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Power system optimization

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Abstract

Long-term gas purchase contracts usually determine delivery and payment for gas on the regular hourly basis, independently of demand side consumption. In order to use fuel gas in an economically viable way, optimization of gas distribution for covering consumption must be introduced. In this paper, a mathematical model of the electric utility system which is used for optimization of gas distribution over electric generators is presented. The utility system comprises installed capacity of 1500 MW of thermal power plants, 400 MW of combined heat and power plants, 330 MW of a nuclear power plant and 1600 MW of hydro power plants. Based on known demand curve the optimization model selects plants according to the prescribed criteria. Firstly it engages run-of-river hydro plants, then the public cogeneration plants, the nuclear plant and thermal power plants. Storage hydro plants are used for covering peak load consumption. In case of shortage of installed capacity, the cross-border purchase is allowed. Usage of dual fuel equipment (gas–oil), which is available in some thermal plants, is also controlled by the optimization procedure. It is shown that by using such a model it is possible to properly plan the amount of fuel gas which will be contracted. The contracted amount can easily be distributed over generators efficiently and without losses (no breaks in delivery). The model helps in optimizing of fuel gas–oil ratio for plants with combined burners and enables planning of power plants overhauls over a year in a viable and efficient way.

Keywords: Mathematical modeling; Power system; Optimization

1. Introduction

World energy systems today are highly dependent on fossil fuels. Fossil fuels share in world energy production is more than 85% and in electricity generation more than 60%. Unfortunately, fossil fuels harm the global ecosystem by emitting noxious gases and toxic substances, causing green-house effect. In order to achieve sustainable development it would be necessary to reduce the dynamics of pollution of environment by reducing emissions of noxious gases, and to create such politically induced energy mix strategies that would focus on increasing the portion of renewable, or at least less harmful energy sources, in the global energy mix. Namely, sustainable development assumes a manner of using fossil fuels and other non-renewable natural resources so as to extend their usefulness for future generations and to give time to new and more efficient energy technologies to develop. Countries that own, produce or export fossil fuels, as well as developing countries, cannot easily turn their back to use of fossil fuels and reprogram their energy systems towards costly and unstable renewable energy sources, at least not for their base-load power needs. It is generally accepted that fossil fuels will remain the dominant primary energy source in the decades to come [2], with an increase in share for natural gas, the lowest fossil fuel greenhouse gas emitter.

Over the past decade importance of natural gas as fuel for power systems has been tremendously increased. Apart from awareness for environmental protection, very successful development of the gas turbine technologies, that mainly use natural gas firing systems, has led to this achievement. By combining gas turbine and steam turbine processes in a unique plant it is possible to achieve efficiency of fuel energy conversion into electricity as high as 56–58%.

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Croatian electric utility HEP has also introduced combined cycle technology into its power generation system. It has a 210 MW_e combined cycle cogeneration plant and two gas turbine blocs (25 MW_e each) with heat recovery boilers for industrial steam production and district heating [4]. In the nearest future a new 100 MW_e combined cycle unit is planned to be built. All these units are solely using natural gas as fuel.

Other thermal power plants of HEP can fire simultaneously natural gas and heavy fuel oil, except Nuclear power plant Krsko, Thermal power plant Plomin which uses bituminous coal and Thermal power plant Rijeka which can fire only heavy fuel oil. Approximately half of the electricity generating capacity of HEP consists of hydro power plants.

For the purpose of covering its natural gas needs, HEP has a long-term gas purchase contract with INA, Croatian oil and gas utility. The contract determines delivery and payment for gas on the regular hourly basis, independently of demand side consumption. Since HEP cannot store natural gas, it must use it promptly and is naturally interested in using it as efficiently as possible.

In this paper, a mathematical model for simulation of HEP power system operation with the option for optimization of natural gas dispatching to various generators is presented. NPP Krsko and run-of-river plants have been considered with invariable load, while all other plant loads were governed by optimization algorithm. The cogeneration plants have priority in dispatching. Storage hydro plants are used for covering peak load consumption. In case of shortage of installed capacity, the cross-border purchase is allowed. Usage of dual fuel equipment (gas–oil), which is available in some thermal plants, is also controlled by the optimization procedure.

2. Mathematical model

The annual electricity consumption is the boundary condition for the model of the electricity production system. Consumption of the year is divided into monthly consumptions and each month is represented by the characteristic day which is the arithmetic mean of all the days in the month. In this paper instead of 12 months, only the 3 months: August, October and December are shown as representative for the three seasons: summer, spring/autumn and winter.

District heating includes the following power plants:

- TPP TETO Zagreb,
- TPP ELTO Zagreb, and
- TPP TETO Osijek.

The model of the electric utility system comprises also hydro run-of-river and storage power plants. There exists a considerable difference in electricity production between dry and wet years. Data for the two extremes are inserted into the program. The degree of the year rainfall amount is chosen as 50%, what represents the arithmetic mean between rainfall amounts for the dry and wet year.

Prescribed fuel prices are as follows:

- coal—2.6 €/GJ,
- natural gas—4.8 €/GJ, and
- heavy oil—5 €/GJ.

Natural gas contracted amount is 87,500 m^3/h. It can not be increased, but must be fully paid even at lower consumption rates.

The import electricity price is actually not known due to market fluctuations. However, it is higher on the spot market than the cost of electricity produced by any local plant. Therefore in order to facilitate the optimization procedure, a value >0.05 €/kWh is considered to be appropriate. In this way, electricity is imported only when the local production is lower than the demand (Tables 1–3).

The mathematical model is written in MS Excel Visual Basic language with the MS Excel Solver as the optimization tool. It is based on the Generalized Reduced Gradient (GRG2) non-linear optimization method [1,2]. It minimizes thermal power plant fuel expenses by changing hourly electric power load factor for the following power plants (Tables 1–3):

- TPP Plomin1,
- TPP Plomin2,
- TPP Sisak1,
- TPP Sisak2,
- TPP Rijeka,
- TPP TETO Zagreb,
- TPP TETO Osijek,
- TPP Jertovec,
- Imported electric energy.

Capital costs, although not negligible, are not included in the target function. Namely, the capital cost of a single unit in competition with other units will push it to the limit in order to increase operation hours and minimize the capital cost per hour. But within the system, which sum of annual operation hours cannot be extended, capital costs do not affect the system performance. The goal is to obtain the optimal performance of the system (relative costs are important) and not to determine the production cost (absolute costs are important) (Fig. 1).

Inclusion of district heat production in the optimization algorithm of electricity production makes the task much more complex. For this reason distribution of the district heat over generating units within TETO Zagreb, ELTO Zagreb and TETO Osijek is achieved by activating firstly the most efficient component and then less efficient component in hierarchic order. According to our investigation, deviation from the heat production optimized solution lies within 2% [3].

Table 1
Thermal power plants technical information [5]

Thermal and nuclear power plants	Fuel	Electrical power (MW_e)	Technical minimum (MW_e)	Power loss factor (MW_e/MW_t)[a]	Power to heat ratio (MW_e/MW_t)	Efficiency (%)	District heat power	
							Max (MW_t)	Min (MW_t)
TPP Plomin1	Coal	98	60			29.00		
TPP Plomin2	Coal	192	90			36.92		
TPP Rijeka	Oil	303	90			37.89		
TPP Sisak1	Oil/gas	198	80			36.73		
TPP Sisak2	Oil/gas	198	80			36.73		
TPP TETO Zagreb								
Block3 TETO	Oil/gas	110	60	0.173	0.377	32.00	200.0	0.0
$CCGT_{TETO}$	Gas	208	25	0.222	1.200	50.00	140.0	0.0
TPP ELTO Zagreb								
$TA30_{ELTO}$	Oil/gas	30	5.5		0.290	21.46	103.4	19.0
$TA12_{ELTO}$	Oil/gas	12	3.5		0.337	17.33	35.6	10.4
GTELTO	Gas	50.4	2		0.466	26.20	108.2	4.3
TPP Jertovec	Gas	83	8			24.50		
TPP TETO Osijek								
PTE_{Osijek}	Gas	48	2		0.444	24.44	108.1	0.0
$TA45_{Osijek}$	Oil/gas	45	10	0.162	0.347	29.27	120.0	0.0
NPP Krško	Nuclear	330	16					

[a]The power loss due to extraction of steam.

Table 2
Run-of-river hydro power plants technical information [5]

Run-of-river hydro power plants	Power (MW)	Capacity (GWh/yr)
HPP Rijeka	36.0	97.0
HPP Miljacka	24.0	121.6
HPP Golubić	6.5	28.7
HPP Gojak	48.0	199.5
HPP Varaždin	86.0	489.2
HPP Čakovec	80.6	385.3
HPP Dubrava	80.6	358.0
HPP Ozalj	5.0	25.0
Small HPP (7)	11.6	52.0
Biological minimum HPP (3)	3.4	18.0
Total	381.7	1.774.3

Table 3
Storage hydro power plants technical information [5]

Storage hydro power plants	Power (MW)	Capacity (GWh/yr)
HPP Senj	216.0	981.0
HPP Sklope	22.5	78.3
HPP Vinodol	84.0	130.7
HPP Fužine	4.0	—
HPP Peruča	41.6	122.5
HPP Orlovac	237.0	374.6
HPP Buško Blato	11.3	—
HPP Zakučac	486.0	1.610.2
HPP Velebit	276.0	334.7
HPP Dubrovnik	108.0	620.0
HPP Đale	40.8	133.2
HPP Kraljevac	59.2	42.2
Total	1.5864	4.4274

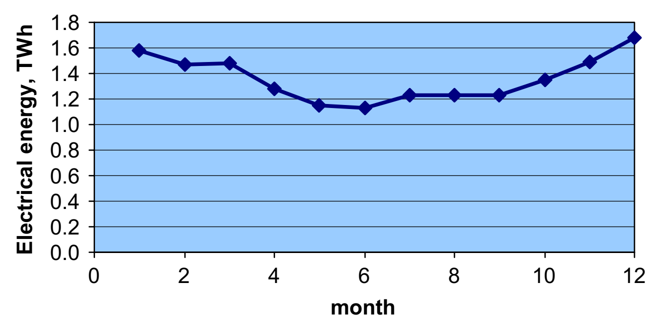

Fig. 1. Consumed electrical energy in the year 2004 [5].

Constraints for the optimization problem are the following:

- sum of current electrical production for all power plants must be equal to the current electrical energy consumption;
- total gas consumption in all plants must not exceed 87,500 m^3/h;
- power plant electrical power must always be within the range of its technical minimum and maximum; and
- oil/gas ratio must be within the range of 0% and 100%.

Fuel consumption in a particular power plant can be determined by as follows:

$$m_f = \frac{P}{\eta H_d} 3600\,(\mathrm{m}^3/\mathrm{h}) \text{ or } (\mathrm{kg/h}), \tag{1}$$

Table 4
Power plant overhauls

Thermal and nuclear power plants	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
TPP Plomin 1	1	1	1	0	1	1	1	1	1	1	1	1
TPP Plomin 2	1	1	1	0	0	1	1	1	1	1	1	1
TPP Rijeka	1	1	0	0	0	0	1	1	1	0	0	0
TPP Sisak 1	1	1	1	0	0	0	1	1	1	1	0	0
TPP Sisak 2	1	1	1	0	1	1	1	1	1	1	0	0
TPP TETO Zagreb												
Block3 TETO	1	1	1	0	0	0	0	1	0	1	1	1
$CCGT_{TETO}$	1	1	1	1	1	1	1	1	1	0	1	1
TPP ELTO Zagreb												
$TA30_{ELTO}$	1	1	1	1	1	1	0	0	0	1	1	1
$TA12_{ELTO}$	1	1	1	0	0	0	0	0	0	0	0	0
GT_{ELTO}	1	1	1	1	1	1	1	1	1	1	1	1
TPP jertovec	0	0	1	1	0	0	1	1	1	0	1	1
TPP TETO Osijek												
PTE_{Osijek}	0	0	1	0	1	1	0	0	0	0	0	0
$TA45_{Osijek}$	1	1	1	1	1	0	0	0	0	1	1	1
NPP Krško	1	1	1	1	0	1	1	1	1	1	1	1

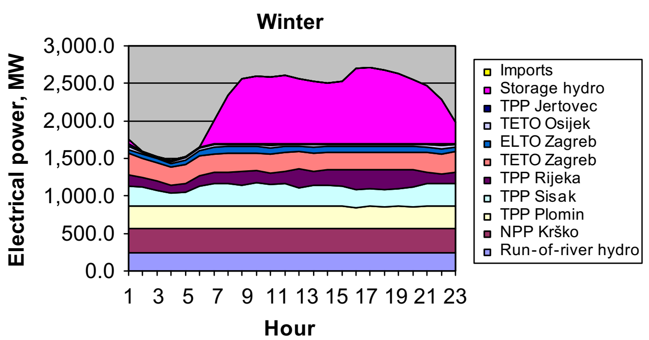

Fig. 2. Distribution of electric energy generation over power plants in winter.

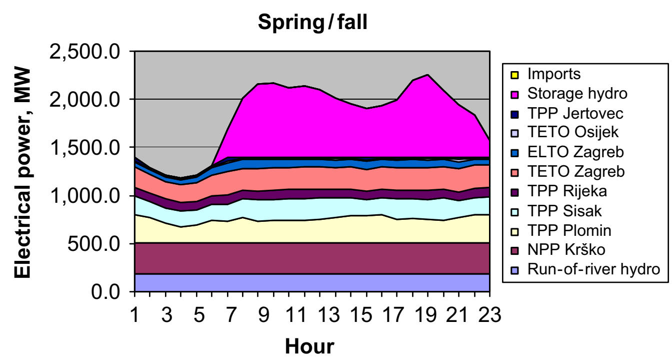

Fig. 3. Distribution of electric energy generation over power plants in spring/fall.

where m_f is the fuel consumption in m^3/h or kg/h, P the electrical power in MW, η the power plant efficiency and H_d the lower heating value in MJ/m^3 or MJ/kg.

3. Results

Chosen power plant operating scenario is shown in Table 4. Most plant overhauls are scheduled during summer time.

Distributions of electric energy generation over plants for each representative day of a season are shown in Figs. 2–4.

Minimum electric power consumption occurs in summer while maximum is met in winter. In the chosen scenario there is no need for import of electric energy due to sufficient amount of water and relatively low electrical energy consumption relative to the installed capacity.

Electric energy generation depending on fuel type for each season is displayed in Figs. 5–7.

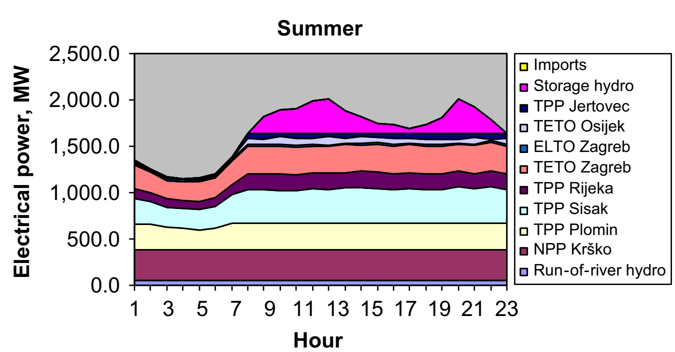

Fig. 4. Distribution of electric energy generation over power plants in summer.

Substantial reduction of hydro energy share can be noticed in summer due to reduced amount of water. Because of limited gas amount and too expensive imported

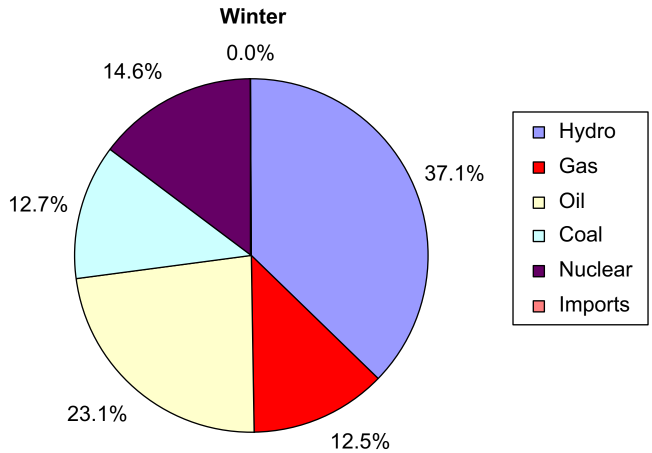

Fig. 5. Electric energy generation depending on fuel type in winter.

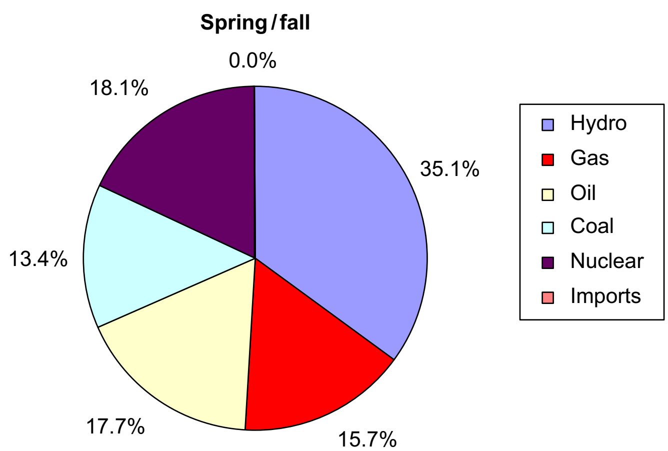

Fig. 6. Electric energy generation depending on fuel type in spring/fall.

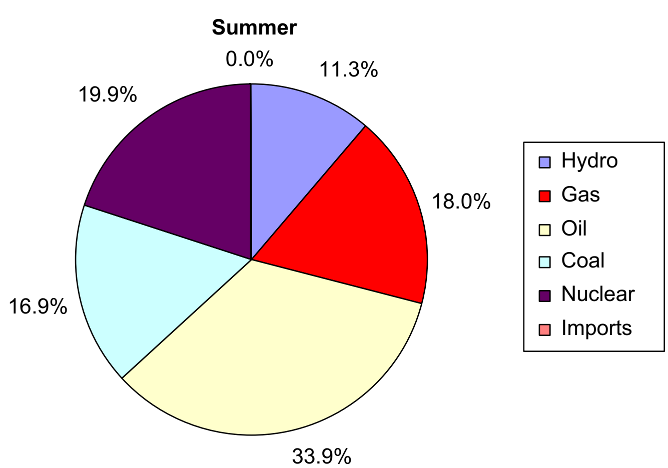

Fig. 7. Electric energy generation depending on fuel type in summer.

electricity, hydro energy share is mostly supplemented with oil share.

Optimized distribution of gas fuel over power plants for each season is displayed in Figs. 8–10.

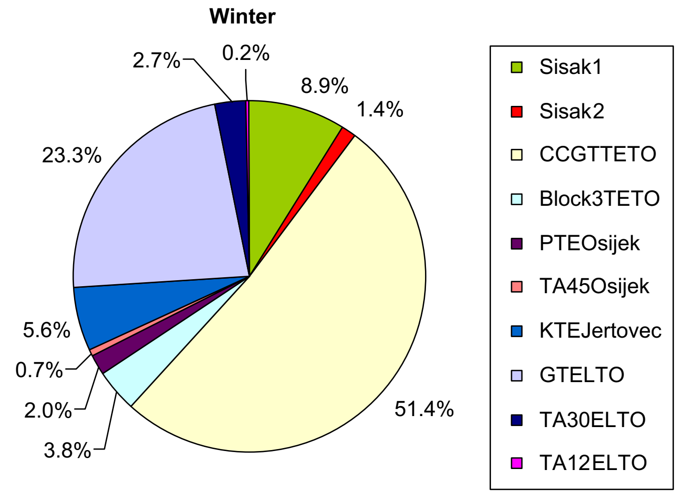

Fig. 8. Distribution of gas fuel over power plants in winter.

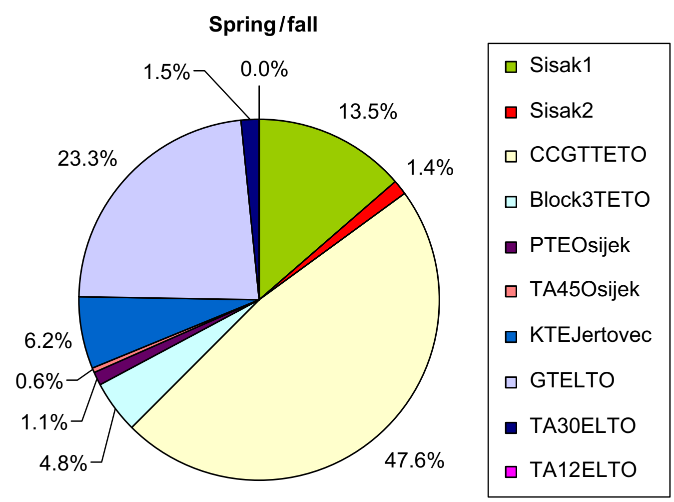

Fig. 9. Distribution of gas fuel over power plants in spring/fall.

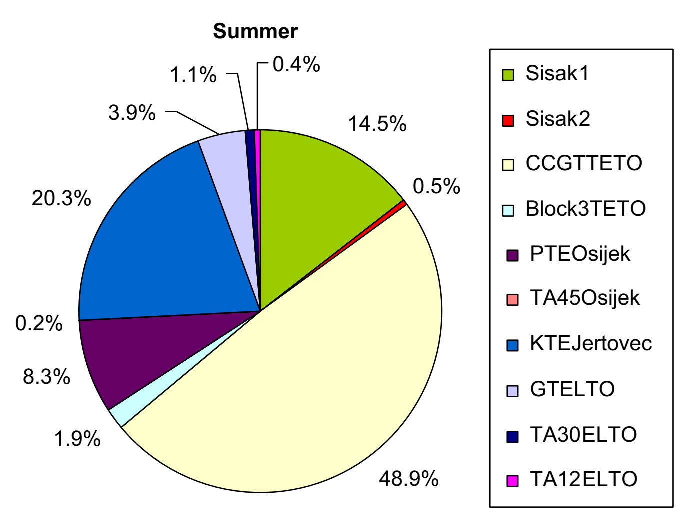

Fig. 10. Distribution of gas fuel over power plants in summer.

Table 5
Specific CO_2 and SO_2 production

	Oil	Gas	Coal
CO_2 production (kg_{CO2}/GJ)	77.5	59.9	99.3
SO_2 production (kg_{SO2}/GJ)	1.2	0.0	0.5

Table 6
Optimization benefits for the year 2004

	HEP	Optimization algorithm
Yearly average gas consumption (m^3/h)	82,844.0	87,090.0
Financial savings (€/a)	0	5,890,000.00
Reduction of CO_2 emissions (t/a)	0	21,590.0
Reduction of SO_2 emissions (t/a)	0	1515.0

Reduction of gas fuel in GT ELTO is noticed during summer due to reduced district heat demands. Surplus of gas from GT ELTO is used in TPP Jertovec and PTE Osijek for electric energy generation.

Efficient utilization of the contracted natural gas amount has gained certain benefits in the form of financial savings and lowered CO_2 and SO_2 emissions. Specific CO_2 and SO_2 emissions depending on fuel type are displayed in Table 5.

In comparison with the HEP average gas consumption in the year 2004, the optimization algorithm has shown substantial advantages. Lower fuel gas utilization by HEP had to be substituted by heavy oil fuel with consequences shown in Table 6.

4. Conclusions

In order to distribute properly contracted amount of natural gas fuel over different power plants within HEP, an optimization code has been developed. It has encompassed the whole Croatian power system together with thermal plants with cogeneration units, hydro plants, nuclear plant Krsko and import/export possibility. It has been shown that the optimization algorithm has potential to improve utilization of gas fuel and accomplish substantial benefits in terms of financial savings and reductions of CO_2 and SO_2 emissions.

References

[1] Lasdon LS, Waren A, Jain A, Ratner M. Design and testing of a generalized reduced gradient code for nonlinear programming. ACM Trans Math Software 1978;4(1):34–50.

[2] Nakata T, Ashina S. Optimization for the operation of electric power generation taking account of distributed regional demand in Japan, Tohoku University, 2002.

[3] Bogdan Z, Loncar D, Serman N. Cost optimization of a cogeneration plant, Euro conference on new and renewable technologies for sustainable development, Madeira Island, Portugal, 2000.

[4] Bogdan Z, Loncar D, Serman N. Optimization model for EL-TO Zagreb cogeneration plant. In: 23rd International Conference on Information Technology Interfaces, Pula, Croatia, 2001. p. 287–95.

[5] Vuk B, at al. Energy in Croatia 2004 Annual Energy Report. Ministry of Economy, Labour and Entrepreneurship Republic of Croatia, 2004.