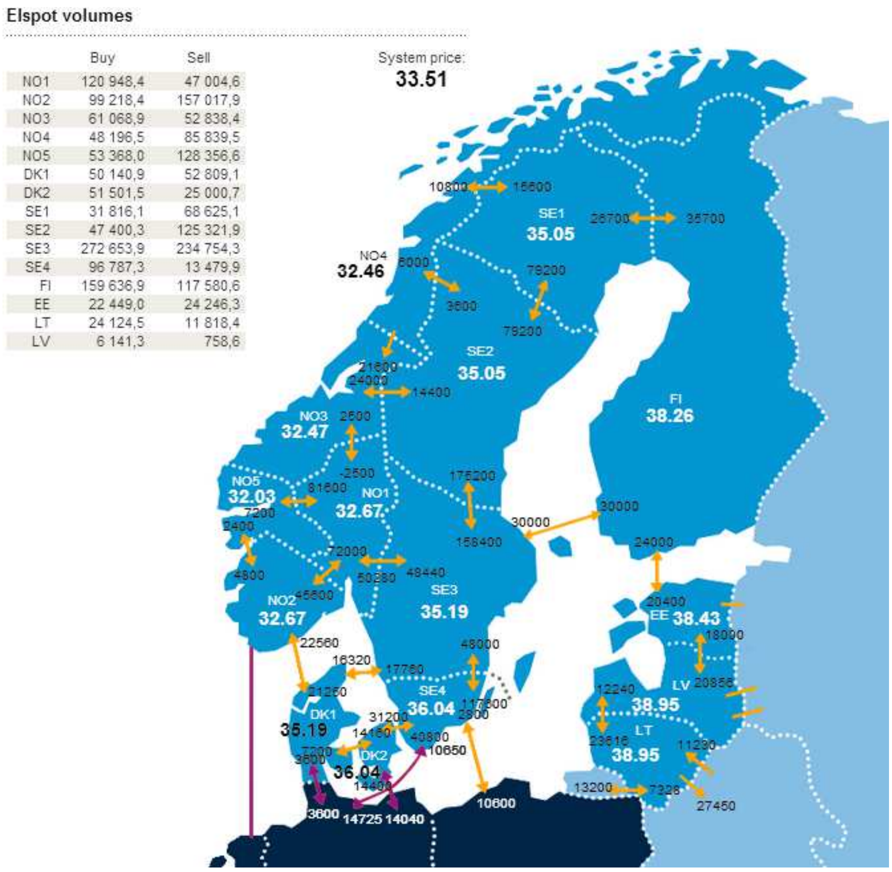

Figure 4. Elspot market overview

Source: NordPoolSpot

Input and output characteristics from power plant units

Initial information used for day-ahead economic dispatch of the power plant operation is the set of input-output characteristics of the boilers, turbines and power units. Input-output characteristics of the power units are presented in this part. The paper focuses on several types of thermal power plant units in Narva Power Plants:

- Condensing power plant units (CP)
- Combined cycle power plant unit (CHP)
- Circulated fluidized bed combustion (CFBC) technology
- Pulverized combustion (PC) technology.

Narva Power Plants units consist of double power units, which mean that one unit has two boilers, turbine and generator. Generally, the power generation unit is described as a system with inputs, outputs, state parameters and environmental impact (Figure 5).

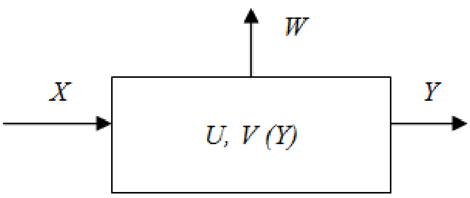

Figure 5. A general model of power generating unit
Source: (Valdma, Tammoja, Keel, 2009)

The following characteristics are used as the static model of the power units (Valdma, Tammoja, Keel, 2009):

- Input-output characteristics:

$$X = X[Y, U, V(Y)] = G_{U,V(Y)}(Y) \quad (1);$$

- Environmental impact characteristics:

$$W = W[Y, U, V(Y)] = W_{U,V(Y)}(Y) \quad (2);$$

- Auxiliary characteristics:

$$P^{aux} = P^{aux}[Y, U, V(Y)] = P^{aux}_{U,V(Y)}(Y) \quad (3).$$

where
X – input vector,
Y – output vector,
U – vector of state parameters,
$V(Y)$ – state vector function,
W – compounds affecting the environment,
P^{aux} - auxiliary power.

The following generating unit characteristics in economic load dispatch (ELD) are considered in this paper:

- electrical and thermal power unit output, auxiliary power;
- generation costs, which depend on:
    - power generating unit capacity,
    - manufacturing fixed costs,
    - power generating unit efficiency and variable manufacturing costs (fuel, environmental and CO_2 emission costs);
- start-up costs.

At the end of 2013, the installed electrical capacity of the Narva Power Plants (NEJ) was 2 265 MW, out of which 8 units were in Estonian Power Plant (EEJ) with the installed electrical capacity of 1 530 MW and 4 units were in Baltic Power Plant (BEJ) with the installed electrical capacity of 735 MW. The only unit working in combined cycle is power generating unit 11 in Baltic Power Plant with the installed thermal capacity of 120 MW (Eesti Energia AS Annual Report 2013). Condensing and combined cycle power plant units of different sizes and technologies are analyzed in this work (Table 1).

Table 1. Condensing and combined cycle of Narva Power Plants units' capacity

Power Plant	Narva Power Plants											
	Estonian Power Plant								Baltic Power Plant			
Number of unit	1	2	3	4	5	6	7	8	9	10	11	12
Type	CP	CP	CP	CP	CP	CP	CP	CP	CP	CP	CHP	CP
Technology	PC	PC	PC	PC	PC	PC	PC	CFBC	PC	PC	CFBC	PC
Electrical capacity, MW	185	185	185	185	195	195	185	215	170	170	215	180
Thermal capacity, MW											120	
Auxiliary power, %	10	10	10	10	10	10	10	10	10	10	10	10

Source: Eesti Energia AS Annual Report 2013, Eesti Energia homepage

Generation costs of the existing power units are usually expressed in terms of a unit cost (euro per megawatt-hour) and include manufacturing fixed and variable costs. Fixed costs consist of operational and maintenance costs (O&M) and personnel costs (euro per megawatt-year). Variable costs are based on fuel costs, environmental costs, CO_2 emission allowances costs.

There are manufacturing fixed costs of the existing power units in Narva Power Plant shown in Table 2. The following initial information for calculation has been taken from Eesti Energia AS Annual Report 2013: operating personnel, produced heat and electricity, payroll expenses, including wages, bonuses and vacation pay, maintenance and repair costs.

Table 2. Manufacturing fixed costs of the power plants

Unit	O&M costs, €/MWh-yr	Personnel costs, €/MWh-yr	Manufacturing fixed costs, €/MWh-yr
EEJ	2,2	0,4	2,6
BEJ	8,3	0,9	9,2
NEJ	5,7	0,8	6,5

Source: Eesti Energia AS Annual Report 2013, author's estimation

Several additional components have been assumed for evaluation of variable costs, such as fuel prices on the market, emission prices for the following years, CO_2 emission allowance prices, and efficiency of the power generating unit.

The prices of fuels mainly used in Narva condensing power plants are shown in Table 3. The future prices of fuels have been evaluated by calculating the linear trends from the historical values from 1999 to 2012 taken from Statistics Estonia. There is no historical information about retort gas, so only future projections are shown in Table 3.

Table 3. Actual fuel prices in 2012 and projections for the years 2013-2015

Fuel	Price escalation, %/y	2012 price, €/MWh	2013 price, €/MWh	2014 price, €/MWh	2015 price, €/MWh
Oil shale	3,5	13,04	13,50	13,97	14,46
Shale oil	2,9	484,6	498,7	513,2	528,0
Retort gas	2,6	78,5	80,6	82,7	84,8

Source: Statistics Estonia, autor's estimation of future prices

The future prices of oil shale and shale oil are presented in Figure 6.

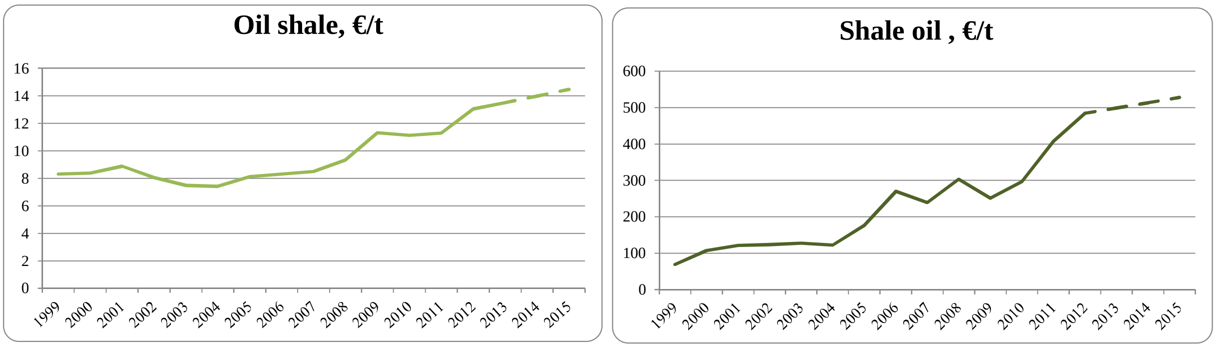

Figure 6. Historical and future prices of oil shale and shale oil

Source: Statistics Estonia, author's estimation of future prices

The effectiveness and reliability of oil-shale-fired power plants depend on oil shale quality, especially on its heating value. Retort gas with a high calorific value, which released during processing from Eesti Energia Õlitööstus Enefit 140 and Enefit 280, is used for power generation. Shale oil is used mainly for start-up of the power units, some part of it could be used during the burning of oil shale, but this amount is marginal and not considered in this work.

The Environmental Charges Act specifies natural resources, air and water pollutants along with the types of waste as conditions and rules of charging (Ministry of the Environment, 2005). According to this Act, pollution charges and resource use charges will gradually increase in the following years (Table 4).

The Act is based on the 'polluter pays' principle. The environmental charges make producers reduce emissions from electricity generation (Ministry of Economic Affairs and Communications, 2011). The Environmental Charges Act obliges the owners of combustion equipment to pay pollution charges for several pollutants emitted into air (e.g. sulphur dioxide, nitrogen oxides, etc.). At present, CO_2 charge has to be paid by all enterprises producing heat, excluding the ones firing biomass, peat or waste (UNFCCC, 2011).

Using oil shale as its main source of fuel, Estonia has ensured its security of supply and the independence of its electricity price from trends in world prices for energy sources. On the other hand, electricity generation from oil shale releases considerable amounts of CO_2 emissions that were allocated in the amount of 10,3 million tonnes of free CO_2 emission allowances to Eesti Energia by the state in 2012. In 2013, free emission allowances for electricity generation were no longer allocated by the state.

Table 4. Emissions' tariffs and other environmental characteristics

Emissions and ohter characteristics	Unit	2013	2014	2015
Carbon dioxide for electricity production (CO_2)	€/t	0,0	0,0	0,0
Carbon dioxide for heat production (CO_2)	€/t	2,0	2,0	2,0
Sulphur dioxide (SO_2)	€/t	86,1	111,9	145,5
Nitrogen oxides (NO_x)	€/t	101,1	111,2	122,3
Carbon monoxide (CO)	€/t	6,4	7,0	7,7
Fly ash	€/t	86,5	112,4	146,2
Bottom ash	€/t	2,1	2,5	3,0
Cooling water	€/m^3	0,002	0,002	0,002
Heavy metals	€/t	1 252	1 265	1 278
Placement coefficient (EEJ)	-	1,2	1,2	1,2
Placement coefficient (BEJ)	-	1,2	1,2	1,2
Landfill coefficient (EEJ)	-	1,0	1,0	1,0
Landfill coefficient (BEJ)	-	1,0	1,0	1,0

Source: Environmental Charges Act

In 2013, emission allowance prices were influenced by the excess supply of allowances prevailing on the market resulting from the global economic slowdown. The price of CO_2 emission allowance traded in December 2013 was 43,3% lower compared to 2012. The future and actual prices of CO_2 are given in Table 5 (Eesti Energia AS Annual Report, 2013).

Table 5. CO_2 prices

Emission allowance prices	Min, €/t	Max, €/t	Average price, €/t
CO_2 December 2013	2,8	6,7	4,5
CO_2 December 2014	2,9	7,0	4,7

Source: Eesti Energia AS Annual Report 2013

The amount of CO_2 emissions in g/MWh by the type of technology is given in Table 6.

Table 6. CO_2 emissions

Power plant and technology	CO_2 emission, g/kWh
EEJ PC	1,4
EEJ, BEJ CFBC	1,0
EEJ PC	1,4

Source: Eesti Energia AS Annual Report 2013

The efficiency of power unit is the relation of power unit's output power to the input power of the unit:

$$\eta_u = \eta_u(P_u) = \frac{P_u}{B_u(P_u)} \tag{4}$$

where
η_u - efficiency of power unit,
P_u - active output power of the power unit,
$B_u(P_u)$ - fuel costs characteristics of the power unit,
u - power units (double-blocks), $u = 1,...,m$,

Most of the plants have been operational for more than 30 years with low thermal efficiencies. Circulating fluidized bed combustion oil shale units (EEJ 8 and BEJ 11) have been renovated and have higher efficiency than other power generating units. The rest of the existing thermal power plants in Estonian Power Plant have $deSO_x$ technology and by the year 2016 will be equipped additionally with $deNO_x$ technology. Characteristics of the fuel costs and incremental fuel costs are calculated on the basis of efficiency. Power generating unit efficiencies in condensing mode at full load are given in Table 7.

Table 7. Efficiency of the power generating unit in condensing mode at full load

Power plant and technology	Efficiency at full load, %
EEJ PC	31,0
EEJ , BEJ CFBC	36,0
BEJ PC	28,0

Source: (Siirde, Tammoja, 2005)

The fluidized-bed energy unit No. 11 of Baltic Power Plant is operated in cogeneration mode to provide the district heating system of Narva. The capacity of cogeneration power plants (CHP) basically follows thermal loading (Hlebnikov, Dementjeva, Siirde, 2009). The efficiency of power generating unit No. 11 in cogeneration mode at full load is given in Table 8.

Table 8. Efficiency of the power generating unit No. 11 in cogeneration mode at full load

Thermal load, MW	Installed electrical capacity, MW	Electrical efficiency at full load, %	Heat efficiency at full load, %
120	190	41,0	78,0

Source: (Siirde, Tammoja, 2005)

Typical generation cost functions are non-linear, for example, quadratic. In order to use linear programming software to solve economic dispatch problem, piece-wise linear approximation is used. The variable cost of the power unit is mainly the cost of the fuel. There are three types of fuel used: oil shale and retort gas are used for electricity generation, and additionally, shale oil to oil shale is used in the starting up process.

Characteristics of the fuel costs the power unit depend on the power unit's efficiency and fuel price from generator's output power:

$$B_u = B_u(P_u) = \frac{C_{fuel}}{\eta_u(P_u)} \tag{5}$$

where
B_u - fuel costs of the power unit,
P_u - active output power of the power unit,
$B_u(P_u)$ - characteristics of the fuel costs of the power unit,
C_{fuel} - fuel price,
$\eta_u(P_u)$ - efficiency of the power unit.

Caracterictics of the incremental fuel cost is derivation of the power unit's fuel cost with respect to active power output:

$$b_u = \frac{\partial B_u}{\partial P_u} \approx \frac{\Delta B_u}{\Delta P_u} \tag{6}$$

Value b_u shows the growth in power unit's fuel cost if the active power load of the power unit is increased by one unit (Valdma, Tammoja, Keel, 2009).

Characteristics of the fuel cost of double power units are given in Figure 7 and Appendix 3.

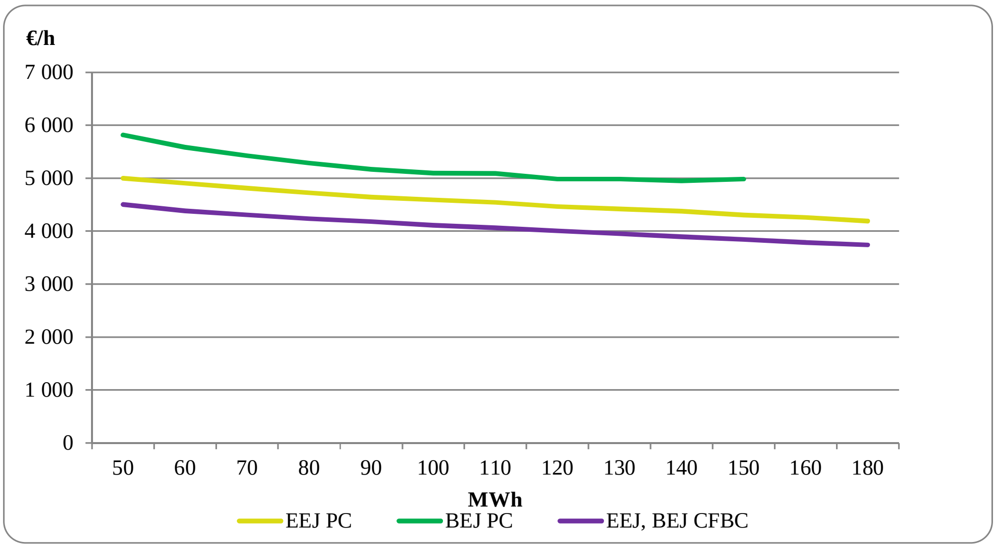

Figure 7. Fuel costs characteristics of the existing power units

Source: Compiled according to the author's estimation

Incremental fuel cost characteristics of double power units are given in Figure 8 and Appendix 4.

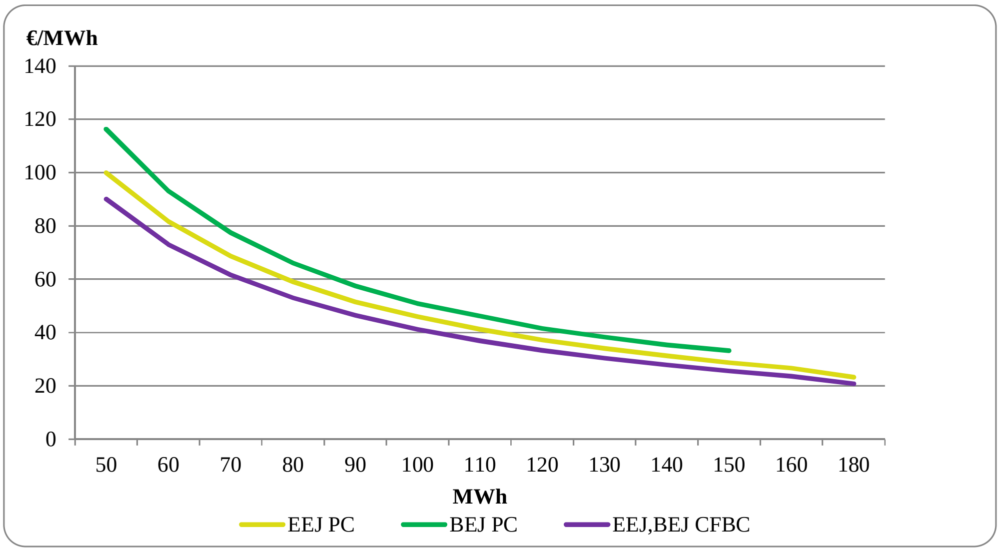

Figure 8. Incremental fuel cost characteristics of the existing power units

Source: Compiled according to the author's estimation

Environmental impact characteristics described in Equation 2 and main inputs are given in Table 4. Characteristics of the environmental impact could be described with the following equation:

$$W_u = W_u(P_u) \tag{7}$$

where

W_u - emission costs of the power unit,

$W_u(P_u)$ - characteristics of the emission costs of the power unit.

CO_2 emission costs have been calculated by using the price of December 2014 and CO_2 emission amounts given in Table 5 and 6.

Start-up costs of the power unit consist of boiler and turbine start-up costs, which depend on the down time. There are three down time zones in Narva Power Plants: cold, warm and hot. Hot zone means that the down time period is from 0 to 20 hours, warm zone's down time is from 21 to 50 hours and cold zone's down time is more than 51 hours. The initial data for start-up calculation are confidential information of the company, so the start-up costs were estimated by the author based on the actual prices in year 2013 and author experience (Figure 9).

Constraints and optimality conditions of the power units' operation

Operating constraints that affect power units (Wood, Wollenberg, 2006):

- availability of power units;
- minimum and maximum electrical and heat generation capacity;
- ramp rate (how quickly the unit's output can be changed);
- minimum amount of time the generator must run;
- minimum amount of time the generator must stay off once turned off.

Emission constraints have also impact on the operation of the power units in Narva. The European Union has issued standards for SO2, fly ash, CO and NOx emissions for large combustion plants in its LCP Directive. The standards apply to all plants with a thermal input of energy more than 50 MW.

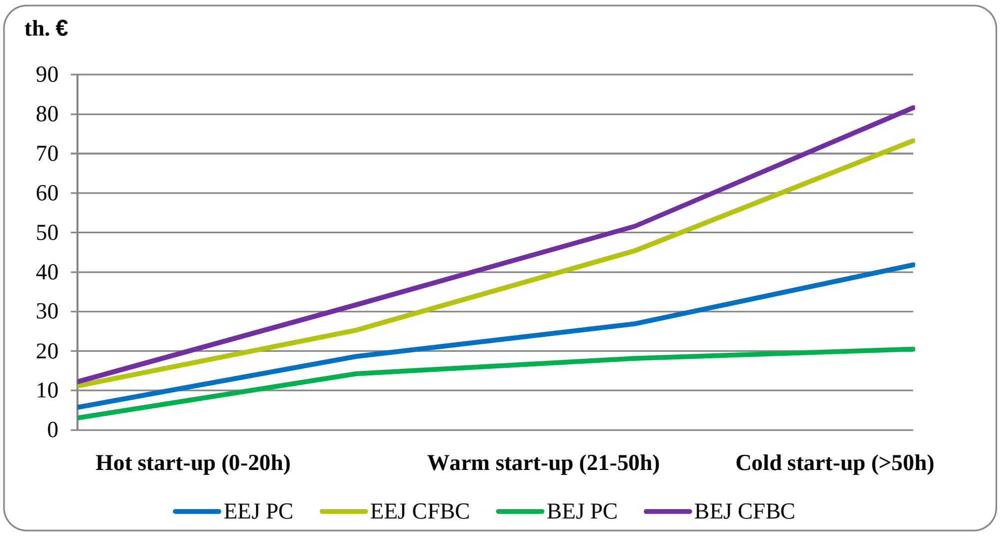

Figure 9. Start-up costs of the existing power units

Source: Statistics Estonia, author's estimation

There is Ambient Air Protection Act in Estonia that regulates activities, which discharge emission of pollutants into the ambient air, damage to the ozone layer, and appearance of factors causing climate change. The regulations linked with the Act and indirectly with the climate change issues are "Procedure for determination of ambient air pollution levels", Regulation No. 120 of Ministry of the Environment, 22 September 2004, and "The ambient air pollution limit values for large combustion plants", Regulation No. 112 of Ministry of the Environment, 2 September 2004.

Narva Power Plants must meet the limits given in Table 9.

Table 9. Emission limit values

Unit by technology/Emissions	SO_2	NO_x	Fly ash	CO
EEJ PC, mg/nm3	2 300	450	200	500
BEJ PC, mg/nm3	3 050	450	200	200
CFBC, mg/nm3	200	200	30	500
NEJ, t/y	24 100			

Source: AS Eesti Energia Narva Elektrijaamad Eesti Elektrijaama keskkonnakompleksluba nr L.KKL.IV-172516; AS Eesti Energia Narva Elektrijaamad Balti Elektrijaama keskkonnakompleksluba nr L.KKL.IV-137279 (in Estonian)

The restrictions also concern emission limit values in tonnes per year that are declared in Eesti and Baltic Power Plants integrated environmental permits No. L.KKL.IV-172516 and

No. L.KKL.IV-137279 respectively. Since 2012, there have been limitations of SO_2 emissions in the amount of 24 100 tonnes a year from Narva Power Plants. Various methods of lowering the SO_2 level have been tested in Narva, and according to Eesti Energia Annual Report 2013, the SO_2 amount emitted from Narva Power Plants was 21 100 tonnes previous year.

The optimatility coditions of condensing and cogeneration power units should be defined separately. The optimality conditions for cogeneration power unit are operation in accordance with the thermal power demand in Narva City, and available minimum and maximum capacity. The thermal power curve based on 2013 actual data is given in Figure 10.

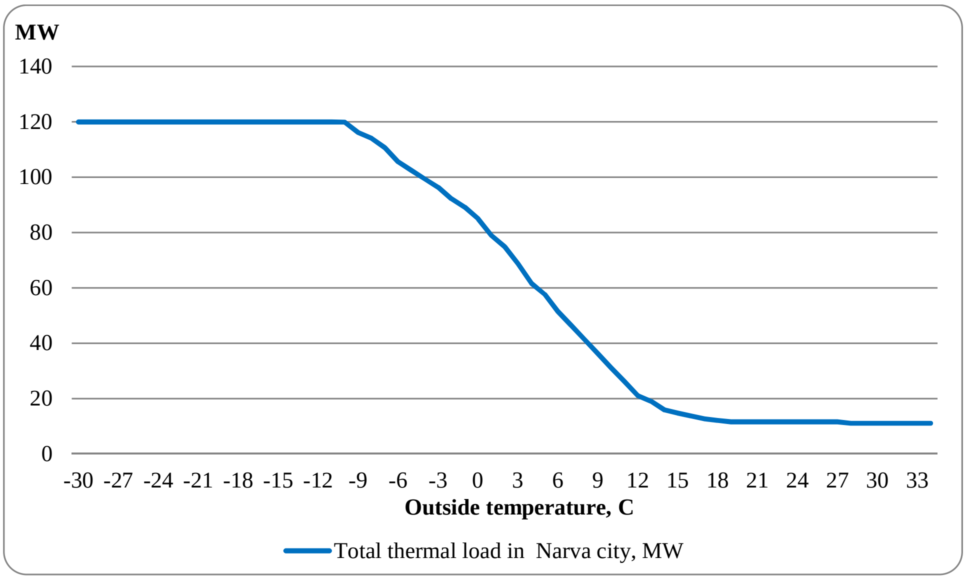

Figure 10. The thermal power curve in Narva
Source: Narva Power Plants historical data

The main rules for optimizing load distribution between units in the condensing power plant could be formulated as: all the units must be loaded in the order of increasing incremental fuel costs, the cross loads of units have to satisfy the constarints listed above.

1.3. Economic dispatch versus unit commitment

Electricity power produced from power plants is changing and has day and week cyclic recurrence. The fluctuations of electrical power generation in Narva Power Plants are caused by the NordPoolSpot prices. For example, during the night hours the electric power generation could be two times less than in daytime and the same for working days and weekends. The fluctuations of NPS prices and electrical power generation in a typical winter week are shown in Figure 11.

Figure 11. Electrical power price and volume fluctuations of a typical winter week
Source: NordPoolSpot

The fluctuations of NPS prices and electrical power generation in a typical summer week are shown in Figure 12.

In addition to the economic dispatch problem between working power units, unit commitment (UC) is a very important problem in day-ahead optimization. Its objective is to determine the optimum schedule of generating units while satisfying a set of system and units' constraints. The unit commitment problem consists in determining the startup and shut down schedule of the units to meet the required demand. Once the unit commitment has taken place, the economic dispatch is responsible for allocating the system demand among the operating units while minimizing the generation cost (Padhy, 2004).

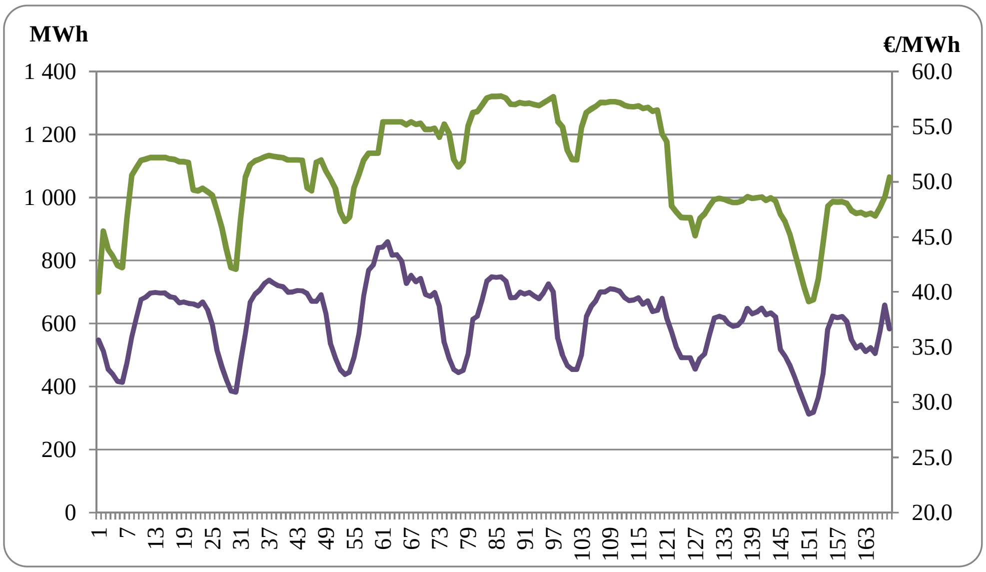

Figure 12. Electrical power price and volume fluctuations of a typical summer week
Source: NordPoolSpot

Usually UC problem is the set up on power system's level, where different types of power plants are in operation. However, optimization of the unit commitment schedules gives economical effect in power plants and at units' level (Valdma, Tammoja, 2009). The main constraints of the unit commitment problem are active power balance, active power operating limits, ramp rate limits, spinning reserve, minimum up time of units and minimum down time of units (Wood, Wollenberg, 1984).

The power plant detailed input characteristics of each power unit component are necessary, especially the fuel costs, because it represents the main cost among generation costs. Moreover, all the power units' technical constraints, that limit their operational flexibility in economic dispatch and unit commitment problem, should be included in the model.

2. ECONOMIC DISPATCH USING OPTIMIZATION TECHNIQUES

2.1. Optimization techniques

The previous solutions to ELD problems have applied various mathematical programming methods and optimization techniques. Wood and Wollenberg (1984) used many optimization techniques for solving ELD problem, such as genetic algorithm (GA), fuzzy, hybrid techniques. The type of modern optimization techniques called Particle Swarm Optimization (PSO) was introduced by J. Kenedy and R. Eberhart in 1995 (Aravindhababu P, Nayar K., 2002). Sheble (1989) proposed a real-time economic dispatch algorithm known as Merit Order Loading (MOL) based on the theory of linear programming, but with impossibility to solve combined cycle (CC) generation dispatch problem. Ongsakul (1999) has made a modification for MOL and sorted CC units based on the unit incremental cost at the highest outputs, but an example with only CC units was provided. Sheble and Brittig (1995) proposed a refined genetic algorithm (RGA) method to solve ELD problem with non-convex cost curve, taking into account the valve point effect. Yang H., Yang P. and Huang (1996) have used non-smoothing fuel cost functions for solving ELD problem. The evolutionary programming based algorithm for ELD with environmental constraints was first time implemented by Wong and Yuryerich in 1998.

The classical economic load dispatch problem has been solved by using classical mathematical optimization methods, such as the Lambda-iteration method, the Newton method or the gradient method (Smallwood, 2002; Hernandez-Aramburo, Green, 2005). Unfortunately, these techniques rely on the essential assumption of the incremental costs' monotonically increasing function, and they do not take into account the constraints imposed by the generators. In addition, the presence of restrictions, such as ramp rate limits, valve points and prohibited operation zones, introduces discontinuities that add additional complexity to the ELD problem (Victoire, Sugnathan, 2008). Therefore, dynamic programming, genetic algorithms, nonlinear programming, artificial intelligence, practical swarm optimization and their modification techniques for solving ELD issues have been presented in Park, Lee and Shin (2005), Sinha, Lai (2009) and Bhattacharya, Chattopadhyay (2009).

The Estonian researchers presented the estimation of input-output characteristics and the principles of optimal dispatch of condensing units in a power plant under incomplete information in 1976 and 1977 (Valdma et al., 1976; Valdma, 1977). Keel, Shuvalova, Tammoja and Valdma introduced the economic dispatch and unit commitment solution for cogeneration power plant with combined cycle in 2001. The principles of min-max optimal load dispatch in condensing thermal power plant were proposed by Valdma, Keel, Liik and Tammoja in 2003. Several papers were provided on the topic of optimal load dispatch solution for the generating units in the power system under probabilistic and uncertain information with the presentation of min-max models (Liik et al., 2004; Keel et al., 2005; Tammoja, Valdma, Keel, 2006; Valdma, et al., 2007). The book “Optimization of Thermal Power Plants Operation” was published in 2009 in Estonian and English, and it introduces the theory and methods of operational optimization for different kinds of thermal power plants (Valdma et al., 2009). The evaluation of optimization efficiency in the power systems for two classic optimization problems - economic dispatch and unit commitment problems of thermal power units - was carried out in paper “On Efficiency of Optimization in Power Systems”. The authors have shown that the maximum efficiency of optimization in load distribution and unit commitment problems in thermal power plants can decrease the fuel cost and economic impacts of thermal units approximately by 10–20%. Moreover, they stated that the optimization is the cheapest possibility of economizing on energy resources, thermal power plants and power systems by minimizing the operation and investment costs and reducing environmental impact (Keel et al., 2011). However, efficiency of optimization in both load distribution and unit commitment was introduced based on the conditions of regulated electricity market, where the electricity prices are relatively stable and under the control of the government. Deregulation of the electricity market makes it necessary to perform the changes in classical algorithm and develop the new model for finding a good solution in a reasonable period of time.

This economic dispatch and unit commitment problem in conditions of the deregulated market for oil-shale-based power units is formulated as a mixed-integer linear programming problem (MILP). The mathematical programming formulation is implemented in the modeling language called the General Algebraic Modeling System (GAMS).

GAMS is a high-level model development environment that supports the analysis and solution of linear, non-linear and mixed-integer optimization problems (Chattopadhyay, 1999). The economic dispatch and unit commitment problem are solved with Cplex 12 solver, which is part of the modeling system GAMS. GAMS/Cplex is a high-performance mathematical programming solver for linear programming (LP), mixed-integer programming (MIP) and quadratic programming (QP) based on the Cplex Callable Library and developed by ILOG[1]. GAMS is tailored for complex, large scale modeling applications, and it allows to build large maintainable models that can be adapted quickly to new situations (Rosenthal, 2014).

GAMS is described in a number of publications including Brooke et al. (1998), Jensen (2006), Kalvelagen (2001, 2002, 2003), Markusen (2005), McCarl (1998), McCarks et al. (2013), McKinney and Savitsky (2003), Robichaud (2010), Andrei (2011) and Rosenthal (2011) (Neculai, 2013).

It includes the following mathematical algorithms:

- primal and dual simplex algorithm,
- barrier or interior-point algorithm,
- network algorithm,
- sifting algorithm,
- concurrent algorithm.

The simplex algorithm is generally attributed to George Dantzig (1914-2005), who is known as the father of linear programming. In 1984, Narendra Karmarkar published a paper describing a new approach to solving linear programs that was both numerically efficient and had polynomial complexity. This new class of methods is called interior-point methods. These new methods have revolutionized the optimization field over the last 30 years, and they have led to efficient numerical methods for a wide variety of optimization problems well beyond the confines of linear programming (Burke, 2013).

[1] ILOG: http://www. ilog.com/products/cplex/

Primal and dual simplex algorithm

Linear programming is constrained minimization of a linear objective over a solution space defined by linear constraints:

$$\min \quad cx \tag{8}$$

$$Ax \le b \tag{9}$$

$$l \le x \le u \tag{10}$$

A is an $m \times n$ matrix, c is a $1 \times n$ vector, and x, b, l and u are $n \times 1$ vectors.

A dual problem could be constructed for every LP problem, where c and $y = [y_1, y_2, ..., y_m]$ are row vectors and b and x are column vectors. The standard form for the primal and dual problem is given in Figure 13.

Primal Problem			*Dual Problem*	
Maximize	$Z = cx,$	$\Leftrightarrow$	*Minimize*	$y_0 = yb,$
subject to			*subject to*	
	$Ax \le b$			$yA \ge c$
and			*and*	
	$x \ge 0$			$y \ge 0$

Figure 13. The primal and dual problem in matrix notation

Source: (Hillier, Lieberman, 2001)

The dual problem uses exactly the same parameters as the primal problem, but in different locations. The primal problem on the left is stated as a maximization problem, to match the standard presentation of duality, recognizing that $\max cx \equiv \min(-c)x$. For a primal maximization problem and a dual minimization problem, the primal objective cx starts low and increases, while the dual objective yb starts high and decreases. This gives an upper and lower bound on the optimum value of the solution (Hafer, 1998).

Generally, the simplex algorithm is an iterative procedure for solving LP problems in a finite number of steps:

- having a trial basic feasible solution to constraint-equations;
- testing whether it is an optimal solution;

- improving the first trial solution by a set of rules and repeating the process till an optimal solution is obtained.

This primal simplex algorithm uses a “three-phase method” (Restrepo, Rodrigo, 1994):

- Phase 0: drive all artificial variables to zero , i.e. eliminate them from the basis;
- Phase I: find a tableau with $x \geq 0$, i.e. a feasible primal program;
- Phase II - generate tableaux that increase the value of Z turning $c \geq 0$, without dropping back into Phase 0 or I, i.e. find a feasible primal program that maximizes the objective function.

According to Hillier and Lieberman (2001), the dual simplex method can be thought of as a mirror image of the simplex method. The simplex method deals directly with suboptimal basic solutions and moves toward an optimal solution by striving to satisfy the optimality test. By contrast, the dual simplex method deals directly with superoptimal basic solutions and moves toward an optimal solution by striving to achieve feasibility. Furthermore, the dual simplex method deals with a problem as if simplex method was being applied simultaneously to its dual problem. The dual simplex method is very useful in certain special types of situations. Ordinarily it is easier to find an initial basic feasible solution than an initial suboptimal basic solution. However, it is necessary to introduce many artificial variables to construct an initial basic feasible solution artificially. In such cases it may be easer to begin with a superoptimal basic solution and use the dual simplex method. Moreover, less iterations may be required when it is not necessary to drive many artificial variables to zero. The phases of the dual simplex method are given below (Restrepo, Rodrigo, 1994):

- Phase 0 - drive all artificial variables to zero, i.e. eliminate them from the basis;
- Phase I - find a tableau with $y \geq 0$, i.e. a feasible dual program;
- Phase II - generate tableaux that decrease the value of y_0 turning $b \geq 0$, without dropping back into Phase 0 or I, i.e. find a feasible basic dual program that minimizes the objective function.

Details of the dual simplex method have been summarized as follows (Hillier, Liebermal, 2001):

- *Initialization:* after converting any functional constraints in $\geq$ from to $\leq$ form, introduce slack variables as needed to construct a set of equations to describe the problem. Find a basic solution, where the coefficients are zero for basic variables and nonnegative for nonbasic variables, so the solution is optimal and go to feasibility test.

- *Feasibility test:* check to see whether all the basic variables are nonnegative. If they are, the solution is feasible, and therefore optimal, so stop. Otherwise, go to iteration.
- *Iteration*:
  - Determining the leaving basic variable by selecting a negative basic variable that has the largest absolute value.
  - Determining the entering basic variable by selecting a nonbasic variable whose coefficient reaches zero first, checking the nonbasic variables with negative coefficientsm, and selecting the one with the smallest absolute ratio value.
  - Determining the new basic solution by solving basic variables by Gaussian elimination (an algorithm for solving systems of linear equations).

Both the primal and dual simplex algorithms will reach the same solution, but arrive there from different directions. The dual simplex algorithm suits the best for problems for which an initial dual feasible solution is easily available. It is particularly useful for reoptimizing a problem after a constraint has been added or some parameters have been changed, so that the previously optimal basis is no longer feasible. In practice, the simplex algorithm is quite efficient and it can be guaranteed that the global optimum is found if certain precautions against cycling are taken (Jensen, Bard, 2003).

The barrier algorithm and interior-point method

Interior-point method was initially proposed by Frisch in 1955. Fiacco and McCormick proved global convergence for general interior-point methods for problem by reformulating this problem as an unconstrained optimization problem. Classical log-barrier methods, one type of interior-point algorithm, were used extensively in the 1960s and 1970s (Doyle, 2003). The basic approach for interior-point method was proposed in 1967 by a Russian mathematician Dikin I. (Hillier, Liebermal, 2001). In 1984, Karmarkar presented an algorithm that solved linear optimization problems in polynomial time. This was a significant improvement over current algorithms (notably the simplex method), which solved worst-case problems in exponential time. It was soon shown that Karmarkar's algorithm was equivalent to the log-barrier method and interest in interior-point methods resurged (Doyle, 2003). After the appearance of Karmarkar's work, it was rediscovered by a number of researchers, including Barns, Cavalier and Soyster. Vanderbei, Meketon and Freedman who presented a modification of Karmarkar's linear programming algorithm in 1986 (Hillier, Liebermal, 2001).

Karmarkar's algorithm falls within the class of interior point methods: the current guess for the solution does not follow the boundary of the feasible set as in the simplex method, but it moves through the interior of the feasible region, improving the approximation of the optimal solution by a definite fraction with every iteration, and converging to an optimal solution with rational data (Strang, 1987). The term interior-point method implies that the solution process maintains strict inequality for constraints that are expressed as inequalities (Doyle, 2003).

The idea of this algorithm could be summarized as follows:

- *Concept 1:* Shoot through the interior of feasible region toward an optimal solution.
- *Concept 2:* Move in a direction that improves the objective function value at the fastest possible rate.
- *Concept 3:* Transform the feasible region to place the current trial solution near its center, thereby enabling a large improvement when concept 2 is implemented (Hillier, Liebermal, 2001).

The barrier algorithm is an alternative to the simplex method for solving linear programs. It employs a primal-dual logarithmic barrier algorithm, which generates a sequence of strictly positive primal and dual solutions. Specifying the barrier algorithm may be advantageous to large, sparse problems (Cplex Solver Manual, 2014).

The primal, dual and interior-point method example solution is given in Figure 14. The example considers x_1 and x_2 variables and 11 constraints that are shown as blue lines. Each iteration of the algorithm is marked as red circle points. The constraints are shown as blue lines.

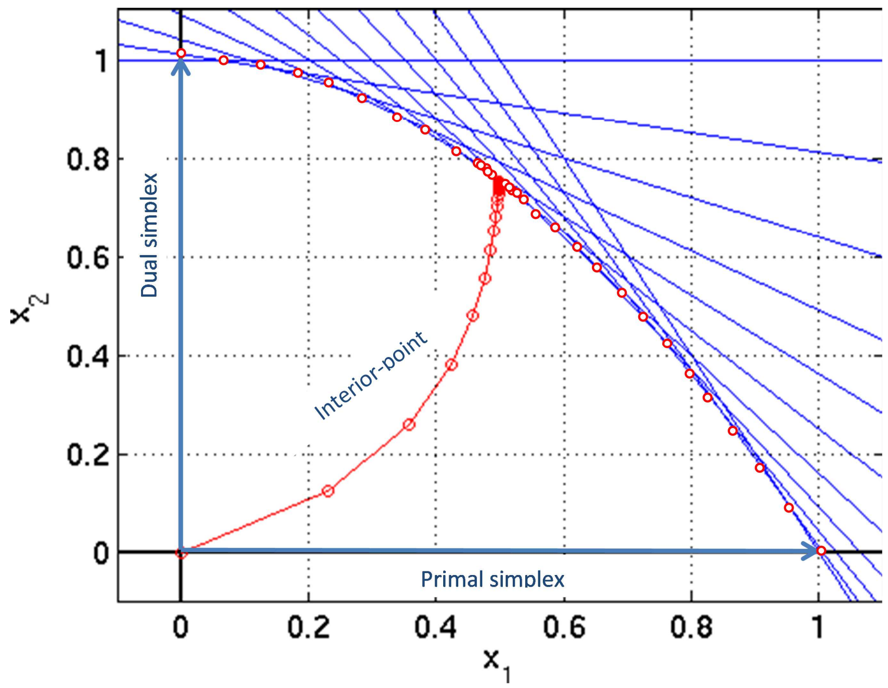

Figure 14. The primal, dual and interior-point method example solution
Source: (Hillier, Lieberman, 2001)

Network, sifting and concurrent algorithm

Network problems involve finding an optimal way of doing something. They are studied under the name of combinatorial optimization. Cplex has a very efficient algorithm for network models. Network constraints have the following properties:

- each non-zero coefficient is either $a+1$ or $a-1$;
- each column appearing in these constraints has exactly 2 nonzero entries, one with $a+1$ coefficient and one with $a-1$ coefficient.

Cplex can also automatically extract networks that do not adhere to the above conventions as long as they can be transformed to have those properties.

Cplex provides a sifting algorithm, which can be effective on problems with many more varaibles than equations and similar to network algorithm. Sifting solves a sequence of LP subproblems where the results from one subproblem are used to select columns from the original model for inclusion in the next subproblem (Cplex Solver Manual, 2014).

The concurrent algorithm is one that can be executed concurrently. The most standard computer algorithms are sequential algorithms, and assume that the algorithm is run from the beginning to the end without executing any other processes. These often do not behave correctly when run concurrently and are often nondeterministic, as the actual sequence of computations is determined by the external scheduler. Concurrency often adds significant complexity to an algorithm, requiring concurrency control, such as mutual exclusion, to avoid problems (Mordechai, 2006).

Cplex is designed to solve the majority of LP problems by using default option settings. These settings usually provide the best overall problem optimization speed and reliability. However, there are occasionally reasons for changing the option settings to improve performance, avoid numerical difficulties, control optimization run duration, or control output options (Cplex Solver Manual, 2014).

Optimization techniques such as primal simplex, dual simplex and interior-point methods are used to solve the ELD problem in this paper. The majority of LP problems solve best using Cplex's dual simplex or interior-point algorithm. Some problems solve faster with the primal simplex algorithm rather than the dual simplex algorithm. Very few problems exhibit poor numerical performance in both the primal and the dual. Therefore, it should be considered trying primal simplex if numerical problems occur while using dual simplex.

2.2. Algorithm for economic dispatch and unit commitment

This section contains a verbal description of the economic dispatch and unit commitment for the existing oil-shale power generating units in day-ahead deregulated market and some requirements regarding the optimization problem.

Problem description

The problem of economic load dispatch is to find the optimal combination of power generation units in both EEJ and BEJ power plants, which minimizes the total manufacturing variable costs of Narva Power Plants under technological and environmental constraints.

Power generation takes into account 12 existing generating units in EEJ power plant EEJ 1-8 and BEJ power plant BEJ 9-12 (Figure 15). The only cogeneration unit that provides electricity and heat is BEJ11 in Baltic Power Plant.

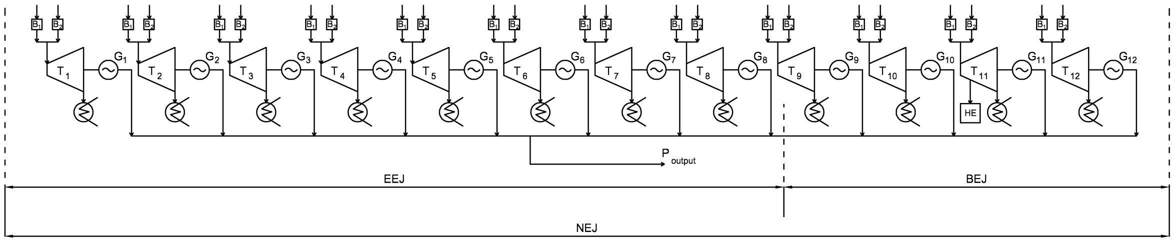

Figure 15. Simplified scheme of Narva Power Plants power units
Source: Prepared by the author

As it is a day-ahead planning, the author assumed that all data are reasonably well known. The day-ahead load demand and electricity prices are determined by supply and demand curves, and they do not take intra-day adjustment supplies into account. The availability of power units, minimum and maximum electrical and heat generation capacity are defined by power plants.

Objectives & expected results

The objective of this part of the paper is to elaborate the day-ahead ELD algorithm for the existing oil-shale-based power units to prove the possibility for minimization of generation costs in a power plant. The total generation costs of the power units, including power units manufacturing fixed and variable costs, have been determined. The manufacturing fixed costs are not dependent on the electricity produced, and therefore are not included in the objective function. Besides the costs, the following detailed results are expected:

- the number of power units required and the number of start-ups,
- the load of each generating units,
- heat and electricity production unbalance with respect to the demand,
- power plant's electricity output,
- power plant's heat output,
- power units' emissions amount,
- primary energy consumption.

There are two most common ways of organizing GAMS programs. The first style places the data first, followed by the model and then the solution statements. The second style emphasizes the model by placing it before the data. For the implemetation of day-ahead economic dispatch, optimization of the first style of organization is used (Figure 16). In this style, the sets are placed first. Then the data are specied with parameter, scalar, and table statements. Next, the model is denied with the variable, equation declaration, equation definition, and model statement. Finally, the model is solved and the results are displayed.

Data:

Set declarations and definitions
Parameter declarations and definitions
Assignments
Displays

Model:

Variable declarations
Equation declaration
Equation definition
Model definition

Solution

Solution
Displays

Figure 16. Organization of GAMS programs
Source: (Rosenthal, 2014)

Indices, sets & variables

Sets are fundamental building blocks in GAMS model. They allow the model to be succinctly stated and easily read. A simple set consists of the set name and elements of the set. Both the name and the elements may have associated text that explains the name or the elements in more detail.

Variables are the entities, whose values are generally unknown until after a model has been solved. The declaration of a variable is similar to a set or parameter declaration, in that domain lists and explanatory text are allowed and recommended, and several variables can be declared in one statement. A crucial difference between GAMS variables and columns in traditional mathematical programming terminology is that one GAMS variable is likely to be associated with many columns in the traditional formulation (Rosenthal, 2014).

The following indices and sets are used in ELD algorithm (Table 10):

Table 10. Indices and sets

Symbol	Description
$D_{\max}$	Set of maximum days in the model $D_{\max} = \{1...n\}$
D_t	Set of days with elements $t \in D : D \subset D_{\max}$
H	Set of time per day, where $h \in H : H = \{1...24\}$
U	Power generating units $u \in U : U = \{EEJ1...BEJ12\}$
U_e	Power generating unit for electricity production $u_e \in U_e : U_e \subset U$
U_h	Power generating unit for heat production $u_h \in U_h : U_h \subset U_e$
E	Production technology set $e \in E : E = \{PC, CFBC\}$
B	Primary energy $b \in B : B = \{OS, SO, RG\}$
W_u^e	Power generation units emissions $w_e \in W_e : W_e = \{SO_x ...HM\}$
W_u^h	Power generation units emissions $w_h \in W_h : W_h = \{SO_x ...HM\}$

Source: Prepared by the author

The following variables are used in ELD algorithm (Table 11):

Table 11. Variables

Variable	Unit	Description
$\eta_u(t)$	%	Power generating unit's u efficiency for the time period t (piece-wise linear approximation variable)
$B_u(t)$	MWh	Power generating unit's u primary energy consumption for the time period t
$P_u(t)$	MWh	Power generating unit's u electricity production for the time period t
$Q_u(t)$	MWh	Power generating unit's u heat production for the time period t
$C_u^B(t)$	€	Power units' u primary energy costs
$C_u^{SU}(t)$	€	Power generating unit's u start-up cost for the time period t
$W_{u,e}(t)$	t	Emission amount of type e for power unit u
$C_u^w(t)$	€	Power units u environmental impact costs
$C_{tot}^{VC}(t)$	€	Total manufacturing variable costs of power units
$C_{tot}^{FC}(t)$	€	Total manufacturing fixed costs of power units
$C_{tot}^{GC}(t)$	€	Total generation costs of power units
$\alpha_{i,t}$	0/1	Controllable variables: $\alpha_{i,t} = 1$ - boiler i is in operation, $\alpha_{i,t} = 0$ - boiler is off
$\beta_{j,t}$	0/1	$\beta_{j,t} = 1$ - turbine j is in operation, $\beta_{j,t} = 0$ - turbine j is off
$\gamma_{u,t}$	0/1	$\gamma_{u,t} = 1$ - power unit u is in operation; otherwise $\gamma_{u,t} = 0$

Source: Prepared by the author

Model formulation

The optimization problem is the following: to find permitted cross active loads of the power units $P_1,...,P_m$, which would guarantee the given NordPoolSpot electricity production volume $P_e^{NPS}(t)$ from overall power plant with minimal manufacturing variable costs $C_{tot}^{VC}(t)$ while meeting the constraints listed below.

Objective Function:

$$\text{Minimize} \qquad C_{tot}^{VC}(t) = \sum_{u=1}^{m} C_u^B(t) + \sum_{u=1}^{m} C_u^w(t) + \sum_{u=1}^{m} C_u^{SU}(t) \tag{11}$$

Subject to the following constraints:

NordPoolSpot electricity production volume:

$$P_e^{NPS}(t) - \sum_{u=1}^{m} P_u(t) = 0 \tag{12}$$

Active power limits to the power units:

$$P_u^{\min} \le P_u(t) \le P_u^{\max}, \; u = 1,...m \tag{13}$$

Thermal load for cogeneration unit:

$$Q^D(t) - \sum_{u=1}^{m} Q_u(t) = 0 \tag{14}$$

Heat power limits to the power units:

$$Q_u^{\min} \le Q_u(t) \le Q_u^{\max}, \; u = 1,...m \tag{15}$$

Ramp rate requirements:

$$P_{u,\tau+1} - P_{u,\tau} \le R_u \tag{16}$$

where

$C_{tot}^{VC}(t)$ - total manufacturing variable costs in time interval t,

$C_u^B(t)$ - power units' primary energy costs in time interval t,

$C_u^w(t)$ - power units' environmental impact costs in time interval t,

$C_u^{SU}(t)$ - power units' start-up costs in time interval t,

$P_u^{\max}$ - maximum power units' electrical capacity,

$P_u^{\min}$ - minimum power units' electrical capacity,

u - power units (double-blocks), $u = 1,...,m$,

$Q^D(t)$ - district heating thermal load,

$Q_u(t)$ - power units' thermal load,

$Q_u^{\max}$ - power unit's u maximum thermal load,

$Q_u^{\min}$ - power unit's u minimum thermal load,

$P_{u,\tau}$ - active power of unit u in time interval τ ($t \geq \tau$),

$P_{u,\tau+1}$ - active power of unit u in time interval τ ($t \geq \tau$),

R_u - ramp rate.

In addition, the following constraints are considered:

Emission limit values:

$$W_{u,e}(t) \leq W_{u,e}^{\max} \tag{17}$$

Retort gas usage limitation:

$$B_{u,RG}(t) \leq B_{u,RG}^{\max} \tag{18}$$

where

$W_{u,e}(t)$ - emission type e of power unit u,

$W_{u,e}^{\max}$ - maximum permitted emission type e of power unit u (Table 9),

$B_{u,RG}(t)$ - retort gas usage of power unit u of time interval t,

$B_{u,RG}^{\max}$ - maximum retort gas usage of the power unit u.

Minimum down-time:

$$T_{u,t}^{down-time} \geq T_{stay-off}^{\min} \tag{19}$$

Minimum up-time:

$$T_{u,t} \geq T_{must-run}^{\min} \tag{20}$$

where

$T_{u,t}^{down-time}$ - down-time of the unit u at the beginning of time interval t,

$T_{stay-off}^{\min}$ - minimum amount of time the generator must run,

$T_{u,t}$ - time period of the power unit running,

$T_{must-run}^{\min}$ - minimum amount of time the generator must stay off once turned off.

Restriction for number of start-ups:

$$m_u(t) \leq m_u^{\max} \tag{21}$$

where

$m_u(t)$ - planned number of start-ups of the time interval t,

$m_u^{\max}$ - maximum number of start-ups during the planned period.

Power units' primary energy costs could be found as:

$$C_u^B(t) = \sum_{u=1}^{m} B_u(P_u) = \sum_{u=1}^{m} \frac{C_f}{\eta_u(P_u)} \tag{22}$$

where

B_u - fuel costs of the power unit u,

P_u - active output power of the power unit u,

$B_u(P_u)$ - fuel costs characteristics of the power unit u,

C_f - fuel type f price,

$\eta_u(P_u)$ - efficiency of the power unit u.

Power units' environmental impact costs are calculated as follows:

$$C_u^w(t) = \sum_{u=1}^{m} W_{u,w} \cdot C_w = \sum_{u=1}^{m} (w_{e,w}^f + w_{h,w}^f) \cdot B_u^f \cdot C_w \tag{23}$$

where

$W_{u,w}$ - amount of the power units' emission type w for the power unit u,

C_w - emissions tariffs for emission type w,

$w_{e,w}^f$ - specific emission type w for electricity production for fuel type f,

$w_{h,w}^f$ - specific emission type w for heat production for fuel type f,

B_u^f - power unit's primary energy consumption for fuel type f,

Power units' start-up costs could be defined as follows:

$$C_u^{SU}(t) = \sum_{p=1}^{m} C_f (\gamma_{u,t} \cdot B_u^{SU}(T_{u,t}^{down-time})) \tag{24}$$

where

C_f - fuel type f price,

$\gamma_{u,t}$ - parameter considering the start-up of unit u in time interval t,

B_u^{SU} - start-up fuel consumption of the power unit u,

$T_{u,t}^{down-time}$ - down-time of unit u at the beginning of time interval t.

Total generation costs could be calculated as:

$$C_{tot}^{GC}(t) = C_{tot}^{VC}(t) + C_{tot}^{FC}(t) \tag{25}$$

where

$C_{tot}^{GC}(t)$ - total generation costs of the power units,

$C_{tot}^{VC}(t)$ - total manufacturing variable costs of the power units,

$C_{tot}^{FC}(t)$ - total manufacturing fixed costs of the power units.

Algorithm of the power unit's optimization

Step 1. Calculate unbalance of the active power (Eq. 12), check the active power limits of the power units (Eq. 13).

Step 2. Find the thermal load demand (Eq. 14) and check the heat power limits of the power units (Eq. 15).

Step 3. Calculate the primary energy costs (Eq. 22), check the retort gas usage limitation (Eq. 18).

Step 4. Calculate power units' environmental impact cost (Eq. 23), check the emission limits (Eq. 17).

Step 5. Check the start-up parameter $\gamma_{u,t}$, if the $\gamma_{u,t} = 1$, check the ramp rate of the power unit (Eq. 16) and minimum up-time (Eq. 20).

Step 6. If $\gamma_{u,t} = 0$, then check the minimum-down time (Eq. 19).

Step 7. Check the restriction of the number of start-ups (Eq. 21).

Step 8. Find power units' start-up costs (Eq. 24).

Step 9. End, delivering the results.

The proposed day-ahead economic dispatch algorithm includes several simplifications:

- the spinning reserve requirenments considered to be without limitations;
- the start-up costs of the turbine and boiler are not considered separately in calculaton of the start-up costs;
- only one type of oil shale with heat value 8.4 MJ/kg is used;
- the shale oil usage is considered only for start-ups;
- the transmission losses and fuel stocks are eliminated.

The listed simplifications could be used for the improvement of the model formulation, when the initial information is collected, the impact of these assumptions is fully assessed and designed. For example, for using fuel mixes in algorithm, the initial information based on the real tests should be fully described and the influence of fuel composition on the emission amount should be estimated.

3. ECONOMIC LOAD DISPATCH SOLUTION IN OIL SHALE POWER PLANTS

The proposed algorithm has been tested to estimate the costs associated with operating the oil shale power plants. The calculation results of the three optimization techniques and comparison of them are shown in the third chapter.

3.1. Implementation of the proposed algorithm

The day-ahead economic dispatch optimization is formulated as a mixed-integer linear programming problem. The proposed algorithm has been implemented in the GAMS/Cplex. The computational tests are carried out in an Intel(R) Xeon(R) CPU X5570 with 8 logical processors and 40.0 GB of RAM memory. The basic structure of a mathematical model coded in GAMS has the following components: sets, data, variable, equation, model and output. The solution procedure is shown in Figure 17.

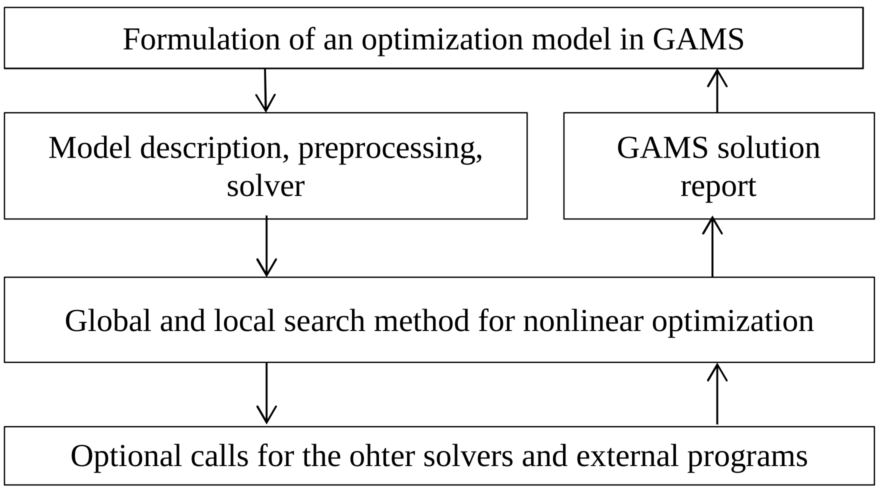

Figure 17. GAMS modeling and solution procedure
Source: (Bisen et al., 2012)

The proposed algorithm is applied to solve economic dispatch problems in case study involving the existing oil-shale-based power plants with 12 generating units.

Implementation of the case study is based on real data of the year 2013. The results are represented in the next chapter as the calculations of one typical week in winter for period 4 February 2013 – 10 February 2013, and one typical week in summer for period 22 July 2013 – 29 July 2013.

For the implementation and testing of day-ahead economic dispatch algorithm, the primal simplex, dual simplex and interior-point methods are selected and used as the most suitable for these types of practical cases. Network and sifting algorithms are used mainly for finding an optimal way of doing something, for example, to determine the optimal way of delivering packages or to develop an airline network. Concurrency adds significant complexity to an algorithm and is not effective for this task, requiring more time for calculation.

3.2. Results and discussions

In order to estimate the effectiveness of the primal simplex, dual simplex and interior-point optimization techniques, 42 test cases having different properties for 12 generating units were considered.

The results of the calculation concerning the electrical and thermal power production that are the same for all cases are provided in Tables 12, 13.

Table 12. Electrical power production

Period	NPS volume, MWh	NPS electricity price, MWh	NEJ electricity output, MWh	Electricity unbalance, MWh
Winter week	262 349	39,45	256 935	5 414
Summer week	182 493	38,01	182 493	0

Source: Compiled by the author according to calculations made on the basis of data provided in Appendix 1 - 6

The electricity market volume is 30% more in winter week than in summer. It is caused by the climate conditions, such as outdoor temperature, humidity, atmospheric pressure, wind, precipitation, etc. The unbalance of electricity is 5,4 GWh, which shows that

Narva Power Plants could not be able to meet the requirenments concerning the NPS volume during winter week. The main reason of electricity unbalance is unavailability of power units due to repair, emergency or cleaning needs. As the NPS prices and volumes are usually lower in summer than in winter, the repairs and overhauls are planned mostly for this period. The average NPS price in Estonia decreased by 4% (-1,4 €/MWh) in the summer week as compared to the winter week in 2013.

Table 13. Thermal power production

Period	Thermal demand, MWh	Heat power price, MWh	NEJ heat output, MWh	Heat power unbalance, MWh
Winter week	14 389	21,03	14 389	0
Summer week	2 032	21,03	2 032	0

Source: Compiled by the author according to calculations made on the basis of data provided in Appendix 1 - 6

There is no unbalance of thermal power, and Narva Power Plants meet the requirenments concerning thermal demand of Narva City during the winter and summer week. The heat power price approved by the Competition Authority is stable during the winter and summer week. The diffrenece of heat power production in the winter and summer week is 86%, which is caused by the climate conditions (Table 13). The average outdoor temperature was -1,0 ºC in winter week and +18,9 ºC during the given summer week (Ilmategija Internetis, 2014).

Using the real data given in Appendix 3 - 6, the computational results of manufacturing variable, fixed, total generation costs and CPU time are given in Table 14, 15.

Table 14. Generation costs and CPU time for the winter week

Algorithm	Manufacturing variable costs, m €	Manufacturing fixed costs, m €	Generation costs, m €	CPU, sec
Interior-point	9,93	1,67	11,60	509
Dual simplex	9,96	1,67	11,63	515
Primal simplex	9,99	1,67	11,66	576

Source: Compiled by the author according to calculations made on the basis of data provided in Appendix 1 - 6

As seen from the results, the minimum variable costs achieved by interior-point algorithm were 9,93 million euros for the test cases of winter week. The total generation costs are 11,6 million euros using this algoritm. The results of generation costs of primal and dual simplex algorithm are very close to interior-point algorithm and are 9,99 and 9,96 million euros respectively. The results of the total generation costs of the reviewed algorithms have a marginal difference: 0,6% for primal simplex algorithm and 0,3% for dual simplex algorithm as compared to interior-point algorithm.

Table 15. Generation costs and CPU time for the summer week

Algorithm	Manufacturing variable costs, m €	Manufacturing fixed costs, m €	Generation costs, m €	CPU, sec
Interior-point	6,88	1,67	8,07	528
Dual simplex	6,88	1,67	8,07	529
Primal simplex	6,88	1,67	8,07	544

Source: Compiled by the author according to calculations made on the basis of data provided in Appendix 1 - 6

The generation costs are the same in all three cases and they are considered to be 8,07 million euros for the given summer week (Table 15). The difference of generation costs between the winter and summer week is 19%, which is caused by the smaller number of power units required. The number of units required to cover the NPS demand during the winter week is 11 and during the summer week it is 8.

CPU time or process time shows the amount of time that a central processing unit (CPU) uses for processing a computer program. The optimal solution of economic dispatch was to be within CPU time 509 seconds summing for winter and 528 seconds for summer week (Table 14, 15) using interior-point algorithm. The CPU time using primal and dual simplex method is 13% and 1% more respectively during the winter week, and 3% and 0,2% more during the summer week. It shows that the results of the interior-point algorithm provide the best performance as compared to primal and dual simplex optimization methods.

In particular, the manufacturing fixed costs are constant through the whole power range. The manufacturing fixed costs apply irrespective of the fact whether the power plant units were used during this day or not. The fixed costs have been defined as O&M and personnel costs in Table 2. The generation costs solution by the components for the winter week is plotted in Figure 18.

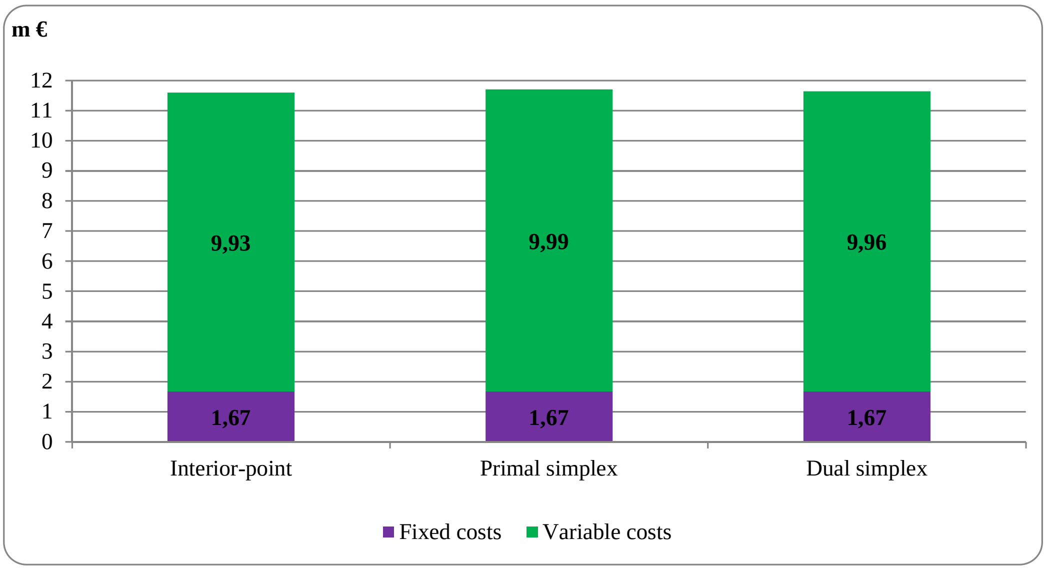

Figure 18. Generation costs by the components during the winter week

Source: Compiled according to the author's calculations

The generation costs solution by the components for the summer week is shown in Figure 19.

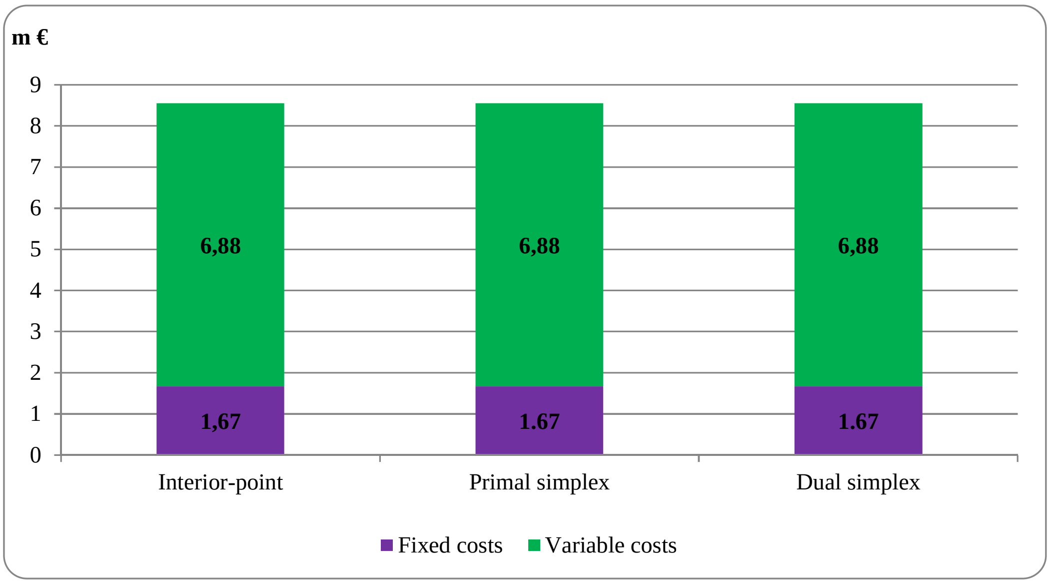

Figure 19. Generation costs by the components during the summer week

Source: Compiled according to the author's calculations

The manufacturing fixed costs composed approximately 17% of the total generation costs during the winter time and 24% of the total generation costs during summer. The manufacturing variable costs by the components for the winter week are provided in Figure 20.

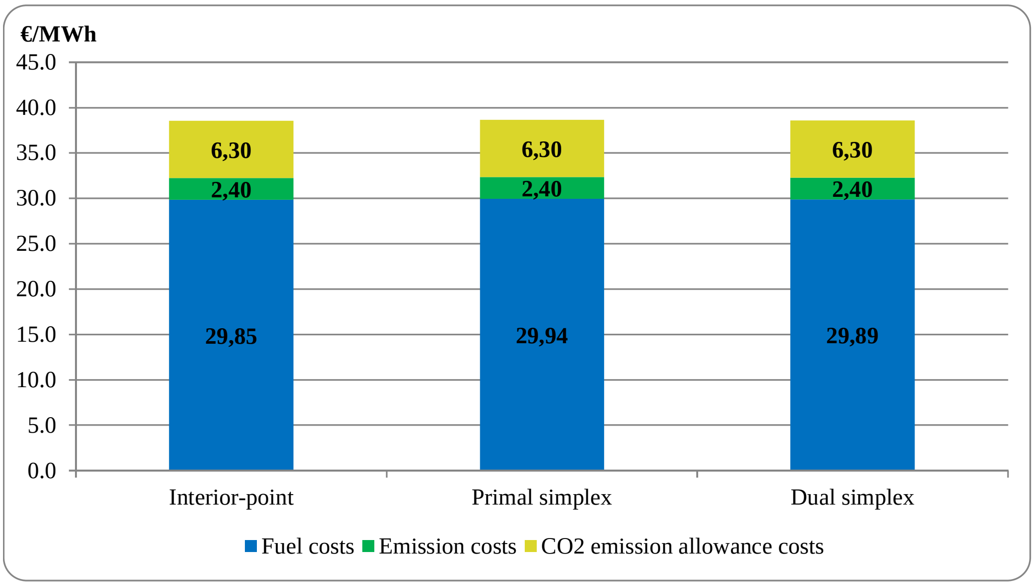

Figure 20. Manufacturing variable costs by the components during the winter week
Source: Compiled according to the author's calculations

The manufacturing variable costs by the components for the summer week are provided in Figure 21.

The manufacturing variable costs are not constant through the whole power range and consist of fuel costs, emissions and CO_2 emission allowance costs. The difference in variable costs is marginal and is considered to be 0,3% using primal simplex algorithm and 0,1% using dual simplex algorithm compared to interior-point algorithm.

The manufacturing variable costs composed 83% of the total generation costs during the winter time and 76% of the total generation costs during summer. The main component of the manufacturing variable costs is fuel cost that makes up 77% of the total generation costs. The emission costs are 23%, where CO_2 emissions allowance costs are 17%.

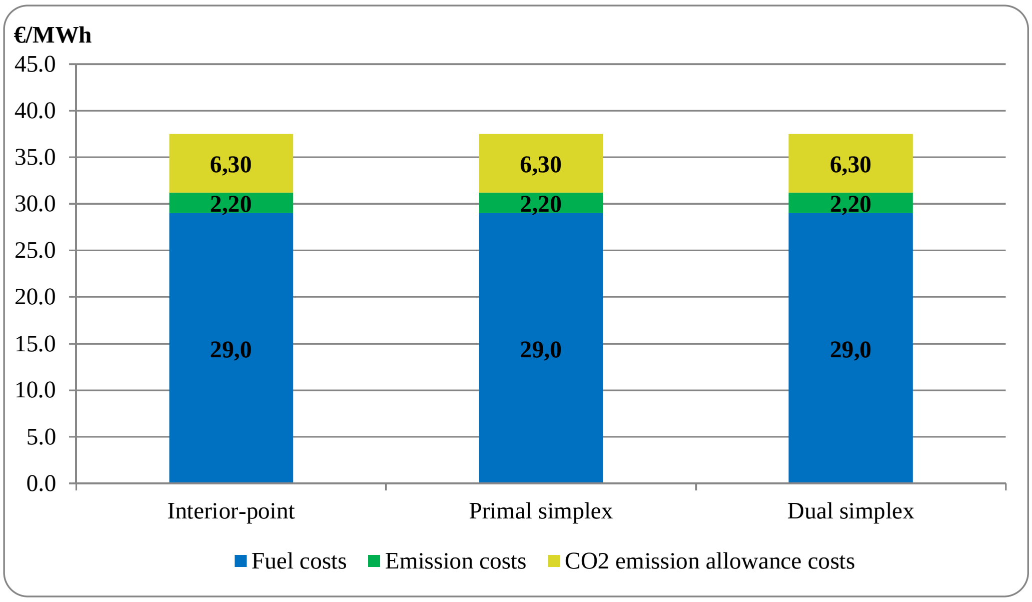

Figure 21. Manufacturing variable costs by the components during the summer week

Source: Compiled according to the author's calculations

Table 16 presents the results of the start-up number and costs calculation. Those costs are typically fuel-costs for warming up. The number of start-ups is different for the given algorithms, and as a consequence, the start-up costs are also different during the winter week. The primal simplex method during the winter week shows the worst result from three algorithms, and the start-up costs are 40% higher when using dual simplex method and 80% more compared to the interior-point algorithm.

Table 16. Number of the required units, number of start-ups and costs in the winter week

Algorithm	Number of required units	Number of start-ups	Start-up costs, m €
Interior-point	11	1	0,02
Dual simplex	11	2	0,06
Primal simplex	11	4	0,10

Source: Compiled according to the author's calculations

The results of the start-up costs during the summer week are the same for all three algorithms and they are provided in Table 17.

Table 17. Number of the required units, number of start-ups and costs in the summer week

Algorithm	Number of required units	Number of start-ups	Start-up costs, m €
Interior-point	8	1	0,04
Dual simplex	8	1	0,04
Primal simplex	8	1	0,04

Source: Compiled according to the author's calculations

During the tests, detailed outputs, such as primary energy consumption and costs, emissions amount and costs, were calculated. The numerical results of them using the interior-point algorithm as the best perfomed in the tests are presented in Table 18 and 19. The outputs results using other algorithms are close to the presented interior-point method's results and are not presented separately.

The main fuel used in Narva Power Plants for heat and electricity production is oil shale and it amounts to around 94% of total primary energy consumption in both winter and summer weeks.

Table 18. Primary energy consumption based on the interior-point algorithm

Period	Oil shale consumption, MWh	Retort gas consumption, MWh	Shale oil consumption, MWh	Total primary energy consumption, MWh
Winter week	767	45	1	813
Summer week	529	35	1	565
Total	1 296	80	2	1 378

Source: Compiled according to the author's calculations made on the basis of data provided in Appendix 1 - 6

The retort gas is used as auxiliary fuel and it makes up around 6% of the total primary energy consumption during the winter and summer week. As the shale oil is used only for start-ups, its consumption is very small and amounts only to 0,2% during the winter and summer weeks (Table 18, Figure 22).

The environmental issues in power generation play an important role. Minimizing the cost associated with those emissions could be considered in detail as a separate task due to the complexity of modelling.

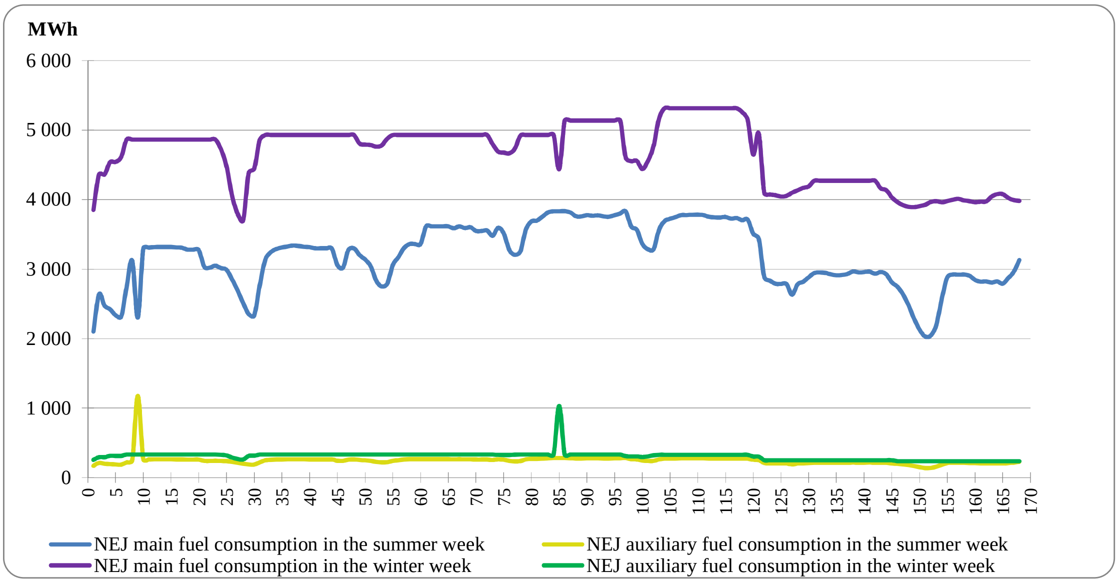

Figure 22. Primary energy consumption based on the interior-point algorithm

Source: Compiled according to the author's calculations

This problem is called an environmental dispatch problem and it includes emission concentration limit values as well as annual limits that are declared in the integrated environmental permits of the power plants. The emissions amounts of SO_x, NO_x, CO_2, fly ash, bottom ash and cooling water are presented in Table 19.

Table 19. Emissions amount based on the interior-point algorithm

Period	SO_x, t	NO_x, t	Fly ash, t	Bottom ash, t	CO_2 for heat production, t	CO_2 emission allowance, t	Cooling water, m3
Winter week	2 903	701	954	366	37	1 074	121 345
Summer week	1 454	447	224	244	5	723	74 772

Source: Compiled by the author according to calculations made on the basis of data provided in Appendix 1 - 6

In order to prove the possibility for minimization of the generation costs in a power plant by using the proposed ELD algorithm the units' optimal electrical power output after using the algorithm is provided. The optimal electrical power output for the winter week is presented in Figure 23.

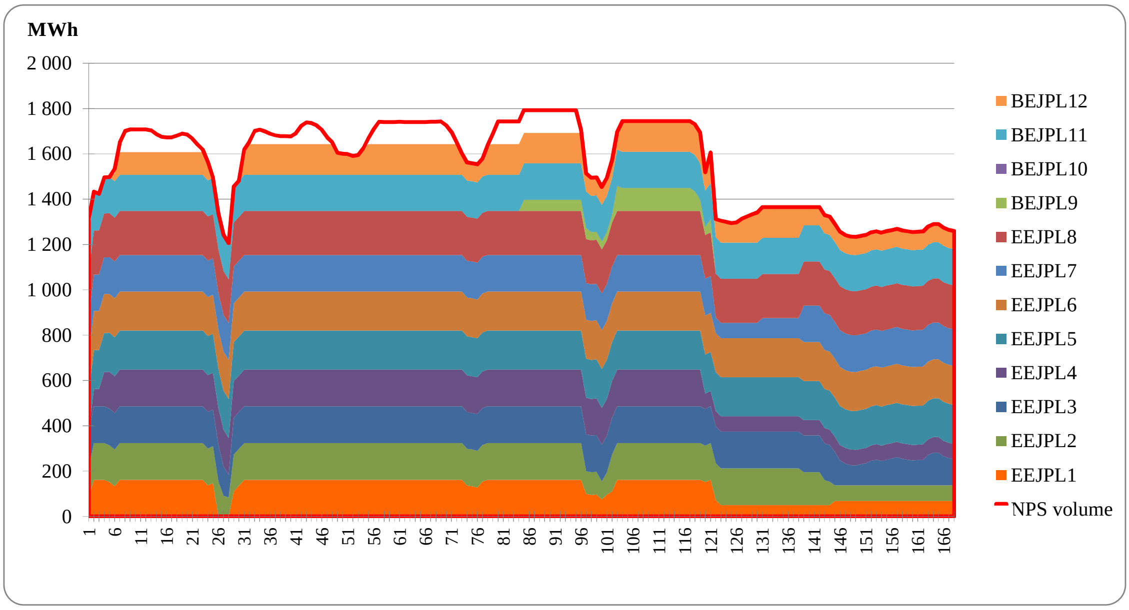

Figure 23. The optimal electrical power output of the power units in the winter week

Source: Compiled according to the author’s calculations

The optimal electrical power output for the summer week is presented in Figure 24.

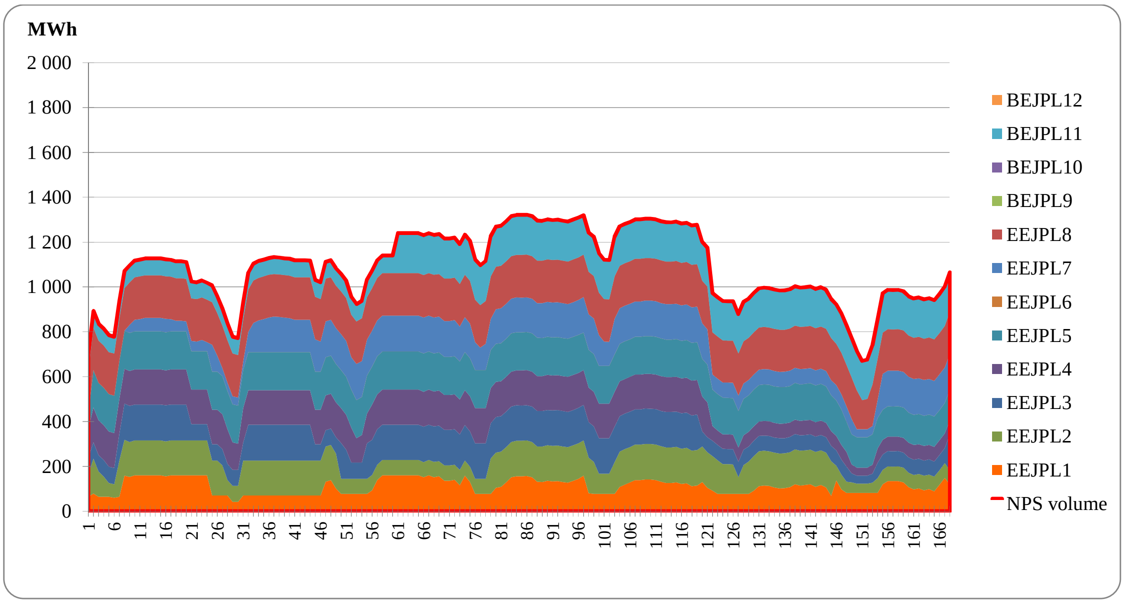

Figure 24. The optimal electrical power output of the power units in the summer week

Source: Compiled according to the author’s calculations

As the results of the optimal electrical power outputs using other algorthms are close to the results of the interior-point method, therefore they are not presented separately.

In order to estimate the effectiveness of optimization techniques and compare the difference in generation costs of the power plants before and after the implementation of the economic dispatch and unit commitment, the hourly manufacturing variable costs are calculated. The manufacturing fixed costs of the power plants remain stable during the estimated periods.

The variable costs of Narva Power Plants, Estonian and Baltic Power Plants in the winter week are presented hour by hour in Figure 25. The efficiency of optimization in load distribution and unit commitment problems in those power plants decrease the manufacturing variable costs on average by 1 million euros or 9% during the week in winter.

As it shown in the figure below, the impact of Estonian and Baltic Power Plant composed 10% and 8% respectively and based mainly on the savings due to the smaller number of start-ups and more economic distribution of the load between the power units.

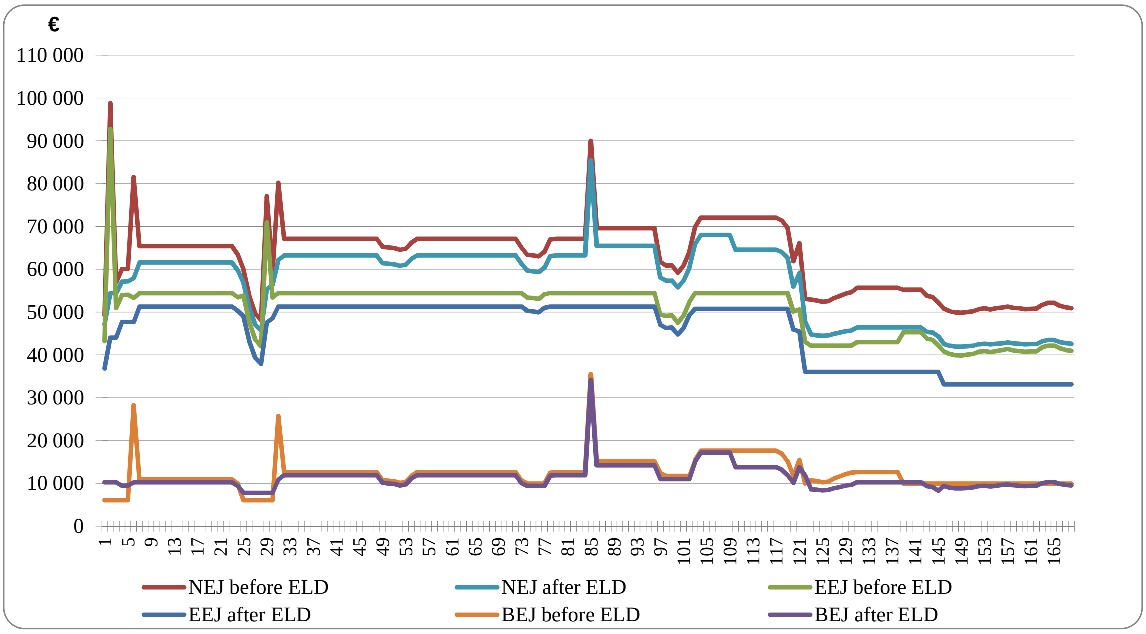

Figure 25. Manufacturing variable costs of the power plants in the winter week
Source: Compiled according to the author's calculations

The number of required units is 11 for the winter week and the number of start-ups decreased from 5 to 1 number. It brings the reduction of start-up costs by 80% after the implementation of ELD algorithm.

The impact of implementation of economic load dispatch during the summer week in Narva Power Plants is presented in Figure 26.

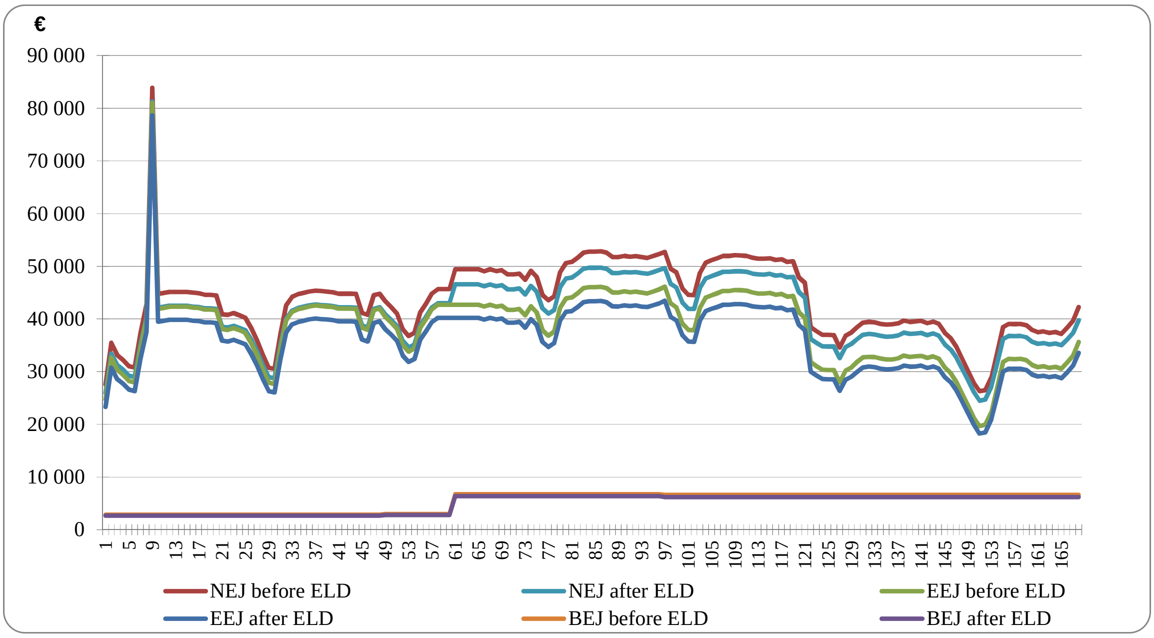

Figure 26. Manufacturing variable costs of the power plants in the summer week
Source: Compiled according to the author's calculations

During the summer week the impact of economic dispatch in Narva Power Plants is around 0,4 million euros or 6% due to more economic distribution of the load between the power units. The impact of Estonian and Baltic Power Plant is almost the same and composes around 6% for each power plant. The share of electricity produced in Estonian Power Plant is around 90% from total generation of Narva Power Plants during summer period. The major impact on the economic distribution of the load between the power units is in Estonian Power Plant. The number of required units is 8 for the summer week and the number of start-ups is 1 for all cases.

CONCLUSIONS

The economic load dispatch and the unit commitment are both essential problems to be solved in order to supply high-quality electric power to the customers in a secured and economic manner. These two problems have been widely studied in case of the regulated electricity market. Nevertheless, deregulation of the electricity market, strict technological and environmental requirements must be taken into account.

There are several techniques used for optimizing the economic dispatch and unit commitment schedules. Solving the economic dispatch problem by using primal simplex, dual simplex and interior-point method are discussed in the thesis. The algorithm of economic dispatch for the existing power generating units of Narva Power Plants is proposed. A number of important factors, such as minimum and maximum available capacity, the electricity market price and volume, technical requirements, emission limitations and optimality conditions are determined.

The day-ahead economic dispatch optimization has been formulated and implemented in the mathematical programming solver GAMS/Cplex. 42 tests have been carried out with different properties for determining the minimum generation costs of the generating power units over a time period. The electricity and thermal power production, unbalance of energy, generation costs by the components, CPU time, results of the start-up costs calculation, primary energy consumption and emissions amounts are calculated. The outcomes are presented as the calculations of one typical week in winter and summer.

The results of used optimization techniques have a marginal difference; the optimization techniques are indicative for day-ahead economic dispatch development and could be useful for a precise performance evaluation of the power plant operation. The outcomes show that the results of interior-point algorithm provide the best performance as compared to the optimization methods of primal and dual simplex. The optimal solution of day-ahead economic dispatch was within 75 seconds for one day, when using interior-point algorithm. The using interior-point algorithm is on average 4% faster than primal and dual simplex optimization. The advantage of using these algorithms is that they allow getting reliable results by using comparatively low input data within a reasonable period of time.

The optimal electrical power outputs for the winter and summer week are presented. The difference between manufacturing variable costs before and after using economic dispatch algorithm to prove the possibility for minimization of the generation costs in the power plant is provided. The efficiency of optimization in load distribution and unit commitment problems in Narva Power Plants could decrease the manufacturing variable costs up to 9% to the power producer in a week time period. The main reasons are more economical distribution of load between the power units and savings in start-up costs.

The proposed algorithm may serve as a basis for more accurate economic dispatch and unit commitment model of Narva Power Plants. The improved economic dispatch model, where the simplifications have been taken into account, could generate short-term as well as long-term business value to the company without any additional investments and costs. The data presented in this work will be helpful for the management, energy planners, researchers and analysts of Eesti Energia AS Narva Power Plants.

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APPENDICES

Appendix 1. Input data

Symbol	Unit	Description
C_e^{NPS}	€/MWh	NordPoolSpot electricity price
P_e^{NPS}	MWh	NordPoolSpot electricity production volume
C_{CO2}	€/t	CO_2 allowance price
C_h	€/MWh	Heat sell price (21,03 €/MWh[2])
$P_u^{\max}$	MW	Power unit's maximum generation electrical capacity
$P_u^{\min}$	MW	Power unit's minimum generation electrical capacity
P_u^{aux}	%	Power unit's auxiliary power
$Q_u^{\max}$	MW	Power unit's maximum generation thermal load
$Q_u^{\min}$	MW	Power unit's minimum generation thermal load
Q_u^{tot}	MW	Cogeneration power unit's total heat and electricity capacity
B_u^f	MWh	Fuel consumption characteristics of fuel type
$B_u^{RG,\lim}$	%	Retort gas usage limit (constant 7% for EEJ power units)
H_f	MJ/kg, MJ/1000 m^3	Heat value of fuel type f
C_f	€/t, €/1000 m^3	Price for fuel type f
C_w	€ /t	Emissions tariffs for emissioon type w
$w_{e,w}^f$	t/MWh_f	Specific emissions type w for electricity production for fuel f
$w_{h,w}^f$	t/MWh_f	Specific emissions type w for heat production for fuel f
k_u^p	-	Placement coefficient for power unit u
k_u^l	-	Landfill coefficient for power unit u
C_u^{SU}	€	Power units start-up costs
R_u	MW/min	Ramp rate (constant 2,0 MW/min)
$T_{must-run}^{\min}$	h	Minimum amount of time the generator must run ($T_{must-run}^{\min}$ = 48h)
$T_{stay-off}^{\min}$	h	Minimum amount of time the generator must stay off once turned off ($T_{stay-off}^{\min}$ = 48h)

[2] According to the District Heating Act § 9 paragraph 4 the thermal heat producers could sell the heat at a price that does not exceed the Competition Authority approved limit. The heat production prices limits approved by Competition Authority could found here: http://www.konkurentsiamet.ee/?id=18308

Appendix 1 continued

Symbol	Unit	Description
$m_u^{\max}$	number	Maximum number of start-ups during the planned period i ($m_u^{\max}$ =60 numbers per year)
$C_u^{O\&M}$	€/MWh	Power unit's O&M costs
C_u^{P}	€/MWh	Personnel costs

Source: Prepared by the author

Appendix 2. Output data

Symbol	Unit	Description
$P_{e,tot}$	MWh	Power plant electricity output total
P_u^e	MWh	Power plant electricity output of each power unit
n_u	nr	Number of power units required
$P_{e,S-D}$	MWh	Unbalance of electricity production
Q_{tot}	MWh	Power plant heat output total
$W_{u,w}$	t	Power units emission's type w amount for power unit u
B_{tot}	MWh	Primary energy consumption total
m_u	nr	Planned number of start-ups during the planned period t
C_u^B	€	Power units primary energy costs
C_u^w	€	Power units environmental impact costs
C_u^{FC}	€	Power units manufacturing fixed costs
C_u^{VC}	€	Power units manufacturing variable costs
C_u^{GC}	€	Power units generation costs
C_{tot}^{FC}	€	Total units manufacturing fixed costs
C_{tot}^{VC}	€	Total manufacturing variable costs
C_{tot}^{GC}	€	Total generation costs
CPU	sec	Central processor unit time

Source: Prepared by the author

Appendix 3. Fuel cost characterictics

Electrical capacity, MW	Fuel cost EEJ PC, €/h	Fuel cost BEJ PC, €/h	Fuel cost EEJ, BEJ CFBC, €/h
50	4 997	5 817	4 502
80	4 724	5 288	4 236
110	4 543	5 091	4 063
140	4 374	4 950	3 893
180	4 191	-	3 742

Source: Compiled according to the author’s estimation

Appendix 4. Incremental fuel cost characteristics

Electrical capacity, MW	Incremental fuel cost EEJ PC, €/MWh	Incremental fuel cost BEJ PC, €/MWh	Incremental fuel cost EEJ, BEJ CFBC, €/MWh
50	99,9	116,3	90,0
80	59,1	66,1	52,9
110	41,3	46,3	36,9
140	31,2	35,4	27,8
180	23,3	-	20,8

Source: Compiled according to the author's estimation

Appendix 5. Minimum electrical and heat power

Day	EET Hour	NEJ MWh	EEJ MWh	BEJ MWh	EEJPL1 MWh	EEJPL2 MWh	EEJPL3 MWh	EEJPL4 MWh	EEJPL5 MWh	EEJPL6 MWh	EEJPL7 MWh	EEJPL8 MWh	BEJPL9 MWh	BEJPL10 MWh	BEJPL11 MWh	BEJPL12 MWh	BEJPL11 Q MWh
4.02.2013	00-01	762	551	211	82	46	36	72	45	135	36	99	36	0	130	45	0
4.02.2013	01-02	834	623	211	82	82	36	72	135	81	36	99	36	0	130	45	0
4.02.2013	02-03	834	623	211	82	82	36	72	135	81	36	99	36	0	130	45	0
4.02.2013	03-04	870	659	211	82	82	72	72	135	81	36	99	36	0	130	45	0
4.02.2013	04-05	870	659	211	82	82	72	72	135	81	36	99	36	0	130	45	0
4.02.2013	05-06	870	659	211	82	82	72	72	135	81	36	99	36	0	130	45	0
4.02.2013	06-07	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	07-08	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	08-09	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	09-10	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	10-11	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	11-12	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	12-13	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	13-14	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	14-15	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	15-16	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	16-17	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	17-18	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	18-19	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	19-20	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	20-21	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	21-22	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	22-23	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
4.02.2013	23-24	906	695	211	82	82	72	72	135	81	72	99	36	0	130	45	0
5.02.2013	00-01	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	01-02	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	02-03	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	03-04	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	04-05	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	05-06	870	695	175	82	82	72	72	135	81	72	99	0	0	130	45	0
5.02.2013	06-07	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	07-08	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	08-09	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	09-10	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	10-11	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	11-12	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	12-13	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	13-14	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	14-15	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	15-16	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	16-17	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	17-18	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	18-19	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	19-20	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	20-21	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	21-22	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	22-23	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
5.02.2013	23-24	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	00-01	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	01-02	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	02-03	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	03-04	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	04-05	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	05-06	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	06-07	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	07-08	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	08-09	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	09-10	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	10-11	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	11-12	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	12-13	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	13-14	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	14-15	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	15-16	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	16-17	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	17-18	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	18-19	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	19-20	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	20-21	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	21-22	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	22-23	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
6.02.2013	23-24	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	00-01	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	01-02	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	02-03	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	03-04	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	04-05	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	05-06	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	06-07	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	07-08	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	08-09	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	09-10	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	10-11	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0
7.02.2013	11-12	905	695	210	82	82	72	72	135	81	72	99	0	0	130	80	0

Appendix 5 continued

7.02.2013	12-13	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	13-14	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	14-15	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	15-16	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	16-17	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	17-18	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	18-19	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	19-20	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	20-21	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	21-22	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	22-23	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
7.02.2013	23-24	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	00-01	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	01-02	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	02-03	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	03-04	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	04-05	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	05-06	941	695	246	82	82	72	72	135	81	72	99	36	0	130	80	0
8.02.2013	06-07	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	07-08	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	08-09	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	09-10	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	10-11	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	11-12	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	12-13	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	13-14	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	14-15	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	15-16	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	16-17	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	17-18	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	18-19	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	19-20	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	20-21	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	21-22	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	22-23	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
8.02.2013	23-24	975	695	280	82	82	72	72	135	81	72	99	70	0	130	80	0
9.02.2013	00-01	939	659	280	82	82	72	36	135	81	72	99	70	0	130	80	0
9.02.2013	01-02	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	02-03	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	03-04	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	04-05	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	05-06	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	06-07	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	07-08	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	08-09	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	09-10	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	10-11	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	11-12	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	12-13	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	13-14	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	14-15	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	15-16	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	16-17	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	17-18	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	18-19	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	19-20	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	20-21	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	21-22	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	22-23	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
9.02.2013	23-24	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
10.02.2013	00-01	831	551	280	46	46	72	36	135	81	36	99	70	0	130	80	0
10.02.2013	01-02	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	02-03	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	03-04	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	04-05	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	05-06	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	06-07	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	07-08	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	08-09	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	09-10	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	10-11	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	11-12	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	12-13	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	13-14	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	14-15	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	15-16	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	16-17	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	17-18	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	18-19	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	19-20	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	20-21	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	21-22	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	22-23	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0
10.02.2013	23-24	804	524	280	46	46	135	36	45	45	72	99	70	0	130	80	0

Source: Prepared by the author

Appendix 6. Maximum electrical and heat power

	EET	NEJ	EEJ	BEJ	EEJPL1	EEJPL2	EEJPL3	EEJPL4	EEJPL5	EEJPL6	EEJPL7	EEJPL8	BEJPL9	BEJPL10	BEJPL11	BEJPL12	BEJ 11 Q
Day	Hour	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh
4.02.2013	00-01	1 235	975	260	162	69	69	162	78	172	69	194	50	0	160	50	120
4.02.2013	01-02	1 422	1 162	260	162	162	69	162	172	172	69	194	50	0	160	50	120
4.02.2013	02-03	1 422	1 162	260	162	162	69	162	172	172	69	194	50	0	160	50	120
4.02.2013	03-04	1 515	1 255	260	162	162	162	162	172	172	69	194	50	0	160	50	120
4.02.2013	04-05	1 515	1 255	260	162	162	162	162	172	172	69	194	50	0	160	50	120
4.02.2013	05-06	1 515	1 255	260	162	162	162	162	172	172	69	194	50	0	160	50	120
4.02.2013	06-07	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	07-08	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	08-09	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	09-10	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	10-11	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	11-12	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	12-13	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	13-14	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	14-15	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	15-16	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	16-17	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	17-18	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	18-19	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	19-20	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	20-21	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	21-22	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	22-23	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
4.02.2013	23-24	1 608	1 348	260	162	162	162	162	172	172	162	194	50	0	160	50	120
5.02.2013	00-01	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	01-02	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	02-03	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	03-04	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	04-05	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	05-06	1 558	1 348	210	162	162	162	162	172	172	162	194	0	0	160	50	120
5.02.2013	06-07	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	07-08	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	08-09	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	09-10	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	10-11	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	11-12	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	12-13	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	13-14	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	14-15	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	15-16	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	16-17	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	17-18	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	18-19	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	19-20	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	20-21	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	21-22	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	22-23	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
5.02.2013	23-24	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	00-01	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	01-02	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	02-03	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	03-04	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	04-05	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	05-06	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	06-07	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	07-08	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	08-09	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	09-10	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	10-11	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	11-12	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	12-13	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	13-14	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	14-15	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	15-16	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	16-17	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	17-18	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	18-19	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	19-20	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	20-21	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	21-22	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	22-23	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
6.02.2013	23-24	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	00-01	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	01-02	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	02-03	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	03-04	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	04-05	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	05-06	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	06-07	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	07-08	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	08-09	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	09-10	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	10-11	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120
7.02.2013	11-12	1 643	1 348	295	162	162	162	162	172	172	162	194	0	0	160	135	120

Appendix 6 continued

7.02.2013	12-13	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	13-14	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	14-15	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	15-16	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	16-17	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	17-18	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	18-19	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	19-20	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	20-21	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	21-22	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	22-23	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
7.02.2013	23-24	1 693	1 348	345	162	162	162	162	172	172	162	194	50	0	160	135	120
8.02.2013	00-01	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	01-02	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	02-03	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	03-04	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	04-05	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	05-06	1 680	1 335	345	162	159	162	162	162	172	162	194	50	0	160	135	120
8.02.2013	06-07	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	07-08	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	08-09	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	09-10	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	10-11	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	11-12	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	12-13	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	13-14	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	14-15	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	15-16	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	16-17	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	17-18	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	18-19	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	19-20	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	20-21	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	21-22	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	22-23	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
8.02.2013	23-24	1 745	1 335	410	162	159	162	162	162	172	162	194	115	0	160	135	120
9.02.2013	00-01	1 626	1 216	410	130	159	162	68	172	172	159	194	115	0	160	135	120
9.02.2013	01-02	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	02-03	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	03-04	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	04-05	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	05-06	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	06-07	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	07-08	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	08-09	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	09-10	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	10-11	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	11-12	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	12-13	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	13-14	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	14-15	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	15-16	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	16-17	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	17-18	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	18-19	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	19-20	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	20-21	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	21-22	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	22-23	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
9.02.2013	23-24	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
10.02.2013	00-01	1 366	956	410	50	69	162	68	172	172	69	194	115	0	160	135	120
10.02.2013	01-02	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	02-03	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	03-04	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	04-05	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	05-06	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	06-07	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	07-08	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	08-09	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	09-10	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	10-11	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	11-12	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	12-13	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	13-14	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	14-15	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	15-16	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	16-17	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	17-18	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	18-19	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	19-20	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	20-21	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	21-22	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	22-23	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120
10.02.2013	23-24	1 290	880	410	69	69	162	68	78	78	162	194	115	0	160	135	120

Source: Prepared by the author