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Modeling and thermoeconomic analysis of the municipal CHP station (PEC) in Stargard Szczecinski

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UNIVERSITY OF ICELAND
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Modeling and thermoeconomic analysis of the municipal CHP station (PEC) in Stargard Szczecinski

Roksana Mazurek

A 30 ECTS credit units Master´s thesis

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ABSTRACT

In the work a municipal combined heat and power station with Kalina cycle has been modeled and analysed, with aim of satisfying the demand for the energy of residents of Stargard.

In the second stage of the work, thermodynamic, economic amd exergy analysis for three proposed variants of the municipal combined heat and power station has been done, where the heat source is geothermal energy or the geothermal energy assisted with the additional renewable energy source – biomass.

PREFACE

This thesis is a final project of Masters Degree Program in the School for Renewable Energy Science in Akureyri, Iceland.

The municipal conventional thermal power station (PEC – *pol. Przedsiębiorstwo Energetyki Cieplnej*) and the geothermal thermal power station (Geotermia) are the main central heating suppliers in Stargard. In spite of relatively a geothermal energy source, the town does not have the installation for the electricity production. Therefore, the aim of this work has been to model the municipal combined heat and power station (CHP) coupling two existing installations with Kalina cycle used for electricity production.

I would like to thank my advisor, Pall Valdimarsson for instructed me in the use of EES, which was essential software for modeling for the purposes of my work, as well as for the support, valuable advices and remarks while writing my thesis.

I would like to thank my second advisor Dušan Holoubek for support, help and valuable remarks in correcting my thesis.

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1 Introduction

The rise in the energy demand, reducing reserves of fossil fuels and also the necessity of the natural environment protection forces taking intensive examinations of applying the renewables, which constitute the alternative to traditional non-renewable energy carriers.

Using reserves of the renewable energy, to a considerable degree reduces a harmful influence of energetics on the natural environment, mainly as a result of limiting emission of harmful substances into the atmosphere. Therefore, a strategic purpose of the politics of the European Union are requirements of increasing the participation of natural resources in the production of electricity and thermal energy production.

Poland as one of members of the Union is obliged to fulfill these requirements and concluded international agreements, therefore the domestic power industry aims at present, at the improvement in the effectiveness of the market economy by exploiting the energy coming from renewable sources.

More and more often, in domestic heating systems appear concepts of using geothermal and biomass energy mainly associated producing the electricity energy and the functional central heating, that is using of cogeneration process.

In Poland is the possibility of exploiting the geothermal energy on over the 60% of the area of the country. The temperature of available geothermal water is in the scope 30-120^{o}C and therefore is used mainly for the purposes heating, what confirms the fact, that in the country exist several geothermal thermal power stations in bivalent systems, in which apart from heating season, the heat is supplied from geothermal sources, however in heating season are started additionally supporting conventional sources.

Appearing recently research results concerning available temperatures of geothermal waters in country also point out to the possibility of their using for the process of generating the electric energy at using for this destination power stations being based on a low-temperature Clausius-Rankine cycle more rarely on Kalina cycle. However, in spite of results of these works, Poland does not have power station powered or co-powered with geothermal energy.

Therefore, in that case of fact, a main purpose of this paper is carrying out the analysis of using Kalina cycle in combination with using geothermal and biomass energy (due to its large energy potential in the country) for the electricity production.

One of the main sources of biomass to energy targets in Poland are wood waste and agriculture. More and more often at implementing the renewables are applied technological solutions consisting often in co-firing biomass with coal, what has economic notable effects, because is not necessary incurring the extra costs associated with the structure of new technological installations, what in case of small and average towns, such like, for example Stargard, is very important.

Due to the fact, that in Stargard Szczeciński area exist possible for the energy application large reserves of the geothermal energy about the average temperature 90^{o}C and appearing more and more often plans for energy using biomass for the production of the central heating in the local municipal thermal power station (PEC) and expanding demand for the electricity, the aim of this paper was modeling and carrying out of thermoeconomic analysis of the combined heat and power station with Kalina cycle powered with the energy of these two renewable energy sources.

The work focused on the electricity production mainly for the purposes of Stargard. At the end of the work are conclusions resulting from analysis of calculations for considered arrangement of power station

2 Geothermal energy

Geothermal energy is one of types of the renewables and is the heat energy accumulated in the fluids, rocks within earth and can be used to heat and electricity production.

High-temperature sources of geothermal energy are used in special installations for the electricity and heat production. Low-temperature geothermal reservoirs are used for reducing the demand for the energy by using in direct heating houses, factories, greenhouses or can be applied in heat pumps, in other words in devices, which take the heat from the earth on the shallow depth and deliver it to inside houses to heating purposes.

2.1 Brief history

One of unconventional forms of the energy is thermal heat energy accumulated below the solid Earth's surface. The hot springs have been used by humanity for centuries, for example, inhabitants of America exploited some geothermal sources, applying hot water for healing purposes and for cooking. Romans used hot springs for the baths. What is more, Maoris – native population of New Zealand – used thermal water for washing, cooking and even for the heating.

In modern times, precisely - in the fourteenth century, in France, geothermal energy was being exploited for heating a few residential buildings. However, as an energy source both for electricity production and for direct applications, geothermal energy was applied to the wide scale only in the twentieth century, when in 1904 in Larderello (Tuscany, Italy) was started up the first experimental geothermal power plant exploiting geothermal steam (Figure 2.1.1, 2.1.2). In 1913 was built there first 250 kW commercial electric plant and at present the power of this electric plant is 810 MW.

2.1.1. First experimental geothermal power plant in Larderello, 1904

(www.geothermal-energy.org, www.reuk.co.uk)

2.1.2 *Geothermal power plant in Larderello – at present*

(www.superstock.com)

2.2 Utilization methods

Geothermal energy can be utilized in two basic ways:

- electricity generation – using geothermal steam (high-enthalpy sources, in which temperatures of the geothermal fluid exceed 150 - 200^{o}C)

- direct uses – to different purposes and in a wide range of temperatures (low-enthalpy sources below 150^{o}C), mainly in recreation, balneology, heat engineering, agriculture, in technological processes etc.

Different abilities of applying the geothermal energy depending on temperature values of its carrier is illustrated on Lindal's diagram (Figure 2.2.1).

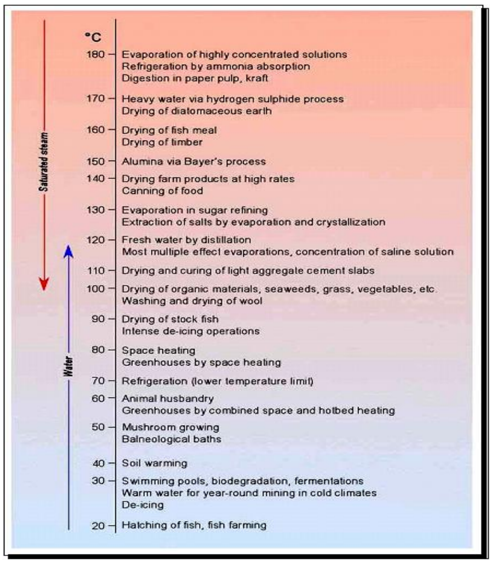


Figure 2.2.1 Lindal's diagram

(www.geothermal.nau.edu/about/directuse.shtml)

2.3 State of utilization

2.3.1 Direct uses

It is estimated, that the proven geothermal energy deposits occur in over 80 countries. The range of application of the geothermal energy grows up constantly and according to the data reported this year (2010) on the World Geothermal Congress in Bali, it is being utilized directly in 78 countries. According to reported estimating from WGC2010, the total installed thermal power for direct uses at the end of 2009 was 48,493 MW_t with a capacity factor of 0.28 (2,450 full load operating hours per year) and the thermal energy consumption was 117,740 GWh (423,830 TJ) (Lund, 2010).

The geothermal energy is most often applied directly for heating purposes, mainly with heat pumps and hot water extracted from the boreholes, and in the second order in balneology and on bathing. Other uses are, for example: greenhouse heating, fish farming, drying agricultural products, preheating the soil, melting the snow, industrial applications, deicing the roadway and pavements, cooling. In table 2.3.1.1 are shown various categories of direct use worldwide of geothermal energy in terms of capacity factor, energy utilization and installed capacity, in year 2005 and 2010.

Table 2.3.1.1 Worldwide direct use of geothermal energy in year 2005 and 2010 (Lund,2010)

Type of the use	**Capacity factor**	**Utilization TJ/yr]**	**Capacity [MW_t]**	**Capacity factor**	**Utilization TJ/yr]**	**Capacity [MW_t]**
	2005			**2010**		
Space heating	0.40	55,256	4,366	0.37	63,025	5,391
Industrial uses	0.71	10,868	484	0.70	11,745	533
Geothermal heat pumps	0.18	87,503	15,384	0.19	200,149	33,134
Greenhouse heating	0.47	20,661	1,404	0.48	23,264	1,544
Snow melting/ Cooling	0.18	2,032	371	0.18	2,126	368
Aquaculture pond heating	0.57	10,976	616	0.56	11,521	653
Swimming and bathing	0.49	83,018	5,401	0.52	109,410	6,700
Agriculture drying	0.41	2,013	157	0.41	1,635	125
Others	0.39	1,045	86	0.72	955	42
Total	**0.31**	**273, 372**	**28, 269**	**0.28**	**423, 830**	**48, 493**

From the above table results that the meaning participation in the worldwide geothermal energy utilization both 2005 and 2010 had geothermal heat pumps as the total installed capacity is 33,134 MW with a capacity factor of 0.19. The largest using of geothermal heat pumps was noticed in China, Europe and North America.

Amongst ten countries about the largest utilizing of the geothermal energy into the direct uses, are mainly: USA, Sweden, China, Germany, Japan, which utilize annually about 63 % of geothermal heat applied in the world. Countries with already a bit smaller consuming of the heat are: Iceland, Netherlands, France, Switzerland, Turkey. (Lund J.W., Freeston D. H., Boyd T., 2005). Capacity factor, total installed thermal capacity and annual energy use reported at the end of 2009 are shown in the table 2.3.1.2.

Table 2.3.1.2 Worldwide direct use of geothermal energy, 2010. *(Lund, 2010)*

Country	Capacity [MWt]	Annual Use [GWh/yr]	Annual Use [TJ/yr]	Capacity Factor
Albania	11.48	11.2	40.46	0.11
Algeria	66.84	583.0	2,098.68	1.00
Argentina	307.47	1,085.3	3,906.74	0.40
Armenia	1	4.2	15	0.48
Australia	33.33	65.3	235.1	0.22
Austria	662.85	1,035.6	3,727.7	0.18
Belarus	4.5	12.3	44.43	0.31
Belgium	117.9	151.9	546.97	0.15
Bosnia & Herzegovina	21.696	70.9	255.36	0.37
Brazil	360.1	1,839.7	6,622.4	0.58
Bulgaria	98.3	380.6	1,370.12	0.44
Canada	1,126	2,464.9	8,873	0.25
Caribbean Islands	0.103	0.8	2.775	0.85
Chile	9.11	36.6	131.82	0.46
China	8,898	20,931.8	7,5348.3	0.27
Columbia	14.4	79.7	287	0.63
Costa Rica	1	5.8	21	0.67
Croatia	67.48	130.3	468.89	0.22
Czech Republic	216.5	358.4	1,290	0.19
Denmark	200	694.5	2,500	0.40
Ecuador	5.157	28.4	102.401	0.63
Egypt	1	4.2	15	0.48

Table 2.3.1.2 Cont.

El Salvador	2	11.1	40	0.63
Estonia	63	98.9	356	0.18
Ethiopia	2.2	11.6	41.6	0.60
Finland	994	2,213	7,966	0.25
France	1,345	3591.7	12,929	0.30
Georgia	26.51	191.5	689.34	0.82
Germany	2,485.4	3,546	12,764.5	0.16
Greece	134.6	260.5	937.8	0.22
Guatemala	2.31	15.7	56.46	0.78
Honduras	1.933	12.5	45	0.74
Hungary	654.6	2,713.3	9,767	0.47
Iceland	1,826	6,767.5	24,361	0.42
India	265	707	2,545	0.30
Indonesia	2.3	11.8	42.6	0.59
Iran	41.608	295.6	1,064.18	0.81
Ireland	134.45	192.2	691.91	0.16
Israel	82.4	609.2	2,193	0.84
Italy	867	2,761.6	9,941	0.36
Japan	2,099.53	7,138.9	25,697.94	0.39
Jordan	153.3	427.8	1,540	0.32
Kenya	16	35.2	126.624	0.25
Korea (South)	229.3	543	1,954.65	0.27
Latvia	1.63	8.8	31.81	0.62
Lithuania	47.6	114.3	411.52	0.27
Macedonia	47.18	167.1	601.41	0.40
Mexico	155.82	1,117.5	4,022.8	0.82
Mongolia	6.8	59.2	213.2	0.99
Morocco	5.02	22	79.14	0.50
Nepal	2.717	20.5	73.74	0.86

Table 2.3.1.2 Cont.

Netherlands	1,410.26	2,972.3	10,699.4	0.24
New Zealand	393.22	2,653.5	9,552	0.77
Norway	1,000	3,000.2	10,800	0.34
Papua New Guinea	0.1	0.3	1	0.32
Peru	2.4	13.6	49	0.65
Philippines	1.67	3.5	12.65	0.24
Poland	281.05	417	1,501.1	0.17
Portugal	28.1	107.3	386.4	0.44
Romania	153.24	351.3	1,265.43	0.26
Russia	308.2	1,706.7	6,143.5	0.63
Serbia	100.8	391.7	1,410	0.44
Slovak Republic	132.2	852.1	3,067.2	0.74
Slovenia	115.6	282	1,015.1	0.28
South Africa	6.01	31.9	114.75	0.61
Spain	141.04	190	684.05	0.15
Sweden	4,460	12,584.6	45,301	0.32
Switzerland	1,060.9	2,143.1	7,714.6	0.23
Tajikistan	2.93	15.4	55.4	0.60
Thailand	2.54	22	79.1	0.99
Tunisia	43.8	101.1	364	0.26
Turkey	2,084	10,246.9	36,885.9	0.56
Ukraine	10.9	33	118.8	0.35
United Kingdom	186.62	236.1	849.74	0.14
United States	12,611.46	15,710.1	56,551.8	0.14
Venezuela	0.7	3.9	14	0.63
Vietnam	31.2	25.6	92.33	0.09
Yemen	1	4.2	15	0.48
Total	**48,493**	**117,740**	**423,830**	**0.28**

From the above reported data results, that direct using of the geothermal energy becomes more and more popular in many states, thanks to the possibility of effective applying its to the production of the useful energy and reducing the greenhouse gases emission.

2.3.2 Electricity generation

According to the International Geothermal Association data, the electricity is being generated in 24 countries and in 2005 the total installed power capacity was 8,933 MW and electricity production was 55,709 GWh. In the sequence of five years, to 2010 the total installed power capacity rose to 10,715 MW, whereas electricity production is 67,246 GWh per year. It means, that in years 2005 – 2010 both the total installed capacity and electricity production increased about 20 % in comparison with 2005. It is estimated, that the rise of the electricity production from geothermal sources has accelerated at present to 75 % and is 350 MWe/year. The degree of using the geothermal energy for the power production is, in five countries, in the range between 14 and 25 %. According to IGA estimating, based on a large number of projects, to 2015 this growth will achieve the value 18,500 MW.

According to IGA/ Bertani data, between 2005 and 2010, the greatest increase in installed capacity was in such countries as: US – 530 MW, Indonesia - 400 MW, Iceland - 373 MW, New Zealand - 193 MW, Turkey 62 MW, whereas the largest percentage increase of installed capacity was noticed in: Papua New Guinea - 833%, Australia - 633%, Turkey - 308%, Iceland - 184% (IGA, 2010). In table above (Table 2.3.2.1) was shown data for countries generating geothermal power in 2010.

Table 2.3.2.1 Countries generating geothermal power in 2010 (Bertani, 2010)

Country	Total installed capacity (MWe)
United States	3,093
Philippines	1,904
Indonesia	1,197
Mexico	958
Italy	843
New Zealand	628
Iceland	575
Japan	536
El Salvador	204

Table 2.3.2.1

Kenya	167
Costa Rica	166
Nicaragua	88
Russia	82
Turkey	82
Papua New Guinea	56
Guatemala	52
Portugal	29
China	24
France	16
Ethiopia	7.3
Germany	6.6
Austria	1.4
Australia	1.1
Thailand	0.3
Total	**10,715**

At present, the most popular type of the geothermal power plant are installations, which for electricity production utilize low-to-medium enthalpy reservoirs with temperatures in range 85 an 150^{o}C and even higher – by 200^{o}C. This type of binary installations fed with water about temperatures between 97 - 110^{o}C have worked for a few years in Germany (Neustadt-Glewe – from 1995) and Austria (Altheim – from 2001; Bad Blumau – from 2003).

2.4 Utilization geothermal energy in Europe

Geothermal energy is utilized for various purposes in 33 European countries and among all continents, Europe is on the second place in terms of direct use of geothermal energy, before Africa, Oceania, the Southern and Northern Americas, and after Asia. The growth of exploiting the geothermal energy in Europe, results mainly from applying geothermal heat pumps and from using geothermal energy on the industrial scale in many countries. Very popular are the heat pumps applied to district heating and air-conditioning particularly in countries, such like: Sweden, Switzerland, USA, Iceland, Turkey, France, Poland. In the case of utilization geothermal energy in industry, is utilized mainly to heating, cooling and to drying wood. It is also used in the infrastructure to heating pavements or runways on airports (Germany, Switzerland) and also to drying the earth (Iceland) and drying paper (New Zealand). At present in Europe, electricity is generated in eight countries, from geothermal steam, mainly in: Italy, Iceland, Turkey, France (Guadalupe), Russia and at using binary systems applying low-to-medium reservoir, mainly in: Austria (Altheim, Bad-Blumau, Simbach/Branau), Germany (Neustadt-Glewe), France (Soultz), Portugal (Azores), Iceland (Husavik, Svartsengi), Turkey (Kizildere). In some countries are conducted research being aimed at starting next binary installations.

In the table below (Table 2.4.1) are data of utilization the geothermal energy in Europe in 2010 (after Lund et al., 2010).

Table 2.4.1 Utilization geothermal energy in Europe, 2010 (after Lund et al. 2010)

Country	Direct use		Generation electricity
	Capacity (MW_t)	Annual Use (TJ/yr)	Installed capacity (MWe)
Albania	11.48	40.46	--
Armenia	1	15	--
Austria	662.85	3,727.7	1.4
Belarus	4.5	44.43	--
Belgium	117.9	546.97	--
Bosnia and Herzegovina	21.696	255.36	--
Bulgaria	98.3	1,370	--
Croatia	67.48	468.89	--
Czech Republic	216.5	1,290	--
Denmark	200	2,500	--
Estonia	63	356	--
Finland	994	7,966	--

Table 2.4.1 Cont.

France	1,345	12,929	16
Germany	2,485.4	12,764.5	6.6
Greece	134.6	937.8	--
Hungary	654.6	9,767	--
Iceland	1,826	24,361	575
Ireland	134.45	691.91	--
Italy	867	9,941	843
Latvia	1.63	31.81	--
Lithuania	47.6	411.52	--
Macedonia	47.18	601.41	--
Netherlands	1,410.26	10,699.4	--
Norway	1,000	10,800	--
Poland	281.05	1,501.1	--
Portugal	28,1	386.4	29
Romania	153.24	1,265.43	--
Russia	308.2	6,143.5	82
Serbia	100.8	1,410	--
Slovak Republic	132.2	3,067.2	--
Slovenia	115.6	1,015.1	--
Spain	141.04	684.05	--
Sweden	4,460	45,301	--
Switzerland	1,060.9	7,714.6	--
Turkey	2,084	36,885.9	82
Ukraine	10.9	118.8	--
United Kingdom	186.62	849.74	--

From illustrated data in the table above, results that in 2010, in the first ten places of countries about the largest utilization the geothermal energy are, in the order: Sweden, where are used only ground heat pumps (for heating purposes), using the seasonal temperature variation, because in Sweden has no real geothermal source, next are: Germany, Turkey, Iceland, Netherlands, France, Switzerland, Norway, Finland, Austria.

3 Geothermal resources in Poland

3.1 Exploitation

In Poland geothermal water are being utilized for centuries in balneology and at present are used mainly for heating purposes, using functional warm water in the municipal sector, to greenhouses heating, in recreation, agriculture and in fish farming, to bathing.

On the area of Poland are available the considerable geothermal water resources about low and medium enthalpy, what is relevant with appearing of underground water about temperature in range 20 – 130^{o}C, which are located at the depth to 3 - 4 km. Temperatures decomposition of geothermal resources on the area of the Polish Lowland at depth 3 and 4 km was shown in figures 3.1.1 and 3.1.2.

On the basis of hydrogeologic data it was estimated, that over 90 % of the geothermal water resources are on the area of: the Polish Lowland, the Podhale (Carpathians), Sudetes.

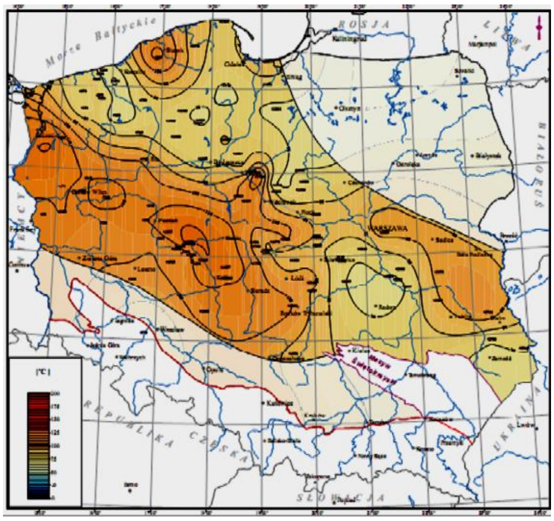


Figure 3.1.1 Maps of temperatures decomposition at depth 3 km (Atlas of geothermal resources,2006)

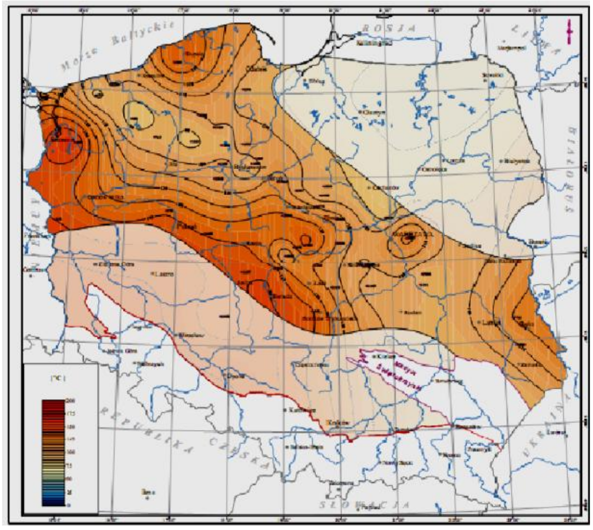


Figure 3.1.2 Maps of temperatures decomposition at depth 4 km
(Atlas of geothermal resources,2006)

Poland possesses considerable energetic potential of geothermal water, however only in the last ten years of the twentieth century began a technical use of its deposits. In Poland, at present operate six geothermal heating plants: in Pyrzyce – from 1996, on Podhale – from 1993 (Bańska Niżna), in Mszczonów – from 1999, in Uniejów – from 2001, in Słomniki – from 2002, in Stargard Szczeciński – from 2005. Specified heating plants generate various quantities of the heat and have a different geothermal and total power. One should add, that in the heating plants are utilized geothermal water about various temperatures, in range 17 – 87^{o}C (Table 3.1.1).

Table 3.1.1 Basic data on geothermal heating plants in Poland (Kępińska,2006; Nowak, Stachel, Borsukiewicz, 2008)

Parameter			**Bańska Niżna**	**Uniejów**	**Mszczonów**	**Słomniki**	**Pyrzyce**	**Stargard Szczeciński**
Year of starting		-	1994/2001	2001	1999	2002	1996	2005
Tank rocks		-	dolomites, Trias/ Eocene, limestones	sandstones, cretaceous			sandstones jura	sandstones cretaceous
Temperature of water in deposit		^{o}C	82 – 87	67 – 70	40	17	61	87
Depth of the borehole		m	2000-3000	~2000	1600- 1700	300	1500-1650	2670
Mineralization		g/l	3.0	6.8 – 8.8	0.5	0.4	120	120
Outflow		m^3/h	120 - 550	68	60	50	2 x 170	300
Installed capacity	geot.	MWt	38	3.2	3.8	0.3	13	-
	total		**42**	**4.6**	**12**	**3.5**	**50**	**14**

In years 2006 – 2008 constructed seven new geothermal bathing centers – four of them were opened in Podhale region: Szymoszkowa, Aqua Park Zakopane, Terma Bukowina Tatrzańska, Termy Podhalańskie, and three of them – in the Polish Lowlands: Termy Uniejów (in 2008), Termy Mszczonów (in 2008), Grudziądz-Marusza (in 2005). (Kępińska, 2010). In plans is a constructure and start of next geothermal heating plants and recreational objects. In the figure below was shown a location of operated and being in realization geothermal heating plants (Figure 3.1.3).

Figure 3.1.3 Poland, 2009: 1. geothermal heating plants in operation,
2. geothermal heating plants in realization (wells drilled or in drilling),
3. spas using geothermal water, 4. Geothermal bathing centers opened in 2005 – 2009,
5. geothermal bathing centers under construction (wells drilled or in drilling). Division into Geothermal provinces after Sokołowski (1993) (Kępińska, 2010)

4 Utilization biomass in Poland - market research

4.1 Exploitation

In the accession treaty on joining the European Union, Poland declared the increase in the participation of the renewable energy sources in the electricity production to the 7.5% in 2010 and up to the 14% in year 2020. However, hydrogeologic conditions of Poland do not permit for getting such a considerable participation of renewable energy sources in the energy production from hydro, solar, wind or geothermal water power industry, therefore biomass energy utilization is most often noticed.

According to the definition proposed by the European Union, biomass is the susceptible to the biological disintegration the different organic substances of the plant, animal origin, residues and waste of forestry, waste of the agricultural industry and fractions of industrial and municipal waste.

Amongst available renewable energy sources in Poland, biomass is the most abundant energy source, which due to its quite low price, can compete with fossil fuels. To energy needs of the country are use mainly:

- wood and wood waste, for instance: pellets, firewood, woodchips, sawdust, wood briquette and other,
- energy plants: basket willow, Pennsylvanian mallow, sunflower, miscanthus and other,
- corn and cereals, chiefly: maize, oats, wheat,
- agriculture residuals: straw, hay, plant and animal waste, pods, leaves, etc.
- municipal waste.

Biomass is used mainly for thermal production in dispersed low- and medium-capacity individual boilers or local boiler plants in individuals houses on the countryside and in small towns, whereas for electricity production, biomass is burned in coal-fired condensing boilers in high-capacity power stations in co-firing process, which is a mature technology employed in Poland.

It is estimated, that Polish technical potential of biomass is relatively high – is amounted to 755 PJ/yr and is used widely for: electricity production ~29% (~218.9 PJ/yr), heating ~70% (528.5 PJ/yr), district heating ~1% (~7.55 PJ/yr). For example, according to estimating, the potential of wood biomass is at about 24.5 PJ/yr to 59 PJ/yr, municipal waste at 2 millions ton/yr and 8 millions waste disposal. To generate energy from this type of biomass is applicable direct combustion technology, due to the low content of sulfur (up to 0.01%) and dust (up to 1%). Examples of installations burning biomass:

- 6 MW in Sępólno Krajeńskie
- 370 kW in Janów
- 8 MW in Nowa Dęba
- 6.5 MW in Frombork
- 2.5 MW in Gryfice
- 4 MW in Kępice
- 21 MW in Pisz

Energy using biomass for the heat and electricity production is a chance for the country for the considerable emission reduction of pollutants to the atmosphere and for partial realization of assumptions of the European Union energy policy. Therefore, in Poland, using coal as the main energy resource, recognized several years ago, the possibility of its gradual substitution of biomass through the implementation process of co-firing of these fuels in power boilers. Currently, co-firing is an advanced and commercial technology in Poland.

Co-firing, consists on leading individually or initially mixed coal and biomass into conventional power boilers. Biomass with coal mixing conduct to lowering the sulfur concentration and to increasing the thermal efficiency as a result of reducing the incomplete combustion loss. Coal fulfils a role as the stabilizer of the process, what enables applying biomass about changeable composition and humidity. One should add, that are three basic concepts co-firing biomass with coal in coal-fired boilers (Al-Mansour,Zuwala,2010; Głodek, 2010):

- direct co-firing – consists in simultaneous burning coal and biomass in one boiler chamber, using the same or separate burners or mills (Figure 4.1.1a),
- indirect co-firing – there are two cases:
  1) burning biomass or biogas in the so-called Dutch oven - enthalpy of the exhaust gases is used directly as the heating fluid in the heat exchangers or in the combustion chamber, in which are cased the heated areas (Figure 4.1.1 d);
  2) gasification or pirolysis in the gasifier - gas coming into existence is directed to the boiler combustion chamber, in which is burnt in the gas burners (Figure 4.1.1b).
- parallel co-firing – biomass and coal are burnt in the separate boilers, jointly producing steam for power generation (Figure 4.1.1c)

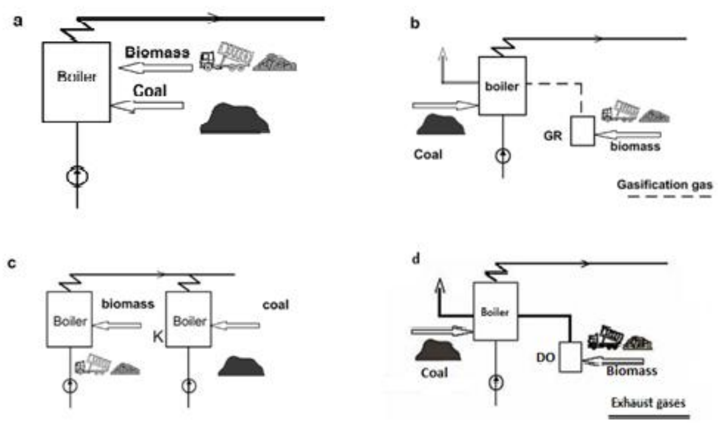


Figure 4.1.1 Biomass co-firing technologies: a) Direct co-firing, b) and d) Indirect co-firing, c) parallel co-firing

(Al-Mansour,Zuwala,2010; Głodek, 2010)

Chosen power stations co-firing coal with biomass (mainly sawdust, chips,agriculture residuals, forest origin) are:

- Dolna Odra SA (in Szczecin and in Nowe Czarnowo near Gryfino) ~ 1992.4 MWe
- Połaniec - 1800 MWe
- Stalowa Wola – 450 MWe
- Skawina – 590 MWe
- Rybnik – 1775 MWe
- Turów (biomass with lignite) (in Bogatynia) – 2,088 MWe

In Poland due to current technical-technological conditioning of proffessional and communal energetics, co-firing is the most profitable solution allowing for using existing coal boilers and the entire infrastructure accompanying it and requires only small investments at modifying of the preparation system and of feeding the fuel to a combustion chamber. Attraction of co-firing fuel blends, biomass with coal results from the fact, that domestic professional energetics has at its disposal constantly considerable reserves of the power.

4.1.1 Boilers for burning and co-firing biomass

Boilers burning biomass are available in a wide power range from a few kW to several hundred MW. Two methods of burning biofuel are applied: 1) burning in a bed, in layer or in the stationary stack; 2) burning of fuel particles suspended or blown into the furnace. Fuel can be fed to the furnace from the top, from the bottom or from the front. The process can be carried out with continuous feeding of fuel or in a discontinuous way with feeding of a single batch of fuel. In the table 1 are shown the types of furnaces for burning biomass, the methods using them and requirements related to the quality of burnt fuel.

Table 4.1.1.1 Types of furnaces for burning biomass, the methods using them and requirements related to the quality of burnt fuel (Głodek, 2010)

Remarks	Type	Power range	Type of biomass
Manual dosage of fuel	Furnaces	2 - 10 kW	Chunk of wood
	Boilers	5 - 50 kW	Chunks, slivers
Pellets	Furnaces and boilers	2 - 25 kW	Pellets
Automatic dosage of fuel	Stoker furnaces	20 kW – 2.5 MW	Chips, wood waste
	Furnaces with the mechanical grate	150 kW – 15 MW	All biomass types
	Dutch oven	20 kW – 1.5 MW	Wood, sawdust
	Rotational stoker furnaces	2 - 5 MW	Pellets
	Cigar furnaces	3 - 5 MW	Pallets of straw

Table 4.1.1.1 Cont.

Automatic dosage of fuel	Furnaces for burning the entire pallets	3 - 5 MW	Pallets of straw
	Furnaces for burning of straw	100 kW – 5 MW	Cut straw
	Fluidized bed furnace BFBC (*Bubbling Fluidized Bed Combustion*)	5 – 15 MW	All biomass types
	Fluidized bed furnace CFBC *(Circulating Fluidized Bed Combustion*)	15 -100 MW	
	Pulverized-fuel fired furnace	5 - 10 MW	All biomass types
Co-firing	Fluidized bed furnace BFBC (*Bubbling Fluidized Bed Combustion)*	50 – 150 MW	All biomass types
	Fluidized bed furnace CFBC *(Circulating Fluidized Bed Combustion)*	100 – 300 MW	
	Cigar furnaces	5 – 20 MW	Pallets of straw
	Pulverized-fuel fired furnace	100 MW – 1 GW	All biomass types

From above considerations result, that Poland has the large enough biomass potential to its energy using both to heating targets and for the electricity production, whereas its burning and co-firing with coal enables the considerable emission reduction of pollutants occurring from the energy production processes. This positive influence of applying biomass as the energy source on the natural environment should encourage both local investors, and national producers of the energy for implementing new technological applications with the biomass participation.

Implementing the technology burning or co-firing is also a stimulus of the development of new technologies is also a stimulus of the development of new technologies, and progress resulting from them in many sectors of the economy, causes the development of the local labour markets and the improvement in economic conditions of the life of the population. *(Głodek, 2010).*

5 Geothermal power plants

5.1 Types of power production cycles

Depending on parameters of geothermal reservoir such like: temperature, quantity of dissolved gases and salts, and also on the way the energy is generated, at present are distinguished three types of geothermal power plants:

- **Dry Steam power plant** – which produce electricity directly from the steam generated in the reservoir. Dry steam get from the deposit is piped directly into the power plant, passing through the turbine, which drives the generator (Geysers in USA, Larderello in Italy). Then, condensed water is injected directly into reservoir in order to replenish water and pressure level. However, this type of power stations are applied in areas, on which geothermal water is found in the state of saturated or superheated steam. The scheme of dry steam power plant was illustrated on figure below (Figure 5.1.1) (www.seas.upenn.edu/~electric/edu-energy2.shtml)

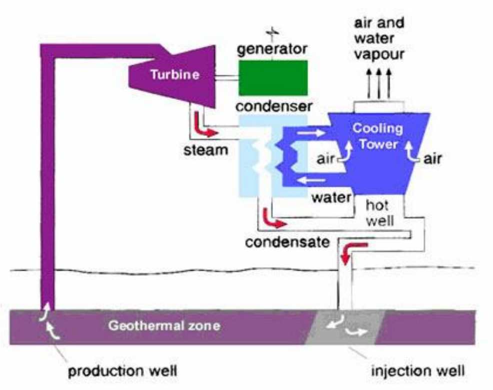


Figure 5.1.1 Scheme of dry steam geothermal power plant

(www.seas.upenn.edu/~electric/edu-energy2.shtml)

- **Flash Steam power plant** – in this type of power plant is used a hot water reservoir (Wairakei in New Zealand, Krafla in Iceland) with temperature of hot fluids usually exceeding ~180°C. Hot water is pumped at high pressure to the surface as a two-phase mixture of water and steam. Then, steam is being obtained after separating drops of brine from steam in the separator (after 'flash' into steam) and then steam enters the turbine, which drives the generator. The unflashed liquid brine is pumped back into the reservoir for re-injection or it can be piped into a second tank, in which can be flashed again to generate steam and then power (Double Flash Steam power plant – Figure 5.1.3). Flash steam power plants (Figure 5.1.2) are widely used for electricity generation as the most of geothermal reservoirs are formed by liquid-dominated hydrothermal systems. (www.seas.upenn.edu/~electric/edu-energy2.shtml)

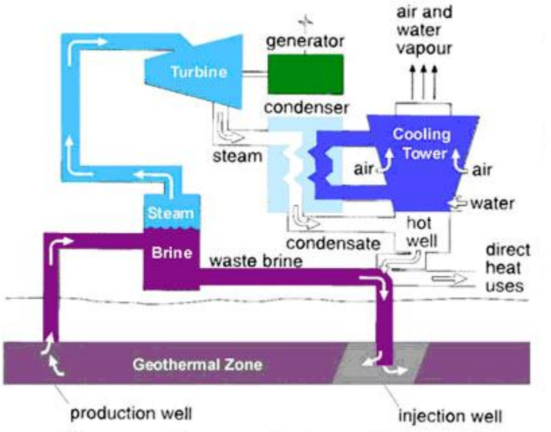


Figure 5.1.2 Scheme of flash steam geothermal power plant (www.seas.upenn.edu/~electric/edu-energy2.shtml)

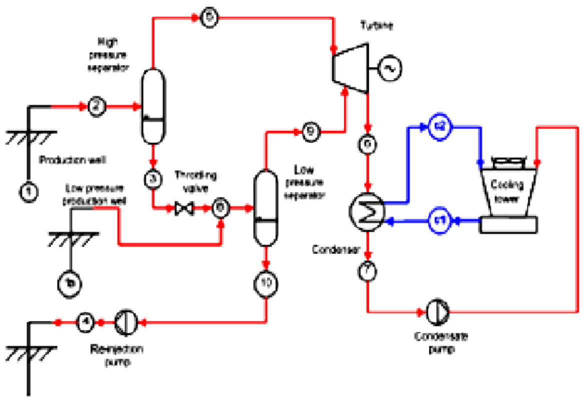


Figure 5.1.3 Scheme of double flash steam geothermal power plant (Valdimarsson, 2010)

Described above two types of power plants, that is Dry Steam and Flash Steam are not applicable in Poland due to high temperatures required, which are not available in the country as Poland is not located in the area of volcanic activity or tectonic activity. It causes, that in the country are not occur conditions for appearing of steam deposits and reservoirs (high-temperature deposits), which could be used for electricity production *(Atlas of geothermal resources, 2006).* However, it is possible utilization of low-to-medium temperature reservoirs of geothermal water (20-130^{o}C) available on the area of Poland, to electricity production at using binary power plant being based on low-temperature Organic Rankine Cycle.

- **Binary power plant** – is used, when parameters of geothermal water, particularly temperatures in range 85-150^{o}C (with low-to-medium enthalpy) are not hot enough to produce energy by using flash or dry steam power plant. The geothermal water from the reservoir is passed to a heat exchanger, in which its heat is transferred into the second fluid with a low-boiling point (such as: isobutane, ammonia, propane, toluene). This fluid operates according to the Organic Rankine Cycle (ORC called also: LTC – Low-Temperature Cycle) or according to Kalina cycle. After heating and vaporizing the binary liquid in the heat exchanger, it is directed into the turbine (Figure 5.1.4), in which expands and next the vapor is condensed to a liquid, which flows to the heat exchanger again and the whole process is repeated. (www.greenarthenergy.com.au/geothermal)

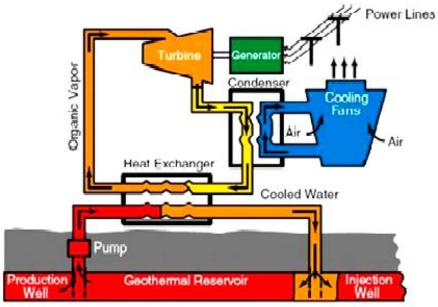


Figure 5.1.4 Model of binary geothermal power plant

www.greenearthenergy.com.au/geothermal

This type of geothermal power plants is the most possible to use in Poland due to the possibility of work at relatively low geothermal water temperatures, which are widely approachable in the country.

The special case of the binary cycle using geothermal water is Kalina cycle, in which as working fluid is applied mixture of ammonia-water (mixture of two inorganic compound).

5.2 Organic Rankine Cycle (ORC)

At present, one of the most promising and practicable solutions, allowing for utilization of geothermal water reservoir about the medium and low enthalpy (low-to-medium temperature, for example in: Poland, Germany, Spain, Austria) to electricity production are indirect system, so-called ORC cycle (Figure 5.2.1) (Nowak, 2008). In this cycle as a working medium is used a chosen organic fluid instead of water, such as, for example: butane, propane, toluene, isobutane, hexane and many others. These working medium perform the same role in the steam arrangements as water, but operate in different pressures range and have a lower boiling point temperature (at ambient pressure) than water. In installation with ORC cycle geothermal water is heat carrier, which is transferred to working medium (organic fluid) in the geothermal heat exchanger. After preheating and evaporating working fluid in the heat exchanger with cost of the geothermal energy, organic substance expands in the steam turbine driving the generator. Then, vapor is condensed in the condenser to the liquid and is directed with the feed pump to the heat exchanger again. The whole process is repeated.

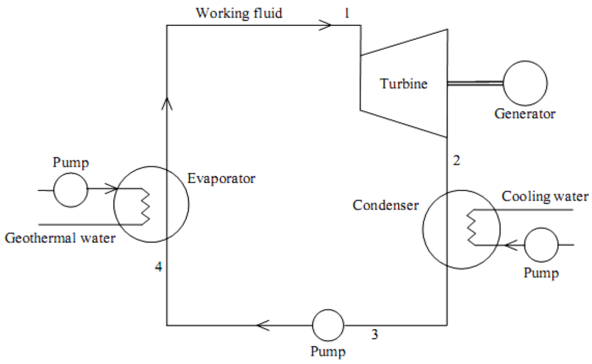


Figure 5.2.1 Model of the Rankine cycle (Madhawa, 2007)

One should add, that energy source for Organic Rankine cycle can be also power biomass-fired boiler or waste heat carrier.

5.3 Kalina cycle

5.3.1 Description of cycle

One of the modification of the technology based on the Rankine cycle is Kalina cycle, in which as a working fluid is used ammonia and water mixture instead of pure fluid such as, for example: propane or isobutane.

Upper heat source for the Kalina system, can be similarly as in case of ORC cycle: geothermal energy, heat from combustion of biomass, waste heat in form of exhaust from a gas turbine and gas engine, from industrial processes (for example: from the steel or cement production), from the gasification, from combustion of municipal waste or even ocean and solar thermal. The temperature of heat source used in this cycle as a rule does not exceed 200^{o}C.

In Kalina cycle (which can have many varieties) the low-temperature heat source (geothermal water, waste heat carrier etc.) transfers heat to the ammonia-water mixture in the heat exchanger, in which is evaporated. Next, in the separator is carried out separating the vapor phase from the liquid phase. Saturated vapor of ammonia-vapor mixture consisting in the 95% of ammonia passes through the steam turbine, whereas liquid from the lower part of the separator flows through the high-pressure recuperator, then is mixed with the vapor from the turbine outlet and is directed to the low-pressure recuperator in order to lowering its temperature. After condensation, the mixture passes through the low- and high-pressure recuperator, in which is preheated and is directed again to the heat exchanger (Figure 5.3.1.1). Besides above described arrangement of Kalina cycle, are applied other solutions.

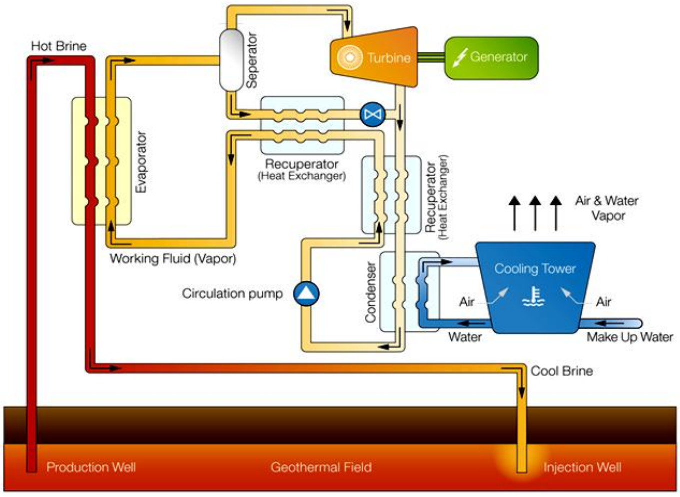


Figure 5.3.1.1 An example of power station with Kalina cycle (www.geysirgreenenergy.com/solutions/lowtemp)

In comparison with standard ORC binary system, Kalina cycle has a thermal efficiency (which is calculated from equation: $\eta_{th} = \frac{w_t - w_p}{q_{IN}} = 1 - \left(\frac{q_C}{q_{IN}} \right)$, where: w_t – specific work of the turbine; w_p – specific work of the feed pump; q_{IN} – heat transferred to the working fluid; q_C – heat rejected to the cooling water) higher about 50%, what is a result of the rise in the boiling point of the mixture during evaporation in a counter-flow heat exchanger and hence of reduction the influence of pinch point. The mixture ammonia-water leaving the heat exchanger has almost the same temperature as the heat source, what enables to reduce the irreversibility of the process and to improve the thermodynamic efficiency of the heat exchanger. One should add, that Kalina cycle has advantages, which distinguish it from ORC plant:

- the working fluid is a binary mixture of H_2O and NH_3,
- composition of the mixture may be varied during cycle in some versions,
- evaporation and condensation occur at variable temperature,
- cycle incorporates heat recuperation form turbine exhaust. (DiPippo, 2008)

5.3.2 Working fluid - mixture ammonia-water. Thermodynamic properties

Water (H_2O) and ammonia (NH_3) have similar physical properties, such as for example: molar mass, in order: 18 and 17 g/mol, have a constant boiling point at the ambient pressure, but the mixture of these two fluids behaves like a new fluid during Kalina cycle process. Main thermo-physical properties of ammonia-water mixture include:

- properties of the mixture can be altered by changing the ammonia concentration,
- the ratio of ammonia to water is not constant during all changes occurring in the cycle,
- properties causes mixed fluid temperature to decrease or increase without a change in the heat content,
- very low freezing temperature,
- a varying boiling and condensing temperature (specified above), what results from the fact, that ammonia has a lower boiling and condensing temperature compared to water and is more volatile component of two in the mixture. It causes, that during heating the liquid mixture, ammonia boils off first and during cooling of the mixture vapor, water condenses first. This feature of the mixture is shown in a phase diagram (Figure 5.3.2.1), which plots temperature vs. ammonia-water concentration for 550 kPa, as each phase diagram plot it for a specific pressure.

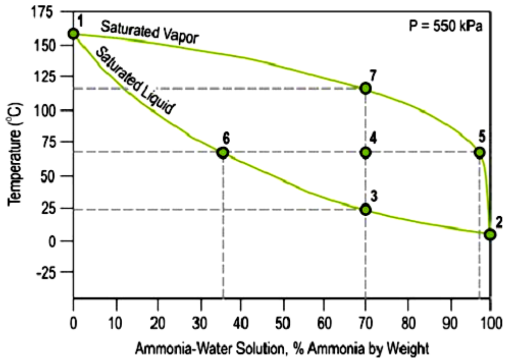


Figure 5.3.2.1 Ammonia-water mixture phase diagram

(Henry, Mlcak, 1996)

On the phase diagram above, point at 156^{o}C is the saturation point of pure water – that is temperature at which water boils or steam condenses at a pressure of 550 kPa, whereas point 2 is the saturation point of pure ammonia (6.9^{o}C) at 550 kPa.

On saturated liquid curve known also as boil point occurs initial vaporization during heating the mixture or complete condensation during its cooling. Whereas on the saturated vapour curve or dew point occurs complete vaporization or initial condensation of the mixture.

Considering 70 percentage content of ammonia in the mixture, it was noticed, that the mixture starts to boil in temperature 21^{o}C, what represents point 3 on the diagram above. Further heating leads to a rise in temperature and vaporization of the mixture, ammonia evaporates first. Before the mixture will reach point 7 on the diagram, that is will be vaporized completely, has two separated components in point 4 (area between both curves) liquid and vapour. As it is shown on the diagram, at the temperature 66^{o}C, point 5 is illustrated vapour, what is mark, that vapour of mixture contains the 97% of ammonia, i.e. the 3% of vapour. The liquid compound in point 6 contains the 36% of ammonia in the water solution. Vaporization the liquid phase is being continued up to the moment of reaching point 7 on the line of the saturated vapour – temperature 116^{o}C. Further supplying the heat causes superheating the mixtures vapour.

5.3.3 State of research

The Kalina cycle was invented by the Russian engineer Alexander Kalina in 1967 and firstly was demonstrated in Paratunka, Kamchatka, Russia. Then, in the early eighties, this cycle has been completely tested in USA. The industry was not ready to use this type of the technology due to it, that at first in 1980-1990 years, the technology development of the energy production was focused mainly on the improvement of high-temperature technologies effectiveness, that is of the large power stations on conventional fuels. Only an awareness of effective increasing the effectiveness of generating the energy and the necessity of the pollutants reduction to the atmosphere contributed to develop the new, ecological and effective technologies of energy production. Such a technology is the Kalina cycle, which is still under development, however, its participation and global roll on the energy production market is beginning to accelerate. Evidence are already existing and planned newly power plants, which constructions are preceded widely by developed in available literature (Dickson & Fanelli, DiPippo, Valdimarsson, Mlcak, Ibrahim, Kovach, Akasaka, Gupta, Rogdakis and other), full thermodynamic, exergy and economic analyses.

5.3.4 Existing installations

In the world are installed only a few plants made on the basis of the Kalina cycle – two power plants in Japan, one in: Iceland, USA and Germany. The first demonstration 3-6 MW plant was built and operated in Canoga Park (California) in USA in years 1991-1997, next two plants were installed in Japan in 1999: one of them – 5 MW incineration plant was built in Fukuoka city and the second – 3.1 MW plant with waste heat recovery from a steel plant, in Sumitomo. Another, 2 MW geothermal plant was built in Husavik, in Iceland and began operation in 2000. The last 3.4 MW geothermal plant was installed in Unterhaching in Germany in 2007. Details of described power plants are given in Table 5.3.4.1 (Ogriseck, 2009).

Table 5.3.4.1 Existing Kalina cycle power plants (Ogriseck, 2009)

Project location	**Country**	**Heat source**	**Electrical output (MWe)**	**Start up**
Canoga Park	USA	515^{o}C exhaust gas of gas turbine	3-6	1991 - 1997
Fukuoka city	Japan	Waste heat from incineration plant	5	1999
Sumitomo city	Japan	98^{o}C water, waste heat of production	3.1	1999
Husavik	Iceland	Geothermal brine at 124^{o}C	2	2000
Unterhaching	Germany	Geothermal	3.4	2007

5.3.5 Benefits for Polish situation compared with the other cycle alternatives

In Poland generating the electricity and the thermal energy constantly is based on using fossil fuels – mainly of hard coal in classical thermal power plants, power plants, combined heat and power plants and the technological processess carried out in them have a negative influence on the environment – the soils, water, ambient air, animals, plants and people. Therefore extremely important in the national energy production is the environment protection connected with the prudent and economical management of renewables energy carriers. Taking into consideration, that Poland ratified the protocol from Kyoto, committed for the reduction of greenhouse gasses emission and in the situation of quickly rising prices of the natural gas and petroleum, urgent using geothermal energy and biomass is necessary everywhere there, where it is possible technically and effective economically. Reserves of fossil fuels deplete gradually, and in Poland still stubbornly is not taking to the required scale on action for the mass electricity and heat production based on other fuels than hard coal. What is surprised in the country situation, as local combined heat and power stations, in which were started slow applying the geothermal energy or biomass, can develop on the basis of Kalina cycle or also ORC, creating the hybrid installations into this way. At financial support from the European Union, Poland in the degree greater than until now can use from renewables energy carriers, because Poland has at its disposal a sufficing potential of the design, the execution of equipment and building-assembly works.

In Polish conditions, possibility of construction of the power stations or hybrid combined heat and power stations based on using the Kalina cycle for power production constitutes the complete novelty for the here and now. These arrangements are perspective, however constitute the interesting alternative for mainly still applied in Poland, outdated, high-emission and less and less of efficient technologies based on consuming hard coal. In contrast to traditional manufacturing units, installations with the Kalina cycle for the power production as the one of the ORC technology, can be applied because of its a very attractive features such, as (benefits of using):

- compact design - do not require large areas under land development,
- few of components,
- small units can be started and remotely controlled without personel contribution – the plant can be made completely automatic,
- good performance at partial load,
- can be used at relatively low temperatures of upper energy source (geothermal, biomass), what means, that these solutions are not material-consuming as do not require using the special construction materials, what is not possible in the conventional power plants,
- long life – more than 20 years,
- quite high cycle efficiency,
- minimum maintanance requirements,
- high turbine efficiency – up to 85%,
- application of Kalina cycle for both electricity and heat production indicate for Poland considerable reduction of the economy dependence on the import of petroleum in the short time, what would increase the energy security of the country,
- enables to increase the participation of the renewable energy, (particularly of a geothermal water, which is the most often applied as the upper heat source in this type technological installations) in the domestic energy balance and in the complete

energy balance of European Community, that is achieving 20% of its participation in 2020,

- can be built as dispersed sources, as in the future perhaps to play a significant role in the decentralization of Polish energetics and to make the energy production independent of one fuel and from the one supplier of the energy,
- no emission or fuel consumption related to it - can contribute to the faster emission reduction of CO_2 about the 20% to 2020 in the country and because of that to fulfil the obligation to the European Union,
- quiet operation – also very important for enviromnent protection, reliability and very high availability,
- connected to the grid leads to various grid benefits: stabilization of grid load, reduction of distribution losses and constraints, so reducing the frequency of blackouts,
- more economical and short payout time.

In compared to the alternative ORC (Organic Rankine Cycle) technology of similar performance, Kalina cycle show the following advantages:

- reduces the heat transfer irreversibility in the heat exchanger (reduces influence of pinch point),
- condensation occur at variable temperature.

6 District heating systems and heating of buildings

District heating system is a heat distribution network with infrastructure, which is used for a production or a heat reception. Every system has a source, in other words, a place, in which the heat is generated. Next, it is transferred from the source to heat distribution networks delivering the heat to recipients - customers.

6.1 Description of district heating systems

For the heat transport as heating fluids are applied:

- steam about different parameters – is used as the heat transfer medium only for powering industrial recipients. Sent steam is saturated or has a temperature close to the saturation temperature.
- hot water – which is used to needs of heating, ventilation, preparing domestic hot water and is used for heat transport for long distance (from a few up to a dozen or so kilometers. At present in Poland, temperatures of hot water are on the level 130/70^{o}C, 130/60^{o}C or 130/50^{o}C. In internal networks, are applied the temperatures of water 95/70^{o}C or 90/70^{o}C.

The parts of heat distribution network are mainly:

- transit network – the sector for length above 0.5 km, on which the heat is not taken,
- arterial network – the sector applied for transferring the heat from the source to the housing estate heat networks or to the branches,
- branch heat network - the sector applied for transferring the heat from conduit to the housing estate networks or to the large central heating consumer,
- housing estate heat network - the sector applied for transferring the heat from branch heat network or intermediate pumping station to individual service pipes of housing or to industrial building,
- service pipes – heat pipes delivering the heat from branch to the building.

Heating networks are formed in the following manner:

- ring and multi-ring network – this heat network has high reliability, as heat is delivered from two directions. Ring heat network is used in Stargard. There will be at least one element in each ring with low flow (stagnant element),
- radial network – enables for transfer the heat only in determined direction (to determined consumers), has a single supply to each consumer, but no stagnant elements,
- so-called spider's heat network – one of the way of radial heat network solution consisting in, that each building is connected with the source with separated pipe. This type of heat network is highly reliable.

The main advantages of water–pipe network are:

- constancy of state of aggregation of heat medium (lack of necessity using devices such like: dehydrators, condensate tanks),
- lower heat loss,

- cheaper and high reliability than steam heat network,
- corrosion-proof due to total filling up with water.

Disadvantage of water-pipe network is (in comparison with steam heat network) is a high heat inertia during quick changes of the load.

6.2 Description of heating buildings

Task of heating is providing the heat to rooms, in which the men stay during winter. It consists in heating surrounding the man in cool seasons, in order to get the thermal balance between the human body and surroundings and of providing adequate conditions for the man under the thermal-physiological consideration.

Among the heating of buildings systems are distinguished:

- local heating (fireplaces, furnaces, electric heaters) – in which heat source is in the heated room,
- central heating – for all rooms of the building is exists only one heat source, which is composed of one or several boilers, placed in cellar (the most often). The rooms are equipped in of diverse type of radiators.
- remote control heating – in which from the one boilerhouse the heat is delivered to smaller or larger group of buildings and even the entire districts and cities – what takes place in Stargard.
- special heating arrangements – in which are used heat pumps, solar energy, biogas and other renewables.

For the purposes of this work, below more widely was discussed the remote control heating.

In the remote control heating the heat is supplied from boilerhouse or combined heat and power station to medical plants, factories, barracks, group of buildings, housing estate, or to the part of the city with the help of heat pipes. This type of buildings heating composes from the following main parts:

- boilerhouse – in which are boilers, chimney, pumps, installation of water treatment, measuring devices and accessories,
- network of pipelines – delivering the heat to different objects, heat carriers are often steam water or hot water,
- thermal centres – in which the heat from the heat network is transferred to the home installation,
- internal pipes network, which distributes the heat to the receivers.

The main advantages of remote control heating are mainly:

- ✓ economical using fuel,
- ✓ reducing of pollutants the atmosphere,
- ✓ eliminating necessity of the transport of fuel and ash to single buildings,
- ✓ reliability of acting thanks to the possibility of using several boilers,
- ✓ minimizing the service (Recknagel, 1994).

In the remote control heating systems, the delivery temperatures generally do not exceed 120ºC (in PEC even 130^{o}C as the this boilerhouse also deliver the heat to the industrial consumers) and temperatures of the return are not higher than 70 ºC (on account of producing the domestic hot water in exchangers of membrane thermal centres). For this system, bigger difference of the temperature between the power supply and return causes, that is smaller required stream of the fluid circulating in the heat network (lower investment and exploitation costs). The larger delivery temperature causes larger heat losses during the transfer.

6.3 Macroscopic models

Also for the purposes of this work, in this chapter is carried out and described model of district heating system for Stargard with aim of checking its action in the time.

In the macroscopic models is ignored the spatial structure of the system, which is lumped into blocks. Output signals are related to relevant inputs. The distribution system and consumers are seen from the water supply station – seen from the viewpoint of the supplier.

The model of district heating system includes dynamic and steady-state approach.

Essential element preceding making the model of the district heating system was analysis of variation of the outside temperature during year in Stargard, what shows the outdoor temperature uration curve – Figure 6.3.1.

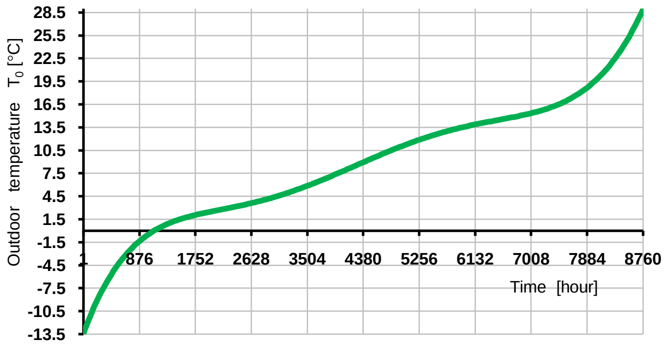


Figure 6.3.1 Duration curve of outdoor temperature

As it can be seen from above scheme that the outdoor temperature is ~ 12^{o}C for 5000 hours (period of heating season in Poland, about 7.5 months).

These models are treated as macroscopic and physical and the district heating is lumped into one model block. The presented models are carried out for radiators, water heat duty, pipe heat loss, building heat loss, building heat storage.

- ✓ Model for radiators (all equations according to Valdimarsson, 2009)

The radiator transfers heat from the district heating water to the indoor air. The relative heat load transferred from water is written as:

$$\frac{Q}{Q_0} = \left(\frac{\Delta T_m}{\Delta T_m}\right)^{(4/3)} = \left(\frac{T_s - T_r}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \cdot \frac{\ln\left(\frac{T_{s0} - T_{i0}}{T_{r0} - T_{i0}}\right)}{T_{s0} - T_{r0}} \right)^{(4/3)} \quad (6.3.1)$$

where:

$\frac{Q}{Q_0}$ - is the ratio of the actual heat output from the radiator to the heat output at design conditions,

T_i – indoor temperature (^oC),

T_s – water supply temperature (^oC),

T_r – water return temperature (^oC),

ΔT_m – logarithmic mean temperature difference for radiator (^oC), which is calculated from relation:

$$\Delta T_m = \frac{(T_s - T_i) - (T_r - T_i)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \quad (6.3.2)$$

- ✓ Water heat duty:

The heat load for the radiator is:

$$Q = C_p m (T_s - T_r) \quad (6.3.3)$$

and the load of water flow can be calculated as:

$$\frac{Q}{Q_0} = \frac{m(T_s - T_r)}{m_0(T_{s0} - T_{r0})} \quad (6.3.4)$$

- ✓ Building heat loss:

Relation for heat loss of the building are written as:

$$Q_{loss} = k_l (T_i - T_0) \quad (6.3.5)$$

in which k_l is constant and is the building heat loss factor. And in this case, relative heat loss can be defined as:

$$\frac{Q_{loss}}{Q_{loss0}} = \frac{m(T_i - T_0)}{m_0(T_{i0} - T_{oo})} \quad (6.3.6)$$

✓ Pipe heat loss:

The heat losses in the pipeline during its flow to the heated buildings are determined by the following relation – which is transmission effectiveness parameter:

$$\tau = \frac{T_s - T_g}{T_l - T_g} = e^{\frac{U_p}{m\ C_p}} \tag{6.3.7}$$

and reference value of τ:

$$\tau_0 = \frac{T_{s0} - T_g}{T_{l0} - T_g} = e^{\frac{U_p}{m_0 C_p}} \tag{6.3.8}$$

where:

U_p and c_p – constant for system.

After combining above equations received:

$$\tau = \tau_0^{\frac{m_m}{m}} \tag{6.3.9}$$

Next, the supply temperature is calculated from:

$$T_S = T_g + (T_r - T_g)\tau = T_g + (T_r - T_g)\tau_O^{\frac{m_0}{m}} \tag{6.3.10}$$

Steady State Model

In this approach is assumed, that buildings are no heat accumulation and return temperature is obtained from equation:

$$\frac{Q}{Q_0} = \left(\frac{T_S - T_r}{T_{S0} - T_{r0}} \cdot \frac{\ln\left(\frac{T_{S0} - T_{i0}}{T_{r0} - T_{i0}}\right)}{\ln\left(\frac{T_S - T_i}{T_r - T_i}\right)} \right)^{(4/3)} = \frac{T_i - T_O}{T_{i0} - T_{O0}} \tag{6.3.11}$$

in which:

$$T_{r,n+1} = (T_S - T_i)e^{-Z} + T_i \tag{6.3.12}$$

According to assumptions for this model the heat load supply is the same as the heat loss, what is written below:

$$Q_{\sup p} = Q_{loss} \tag{6.3.13}$$

and mass flow is calculated from relation:

$$m = \frac{k_l(T_i - T_0)}{C_p(T_s - T_r)} \tag{6.3.14}$$

where:

$$k_l = \frac{m_0 C_p (T_{s0} - T_{r0})}{T_{i0} - T_{00}} \tag{6.3.15}$$

Heat exchangers

In the heat exchanger heat is transfer from one flow stream to another without mixing the fluids. Equation for heat exchanger is defined as:

$$Q = m_h C_p \left(T_{h1} - T_{h2}\right) \tag{6.3.16}$$

where: T_{h1}, T_{h2} – inlet and outlet temperatures of the hot fluid,

and:

$$Q = m_c C_c \left(T_{c1} - T_{c2}\right) \tag{6.3.17}$$

where: T_{c1}, T_{c2} – inlet and outlet temperatures of the cool fluid,

$$Q = UA\Delta T_m$$

$$\Delta T_m = \frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln \frac{T_{h1} - T_{c2}}{T_{h2} - T_{c1}}} \tag{6.3.18}$$

Reference values are marked with subscript *o*.

For geothermal district heating network the reference values are:

- Indoor temperature $T_{i0} = 20^oC$
- Supply water temperature $T_{s0} = 80^oC$
- Return water temperature $T_{r0} = 40^oC$.

And for a fuel fired network:

- Indoor temperature $T_{i0} = 20^oC$
- Supply water temperature $T_{s0} = 90^oC$
- Return water temperature $T_{r0} = 70^oC$.

Reference outside temperature for Stargard is $T_{oo} = -16^oC$ and ground temperature was assumed at 15^oC. The model was done in EES program and below are plotted some figures resulting from analysis.

Results of simulation

Steady-state modelling

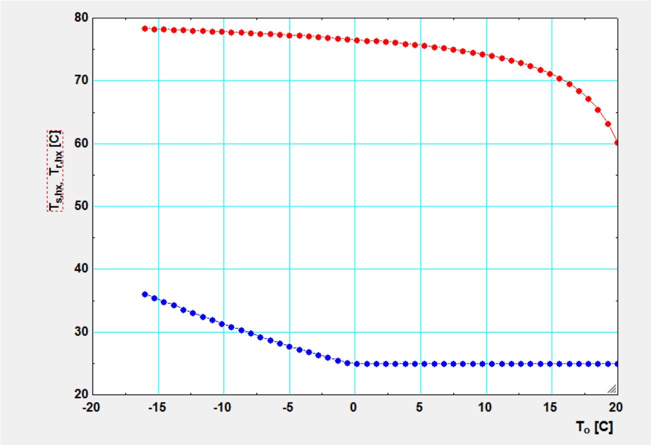


Figure 6.3.1 Temperature in the heating system

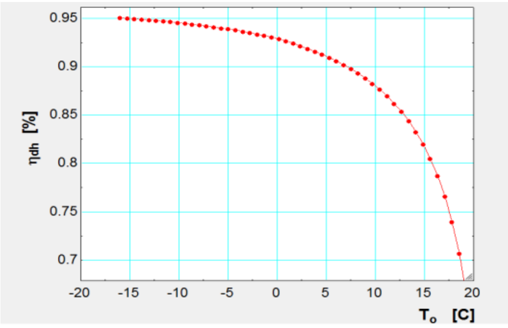


Figure 6.3.2 Effectiveness with outdoor temperature

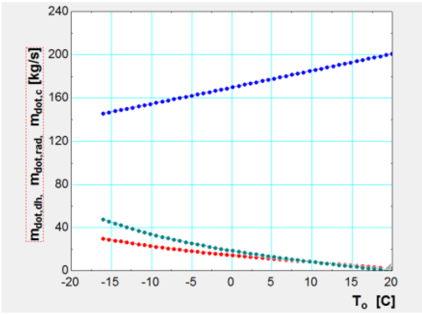
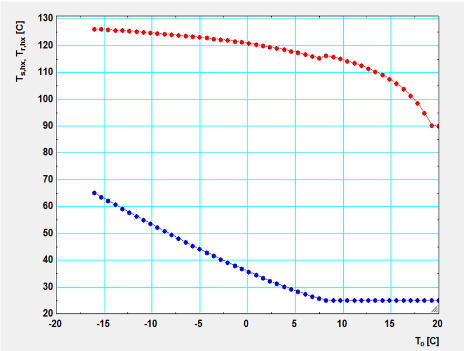


Figure 6.3.3 Mass flow of geothermal system

On figure 6.3.1 is shown the temperature in the different locations of the network. It is possible to notice that T_s and T_r decreases along with a rise in outdoor temperature T_o. Figure 6.3.2 illustrates the relationship between outdoor temperature and effectiveness of the heating system. How it is easy to notice that also heat load decreases as T_o increases. On figure 6.3.3 is shown decreasing of mass flow along with a rise in outdoor temperature.

From above modelling results, that for needs of the heating system in Stargard about parameters 130/70^{o}C the designed system would have too low parameters of the work (temperatures) and would not ensure Stargard full of the demand for the central heating of residents. Using the system, in which the return temperature is 70^{o}C is too high for the geothermal source with temperatures 80-90^{o}C, because the degree of its exploiting seems to be too low and ineffective economically. To the purpose of economy improvement of the used geothermal source, the return temperature should be lower.

Therefore was also designed heating system to higher parameters – 130/70°C, for which the way of modeling is identical for like in the previous case of the system to lower parameters. Calculations results are presented below.



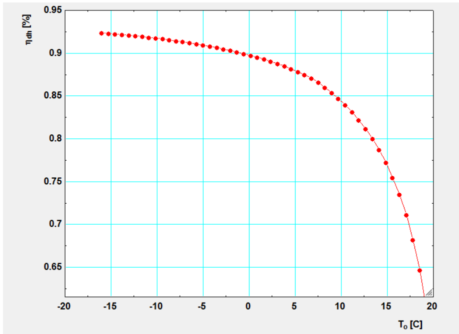


Figure 6.3.4 Temperature in the heating system   *Figure 6.3.5 Effectiveness with outdoor temperature*

From figure 6.3.4 results, that along with a rise in outdoor temperature drops the central heating demand (for heating purposes for example), hence the supply temperature is lower. At the ambient temperature 20°C, for example, the water is supplied to sanitary destinations mainly, that is apart from the heating season the supply temperature is fixed. The same is in case of return temperature.

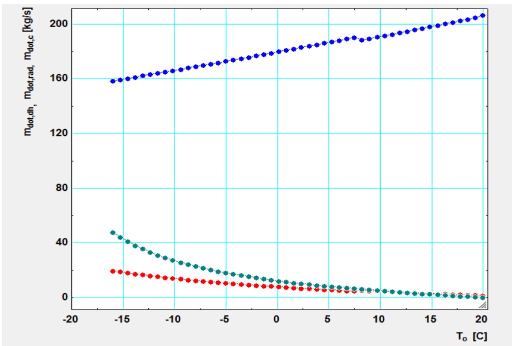


Figure 6.3.6 Mass flow of geothermal plant

Modelling results demonstrated, that system at geothermal conditions existing in Stargard, the modeled system would not satisfy demand for the central heating, because in both cases of the designed installation the mass flow is not enough to maintain indoor temperature 20°C (required mass flow is 330 m^3/h), therefore this system requires assisting by additional alternative energy sources in the form for example steam water produced in biomass or with co-firing biomass with coal.

6.4 Heat loss model

In modeling were also taken into account heat losses during its transfer to buildings (consumers) and the heat loss on the return to power plant. Heat losses during the transfer heat to recipients were estimated from the relation:

$$Q_{sloss}=m_{dh}*c_p*(T_{sdh}-T_{shx}) \qquad (6.4.1)$$

where:

T_{sdh} - the supply water temperature from power plant to district heating, (^oC)

T_{shx} - the supply water temperature from district heating to the building (inflow to the building, (^oC)

m_{dh} - mass flow of water, (kg/s)

and heat losses during return to power plant from equation below:

$$Q_{rloss}=m_{dh}*c_p*(T_{rhx}-T_{rdh}) \qquad (6.4.2)$$

where:

T_{rhx} - the return water temperature from the building to district heating, (^oC)

T_{rdh} - the return water temperature from the district heating to power plant, (^oC)

$T_{rdh}=(T_{rhx}-T_{ground})*tau+T_{ground}$

Results of modeling for two cases of system (80/40^oC and 130/70^oC) are presented below (Figure 6.4.1):

a) b)

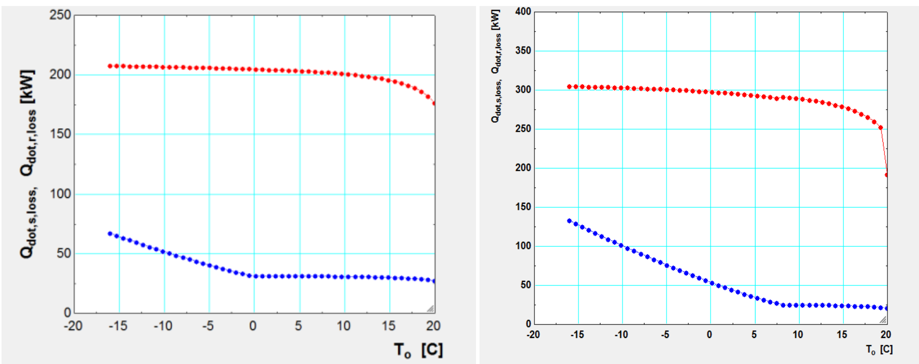


Figure 6.4.1 Heat losses during its transfer to the buildings: a) for 80/40^oC ; b) for 130/70^oC

On above figures it is visible that heat losses are higher in a system with higher temperatures of supply and return.

6.5 Network model

In the heat distribution network modeled for the purposes of the work, water is a heat carrier about the medium or high temperature. The heat network in Stargard is relatively recently modernized ring heating network and in this respect in the project was not taken into account its modification, whereas for comparison, model ways of supplying central heating consumers for the model of the heating network about parameters 80/40^{o}C and 130/70^{o}C were shown below.

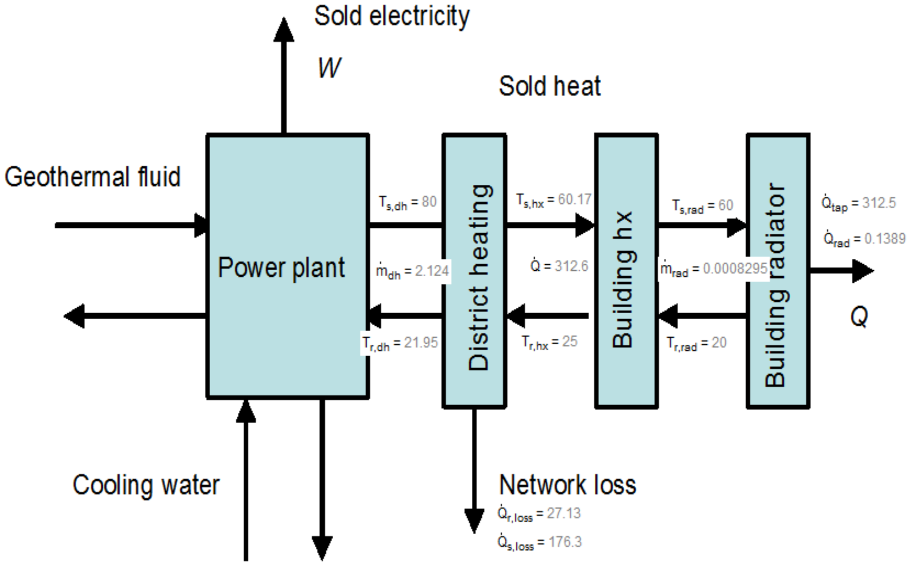


Figure 6.5.1 Model of geothermal heating plant for Stargard (80/40^{o}C) for outdoor temperature 20^{o}C

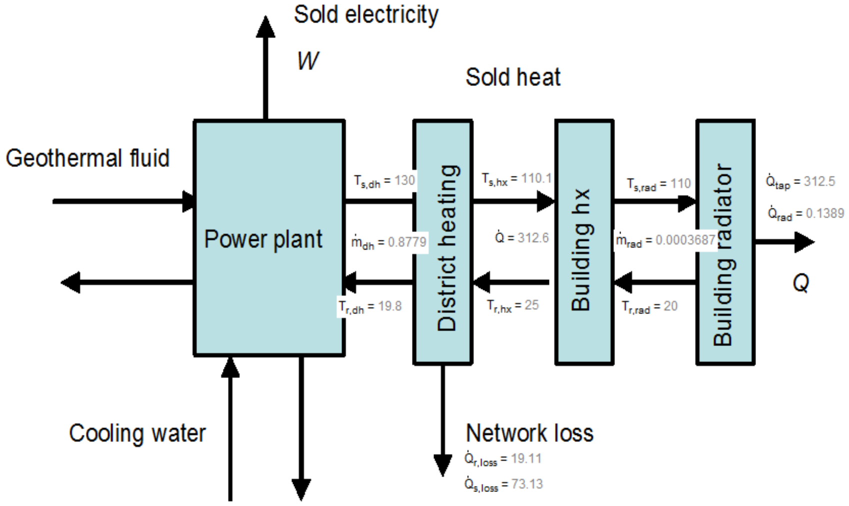


Figure 6.5.2 Model of geothermal heating plant for Stargard (130/70^{o}C) for outdoor temperature 20^{o}C

7 Cogeneration

Electricity and thermal energy production can be carried out in separated systems, such as: power stations and thermal power stations, as well as in associated arrangements - combined heat and power stations (CHP).

Cogeneration, that is associated generating of thermal and electric energy, is commonly well-known technology, defined as a thermodynamic process of chemical energy conversion of primary fuels to the useful carriers form – electricity and heat, which is being carried out in a single device (gas turbine, gas engine) or in the set of mutually connected devices (for example: gas turbine, waste-heat boiler and steam turbine). The scheme of the cogeneration process and effect of functioning of divided energetics in the comparison with associated energetics were shown on figure 7.1.

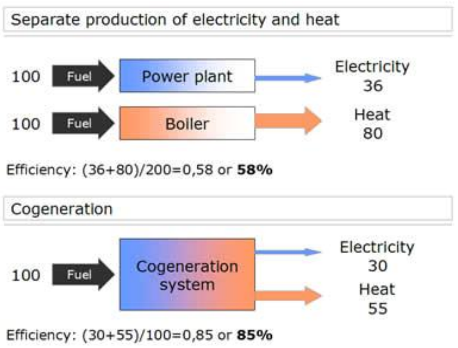


Figure 7.1 Scheme of cogeneration principle (www.eubia.org)

The main advantages of cogeneration are:

- enhanced security of energy supply,
- Kyoto Protocol obligations & CDM,
- reduced CO2 emissions, making a valuable contribution to the environment, particularly in light of,
- no transmission & distribution losses,
- conservation of valuable fuel resources, *(www.energymanagertraining.com)*
- high efficiency of energy conversion,
- as the least harmful influence on the environment – low emission of harmful gasses, dusts, noise, untreated sewage discharge and relatively small consuming water,
- beneficial rates of the profitability – the short payout time, high profit value.

It is estimated, that the development of cogeneration can achieve energy efficiency levels of around 90%, what would enable to avoid CO_2 emission of some 250 million tones to the 2020 in European Union. However, accomplishing these purposes is made conditional above all on two indicators, directly connected, which are:

- sort of the production technology of thermal energy and electricity – that is applying separated or associated systems,
- type of applied fuel – solid, liquid, gas.

7.1 Cogeneration in Poland

The cogeneration in Poland is not a new phenomenon, because stormy development of associated systems of the small and average power was in the last decade of the nineties. These arrangements were built with applying piston internal-combustion engines and gas turbines fed with gas fuels. The appearance of these arrangements enabled the construction of gas combined heat and power stations of the medium scale being based on gas-steam block with the gas turbine, which were fitted very precisely to needs of recipients and became a crucial point in the development of the entire electrical power engineering sector. At present, amongst the large arrangements a dominating role have the gas-steam combined heat and power stations, which appeared in Polish elektroenergetics at the end of the twentieth century.

In Poland exist also the combined heat and power stations consuming only a hard coal or co-consuming biomass with coal, because biomass is used in the electroenergetics mainly in this process.

The main gas-steam combined heat and power stations (CHP) and examples of combined heat and power stations co-consuming biomass with coal in Poland are in table 7.1.1.

Table 7.1.1 The main gas-steam combined heat and power stations and examples of combined heat and power stations co-consuming biomass with coal in Poland (www.ecg.com.pl, www.ec.lublin.pl, www.ec.zgora.pl, www.ens.pl, www.ec.rzeszow.pl, www.pec-siedlce.com.pl, www.ecwybrzeze.pl, www.dalkia.pl, www.pke.pl)

Gas-steam CHP	Electric power (MWe)	Heat power (MWt)
Gorzów	97.5 (achievable)	270 (achievable)
Lublin-Wrotków	235	150
Zielona Góra	190	135
Nowa Sarzyna	116	70
Rzeszów	101	76
Siedlce	14.6	22.4
CHP co-consuming biomass with coal (examples)		
Wybrzeże (composed of two CHP: in Gdańsk and Gdynia)	342	1235 (total)
Dalkia Poznań ZEC	275	930
Gorzów	275	930
'Bielsko-Północ' (EC2) in Czechowice-Dziedzice	55	172

In Poland in 2009 produced a total of 152 TWh of the gross electricity, from what 15.8% constituted the energy generated in cogenerational sources. The majority of this energy was produced in sources of the high-efficient cogeneration. In the same year, the heat production was 495 PJ/yr.

The purpose of Poland, according to energy policy guidelines to 2030, is doubling the energy production in the high-efficient cogeneration from the level of 24.4 TWh in 2006 to 47.9 TWh up to 2030, whereas participation of the generated electricity in cogenerational sources is supposed to grow from 16.2% up to 22% to 2030. The realization of these assumptions is supposed to be achieved through the modernization of existing installations and through the construction of the new manufacturing units.

7.1.1 Electricity demand

The main factor providing the technical and economic effectiveness for the combined heat and power stations is optimum fitting its arrangements to conditions existing in the place of the installation is. The selection of manufacturing powers of the arrangement and the relevant technological scheme requires earlier determining the demand for individual heat carriers, which is variable independently from installation arrangement parameters, in the twenty-four hour and seasonal cycle depending on the type of the consumer, the day and other factors. One should add, that the value of electricity and heat production results from structural parameters of manufacturing devices.

In order to carry out analysis of the profitability of construction of the combined heat and power station is necessary determining the basic energy quantities characterizing work of the installation, which are:

- electricity production,
- heat production,
- consumption of chemical energy of fuel.

Designing of this type installation is necessary to take into consideration mainly:

- electricity demand,
- heat demand,
- conditions of surroundings are variable in the time,
- demand for every energy carrier is changeable,
- prices of fuels, electricity and heat are variable in time.

Therefore, in order to carry out analysis of designed combined heat and power plant with Kalina cycle (for Stargard) was created systematic graphs enabling to determine the quantities of required electric and heat demand during year and the systematic graph of outdoor temperature, because its changeability influences momentary values of the demand magnitude for power and efficiency of steam turbine, power of heat exchangers, thermal power. The systematic graph of outdoor temperature for the region of Stargard is presented on figure 7.1.1.1.

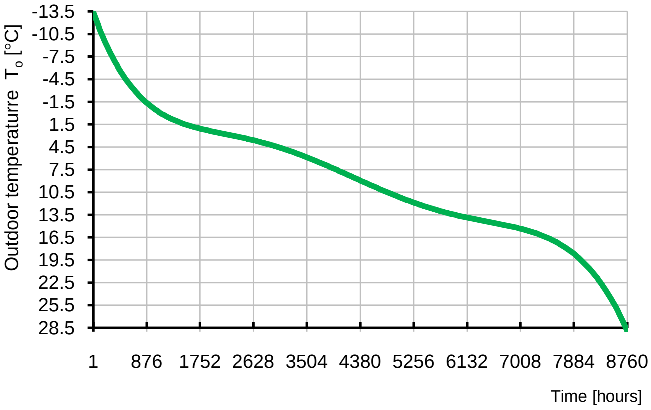


Figure 7.1.1.1 Systematic graph of outdoor temperature

On the basis of data source informing, that one resident of Stargard consumes on average 618 kWh/year of electricity and the population number is 69,951 estimated approximate electricity demand for the town from relation:

$$0.618 \text{ MWh/year/person} * 69{,}951 \text{ persons} = 43{,}230 \text{ MWh/year}$$

and obtained systematic graph of electricity demand for Stargard (Figure 7.1.1.2).

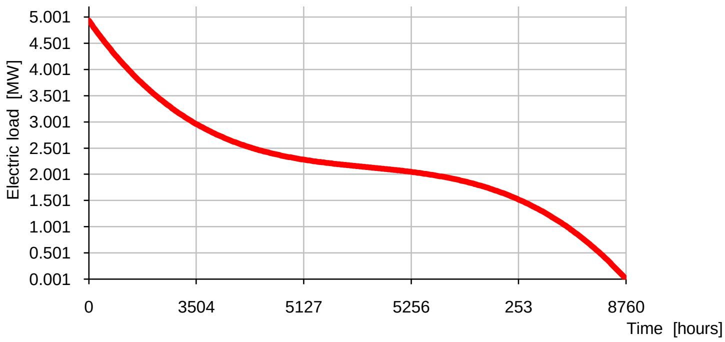


Figure 7.1.1.2 Systematic graph of electricity demand for residents of Stargard

Possible surpluses or deficits of electricity (particularly to industrial, technological needs) can be sold to the power grid or completed from it. On the basis of the above graph it is possible to estimate the optimum turbine power for Kalina cycle on the level ~4.3 MW.

7.1.2 Heat demand

According to assumptions the designed installation is supposed also to satisfy the heat demand. To this purpose was also carried out the systematic graph of heat demand (Figure 7.1.2.1) for the town using the systematic graph of the outside temperature.

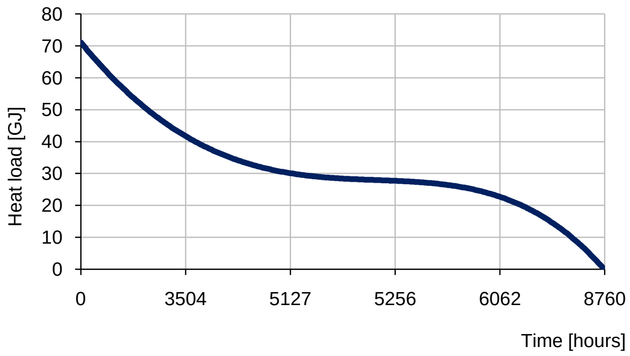


Figure 7.1.2.1 Systematic graph of heat demand for Stargard

Heat demand changing along with the outside temperature was calculated from the following relation:

$$\dot{Q}_g = \dot{Q}_{g\,max} \frac{T_w - T_z}{T_w - T_{z\,min}}$$

where:

Q_{gmax} - maximum heat demand (for minimum outdoor temperature),
T_w - indoor temperature (20^oC),
T_z - outlet temperature,
T_{zmin} - minimum temperature for region of Stargard: $T_o = -16^oC$.

From the above graph it is possible to conclude, that the optimum heat amount, which should be delivered to recipients during year is on level 50 GJ.

8 PEC Stargard - description of existed thermal power station and heat network in Stargard

The heat source for Stargard Szczeciński is the local thermal power plant (PEC– Przedsiębiorstwo Energetyki Cieplnej) on installed heat power of 116.2 MW, equipped with fine coal boilers. The heat is supplied to the heat distribution network with a length 57.8 km, working with 444 local thermal nodes houses substations. In 1998 was made a decision about the utilization the geothermal water for heating purposes in Stargard Szczeciński, when the town had at its disposal the centralized heating system providing the heat for about 75% inhabitants.

In the first stage of the investment, according to project, the energy of the geothermal water was supposed to be applied for the needed thermal energy production for hot municipal water system. In the next stages it was supposed to be used for the recreational and production purposes, mainly in the breeding and agriculture etc.

8.1 The existing coal fired power plant of PEC

The thermal power plant (PEC) in Stargard was formed in 1957 and the existing heating system is supplied from the heating station, in which are installed seven fine coal boilers: five boilers WR-10 about the power of 11.6 MW each and two boilers WR-25 about the power of 29.1 MW each. Each year in the boilers are burnt at about 29, 903 Mg of fuel – of fine coal. Like it was mentioned before, the total installed heat power of the heating station is 116.2 MW. According to the data from 2009 and 2010, yearly heat production for central heating and tap water was 617, 132 GJ, the quantity of the heat purchased from ‚Geotermia‘ was 88,845 GJ in 2009. The total quantity of the heat energy was 624, 482.2 GJ (2009, 2010). One should add, that the temperature of the heating medium is 130/70^{o}C in the maximum heat load and the flow rate is 1200 m^{3}/h.

Produced heat in the fine coal power plant of PEC is distributed to the local consumers, which are mainly: the housing industry, governments and institutions (including educational system), industry, other recipients.

8.2 Geotermia Stargard (working parameters)

Geothermal installation started in Stargard Szczeciński in 2005 (Figure 8.2.1, 8.2.2) is different than other existing heat plants in Poland due to the values of exploited geothermal water temperature – 87^{o}C. That is why, it consists only with geothermal dublet – production hole GT-1, injection hole GT-2 and of course, from the geothermal heat exchanger of the power 14 MW. Estimated exploitation productivity of the geothermal dublet is 300 m^{3}/h.

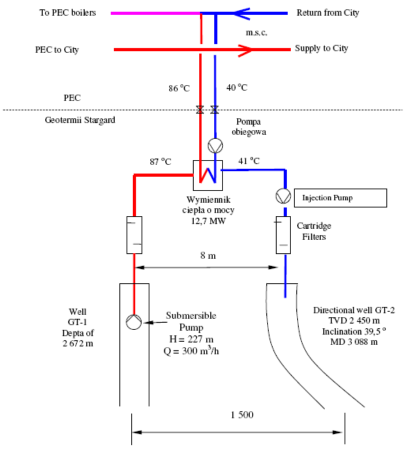


Figure 8.2.1 Scheme of existing geothermal thermal power plant in Stargard Szczecinski (Material received from the advisor of the Thesis)

Figure 8.2.2 Inside of the geothermal power station (Geotermia) in Stargard Szczeciński (Kubski, 2008)

Geothermal water, of which mineralization is 120 g/l is extracted with production hole for depth of the about 2670 meters and is injected to the deposit with sink hole, carried out as the directional hole, of which the head is remote from the head of the production hole at about 8 meters. The distance between the bottom ends of the both holes is 1500 meters. Working parameters of the described geothermal installation are shown in table 8.2.1.

Sformatowano: Czcionka: Arial, 14 pt, Kolor czcionki: Automatyczny

Table 8.2.1 Working parameters of geothermal installation in Stargard Szczeciński

Parameter		***Geotermia* Stargard**
Year of starting		2005
Temperature of water in deposit	[^{o}C]	86.9
Temperature of water on outflow	[^{o}C]	87
Total thermal power	[MW_t]	14
Depth of deposit	[m]	2670
Estimated exploitation flow rate	[m^3/h]	300
Mineralization of geothermal water	[g/l]	120

The geothermal power plant was started with the flow rate equal 150 m^3/h, however a fall in the productivity of the installation to 80 m^3/h took place relatively quickly, what was a result of the serious technical problems (corrosion, silting holes) and many failures, associated with the injection of the geothermal water (of geothermal heat exchanger and pump in it). In spite of many modernization works – mainly cleaning the injection hole, change of the pump, exchange of the function of holes, have not managed to solve technical problems by now, what caused considerable limiting the thermal power and the quantity of the heat removes to the Enterprise of the Heat Power Engineering (PEC) and hence to the municipal heating network. Next economic problems were a result of mechanical problems enough big, that with their result, in year 2007 were announced bankruptcy of ‚Geotermia' Stargard. However, purchase of the heat from geothermal installation lasted till July this year.

8.3 Coupling PEC with Geotermia (CHP)

In the destination of coverying the heat demand of Stargard, according to the project was assumed the cooperation of the geothermal installation with the existing boilerhouse – PEC. The way of coupling both installations is illustrated on Figure 8.3.1. In this type of arrangement, the geothermal water was directed with the help of the borehole pump to the heat exchanger, in which its heat is transfered to the tap water and then geothermal water is injected again to the same water-bearing layer through the injection hole.

Thermal power of geothermal installation was supposed to be used the entire year, what it marked, that it would be enough to the heat production in the summer. This would be enable for PEC to close-down the fine coal boilers, what would contribute of limiting consuming the hard coal in the classical thermal power station and in the process for considerable reducing emission of harmful substances into surroundings. However, many different mechanical and geological problems made impossible to achieve expected and obvious ecological, energy and economic effects resulting from such cooperation.

In spite of many mechanical problems with which struggled ‚Geotermia‘ Stargard in years 2005 – 2010, taking into account still promising and possible to exploit geothermal conditions existing in Stargard and awareness that the Enterprise of PEC is planning increasing the participation of the renewable energy sources in the most immediate time - the biomass and geothermal energy particularly – in the production of the thermal energy as well as considering the significant demand of the town for the electric energy, this work is an attempt to use and to couple the geothermal potential (Geotermia), biomass energy (co-firing with coal) and potential of the municipal heating system (which has PEC) in one energy installation, which is the designed arrangement of the geothermal combined heat and power station for Stargard Szczeciński.

On account of the constantly growing demand of the town for the electric and thermal energy and hence to the possibility of the realization of the cogeneration process in Stargard and taking into account relatively low temperatures of available geothermal water (~90^{o}C), in the concept of combined heat and power station, for generating the electricity suggested using the low-temperature Kalina cycle allowing on relatively high-efficient and ecological realization of energy processess based on exploiting the geothermal energy potential and also biomass potential in case of Stargard. The cogeneration process (CHP arrangements) can be carried out by coupling both types of existing intallations in Stargard – ‚Geotermia‘ Stargard with PEC (local boilerhouse, in which can be used boiler co-fired biomass with coal or biomass fired boiler instead of fine coal boiler). One of the installation models was illustrated on the picture below (Figure 8.3.1).

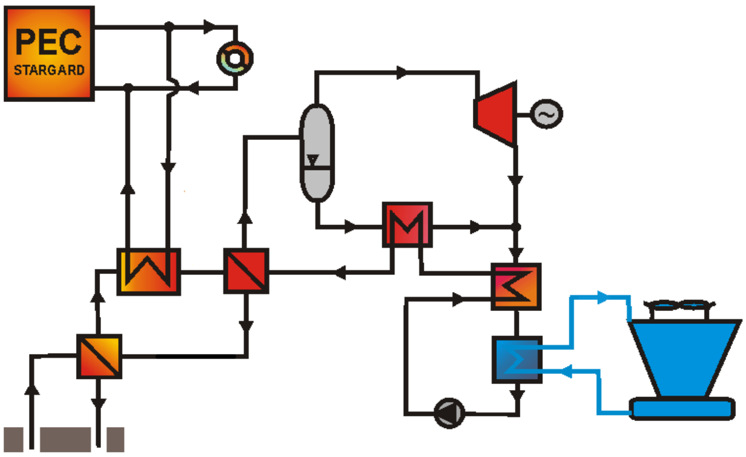


Figure 8.3.1 Scheme of the model CHP (being coupling PEC with Geotermia) based on using geothermal and biomass energy

8.4 District heating system and possible improvements

Stargard has the municipal district heating system, which is consisted of the local boilerhouse (PEC) about the power 116.2 MW and the heating networks length is 57.8 km working with 444 local thermal nodes houses substations. How it was wrote above, temperature of tap water is 130/70^{o}C and flow rate is 1200 m^3/h.

At present, the central computer controls the technological processes (what influences the effectiveness of the entire heating system), as in the thermal power station were performed the comprehensive modernization and the automation. Moreover, also was carried out the modernization of the heating system by making proper network connections replacing until recently existing radial layout of the network, with ring-shaped arrangement (Figure 8.4.1a,b), permitting for failure-free supplying heat input and consisting in eliminating gaps in its supply. In case of the breakdown of the water main line fragment this section is being excluded, and the heat is being supplied to the recipients from other direction of the flow. Also were automated and metering the thermal centres.

In the heating network modernization program was included an exchange of technically worn out section on new, based on the technology of preinsulated pipes and structure the next heat-pipes.

a) b)

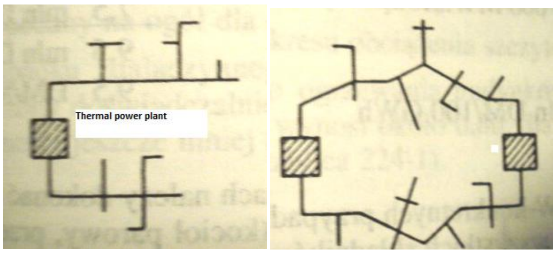


Figure 8.4.1 Different types of heating networks: a) radial network, b) ring network

From the main heating system use about 65 % of the whole of the residents of Stargard Szczeciński. In years 2004-2007 were liquidated altogether 8 local boilerhouses, connecting recipients to the main system. PEC is planning the liquidation of next local boilerhouses in the next years, as well as connecting to the municipal heat distribution network recipients, who use, at present, the individual heating with atile stoves.

9 Modeling and thermodynamic analysis of CHP installation with Kalina cycle

More and more common and known way to achieve ecological and economic benefits is connecting different types of the renewables for the electric and thermal energy production. Using diverse clean energy carriers lead for limiting utilization the fossil fuels and hence for the improvement in the state of the natural environment and its protection in the future, what is exquisitely important in the destination of protecting it from irreparable damages. As a result of the industry development, Poland is one of the countries contending with the problem of the environment transformations, therefore one of the way of the universal using renewable energy sources (natural wealth) is hybrid combined heat and power station. Its functioning consists in generating the energy with the simultaneous application two or more renewable energy sources or other than renewables.

Taking into account the plans of PEC connected with using the biomass energy and in spite of bankruptcy of Geotermia Stargard, but necessity of further developing the potential of the geothermal energy for the production of the thermal energy and also the necessity of the environmental protection and the necessity to provide the heat and electricity to Stargard, were made three models of municipal hybrid combined heat and power station with Kalina cycle, based on using geothermal energy and biomass along with fine coal energy (or only biomass energy) and incurred by coupling two installations existing in Stargard Szczeciński – Geotermia with PEC (the local thermal power plant).

Models

Enterprise of Thermal Power Engineering – PEC has a main contribution to supplying Stargard with the thermal energy, as about 65% of all households benefits from the heat system produced by PEC. In spite of ambitious plans of PEC, the thermal energy production after Geotermia fall, is produced again, only at using the fossil fuel - of fine coal, that is of lack of the rational management of environment resources and to its degradation. However, the growing energy demand requires to the need to use of the big accesssible potential of the geothermal and biomass energy. Therefore, with aim of meeting demand for growing needs to the thermal and electric energy of residents of Stargard and nearby towns and of ensuring the long-term supply of the energy, this Master's Thesis is an attempt of modelling and carrying out of thermoeconomic analysis for three models of the hybrid combined heat and power station with Kalina cycle (hybrid CHP with Kalina cycle) at the different assumptions of temperature and flow rate of the upper heat source for Kalina cycle enabling for electricity production:

- CHP with using geothermal water about the temperature 87^{o}C
- CHP with superheated steam water in boiler with co-firing
- CHP wit superheated steam water in biomass boiler

In all variants of the combined heat and power station mainly focussed on the amounts of efficiency and electricity production obtained in Kalina cycle due to the necessity of the decentralization of electricity supplies in the country and growing constantly demand of Stargard for this energy form and needs to increase the participation of the renewables in its production due to the required environmental protection.

One should add, that in all variants of installation, for cooling the condenser of Kalina cycle was used forced-draught cooling tower due to the long distance of the existing PEC thermal power station from the natural tank of water and for the attempt to apply of this type of cooling (still rarely applied in Poland) in combination with Kalina cycle.

9.1 CHP with using geothermal water about temperature 87^{o}C (Variant 1)

In this chapter have been presented an arrangement of the combined heat and power station with Kalina cycle, in which geothermal water about temperature T_{g1}=87^{o}C (available on outflow temperature of geothermal water in Stargard) is directed from the deposit to the geothermal heat exchanger (GHE), in which after partial transferring the heat to the network water to district heating needs. Then, geothermal water about lower temperature T_{g2}=75^{o}C flows to the vapourizer, in which transfers heat to the working medium of Kalina cycle, that is to ammonia-water mixture and next, is directed again to the deposit. Kalina cycle was described above.

However, after getting back heat in geothermal heat exchanger network water is directed to central heating consumers - to the district heating system. On account of relatively low parameters of used geothermal water for the heat production and hence the get low temperature of network water to thermal needs, is required its heat up to temperature 130^{o}C in the PEC boilerhouse. Scheme of the technical solution being based on an installation (started in 2005 in Stargard), being thermal coupling two installations - Geotermia and PEC is shown in Figure 9.1.1.

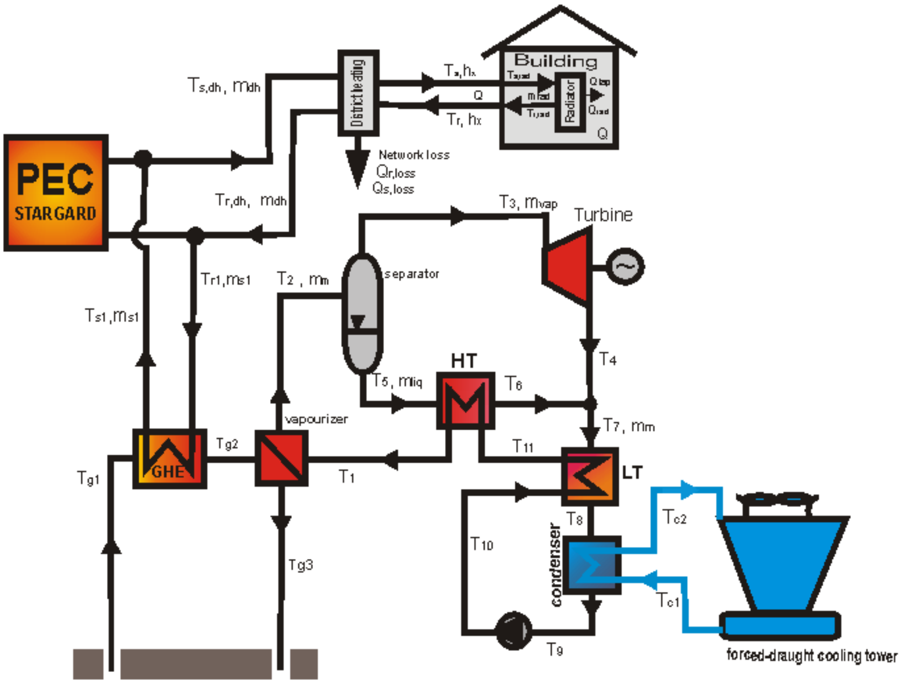


Figure 9.1.1 Scheme of the combined heat and power station being thermal coupling two installations - Geotermia and PEC

In the chapter have been presented calculations results for illustrated on the above figure the combined heat and power station with mixture ammonia-water, for which detailed scheme of the thermodynamic phase changes at pressure 550 kPa were shown on Figure 5.3.2.1. Calculations being aimed obtaining thermodynamic parameters of mixture and parameters of the work of Kalina cycle were made in EES program.

Essential element of analysis was estimating a stream of working medium vapour, values of the net power, power of the turbine, the electric power of the generator, the efficiency of Kalina cycle at assumptions different values of the pressure of mixture in the point 1 before vapourizer ($P_{high,\ 1}$) and for different values of the ambient temperature (changing in individual months, according to data from 2005 for West Pomeranian Province).
Results of calculations were presented in the tables 9.1.1 – 9.1.3.

In this variant, calculations were made taking following data and assumptions:

- as the upper heat source for CHP is used geothermal water about temperature T_{g1} = 87°C,
- Kalina cycle is powered geothermal water about temperature T_{g2} = 75°C,
- geothermal water flow rate is 300 m^3/h,
- temperature differences between fluids transfer heat in the geothermal exchanger is 5 K,
- specific heat capacity of water is c_w = 4.186 [kJ/kg*K],
- calculations were done for the scope of pressures of mixture: 10 - 23.5 bar and for the variable liquefying temperatures of working medium,
- in Kalina cycle circulates mixture composed of: ammonia - 82 % , water – 18%.

Table 9.1.1 Power and efficiency of Kalina cycle depending on the pressure of ammonia-water mixture at constant temperature of cooling water for each month – red frame gives 8.28°C(for March)

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$T_{source,in}$ [C]	$\dot{m}_{mvap}$ [kg/s]	$\dot{W}_{net}$ [kW]	$\dot{W}_{gen}$ [kW]	$\eta_{l,real}$ [%]
Run 1	10	0.82	8.28	75	34.25	756.6	987.3	3.251
Run 2	11.23	0.82	8.28	75	31.48	1179	1399	5.066
Run 3	12.45	0.82	8.28	75	28.82	1418	1639	6.094
Run 4	13.68	0.82	8.28	75	26.25	1558	1757	6.695
Run 5	14.91	0.82	8.28	75	23.75	1608	1800	6.911
Run 6	16.14	0.82	8.28	75	21.31	1587	1768	6.82
Run 7	17.36	0.82	8.28	75	18.91	1520	1691	6.53
Run 8	18.59	0.82	8.28	75	16.54	1400	1562	6.017
Run 9	19.82	0.82	8.28	75	14.19	1242	1392	5.335
Run 10	21.05	0.82	8.28	75	11.85	1060	1197	4.555
Run 11	22.27	0.82	8.28	75	9.519	841.5	964.5	3.615
Run 12	23.5	0.82	8.28	75	7.179	618.3	725.8	2.657

It results from the above table that the largest net power of the cycle (1608 kW), the electric power (1800 kW) and the efficiency (6.9 %) obtained for the pressure of mixture equal of 14.91 bar the smallest for 23.5 bar (617.9 kW) at assumption the fixed temperature of cooling water at ambient temperature (for March – 8.28°C). The variation of the net power and the efficiency of Kalina cycle depending on the pressure of the working substance illustrates the following graph (Figure 9.1.1).

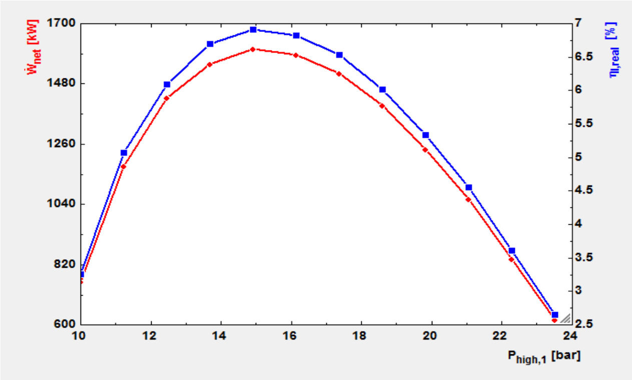


Figure 9.1.2 Changes of the net power and efficiency of the cycle in the function of the working pressure of mixture ($P_{high,1}$)

One should add, that to the electric power value of cycle affects the stream jet of the working medium (m_{vap}) on inflow to the turbine, what is presented on graph below (Figure 9.1.2). For pressure 14.91 bar this stream jet is 23.75 kg/s.

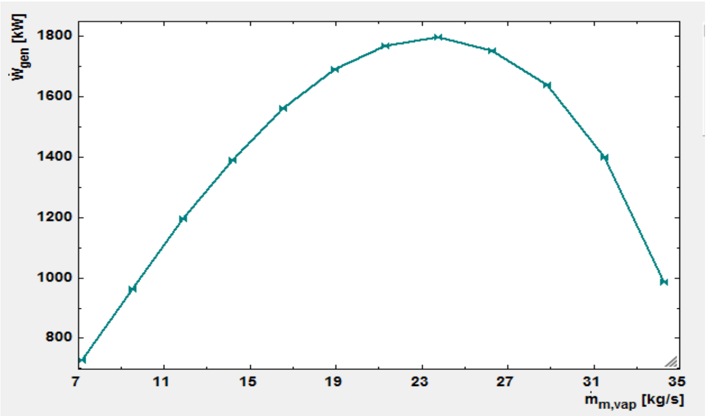


Figure 9.1.3 Change of the electric power of the cycle in the function of the mass flow of working fluid (m_{vap})

Next, similar calculations were performed for constant upper pressure of mixture, for which obtained value of net power is the largest (and hence for the permanent value of the pressure of mixture ammonia-water jet on the inflow to the turbine) at assuming variable temperatures of cooling water. Obtained calculations results are in the table below (Table 9.1.2).

Table 9.1.2 Power and efficiency of Kalina cycle depending on cooling water (liquefying of vapour of working medium) temperatures at constant pressure of working fluid

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$\dot{W}_{net}$ [kW]	$\dot{W}_{gen}$ [kW]	$\eta_{I,real}$ [%]
Run 1	14.91	0.82	4.54	1888	2083	7.68
Run 2	14.91	0.82	5.35	1829	2024	7.527
Run 3	14.91	0.82	8.28	1608	1800	6.911
Run 4	14.91	0.82	13.36	1228	1411	5.712
Run 5	14.91	0.82	17.79	899.1	1074	4.505
Run 6	14.91	0.82	21.69	617.3	785.5	3.32
Run 7	14.91	0.82	24.09	447.6	611.3	2.52
Run 8	14.91	0.82	24.03	451.8	615.6	2.541
Run 9	14.91	0.82	19.24	796.3	968.9	4.094
Run 10	14.91	0.82	14.68	1126	1306	5.353
Run 11	14.91	0.82	8.61	1583	1774	6.834
Run 12	14.91	0.82	5.41	1824	2019	7.513

Collected calculations results in the table above demonstrate, that the largest net power (1888 kW) and the efficiency (7.68 %) of cycle obtained for the lowest temperature in year equals -0.46°C (cooling water - 4.54°C) (in January), that is for possibly the largest widening the upper and bottom temperature of cycle, what influences for reducing the divergence between Kalina cycle and with Carnot cycle. On figure 1 have been presented the values of net power and efficiency of cycle depending on changes of condensation of working medium vapour.

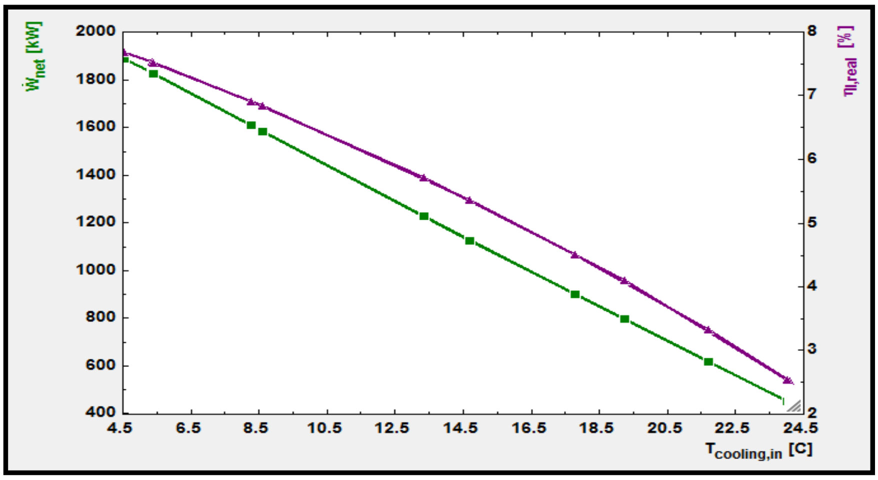


Figure 9.1.4 Variation of net power and efficiency depending on temperatures of the working medium vapour condensation

The lowest values of net power and efficiency acquired for the highest temperatures of cooling water, what marks, that for summer months, mainly for June (21.69°C) – 617.3 kW, for July (24.09°C) – 447.6 kW, for August (24.03°C) – 451.8 kW.

On the figure below (Figure 9.1.5) is illustrated the scheme one of the model solutions of combined heat and power station being coupling PEC with Geotermia supplying geothermal water, which temperature is 87°C.

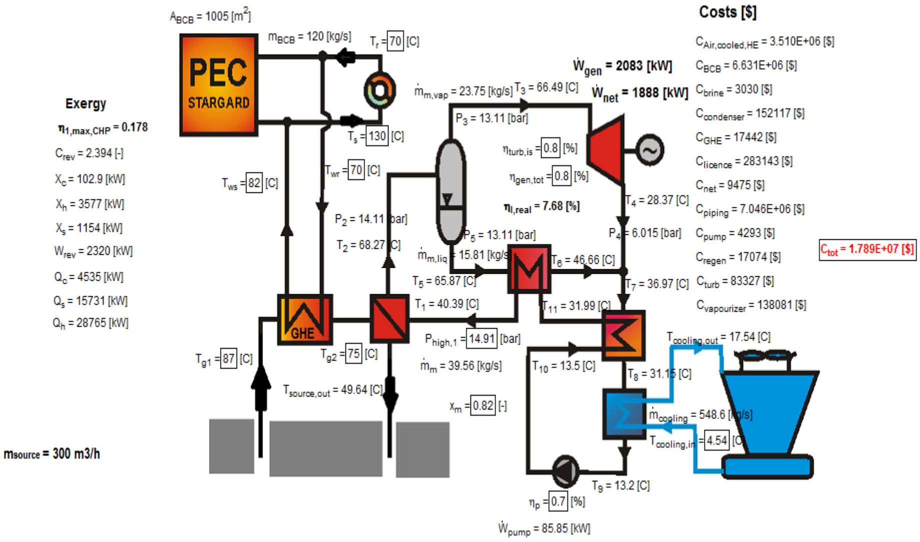


Figure 9.1.6 Model of the combined heat and power station (for Stargard) being coupling PEC with Geotermia supplying geothermal water about temperature Tg1 = 87°C

On the above scheme (Figure 9.1.5) also are included the investment costs (Costs in $) and exergy analysis (Exergy) being the components of economical and exergy analysis, which are in farther parts of this Master's Thesis.

From the above graphs and scheme results, that even the maximum turbine power (W_{turb} = 2083 kW) and net power (W_{net} = 1888 kW) of this type of installation with Kalina cycle, obtained for the most beneficial case for this variant - for working fluid pressure – $P_{high,1}$ = 14.91 bar is relatively low and in this case insufficient for covering the all-year-round demand for the electric energy of residents of Stargard (what requires using the upper heat source about the higher temperature). That is why, at this Thesis was suggested other type installations exploiting the geothermal energy altogether with other upper heat sources about higher temperature - the energy of biomass co-fired with coal and/or biomass energy, what is presented and described below.

9.2 Cycle with superheated steam water in boiler with co-firing (Variant 2)

In the concept of the this model was described the solution of the combined heat and power station, in which geothermal water flowing to the geothermal heat exchanger from the production hole, transfers heat in it to water and from it is injected back to the deposit with injection hole. However, water about temperature T_{w1} is directed to the installed in PEC co-firing biomass with coal boiler, in which after vapourizing and superheating its vapour, is led to vapourizer, in which transfers heat to working medium of Kalina cycle – ammonia-water mixture. In the boiler is also held a process of heating network water to district heating demand. The scheme of this type solution are illustrated on picture below (Figure 9.2.1).

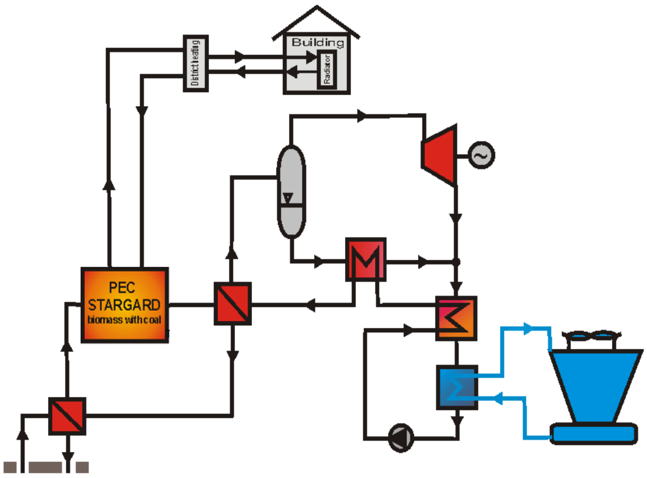


Figure 9.2.1 Scheme of the combined heat and power station with superheated steam water in co-firing biomass with coal boiler

Like previously, in this part of Thesis have been also presented calculations results carried out in EES program, for shown above the arrangement of the combined heat and power station with co-fired biomass and coal boiler.

In the tables 9.2.1 – 9.2.3 were presented results of calculations.

In this solution, in order to do calculations were made following similar data and assumptions to described previously (in variant 1):

- geothermal water flow rate is 300 m^3/h,
- in Kalina cycle circulates mixture composed of: ammonia - 82 % , water – 18%.
- temperature of geothermal is $T_{g1} = 87^oC$,
- Kalina cycle is powered by superheated stream water about temperature $T_{w2} = 130^oC$,
- temperature differences between fluids transfer heat in the geothermal exchanger is 5 K,
- specific heat capacity of water is $c_w = 4.186$ [kJ/kg*K],
- calculations were done for the scope of pressures of mixture: 15 - 35 bar (as at range of pressures 10 – 23.5 bar obtained very low values of electric power) and for the variable liquefying temperatures of working medium.

Table 9.2.1 Power and efficiency of Kalina cycle depending on the pressure of ammonia-water mixture at constant temperature of cooling water for each month – red frame gives 8.28^{o}C (for March)

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$T_{source,in}$ [C]	$\dot{m}_{mvap}$ [kg/s]	$\dot{W}_{net}$ [kW]	$\dot{W}_{gen}$ [kW]	$\eta_{I,real}$ [%]
Run 1	15	0.82	8.28	130	62.17	5917	6412	13.94
Run 2	16.82	0.82	8.28	130	60.18	6615	7112	15.58
Run 3	18.64	0.82	8.28	130	58.26	7131	7631	16.79
Run 4	20.45	0.82	8.28	130	56.4	7525	8030	17.72
Run 5	22.27	0.82	8.28	130	54.59	7785	8296	18.34
Run 6	24.09	0.82	8.28	130	52.82	7972	8489	18.78
Run 7	25.91	0.82	8.28	130	51.1	8071	8594	19.01
Run 8	27.73	0.82	8.28	130	49.4	8109	8640	19.1
Run 9	29.55	0.82	8.28	130	47.72	8090	8627	19.05
Run 10	31.36	0.82	8.28	130	46.06	8020	8565	18.89
Run 11	33.18	0.82	8.28	130	44.42	7896	8450	18.6
Run 12	35	0.82	8.28	130	42.79	7736	8299	18.22

On the basis of the above table it is possible to state, that the largest electric power (8640 kW), net power of the cycle (8109 kW) and the efficiency (19.1 %) obtained in case of the pressure of mixture equal of 27.73 bar and the lowest for 15 bar (5917 kW) at assumption the fixed temperature of cooling water at ambient temperature (for March – 3.28^{o}C). Obtained results of calculations were presented on the following graph (Figure 9.2.1).

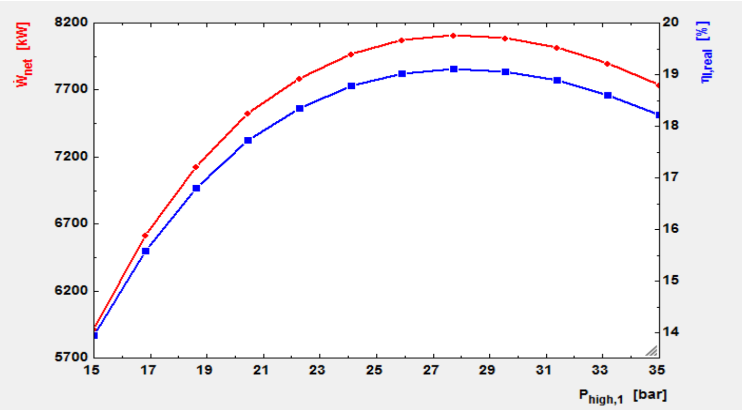


Figure 9.2.2 Net power and efficiency of the Kalina cycle as a the function of the vaporizer pressure ($P_{high,1}$)

However on figure 9.2.2 is shown the variation of the electric power depending on a jet of steam of the working medium on inflow to the turbine.

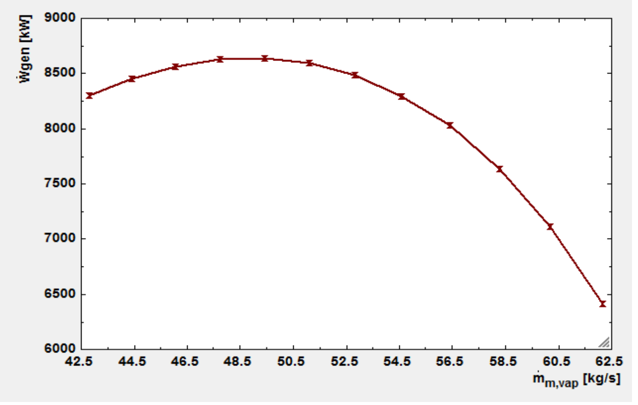


Figure 9.2.3 Electric power of the cycle as a function of the mass flow of working fluid (m_{vap})

The largest possible to obtain the jet stream in this range of pressures (15-35 bar) is 62.17 kg/s for pressure $P_{high,1}$=15 bar, whereas at pressure $P_{high,1}$ = 27.73 bar this stream is 49.4 kg/s.

For this variant of installation also were done calculations for variable temperatures of cooling water at assuming constant upper pressure of mixture, for which obtained value of net power is the largest. Calculations results are in the table 9.2.2.

Table 9.2.2 Power and efficiency of Kalina cycle depending on cooling water (liquefying of vapour of working medium) temperatures at constant vaporizer pressure

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$\dot{W}_{net}$ [kW]	$\dot{W}_{turb}$ [kW]	$\eta_{I,real}$ [%]
Run 1	27.73	0.82	4.54	8768	9305	20.03
Run 2	27.73	0.82	5.35	8623	9159	19.83
Run 3	27.73	0.82	8.28	8109	8640	19.1
Run 4	27.73	0.82	13.36	7231	7752	17.77
Run 5	27.73	0.82	17.79	6477	6989	16.55
Run 6	27.73	0.82	21.69	5814	6316	15.39
Run 7	27.73	0.82	24.09	5415	5910	14.66
Run 8	27.73	0.82	24.03	5425	5921	14.67
Run 9	27.73	0.82	19.24	6226	6734	16.11
Run 10	27.73	0.82	14.68	7000	7518	17.4
Run 11	27.73	0.82	8.61	8051	8581	19.01
Run 12	27.73	0.82	5.41	8612	9148	19.82

The table 9.2.2 illustrates, that during year it is possible to obtain the highest efficiency equals 20.03 %, net power (8768 kW) and electricity (9305 kW) of cycle. Figure 1 is shown the variation of net power and efficiency of cycle depending on temperature condensation of working medium vapour.

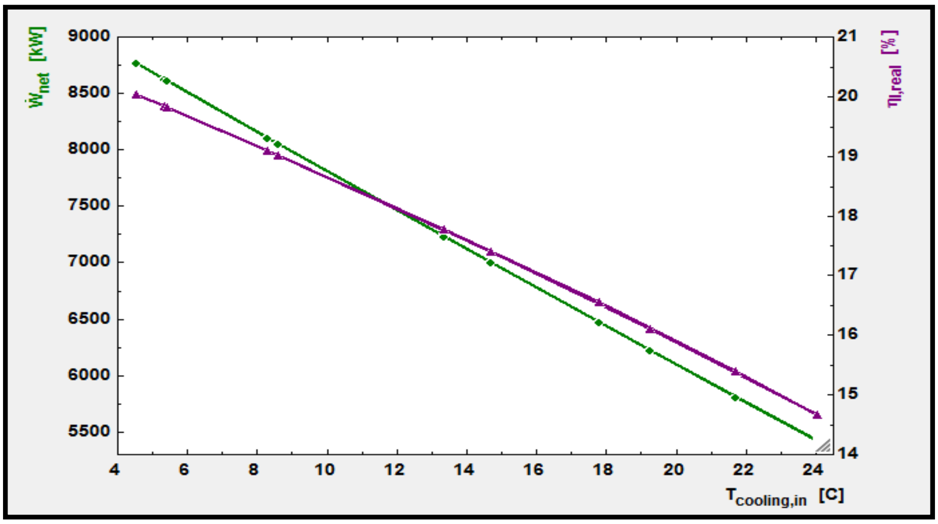


Figure 9.2.4 Efficiency and net power depending on temperatures of the working medium vapour condensation

The figure 9.2.5 presents the model solutions of combined heat and power station with Kalina cycle powered by steam water produced in installed co-firing biomass with coal in PEC.

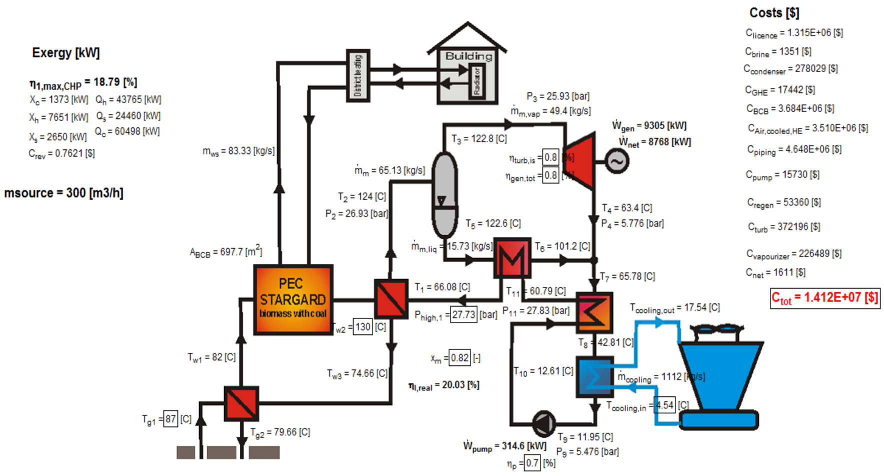


Figure 9.2.5 Model of the combined heat and power station with boiler co-firing biomass with coal

Like in previous variant, on the scheme (Figure 1) of power station also are included an exergy analysis (Exergy) and investment costs (Costs in $).

On the basis of presented calculations results it is possible to state, that obtained power of turbine on the level 9305 kW is larger than required turbine for electricity production. Possible surpluses of the electric energy can to be sold to the power grid. As can be seen to the combined heat and power station with modeled (for this variant) Kalina cycle for Stargard, is required turbine about relatively low power ~ 3.8 MW.

9.2.1 Biomass and coal

Reducing reserves of fossil fuels and the dangerous increase of the environmental pollution caaused by using them for energy production are a base for taking action being aimed at replacing fossil fuels with the renewable energy sources. One of such meaning energy substitutes of fossil fuels – of coal particularly – is biomass recently, which is the third renewables, as for the quantity in the world. It includes both by-products of forestry, products of wood industry, products of municipal waste disposal (wood chips, sawdust, wood waste) and of agriculture and energy crops of quick-growing trees and grasses (willow *Salix*, Pensylvanian mallow etc.). Therefore, using biomass seems beneficial both from a point of view of reducing emission, as well as the economic effectiveness of the production of the electric energy. That is why, at this work was made an attempt to use also biomass energy for thermal energy production and for electricity at using Kalina cycle.

Biomass and coal have the same chemical composition, however a content of main elements is different: of coal, sulphur, nitrogen, oxygen, hydrogen, chlorine, these differences were described in table 9.2.1.1.

Table 9.2.1.1 Biomass properties as fuel in comparison with coal (Kubica, 2010)

Component	**Designation**	**Unit**	**Biomass**	**Coal**
Coal	C	%	44 - 51	75 – 85
Hydrogen	H	%	5.5 – 7	4.8 – 5.5
Oxygen	O	%	41 – 50	8.8 – 10
Nitrogen	N	%	0.1 – 0.8	1.4 – 2.3
Sulphur	S	%	0.01 – 0.9	0.3 – 1.5
Chlorine	Cl	%	0.01 – 0.7	0.04 – 0.4
Volatiles	V	%	65 – 80	35 – 42
Ash content	A	%	1.5 – 8	5 – 10
High-heat value	HHV	MJ/kg	16 – 20	21 -32
Composition of ash				
SiO_2	-	%	26 – 54	18 – 52.3
Al_2O_3	-	%	1.8 – 9.5	10.7 – 33.5
CaO	-	%	6.8 – 41.7	2.9 – 25
Na_2O	-	%	0.4 – 0.7	0.7 – 3.8
K_2O	-	%	6.4 – 14.3	0.8 – 2.9
P_2O_5	-	%	0.9 – 9.6	0.4 – 4.1

One of the most disadvantageous features of biomass is high and changeable content of moisture - from 10 to 60 % (changes depending on the sort of biomass and the period of seasoning), what is a consequence of its the lower high-heat value and calorific value and it is often determined with statement, that: 2 tones of biomass under the energy account are equivalent for 1 ton of the hard coal. The majority of technical problems associated with combustion biomass in coal boilers it is possible to avoid applying technologies of co-firing biomass with coal.

Co-firing of fuel blend, biomass with coal, in Polish technological-technical conditions of the power industry is a favourable solution, as enables often to use existing coal boilers along with the entire infrastructure and hence requires the low investments at the modification of the preparation and charging the fuel to the boiler.

An advantage of co-firing is a possibility of using biomass at once in boilers about low or even high powers (by a dozen or so kW to sometimes 100 MW) acquiring the high effectiveness of conversion. Co-firing biomass with coal enables to increase the thermal efficiency (towards combustion only coal in the boiler), what is a result of reducing losses of incomplete combustion. Coal in this process is the stabilizer of the combustion process, what makes possible to use biomass about variable composition (particularly moisture).

Technological limiting applying co-firing is the participation of biomass dependent on the stability of its delivers, quality parameters (moisture) and from the organization of the combustion process. The content of moisture is the next limiting - biomass should contain below 30%.

In spite of described above limitations co-firing biomass with coal is effective technological solutions of implementing the renewables to the process of generating the energy in Poland.

9.3 Cycle with superheated steam water in biomass boiler (Variant 3)

In this chapter have been presented combined heat and power station with Kalina cycle powered by superheating steam water in biomass boiler. This arrangement of installation is very similar to described above variant 2 with boiler co-firing biomass with coal. It differs only a type of the used boiler to superheating steam water – biomass boiler. According to assumptions, the way of powering Kalina cycle is the same (in this case from biomass boiler), that is with superheated steam water about temperature 130^{o}C flowing to the vapourizer. One should add, that cycle of working medium-ammonia-water mixture and of superheated steam water is carried out in the same way, and the model of such type technical solution is similar like in variant 2, described in the previous chapter. The model of solution with biomass boiler is shown in figure 9.3.1.

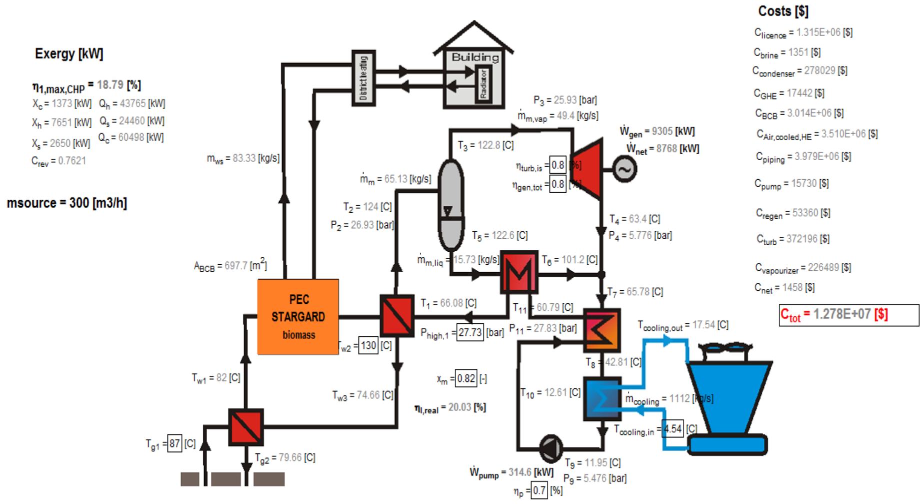


Figure 9.3.1 Model of the combined heat and power station with biomass boiler

In calculations were used analogous method, data and similar assumptions (in this case for biomass boiler) like in previous variant.

For Kalina cycle obtained identical calculations results like in variant 2.

Both installations differ in only the way of process operation of combustion fuel (biomass with coal or biomass) and charging fuel to the boiler what is connected with amount of investment and exploitation costs received in both cases.

For the purposes of this chapter, below was presented the model results of calculations (Table 9.3.1-9.3.2) (net power – W_{net}, efficiency, turbine power – W_{turb}, generator electric power – W_{gen} etc.), whereas received graphs are analogous to presented in the previous chapter.

Table 9.3.1 Power and efficiency of Kalina cycle depending on the pressure of ammonia-water mixture at constant temperature of cooling water for each month – red frame gives 8.28°C (for March)

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$T_{source,in}$ [C]	$\dot{m}_{mvap}$ [kg/s]	$\dot{W}_{net}$ [kW]	$\dot{W}_{gen}$ [kW]	$\eta_{I,real}$ [%]
Run 1	15	0.82	8.28	130	62.17	5917	6412	13.94
Run 2	16.82	0.82	8.28	130	60.18	6615	7112	15.58
Run 3	18.64	0.82	8.28	130	58.26	7131	7631	16.79
Run 4	20.45	0.82	8.28	130	56.4	7525	8030	17.72
Run 5	22.27	0.82	8.28	130	54.59	7785	8296	18.34
Run 6	24.09	0.82	8.28	130	52.82	7972	8489	18.78
Run 7	25.91	0.82	8.28	130	51.1	8071	8594	19.01
Run 8	27.73	0.82	8.28	130	49.4	8109	8640	19.1
Run 9	29.55	0.82	8.28	130	47.72	8090	8627	19.05
Run 10	31.36	0.82	8.28	130	46.06	8020	8565	18.89
Run 11	33.18	0.82	8.28	130	44.42	7896	8450	18.6
Run 12	35	0.82	8.28	130	42.79	7736	8299	18.22

Table 9.3.2 Power and efficiency of Kalina cycle depending on cooling water (liquefying of vapour of working medium) temperatures at constant vaporizer pressure

1..12	$P_{high,1}$ [bar]	x_m [-]	$T_{cooling,in}$ [C]	$\dot{W}_{net}$ [kW]	$\dot{W}_{turb}$ [kW]	$\eta_{I,real}$ [%]
Run 1	27.73	0.82	4.54	8768	9305	20.03
Run 2	27.73	0.82	5.35	8623	9159	19.83
Run 3	27.73	0.82	8.28	8109	8640	19.1
Run 4	27.73	0.82	13.36	7231	7752	17.77
Run 5	27.73	0.82	17.79	6477	6989	16.55
Run 6	27.73	0.82	21.69	5814	6316	15.39
Run 7	27.73	0.82	24.09	5415	5910	14.66
Run 8	27.73	0.82	24.03	5425	5921	14.67
Run 9	27.73	0.82	19.24	6226	6734	16.11
Run 10	27.73	0.82	14.68	7000	7518	17.4
Run 11	27.73	0.82	8.61	8051	8581	19.01
Run 12	27.73	0.82	5.41	8612	9148	19.82

The tables above illustrate, that calculation for this variant was done for the same range of pressures like in variant 2 and obtained the same scopes of characteristic thermodynamic parameters of Kalina cycle, for example: net power - W_{net}, efficiency, power of the turbine – W_{turb}, jet stream of the working medium – m_{vap} etc. Exergy calculations were also taken into account.

In two described variants (2 and 3) of the combined heat and power station with Kalina cycle, in which were used boilers for heating and superheating water steam, obtained higher turbines powers and efficiencies of the arrangements in comparison with the arangement (variant 1) without additional heated the water – with using in vapourizer geothermal water about temperature 87°C. Thermal fficiency of this arrangemet is 20.03 %. Substantial increase in efficiency and presented arrangements with Kalina cycle working in the same scope of temperatures liquefying of working medium vapour, results mainly from the value of heat stream supplying to the arrangement in the vaporizer, value of mixture pressure before and behind the vaporizer, of mass flow.

9.4 Equipment

According to design assumptions with main components (the same for all variants) of the modeled arrangement of the combined heat and power station with Kalina cycle are: geothermal heat exchanger, vapourizer, the boiler co-firing biomass with coal (or only biomass) for generating steam water powering vapourizer and auxiliaries, turbine-generator and auxiliaries, condenser, feed water system, forced-draught cooling tower, separator, low- and high-pressure recuperator, heat pipe for supplying the town into heat.

In the boiler with coal can be burnt dust of tree (as the type of biomass) due to its relatively good properties. It contains low moisture in range 3.8 - 6.4 %, the calorific value is between 15.2 - 20.1 MJ/kg.

Vapourizer for Kalina cycle is the same type like utility unit designed for Rankine cycle.

Due to similar physical properties of ammonia (NH_3) and water (H_2O), for example molecular weights, of ammonia – 17.03 kg/kmol and of water – 18 kg/kmol, in Kalina cycle is used conventional steam turbine (the same as in ORC) and that is why, no especially designed equipment is required.

In this installation is used forced-draught cooling tower on account of the long distance of existing installations (PEC and Geotermia) from natural sources of water (lakes and rivers) available on the area of Stargard. Therefore, exists a need to use air for cooling circulating water flowing from the condenser. This type of cooling towers are designed with the thought about the application in the most adverse conditions, so, as: high air temperature, lack of the enough water resources. The technical solution of project and structure of this type cooling tower can be commissioned to UNISERV company as th only company designing and building cooling towers in Poland.

9.5 Exergy analysis

As part of thermodynamic analysis has been also done model exergy analysis for all proposed variants of the combined heat and power station with Kalina cycle.

Exergy is the maximum theoretical useful work (or maximum reversible work) obtained as a system interacts with an equilibrium state. Exergy analysis provides accurate information of the actual inefficiency in the system and the true location of these inefficiencies (Murugan, 2008).

In order to determine effects of electricity production in the modeled combined heat and power station (for all variants) have been done calculations of the heat and exergy flow.

The exergy $(\dot{X})$ and heat $(\dot{Q})$ flows calculated being based on equations below (Valdimarsson, 2003):

and exergy and energy balances are:

$$\dot{Q}_h - \dot{Q}_s - \dot{Q}_c = \dot{W} \quad (9.5.1)$$

$$\dot{X}_h - \dot{X}_s - \dot{X}_c = \dot{W}_{rev} \quad (9.5.2)$$

Next, calculated heat capacity flow ratio power station from relation:

$$C_{rev} = \frac{c_C m_C}{c_h m_h}\bigg|_{rev} = \frac{\ln\left(\frac{T_h}{T_s}\right)}{\ln\left(\frac{T_c}{T_0}\right)} \tag{9.5.3}$$

The next element of analysis was calculation of first law maximum efficiency from equation below:

$$\eta_{I,max,CHP} = \frac{\dot{W}_{rev}}{\dot{Q}_h - \dot{Q}_s} = \frac{\dot{X}_h - \dot{X}_s - \dot{X}_c}{\dot{Q}_h - \dot{Q}_s} \tag{9.5.4}$$

Calculations results mainly for heat capacity flow ratio power station (C_{rev}) and first law maximum efficiency ($\eta_{I,max,CHP}$) for three variants are in tables 9.5.1 - 9.5.3.

Table 9.5.2 Capacity flow ratio power station (C_{rev}) and first law maximum efficiency ($\eta_{I,max,CHP}$) for variant 1 (for $P_{high,1}$ = 14.91 bar)

$\eta_{1,max,CHP}$ [%]	C_{rev} [-]	Q_h [kW]	Q_s [kW]	Q_c [kW]	X_c [kW]	X_h [kW]	X_s [kW]
0.178	2.394	28765	15731	4535	102.9	3577	1154
0.1757	2.401	28482	15449	4535	102.6	3504	1112
0.1672	2.426	27460	14427	4535	101.6	3247	966.3
0.1529	2.436	25688	12818	4535	99.85	2826	757.7
0.1402	2.466	24143	11304	4535	98.38	2484	586.3
0.1288	2.498	22782	9943	4535	97.11	2203	451.7
0.1219	2.518	21945	9106	4535	96.35	2039	377.8
0.122	2.518	21966	9127	4535	96.37	2043	379.6
0.136	2.478	23637	10798	4535	97.9	2377	534.1
0.1492	2.44	25228	12389	4535	99.41	2721	706.6
0.1662	2.428	27345	14312	4535	101.5	3218	950.6
0.1755	2.401	28461	15428	4535	102.6	3499	1109

From above table results that the highest achievable value of first law maximum efficiency ($\eta_{I,max,CHP}$) is 17.8 % at capacity flow ratio power station 2.394 (C_{rev}), whereas the lowest efficiency for this upper pressure of working medium is 12.19 % at C_{rev} = 2.518.

The variation of efficiency of Kalina cycle (for upper pressure of working medium 14.91 bar) along with the change of the ambient temperature is ilustrated on figure 9.5.1.

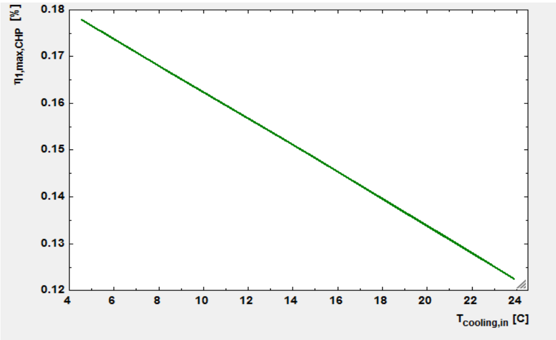


Figure 9.5.1 Variation of efficiency of Kalina cycle during year

However on figure 2 is shown, that the highest value of capacity flow ratio C_{rev} in the checked scope of pressures (10-23.5 bar) obtained for 10 bar.

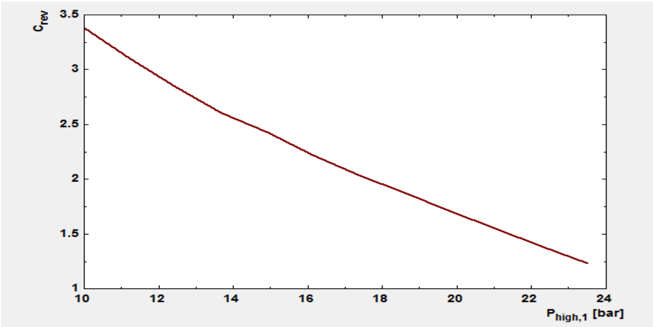


Figure 9.5.2 Values of capacity flow ratio C_{rev} in the scope of pressures (10-23.5 bar)

Table 9.5.3 Capacity flow ratio power station (C_{rev}) and first law maximum efficiency ($\eta_{I,max,CHP}$) for variant 2 and the same for variant 3 (for $P_{high,1}$ = 27.73 bar)

$\eta_{1,max,CHP}$ [%]	C_{rev} [-]	X_h [kW]	X_s [kW]	X_c [kW]	Q_h [kW]	Q_s [kW]	Q_c [kW]
0.2537	0.7621	7651	2650	102.9	43765	24460	4535
0.2516	0.7643	7546	2587	102.6	43482	24177	4535
0.244	0.7619	7173	2376	101.6	42460	23211	4535
0.231	0.7455	6553	2044	99.85	40688	21600	4535
0.2192	0.7568	6037	1754	98.38	39143	20055	4535
0.2089	0.7667	5602	1517	97.11	37782	18694	4535
0.2026	0.7728	5344	1381	96.35	36945	17857	4535
0.2027	0.7727	5350	1384	96.37	36966	17878	4535
0.2154	0.7605	5873	1664	97.9	38637	19549	4535
0.2275	0.7489	6396	1955	99.41	40227	21140	4535
0.2432	0.7534	7132	2361	101.5	42345	23147	4535
0.2514	0.7644	7538	2582	102.6	43461	24156	4535

For these two variants of CHP the highest achievable value of first law maximum efficiency ($\eta_{I,max,CHP}$) is 25.37 % at capacity flow ratio power station 0.7621 (C_{rev}) and the lowest – 20.26% at C_{rev} = 0.7728.

As in previous case, below are presented the changes of efficiency of installation during year- Figure 9.5.4 and for capacity flow ratio depending on upper pressure of ammonia water mixture in range of pressures 15-35 bar.

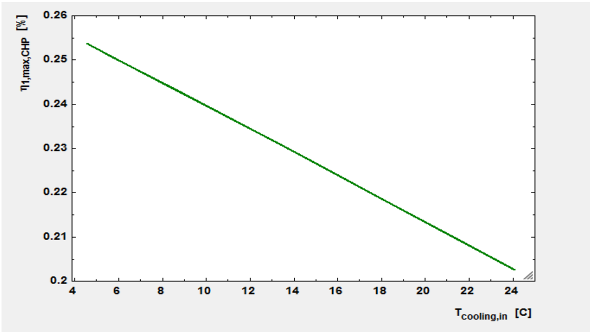


Figure 9.5.4 Variation of efficiency of Kalina cycle during year for variant 2 and 3

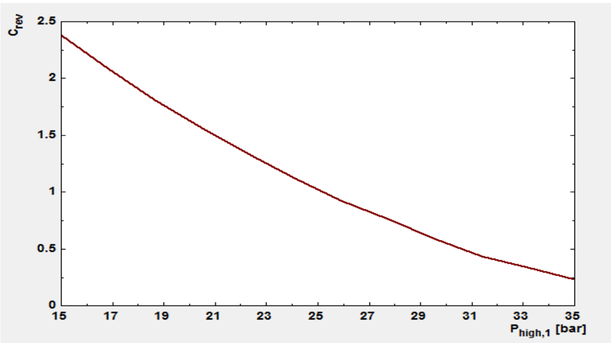


Figure 9.5.5 Values of capacity flow ratio C_{rev} in the scope of pressures (15-35 bar)

Analysis shows, that for both cases of arrangements with heating water in the boilers exergy efficiency is higher (in range 20.26 % - 25.37%) than in the case without additional heating water (12.2 % - 17.8%).

10 Software and calculations algorithm

In the destination of doing the calculations for described at this work the ammonia-water mixture, being the working medium of the Kalina cycle, used to the electricity production in the modeled combined heat and power station for Stargard Szczeciński, were used three computer programs.

10.1 EES

First of them is the program named Engineering Equation Solver (EES), which is intended for doing calculations in thermodynamics and related fields of knowledge as: of heat flow, energy management, fluid mechanics. It is window application, working in Windows software, having the built-in solver of non-linear algebraic sets of equations and extended databases, containing properties of substances being found in the widely comprehended thermal engineering. The producer of this software is company F-Chart Software, acting on the USA area.

One should add, that EES is the general equation-solving program that can numerically solve thousands of coupled non-linear algebraic equations and can also be used to solve differential and integral equations, provide uncertainty analyses, do optimization, convert units, perform linear and non-linear regression, check unit consistency and generate publication-quality plots. A major feature of this program is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability.

10.2 REFPROP

Reference Thermodynamical and Transport Properties (Refprop), version 7.0, which was also used for calculating basic physical properties of ammonia-water mixture as, for example: saturation temperature at determined pressure values, enthalpy, entropy, internal energy, etc.

REFPROP similarly to the higher described EES software, is a scientific program that uses equations for calculating the thermodynamic and transport properties of fluids at different temperature and pressure. This equations are generally used and are the most accurate equations available worldwide.

This program is authorized and distributed by National Institute of Standards and Technology (NIST).

The calculations of the properties, characterized Kalina cycle for the modeled combined heat and power station and the primary Kalina cycle, were done according to the computational algorithm, received directly from the advisor of the Thesis.

10.3 ACHE 2.0

The program was used to general designing and performing calculations for the forced-draught cooling tower, with simplified equations and procedures. This software provided the methods for estimating size, price of some components at the planning stage.

The developer of this software is Hudson Products Corporation, which main office is located in Sugar Land in Texas.

11 Economical analysis – capital costs of the power station

For proposed at the work arrangements of the combined heat and power station with Kalina cycle was also performed economical analysis, which constitutes the essential element in the process of design the installations generating the energy.

In analysis were included mainly costs of devices being essential storage elements of combined heat and power station, in other words, costs mainly of:

- heat exchangers (geothermal heat exchanger, vapourizer, low- and high-pressure recuperator),
- condenser with forced-draught cooling tower,
- boiler co-firing biomass with coal and biomass boiler,
- steam turbine for Kalina cycle,
- separator,
- fed pump,
- pipelines,
- costs of pumping,
- licence for the building site and using the installation.

In analysis were omitted structure costs of heat-pipes, of installation of distribution network and costs of geothermal boreholes, because the entire infrastructure of the transfer and the delivering the heat already exists in Stargard. Analysis also concerned costs of the heat and electricity production.

In all models final prices of heat exchangers are dependent on the market price of 1m^2 of their area of the heat transfer. Average normal price of heat exchanger is 30 \$/m^2 (21.88 €/m^2 according to the current rate of currencies). Therefore, essential element of analysis is determining the heat transfer area of every exchanger, from the equation below:

$$A = \frac{Q_{HE}}{LMTD \cdot U}$$

where:

Q_{HE} – thermal power of given heat exchanger, [kW],

LMTD – the log–mean-temperature-different, [K],

U – the overall heat transfer coefficient of heat exchanger, [W/m^{2}K]

Analogous calculations were done for all heat exchangers.

However, prices of fed pump, steam turbine, boiler are dependent on the market price of 1kW per power. As average normal prices per 1kW assumed: for pump – 50 \$ (36.46 €/kW), for turbine – 40 \$ (29.17 €/kW), for co-firing biomass with coal boiler – 220 \$ (160.45 €/kW). The price of these all components (for all variants) calculated from relation:

$$\text{Cost} = \text{Price of } 1\text{ kW} * Q \quad [\$/\text{kW}, (€/\text{kW})]$$

Table 11.1 Prices per 1 kW of devices

Device	**Average normal price per 1kW \$/kW (€/kW)**
Pump	50 (36.46)
Turbine	40 (29.17)
Co-firing biomass with coal boiler	220 (160.45)
Biomass boiler	180 (132.05)

Investment costs of power station are a sum of all components taken into account above, that is: $C_{tot} = C_{vapourizer} + C_{condenser} + C_{regen} + C_{brine} + C_{pump} + C_{turb} + C_{licence} + C_{piping} + C_{GHE} + C_{BCB} + C_{cooling\ tower}$

where:

$C_{cooling\ tower}$ – total costs of forced-draught cooling tower (designed at using Ache 2.0 Software)

The model calculations results for all variants are shown below:

11.1 Variant 1 – combined and heat and power plant using geothermal water about temperature 87^{o}C

As an example, for vapourizer:

A = 1,971 m^2 * 30 \$/m^2 (21.88 €/m^2) = 59,119 \$ (43,125 €)

In this model the capital costs of heat exchanger equals about 59,000 \$ (43,000 €).

For boiler:

Cost = 220 \$/kW*30,139 kW = 6 630 580 \$ (4 835 670.69 €)

$C_{tot} = C_{vapourizer} + C_{condenser} + C_{regen} + C_{brine} + C_{pump} + C_{turb} + C_{licence} + C_{piping} + C_{GHE} + C_{BCB} + C_{cooling\ tower}$ = 59, 119 + 35, 951 + 478.2 + 10,317 + 3,777 + 29,033 + 92,746 +6 787 *10^6 + 17,442 + 6 630 580 + 3 510 000 = 17 180 000 \$ (12 529 344 €)

Total price of power station is about 12 500 000 €

11.2 Variant 2 - cycle with superheated steam water in boiler with co-firing

For vapourizer:

A = 7516 m^2 * 30 \$/m^2 (21.88 €/m^2) = 225,489 \$ (164,448 €)

In this model the capital costs of heat exchanger equals about 225,500 \$ (164,456 €).

For boiler:

Cost = 220 \$/kW*16,745 kW = 3 683 400 \$ (2 686 297 €)

$C_{tot} = C_{vapourizer} + C_{condenser} + C_{regen} + C_{brine} + C_{pump} + C_{turb} + C_{licence} + C_{piping} + C_{GHE} + C_{BCB} + C_{cooling\ tower}$ = 225, 489 + 278, 029 + 53360 + 1351 + 15,730 + 372,196 + 13,100 000 + 4 548 *10^6 + 17,442 + 3 684 000 + 3 510 000 = 14 120 000 \$ (10 297 692 €)

Total price of power station is about 10 300 000 €

11.3 Variant 3 - cycle with superheated steam water in biomass boiler

In this model only assumed only other price for 1 kW of the boiler (because biomass boilers are cheaper than co-firing biomass with coal boilers).

For vapourizer:

A = 7158 m^2 * 30 \$/m^2 (21.88 €/m^2) = 214,757 \$ (156,662 €)

In this model the capital costs of heat exchanger equals about 215,000 \$ (157,000 €).

For boiler:

Cost = 180 \$/kW*16,745 kW = 3 014 000 \$ (2 198 105 €)

$C_{tot} = C_{vapourizer} + C_{condenser} + C_{regen} + C_{brine} + C_{pump} + C_{turb} + C_{licence} + C_{piping} + C_{GHE} + C_{BB} + C_{cooling\ tower}$ = 214, 757 + 250, 088 + 36,720 + 11,290 + 19,088 + 348,305 + 12,210 000 + 5 586 $*10^6$ + 17,442 + 3 014 000 + 3 510 000 = 15 900 000 $ (11 595 843 €)

Total price of power station is about 11 600 000 €.

It results from economic analysis, that variant 2 is the most beneficial solving the agreement of the installation, that is the combined heat and power station with the boiler co-firing biomass and coal, which investment costs are about 10 300 000 €. One should add, that as a result of thermodynamic analysis, for this variant of the combined heat and power station, were obtained good parameters of its work such like: turbine powers and efficiencies. It is possible to state, that this arrangement is the most profitable economically among all variants presented in this paper.

12 Environmental analysis

At present, extremely important issue associated with the use of energy installations is their harmful influence on the natural environment, therefore the main task setting for producers of electricity and thermal energy is pursuing to reducing their interference in the natural environment through limiting emission of pollutants to the atmosphere. Many energy and ecological advantages result from applying the associated electricity and heat production at using of renewables.

Utilization the geothermal energy for the electricity and the thermal energy production is one of ways of preventing emission into atmosphere of large amounts of gasses and dusts,which arise while burning fossil fuels. The next method, which is described at this work, is using co-firing biomass with coal in manufacturing individuals. Combustion coal causes substantial emission of carbon monoxides (responsible for appearing of the greenhouse effect), sulfur dioxide and nitrogen oxides (causing appearing of acid rains), of organic pollutants, mainly of aromatic hydrocarbons, of volatile ash (which contains of heavy metals and radioactive elements) and volatile organic compounds.

Co-firing coal with biomass (that is addition of biomass to coal) or burning only biomass in boilers considerably reduces emissions of CO_2, NO_x, SO_2 and organic pollutants independently of the applied burning technology and co-firing enables for increasing the efficiency of converting the chemical energy of coal.

By combustion biomass or coal with biomass is possible limiting model values of emission, estimated on the basis of pollutants concentrations in air on the area of the district Stargard Szczeciński (Table 12.1).

Table 12.1 The levels of concentrations of main pollutants in air (www.wios.szczecin.pl)

Type of pollutants		Emission
SO_2	[Mg/year]	*477*
NO_2	[Mg/year]	*1186*
CO	[Mg/year]	*3331*
Dust	[Mg/year]	*1073*
Pb	[Mg/year]	*892,85*

Table 12.1 Cont.		
As	[kg/year]	*79,66*
Cd	[kg/year]	*121,96*
Ni	[kg/year]	*418,2*
BP	[kg/year]	*157*
C_6H_6	[Mg/year]	*12,29*

As a result of replacing the energy coming from coal, with energy from renewable sources are obtained benefits called the ecological effect, which is measurable economic quantities definite in [€/kWh] of electric energy or in [€/GJ] of thermal energy, which is achieved thanks to replacing coal with the energy from renewable sources. In the following table is placed model results of ecological effects analysis of co-firing biomass with coal in energetics (Table 12.2).

Table 12.2 Ecological effects of co-firing biomass with coal in energetics

No.	**Type of boiler**	**Power of boiler [MW]**	**Type of coal/biomass mixture [% of biomass]**	**Ecological effect [€/GJ]**
1.	OR – 32 (stoker-fired steam)	25.68	Coal/pellets 9 15.1	0.59 0.87
2.	OR – 32 (stoker-fired steam)	25.68	Coal/chips 3.2 5.0	0.32 0.30
3.	WLM 2.5 (stoker-fired water)	2.91	Coal/chips 15	0.94
4.	WR 25 (stoker-fired water)	29.08	Coal/sludge precipitates 2.5 d.m 3.6 d.m	-0.24 -0.24
5.	CYMIC-135 (CFB)	104	Coal/chips 9.4	0.38
6.	OP-130 (pulverized fuel)	90.1	Coal/chips 3.3 5.0	0.052 0.14

To sum up, it is possible to state, that main benefits resulting from using biomass in processes of co-firing are:

- reducing emission pollutants to the atmosphere,
- increasing of the energy safety of country (diversifying supplies of the energy),
- limiting consuming non-renewable fossil fuels,
- possibility of waste post-industrial recycling, sewage deposits, bone meal with the guaranteed ecological effect. Productive using waste of forest cuttings, urban greenery, wood in the secondary form, moreover of waste of the wood industry, furniture, pulp and paper industry,
- production ecologically clean energy without incurring extra costs for the modernization of combustion process, at keeping a proper participation of biomass in mixture, for dust boilers - 5 %, for stoker-fired boilers - 10%, and for CFB ~ 20-30%,
- modern technology development connected both with acquiring product ranges of biomass as well as processing them in the process of conversion to electricity energy and heat,
- fulfilling the obligation of the production or the purchase of the energy from renewables resulting directly from the act energy law.

13 Conclusions

The object of modeling and thermoeconomic analysis at this work, was the combined heat and power station with Kalina cycle, arising as a result of coupling two types of the installation existing in Stargard Szczeciński - of local boilerhouse PEC with Geotermia. Calculating basic parameters of its work was an aim of analysis of the combined heat and power station, for which three models were made, mainly of mass flow of working medium, efficiency, power of the steam turbine along with the generator, and hence of possible generated electric power and determining on this base the possibility of using Kalina cycle to needs of the electricity production for Stargard Szczecinski, that is estimating if the value of the electric energy generated using Kalina cycle is sufficient to full satisfying the demand for electricity of Stargard residents.

At work was modeled mainly Kalina cycle with mixture ammonia-water as the working medium supplied depending on the variant - with energy of geothermal water about the low temperature (variant 1) or with energy of geothermal water with supported biomass energy (variant 3) or with energy coming from co-firing biomass with coal (variant 2). However ,the heating system of the town is based on solution the heating system existing in Stargard about parameters of network water 130/70^{o}C.

An idea of the work was superstructure of the existing heating system - with arrangement for the electricity production with Kalina cycle. However, making the model of the heating distribution network for Stargard was required for the purposes of this work.

Analysing results of calculations of the electric power on account of the size get and the efficiency of the arrangement, one should state, that amongst described variants at the work of the combined heat and power station, the most favourable solution is powering Kalina cycle with geothermal energy assisted coming from co-firing biomass and coal. Obtained electric power of generator in this case is equal 9,305 kW, whereas efficiency of arrangement is 105.2%, what enables full covering the demand for the electric energy of residents of Stargard at lower investment costs of the arrangement compared with variant 3 (at exploiting biomass energy as fuel in the boiler). On account of using the forced-draught cooling tower for cooling the steam of the working medium (due to lack of enough natural resources of water) in all three variants of the arrangement the greatest electric power and the efficiency of the circulation were get for the winter season (that is of the lowest temperatures in the sequence of the year, that is mainly for months: December, January, February), whereas the lowest for summer months - June, July, August. The value of the power and the efficiency of Kalina cycle will be dependent on the outside temperature, as the temperature of cooling the steam of the working substance changes along with the temperature of surroundings.

The carried out thermodynamic analysis showed, that parameters of geothermal water, that is the temperature – 87^{o}C and mass flow are insufficient to full satisfying the demand for the central heating and the electric energy of Stargard residents, therefore additional using the boiler co-firing biomass with coal in order to improve parameters of the upper heat source for is required for Kalina cycle and for the heating network.

On the basis of economical analysis results for three variants of combined heat and power station it is possible to state, that the arrangement with the boiler co-firing biomass with coal is the most profitable in terms of the incurred investment expenditure on its structure as well as to the quantities of obtained parameters of its work.

One should add, that investment costs can seem relatively high, although this type of installation can contribute to relatively quick increasing the participation of renewable energies to the heat and electricity production on the Stargard area.

14 Recommendations for further work

Later works associated with using Kalina cycle for electricity production for Stargard would concern analysis of the possibility of applying other range of working pressures, of temperatures or the percentage composition of the working medium of ammonia-water mixture or powering the cycle additionally with waste energy coming from industrial processes and hence with attempt to get better parameters of the work of the combined heat and power station.

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