

Feasibility Study of Binary Geothermal Power Plants in Eastern Slovakia

Analysis of ORC and Kalina power plants

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UNIVERSITY OF ICELAND



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of Akureyri

FEASIBILITY STUDY OF BINARY GEOTHERMAL POWER PLANTS IN EASTERN SLOVAKIA

Analysis of ORC and Kalina power plants

Martina Kopuničová

A 30 credit units Master's thesis

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the University of Akureyri

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ABSTRACT

Slovakia is among the countries of the European Union which signed the regulation related to renewable energy source utilization.

According to European Union statistics from 2005, Slovakia is number 22 in terms of renewable energy usage, with 6.7% of its energy from renewable sources. The regulation states that by the year 2020, Slovakia must increase its usage to 14%, which means doubling the renewable fraction of total energy consumption.

Slovakia is one of the countries in central Europe with high geothermal resources occurrence which are not used sufficiently. The disadvantage of these sources is a low temperature. These low temperature sources can be used directly for district heating or to produce electrical power.

For low temperature source utilization the most applicable power generation is using small binary power plants - Organic Rankine Cycle (ORC) or Kalina cycle.

The aim of this work is to model the ORC and Kalina cycle using data obtained from East Slovakian sources and to compare these two systems in terms of efficiency, power output, usability in Slovakian conditions and financial feasibility. The largest source in Eastern Slovakia is located in a place near Kosice city – Durkov. (Giese, 1998)

Results of the modeled thermodynamical comparison show that the Kalina cycle is more feasible in Durkov area conditions. Looking at the basic investments analysis the decision of which modeled power plant is better is a complicated one to make.

PREFACE

This thesis is submitted to the School for Renewable Energy Science in Akureyri, Iceland as a part of the master (M.Sc.) degree studies. The work on this thesis is the finishing project of the one year master degree study in Iceland in the geothermal energy specialization.

The work in this M.Sc. project deals with modeling, comparison and discussion of two small geothermal binary power plants and which of them is more feasible to build in the East Slovakian Durkov geothermal area. The aim of the work was to build two very simple models of binary Organic Rankine Cycle and Kalina cycle power plants. Focusing on a thermodynamic analysis of the cycles and, to a lesser extent, also on investment analysis, the comparison and main conclusions were conducted.

My work was based on data obtained from several papers describing projects that were planned to be done on the Durkov geothermal area.

Thanks to the never ending support of prof. Dusan Holoubek from the Technical University of Kosice, Slovakia and his wide variety of sources concerning the Durkov area I could find basic information about the utilization possibilities of the given area and also read about a couple of projects which were planned, for the last few years, to be done there. During the modeling Dr. Pall Valdimarsson from University of Iceland in Reykjavík was a useful and patient advisor describing to me all the necessary thermodynamic nuances in both cycles and introducing me to the EES program for basic modeling. The main sculpture of this work was built and the basic aims and procedures were stated together with Dr. Guðrún Sævarsdóttir from Reykjavík University, Iceland.

I would like to use this opportunity to thank these people; not only my project advisors for their useful and patient advice but also my academic advisors, Dr. Axel Bjornsson and Dr. Hrefna Kristmannsdóttir, for their time and willingness to help me any time.

I would also like to thank my colleagues from the School for Renewable Energy Science Michal Pachocki for patient additional thermodynamic lessons about the cycles, Pawel Lech for an introduction and help with EES program, Maciej Lukawski for corrections in EES code, Peter Whittaker for help with Kalina understanding and to Pedro Almeida for consultation of my results and conclusions. The biggest thanks are to my family, who supported me all year in my studies and also during the hard times while completing this work. Lastly I would like to thank the people who supported me during my stay in Iceland, who were standing close to me or behind me all the time and were always willing to help me and give me good advice.

For ten years the Durkov geothermal area was only under survey and testing and several projects were started but the field stayed without any progress in utilization. I decided to work on this project hoping that this work could “move the wheels” and show involved people that even three geothermal wells in given area can produce a sufficient amount of electricity for several consumers and also to utilize the geothermal brine temperature for a district heating system. In my opinion it is a loss that we are not using “free” energy which was given to us.

Hope this work will be useful for future planning in Durkov geothermal area potential utilization.

Martina Kopunicova, Akureyri, Iceland, 17th of February 2009

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1 INTRODUCTION

Today, when demand for energy is increasing with more developed technologies it is important to think about energy sources by themselves. A question which is coming forward these days is very simple. Do we have enough energy sources to satisfy our increasing energy demand? To answer this question and to solve problems related to increasing energy demand the European Union is focusing the attention of experts and everyday people to the use of renewable energy sources (RES).

Can energy obtained from renewable sources answer the “energy demand question”? Renewable sources of energy are an essential alternative to current widely utilized fossil fuels. Wind power, solar power (thermal and photovoltaic), hydro power, tidal power, biomass and geothermal energy are considered as renewable sources.

The problems with using traditional energy sources (coal, gas, oil) is their limited amount and greenhouse gas emissions. Using renewable sources helps to decrease the increasing demand for primary energy sources and to reduce greenhouse gas emissions from energy generation and consumption. Another advantage presented by local renewable sources is the reduced dependence on imported fossil fuels; particularly oil and gas (Jahnátek, 2008).

The European Commission set a brave target for the utilization of renewable energy sources. By 2020 the use of renewables should be 20% in overall energy mix. The European Union plans to focus efforts on the electricity, heating and cooling sectors and on biofuels. In transport, which is almost exclusively dependent on oil, the Commission hopes to increase the current target of a 5, 75% share of biofuels in overall fuel consumption to a 10% share by 2020.

The question rising up from these targets is if all European Union countries have opportunities for renewable energy utilization and if recent technologies can handle these sources.

Slovakia is a part of the European Union so the problem with energy demand is touching it as well. It is rich in renewable sources of energy, so it has the potential to fulfill the EU requirements. In addition to biomass and hydropower utilization there is the possibility to utilize the large geothermal potential of the country.

Geothermal energy can be widely used for heating and cooling but also for producing electricity. Including low and high temperature sources we can choose from several options in order to utilize these sources of geothermal energy (Jahnátek, 2008).

Durkov geothermal field is one of the places in Eastern Slovakia which offers large thermal potential in a low-to-medium temperature field. This potential can be changed to electric power using small geothermal binary power plants or it can be used directly for district heating or recreation purposes.

2 BACKGROUND INFORMATION

2.1 Utilization of geothermal resources in Europe

Electricity generation is the most important form of utilization of high-temperature (>150 °C) geothermal resources. The medium-to-low temperature resources (<150 °C) are suited to many different types of application.

The classical Lindal diagram (Fig.1) shows the possibilities of geothermal fluid usage at different temperatures. The diagram has changed a little since it was designed. The generation of electric energy in binary cycle plants can now be added above 85 °C. The lower limit of 20 °C is exceeded only in very particular conditions, or by the use of heat pumps.

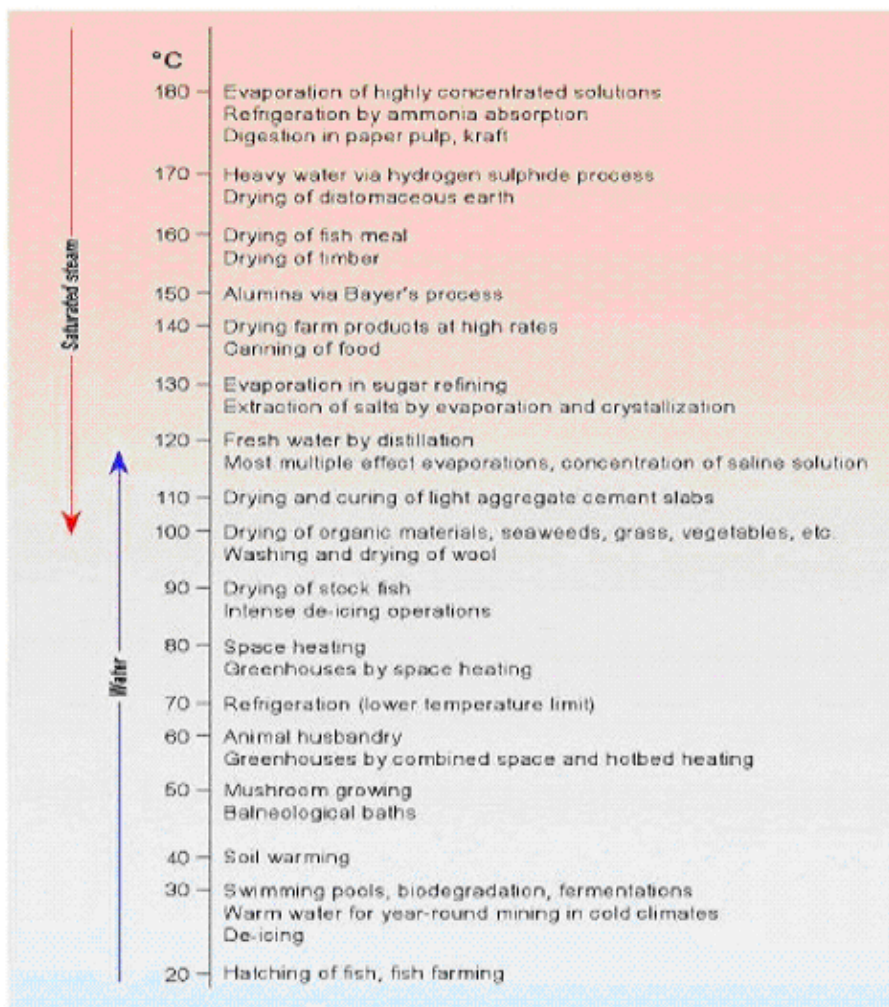


Fig. 1: Lindal Diagram (Lindal, 1973)

The Lindal diagram emphasizes two important aspects of the utilization of geothermal resources (Gudmundsson, 1988): with cascading and combined uses it is possible to enhance the feasibility of geothermal projects and the resource temperature may limit the possible

uses. Existing designs for thermal processes can, however, be modified for geothermal fluid utilization in certain cases, thus widening its field of application (Gudmundsson, 1988).

Electricity generation mainly takes place in conventional steam turbines and binary plants, depending on the characteristics of the geothermal resources.

Geothermal resources can also be utilized directly. Direct heat is one of the oldest, most versatile and most common forms of geothermal energy utilization. Bathing, space and district heating, agricultural applications, aquaculture and some industrial uses are the best-known forms of utilization, but heat pumps are the most popular and widespread (Dickson & Fanelli, 2003).

In the race to find alternative energy sources, geothermal energy is gaining favor. Geothermal energy is a continuous source of energy. Since the heat is trapped inside the earth, it is not depleted. With the steep price increases of oil and gas emission concerns, geothermal energy is generating greater interest everywhere. This, coupled by the fact that geothermal costs are decreasing as traditional energy sources are increasing in cost, leads researchers to believe that geothermal energy will play a greater role in the global quest for alternative energy.

The only major barrier of geothermal energy success is the high cost of setting up and drilling the hot water from under the surface of the earth. The prices are comparable to drilling in the oil and gas industry. However, research shows that those costs are dropping. Already in the EU, geothermal plants are found in Iceland, Greece, Italy, Turkey, Germany and Austria. The potential areas for geothermal generation capacity are in the north western and central western coast of Italy, western part of Turkey, and parts of Portugal, Spain, France and Germany. In Iceland, 85% of all houses are heated using geothermal energy and 30% of all their electricity is generated from geothermal energy. Italy's geothermal market is maturing, with installed capacity expected to increase to 1 200MWe – 1 500MWe by 2020. Most recently, Germany has close to 150 plants, stimulating the industry by passing laws in favor of making projects financially viable. Geothermal energy grows more promising as its advantages begin to outweigh its high implementation costs.

Geothermal heat was recognized first by the hot springs ancient cultures enjoyed at various hot spots around the world. Its capability to produce electricity came to light almost a century ago thanks to Italian Prince Piero Ginori Conti. Since then, as technology and understanding increased, two specific methods of creating energy have enabled people to generate both heat and electricity (Sullivan, 2008).

Countries Generating Geothermal Power in 2000 (21) (Sullivan, 2008)

Australia, China, Costa Rica, El Salvador, Ethiopia, France (Guadeloupe), Guatemala, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Philippines, Portugal (Azores), Russia, Thailand, Turkey, United States

Potential New Countries by 2010 -- Based Upon 2007 Interim Survey (22 for potential total of 46)

Armenia, Canada, Chile, Djibouti, Dominica, Greece, Honduras, Hungary, India, Iran, Korea, Nevis, Rwanda, Slovakia, Solomon Islands, St. Lucia, Switzerland, Taiwan, Tanzania, Uganda, Vietnam, Yemen (Gawell & Greenberg, 2007).

2.2 European Union energy policy

The European Union deals with different sectors ranging from human rights to education, public health, culture, environment and energy.

In the energy and environmental sectors the EU is working to reduce the effects of climate change and establish a common energy policy.

“Energy is the driving force of the society. Pressing issues such as climate change, an increasing dependence on oil and other fossil fuels, and rising costs are causing us to rethink the way we produce and consume it. In this respect, renewable energy sources represent an important part of the solution towards a sustainable energy future.” Andris Piebalgs, European Commissioner for Energy. As a part of this policy, in March 2007 the European head of state government agreed on binding targets to increase the share of renewable energy by 2020 to 20% of the European Union’s final energy consumption (8,5% in 2005) as well as to increase the level of biofuels in transport fuel to 10% by 2020. To meet this common target, each member state needs to increase its production and use of renewable energy in electricity, heating and cooling and transport. The European Commissioner for Energy said that it would be nice to reach 12,7% by 2020, which is well below the target 20% that the EU has set for itself.

The question rising up for member states is “How can the European Commission assist in this ambitious plan?”.

First, the Commission is doing its utmost to make electricity and gas markets function better by ensuring effective competition and creating suitable conditions for the expansion of renewable energy. The Commission is also eager to promote the expansion of renewable in all its forms. This means not only increase in utilization of renewable energy but each Member State has also committed to a 10% target for renewable energy in transport, which will be primarily met through the use of biofuels and, no matter if they are imported from outside, they will be undoubtedly helpful in reaching the assessed target. A main stress is also put on energy efficiency improvement. An Action Plan was adopted in the autumn of 2007 that foresaw a 20% improvement in energy efficiency compared to what would normally have happened by 2020. The parts of the solution in this step are new legislative proposals for the improvement of the energy efficiency in buildings, energy labeling related with proper knowledge about used sources and performance standards for several categories of electrical products. Technology will play a major role in the energy field. The strategic energy technologies plan worked out by Commissions aims to include nuclear fission and carbon capture and storage to help with energy problems (Piebalgs, The EU energy context, 2008).

Reaching targets formulated by the European Commission in practice means that everyone needs to do their share taking small, important steps. Using less energy and choosing renewable energy to heat homes, for electricity supply and as fuel for cars. It can all contribute toward reaching the goals.

Besides the production and utilization of renewable energy there are other benefits that should be mentioned. An increase in the development of new technologies will create the need for a knowledge-based industry and new jobs, increased competitiveness, new export opportunities and economic growth. Undoubtedly using renewable for our energy demands for heating and cooling and also in other sectors means lower greenhouse gas emissions and the reduction of air pollution, which is caused mainly by these gases. Furthermore, the increased use of energy produced from renewable sources means diversifying energy sources and reducing dependence on imported oil and gas.

The European Union also considers three different applications for renewable energy sources: generation of electricity, heating and cooling and biofuels for transport. These three applications represent different technological processes and industrial sectors, but all can contribute to the EU's aim of a more sustainable, secure and competitive energy supply. These are the most important goals in European Union policy.

Renewable energy is already helping to generate electricity in member states of the EU (Tab. 1). Under EU legislation, all EU countries have set national targets for the proportion of electricity consumption that should be obtained from renewable sources. If all the Member States achieve these targets, over one-fifth of the electricity consumption in the EU would be produced from renewable energy by 2010. But increased efforts are still needed to achieve this target.

Tab. 1: Contribution of renewable to electricity production (EU-27, 2005)

	TWh*
WIND	70.5
SOLAR PHOTOVOLTAIC	1.5
BIOMASS	80.0
HYDRO	306.9
GEO THERMAL	5.4
TOTAL RENEWABLE ENERGY SOURCES	464.4
TOTAL ELECTRICITY GENERATION EU-27	3 309
SHARE OF RENEWABLE ENERGY SOURCES	14.0 %

Source: Eurostat
*Terawatt-hour

The largest energy sector, ahead of electricity or transport is heat production. The heating and cooling sector accounts for half of the EU's final energy consumption, serving to heat homes and buildings, produce domestic hot water and supply heat for industry.

Renewable energy sources like biomass, solar and geothermal energy have huge potential in the heating and cooling sector. However, so far only 10% of total heating and cooling demands are covered by renewables (Tab. 2). This means that more effort needs to be made to integrate renewable technologies into the heating and cooling industries. There is also potential in combined heat and power plants that simultaneously generate electricity and heat using primary energy sources together with renewable energy sources.

Tab. 2: Contribution of renewables to total heat needs (Eu-27,2005)

	Mtoe*
BIOMASS	56.2
SOLAR THERMAL	0.7
GEO THERMAL	0.7
TOTAL RENEWABLE ENERGY SOURCES	57.6
TOTAL HEAT NEEDS	576
SHARE OF RENEWABLE ENERGY SOURCES	10%

Source: Eurostat
*Million tons of oil equivalent

European Union Members States will have to develop national action plans with a view to meet their own targets that will globally meet this target and also to set specific objectives for electricity, heating and cooling and use of biofuels in transport. The plans will reflect national circumstances, given the differences in renewable energy sources that are available for each country.

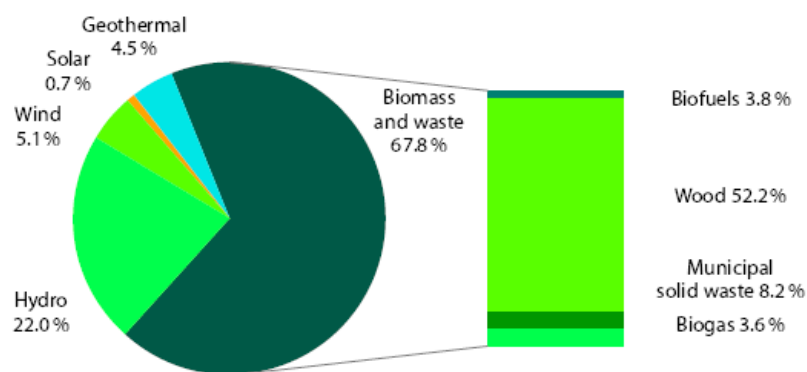
Why is the European Union putting so much effort to the application of renewable energy into everyday life? The answer is visible in a smaller or larger scale – climate change.

Renewables in the EU are highly supported and EU turnover is around € 30 billion and has provided around 350 000 jobs so far. The EU is a world leader in renewable energy. Production of renewables has risen steadily and costs have come down but renewable energy still represents only a small share of the EU’s total energy mix relative to the dominance of gas, oil and coal. Renewable energies are generally still not competitive with conventional energy sources because the external impacts, such as environmental ones, are not fully taken into account. Different renewables are at different stages of technical and commercial development. Some of them are already economically viable but there is still great potential for renewable energies to increase their market share and establish themselves as cost-effective, widely-used energy options (Tab. 3) (Fig. 2).

Tab. 3: Renewable final energy consumption 2000 – 2005 (Mtoe*) EU-27 (Piebalgs, Renewables makes the difference, 2008)

2000	2003	2004	2005	SHARE IN CONSUMPTION (2005)
87.0	93.8	99.4	104.2	8.5 %

Source: Eurostat
*Million tons of oil equivalent



Source: Eurostat

Fig. 2 Primary energy production from renewable energy sources, breakdown by individual source (EU-27, 2005) (Piebalgs, Renewables makes the difference, 2008)

2.2.1 Geothermal energy in Energy policy of European Union

The European Geothermal Energy Council (EGEC) prepared a list of priorities for Research and Development (R&D) in the geothermal sector. The paper was discussed during the workshop organized by EGEC in Brussels on 5.9. 2008.

The conclusions are presented in the final version of the Research Agenda for Geothermal energy (strategy 2008 to 2030). The R&D topics are proposed to help countries reduce the costs in order to reach for 2020 and beyond the targets forecasted for geothermal energy. The plan for geothermal energy set by European Commission is heat production of 11 Mtoe and electricity production between 40 000 and 80 000 GWh/y for all of Europe.

The objectives of the European Commission are an increase of R&D for heating and cooling by increasing knowledge about usable geothermal potential, improvement plant efficiency, decreasing installation and operational cost and wider usage of geothermal heat pumps. The focus in R&D for electricity production from geothermal sources is on the development of technologies for the exploitation of geothermal resources, proving the sustainability of Enhanced Geothermal Systems (EGS) technology and also the development of enabling technologies and demonstrators for microgeneration and cogeneration with low temperature water (<120°C), also in hybrid plants (e.g. biomass and geothermal) (Council, 2008).

There are several steps that need to be taken to reach all these goals for development.

The first stage was the consultation process in order to have a large consensus on the contemporary state of geothermal energy. The second stage was the definition of the Research Agenda. It set out research technologies development priorities. These are planned to be presented to the relevant authorities at national, European and world levels. The third step will be to implement the research agenda in adopting management structure and procedures. The implementation will need the support from a range of sources: International programs, European Council programs, other sources of European funding, national research programs, industry funding and third-party finance.

In 2007 a total of approximately 2,5 Mtoe (Million Tons of Oil Equivalent) has been supplied by geothermal heating within the European Union -27(Fig. 3), and more than 1 Mtoe in other European countries (Council, 2008).

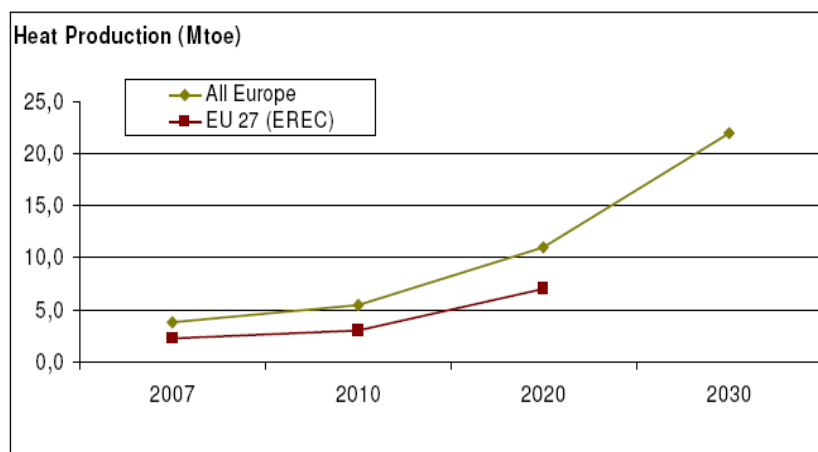


Fig. 3: Heat production in European countries and countries of EU (Council, 2008)

The installed thermal capacity (including geothermal heat pumps) in 2007 amounts to cca. 10 000 Wth (MegaWatt thermal) in EU-27 and 15 000 for all Europe.

The target of this sector for all of Europe is to reach 20 000 MWth in 2010, 40 000 MWth in 2020 and 80 000 MWth in 2030 (Fig. 4).

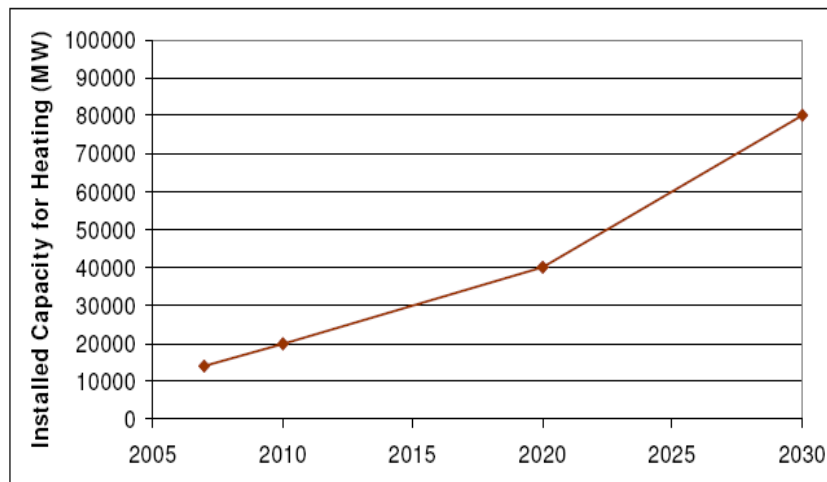


Fig. 4: Targets of European Commission in heating and cooling sector by geothermal energy (Council, 2008).

In the utilization of geothermal energy for producing electricity in European countries there has not been much progress in development. That is why the European Commission set up a plan for increasing numbers in this sector. Installed geothermal electricity capacity in the EU – 27 is approaching 1 GWe (GigaWatt-electric) which present 10% of the world geothermal installation. Other European countries account for approximately 0,5 GWe. The gradual introduction of new developments will boost the growth rate. The plan is to reach targets for Europe of 1,4 GWe for 2010 and 6 to 10 GWe installed in 2020 and 15 to 30 in 2030. But EGEC still recognizes problems related with these targets. These targets can only be reached by reducing the cost of R&D and cost of geothermal energy technologies (fig. 5).

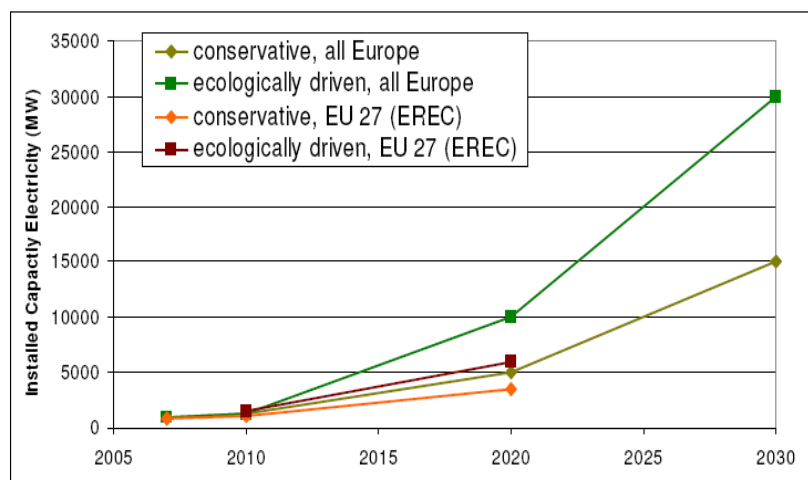


Fig. 5: Targets for Europe in electricity production from geothermal energy (Council, 2008).

The European Council's main priorities are focused on geothermal heat pumps, which should improve underground systems, increase efficiency and improve the performance. Geothermal energy storage plans are related to the storage of heat or cold, combined problem solutions and the integration of waste heat. Hybrid heating and cooling systems are focused on solar and biomass utilization for heating and cooling and the use of geothermal boreholes as a heat sink in cooling applications. Research and design of geothermal systems is last on the list of priorities that require small R&D financing.

High priority and the need of large financing need to be allocated for drilling improvements, resource identification and enhanced geothermal systems. The list of secondary research areas includes low enthalpy electricity production, combined heat and power, supercritical fluid, supercritical zones in geothermal fields and also exploitation, economic, environmental and social impacts. Also included in the plans are the optimization of district heating and direct use of geothermal energy (Council, 2008).

The EU is working to reduce the effects of climate change and establish a common energy policy for all members of this institution. Part of this policy is the earlier mentioned agreement from March 2007 of the European Heads of State or Government on binding targets to increase the share of renewable energy. The target was estimated at 20% of the EU's final energy consumption by the year 2020 (8,5% in 2005). To meet this common target, each Member State needs to increase its production and use of renewable energy in electricity, heating and cooling and transport. The renewable targets are calculated as the share of renewable consumption to gross final energy consumption. Renewables consumption comprises the direct use of renewables (e.g. biofuels) plus the part of electricity and heat that is produced from renewables (e.g. wind, hydro), while final energy consumption is the energy that households, industry, services, agriculture and the transport sector use. The denominator for the RES share also includes distribution losses for electricity and heat and the consumption of these fuels in the process of producing electricity and heat. The target for the Slovak Republic is 14% (Commission, Slovak Republic Renewable Energy Fact Sheet, 2008).

2.3 Utilization of geothermal energy in Slovakia

Slovakia (Slovak republic) is a small country in the middle of Europe (Fig. 6) with a population over five million and an area about 49 000 km². It is a member state of the European Union, NATO, UN, OECD, WTO, UNESCO and other international organizations.

2.3.1 Slovakia as a part of the European Union.

Slovakia has borders with Poland to the north, Hungary to the south, Ukraine to the east and Czech Republic and Austria to the west. Slovakia is well known for its diversified landscape; from lowlands to mountains and from dryer parts to large river basins. The Slovak landscape is primarily noted for its mountainous nature, with the Carpathian Mountains across most of the northern half of the country. Close to the polish border on the north lie the High Tatras Mountains and close to them the Low Tatras Mountains. There are some major rivers crossing the country. The biggest one is the Danube, the longest one is the Váh and another well known is the Hron.

The Slovak climate is typical with its relatively warm summers and cold, cloudy and humid winters (Commission, Renewable energy sources - potential and prospects, 2008). The area of Slovakia can be divided into three kinds of climatic zones. The first zone can also be divided into two subzones. The three major climate zones are lowlands, basins and mountains climate.

Slovakia is a high-income economy with one of the highest growths of GDP (8,9%) among the members of OECD in 2006. The annual GDP growth in 2007 was estimated at 10,4% with a record 14,3% reached in the fourth quarter. Although Slovakia's GDP comes mainly from the tertiary (services) sector, the country's industry plays an important role within the economy. The main industry sectors are car manufacturing and electrical engineering. Since 2007 Slovakia has been the world's largest producer of cars per capita. The Slovakian economy has overcome the difficult transition from a centrally planned economy to a modern high-income market economy. Slovakia adopted the euro currency on 1 January 2009 as the 16th member of the Eurozone. The euro in Slovakia was approved by the European commission on 7 May 2008. The Slovak koruna was revalued on 28 May 2008 to 30.126 for 1 euro, which was also the exchange rate for the euro (Union, 2008).

One of the most important dates was the 1st of May 2004, when Slovakia joined the countries in the European Union. Together with this historically very significant step there were several steps taken before joining the European Union. Membership in the EU means not just the advantages of being guided by the big institution but also fulfilling the requirements related to contributions to the EU (Union, 2008).



Fig. 6: Location of Slovak Republic (Union, 2008)

2.3.2 Renewable energy potential in Slovakia

The utilization of RES in the total power consumption of Slovakia has grown in the last decades. The shares of RES in gross domestic power consumption reached 4,3% in 2005. However this growth was not sufficient from the existing potential viewpoint and national obligations. It is necessary to support the development of RES with further measures, especially in the legislative field and awareness of the public.

Current Slovakian imports can easily be described as accounting for almost 100% of consumed oil and natural gas. Considering this fact the share of RES in overall energy consumption is 4% on and this number is very low. There were several institutional and financial tools and schemes created in order to support the exploitation of RES (Commission, Slovak Republic Renewable Energy Fact Sheet, 2008).

Most developed in utilization so far are wind energy and energy from biomass (Fig.7). RES will be one of the important parts of Slovakia's power source structure, but their ability to replace other sources in the forthcoming years is still limited.

The potential of RES is an energy, which can be changed to other forms of energy per one year and its amount is provided by natural circumstances. Solar energy has the largest overall energy potential. The part of the potential which can be utilized after the implementation of available technology is called technical potential.

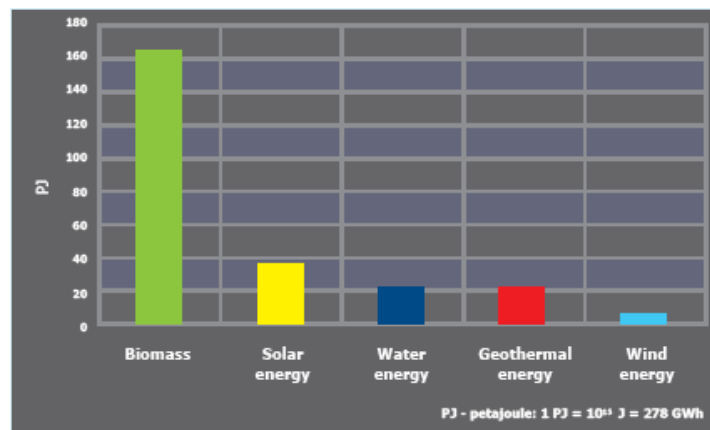


Fig. 7: RES technical potential in Slovak Republic (Commission, Slovak Republic Renewable Energy Fact Sheet, 2008)

The strategy of higher utilization of RES in SR which was approved in 2007 sets targets for electricity and heat production up to the year 2015. Based on these targets it is possible to set binding targets in the SR for the year 2020, which comes from the spring proceedings of the European Commission in 2007. RES can be used for heating and cooling, production of electricity and as biofuels. The most prospective RES for the important year 2020 are those that can be utilized for heating and cooling (Tab. 4) (Commission, Renewable energy sources - potential and prospects, 2008).

Tab. 4: Utilization of RES and share of gross domestic energy consumption (Commission, Renewable energy sources - potential and prospects, 2008)

	2002		2003		2004		2005	
	[PJ]	(GWh)	[PJ]	(GWh)	[PJ]	(GWh)	[PJ]	(GWh)
RES gross consumption	10,9		12,7		16,1		17,4	
Primary electricity production from water and wind energy	19,0	5 268	12,5	3 481	14,8	4 106	16,7	4 645
Total	29, 9		25,2		30, 9		34,1	
RES share of gross domestic power consumption* (%)	3,8%		3,2%		3,9%		4,3	

* Gross domestic power consumption is equivalent of primary power sources, or total power consumption, which were used in the energetics statistics till the year 2002.

2.3.3 Electricity production from RES

According to the Directive 2001/77/ES regarding the support of electric energy produced from the renewable energy sources, all the member countries are obligated to increase their share of RES electricity production to reach their indicative target in the year 2010. For the Slovak Republic the indicative target is specified at 31%, however it is more realistic to reach 19%.

In accordance with the Strategy of Higher Exploitation of RES in the SR it is possible to reach the set goals for 2010 using new 244 MW of installed power. Small hydropower plants have the potential to cover from 60 up to 100 MW within the horizon of 20 years and the big power plants are able to increase safety in the electricity supply (Tab. 5) (Commission, Renewable energy sources - potential and prospects, 2008).

Tab. 5: Estimation of RES electricity production till the year 2030 without big water power plants (Commission, Renewable energy sources - potential and prospects, 2008)

	2005	2010	2015	2020	2030
RES electricity production (TWh)	0,3	1,2	2,3	3,1	4,4
Share in power consumption (%)	1	4	7	9	11

In the Slovak Republic, large-scale hydro energy is the only RES with a notable share in total electricity consumption. Between 1997 and 2004, this market share has stabilized. The share taken up by small-scale hydro energy has decreased by 15% per year on average over the same period. An extended development program with 250 selected sites for building small hydro plants have been adopted. Additional mid-term potential of all RES is biomass. The Government has decided to only use this source in remote, mountainous, rural areas, where natural gas is not available.

Between 1997 and 2004, the Slovak republic moved further away from its RES target. The Strategy of Higher Utilization of RES in the Slovak Republic was approved in April 2007. Policy related to renewable energy sources used for electricity production includes measures:

In the Act of Energy (2004) a measure that gives priority regarding transmission, distribution and supply was included

Guarantees of origin are being issued

Tax exemption is granted for RES electricity. (This regulation is valid for the calendar year in which the facility commenced operation and then for five consecutive years).

Since 2005 a system of fixed feed-in tariffs has been in place

Subsidies up to € 100 000 are available for the (re)construction of RES electricity facilities.

In 2005 the National Program of Biofuels Development was adopted. Legislation concerning the minimum amount of biofuels on the Slovakian market and a decree laying down the requirements for fuel quality and maintenance of records of fuels were scheduled for 2006.

RES heating is promoted through the Program supporting Energy Savings and Utilization of RES (2003) (Commission, Slovak Republic Renewable Energy Fact Sheet, 2008).

2.3.4 Geothermal utilization in Slovakia

In relation with European Commission requirements the Slovak republic confirmed a Conception of utilization of renewable energy sources on the 23rd of April, 2003. The conception defines the basic scope in research in utilization of renewables in Slovakia.

Systematic research of geothermal energy sources with the realization of geothermal drillings started in Slovakia in 1971.

Within the basic exploitation financed by the state budget in years 1971 – 1994 the characteristics of surface and depth structure of the Western Carpathians together with the spatial distribution of geothermal waters and spatial characteristics of earth heat distribution were mapped through the realization of 61 geothermal boreholes. An informative projection about the amounts of geothermal energy and water was obtained. One of the most significant results was the determination of 26 perspective geothermal areas with beneficial conditions for energy utilization of geothermal waters.

The total utilization potential of these boreholes with 210 – 2800 m depth presented 904 l/s of geothermal water with temperatures at the wellhead from 20 to 92 °C and mineralization of 0,4 – 90 g/l. In heat power they presented 176 MWt of geothermal energy, from which 31 MWt (131 l/s) presented reinjection exploitation of 145 MWt (773 l/s) in single boreholes. The results obtained during more than two decades of geothermal source investigations in Slovakia are summed up in “Atlas of geothermal energy in Slovakia”, which was published by the State geological institute of Dionýz Štúr in 1995. The basic information in this atlas is the results obtained by basic investigations which gathered information about the tertiary filling of basins and folds, the pretertiary underlay of the whole inner Western Carpathian and about temperature field and hydrogeothermal conditions (Fendek M. , 1998).

Results from these investigations were also used in publication from the European Commission’s Atlas of Geothermal Sources in Europe (Publ No. EUR 17 811 of the European Commission).

Based on results from basic research and a survey of geothermal sources it is possible to state that the Slovak republic has, thanks to its natural conditions, significant geothermal energy potential, which was evaluated to be 5 538 MWt. Sources of geothermal energy are

represented mostly by geothermal waters that are bounded in triassic dolomites and limestones of innercarpathian tectonical units, and to a lesser extent to neogene sands, sandstones and conglomerates. These rocks are collectors of geothermal water beyond the spring areas that are located in 200 – 5 000 m depth, and geothermal water with temperatures between 15 – 240 °C can be found there. Based on the expansion of collectors and activity in the geological field, 26 prospective areas or structures suitable for obtaining geothermal energy were defined in the Slovak republic's territory (Fig. 8).

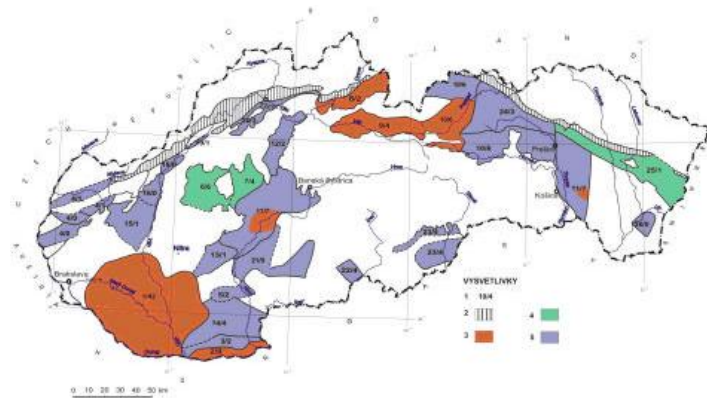


Fig. 8: Prospective areas of geothermal water in Slovakia (Fendek M. , 1998)

In Slovakia there are 116 registered geothermal boreholes with which 1 787 l/s of water with temperature at the wellhead 18- 129°C were verified. Geothermal water was obtained by 92 – 3 616 m deep drillings. Flow from the wells at the wellhead was at intervals from tenths to 100 l/s. Predominantly Na-HCO₃, Ca-Mg-HCO₃ and Na-Cl types of water with mineralization 0,4 -90,0 g/l can be found. The heat capacity of water in utilization until reference temperature 15 °C is 306,8 MWt, which presents 5,5 % of the total potential of geothermal energy in Slovakia, which was estimated by geological survey to be 5 538 MWt (Fendek M. , 1998).

Currently 36 localities are utilizing geothermal energy from geothermal waters for agricultural use, for heating buildings and for recreation purposes with overall used heating power at 131 MWt, which represents 2,3% from the geothermal energy potential in Slovakia and 42,7% from the heating power of registered geothermal boreholes..

In the agricultural sector, 12 localities are utilizing geothermal water for greenhouse heating for the fast production of vegetables (cucumbers, tomatoes, paprika, etc.) and also for flowers.

In 32 localities the geothermal water is used for recreation purpose, mostly for filling swimming pools (Poprad, Bešeňová, Galanta, Štúrovo, Rajec etc.).

From the above mentioned utilization examples it is quite visible that the use of Slovakian geothermal energy potential is unsatisfactory. The main reasons for the existing state of renewables utilization are the high financial costs for realization of geothermal drillings, the cost for necessary techniques and technologies and very small awareness about the need for support for the realization of projects from domestic but also from foreign subsidies. However in recent years there has been a significant increase in interest about geothermal energy utilization.

For an illustration of the contribution of geothermal energy source utilization it is good to mention that during the production of 25 MWt thermal energy from geothermal sources it is possible in Slovakian conditions to save around 42 600t of brown coal (counting 200 days for heating) or 16 million m³ of natural gas. By replacing these fuels it is possible to decrease solid matter emissions from brown coal utilization by 208 t/year, SO₂ by 790 t/year, NO_x by 125 t/year and CO₂ by 42 t/year (Fendek M. , 1998).

The most perspective geothermal areas defined in basic geothermal national investigations are Košická kotlina – Ďurkov area, Popradská kotlina, Liptovská kotlina, Skorušinská panva – Galanta area, Žiarská kotlina, Komárňanská vysoká ryha and Hornonitrianská kotlina.

The basic geothermal source investigation in Slovakia has been finished. There were 26 prospective localities found. Investigations in the five most perspective areas have also been conducted. The result of this geological survey is knowledge about the hydrogeothermal conditions, amount of geothermal water and its parameters and the potential amount of geothermal energy.

The questions usually related to renewable energy source utilization are regarding the sustainability and feasibility of these sources. There are some indisputable advantages in the utilization of geothermal energy:

- domestic source of energy, independent in case of international conflicts
- cheaper source of energy than fossil fuels
- it is one of the renewable energy sources
- decreasing the load on transport communications by reduction of fossil fuels transport,
- decreasing the danger of environmental damage by the reduction of transport, processing and utilization of fossil fuels
- allows control over the price of energy
- operation is safe, with minimum impact on environment and soil.

Utilization of geothermal energy is also the moving force behind the development of small and middle rank businesses in regions. These are usually utilized for the production of fast grown vegetables and flowers, fish and poultry farming, during the construction and utilization of facilities for recreation and rehabilitation purposes (Fendek & Bím, Hodnotenie energetického potenciálu geotermálnych vôd na Slovensku, 2005).

An unnecessary basis for expansion in the field of geothermal energy lies in data about distribution, quantity and quality of sources, and in data about conditions for its optimal utilization for different purposes. This complex of information is presented by geological research and survey (Fendek & Bím, Hodnotenie energetického potenciálu geotermálnych vôd na Slovensku, 2005).

2.3.5 Geothermal area in Eastern Slovakian Kosice basin – Durkov.

Slovakia is committed to exploiting its domestic geothermal sources. The results of geological investigations put Slovakia in the regions of the world with a high geothermal potential. From 26 geothermal areas in Slovakia the most prospective one is the Košice basin in Eastern Slovakia neogene.

The presence of geothermal water in Eastern Slovakian neogene was verified approximately 10 years ago by survey drills for crude oil and natural gas occurrence.

Most known and most prospective areas of geothermal water fields in the Eastern Slovakian neogene are in Košická kotlina Ďurkov, Rozhanovce, Kecerovské Pekľany and in Prešovská kotlina Prešov and Renčišov.

One of the most prospective localities in Slovakia is a mesozoic structure in Košická kotlina which is situated between Slanské vrchy (Slanské vrchy Mountains) and Slovenské rudohorie (Ore Mountains) with an area around 868 km².

From all of the realized geothermal drills in this area, the most investigated geothermal drills are in Ďurkov locality (drills GTD-1, GTD-2 and GTD-3) (Wittenberger & Pinka, 2005).

The results of this investigation show that it is possible to obtain 500 MWt of power from geothermal water with temperatures higher than 150 °C and depths of around 3000 m. It would be possible to use this power for heating buildings in nearby Košice and possibly for electricity production.

The aim of the mentioned drills was to verify possibilities for the exploitation of thermal water from reservoirs to produce heat and electricity energy. During drilling the following information was obtained:

- geological data about sediments (lithology, stratigraphy)
- physical data about sediments
- hydrodynamical and thermodynamical parameters (Tab. 6)
- parameters of geothermal reservoir
- physical – chemical properties of geothermal water and gases

Based on these parameters it is possible to verify the industrial significance of the locality and specify its thermal-energy potential.

From thermodynamic properties modeling and from the fact that geothermal water is strongly Cl-Na type it is prudent to expect incrustation during the operation (mostly carbon incrustation) and also to expect a certain amount of corrosion. From these reasons it will be necessary to use ecological inhibitors and maintain in-system minimal pressure 2,1 – 2,2 MPa (Wittenberger & Pinka, 2005).

Tab. 6: The results of hydrodynamic tests (Wittenberger & Pinka, 2005)

Geothermal drill	GTD 1	GTD 2	GTD 3
Q [l.s-1] flow	56	50	65
Qmax [l.s-1] maximum flow	66	70	120
T head [°C] wellhead temperature	125	129	126
T bottom [°C] well bottom temperature	144	154	131
P head [MPa] wellhead pressure	0,92	1,4	2,2
P bottom [MPa] well bottom pressure	29,3	27,4	21,9
H [m] depth of the drill	3210	3250	2252

2.3.6 Geological settings in Kosice basin.

Kosice basin is filled with thin layer of fluvial Quaternary sediments (up to 10m), Neogene sediments-Sarmatian clays (thickness 500-1000m), Badeniain calcareous sandy clays (thickness up to 1300 m) and Carpathian calcareous claystones with conglomerates at the base (thickness up to 400 m). The thickness of Mesozoic dolomites which form underlying layers of Neogene rocks rise westward from 300 to 2000 m. Mesozoic dolomites deepen from west to east. From a lithologic viewpoint there are dark grey breccia dolomites with calcite veins, which are incorporated into the Mesozoic mantle of Cierna Hora (Black Mountains).

Kosice basin is folded by 3 main fault zones – Carpathian direction, transversal direction and Hornad direction. Faults cut the basin into smaller structures, mainly the Carpathian and transversal directions are important. One of them is the Durkov structure located in SE part of Kosice basin, restricted by the Slanske Mountains on the eastern side. The Slanske Mountains are formed by Neovolcanic rocks – andesites and pyroclastic rocks that were formed later than the Mesozoic reservoir dolomites. Because of the higher geothermic gradient they influence the eastern side of Kosice basin.

The presence of a geothermal reservoir is caused by the temperature gradient in Neogene rocks of 50,3 °C/km and in Mesozoic rocks of 32,3 °C/km, heat flow in the region is 109,9 mW/m² (Wittenberger & Pinka, 2005).

Investigation wells GTD 1, GTD 2 and GTD 3 are located in the Durkov geothermal structure and proved the existence of a geothermal water reservoir. The Durkov geothermal structure is called the depression of a Neogene basement where Mesozoic dolomites occur at depths of 2000 m or more and their thickness is at least 1000 m. All the wells were drilled through Neogene rocks and the geothermal reservoir was found on top of the Mesozoic dolomites,

just below the Neogene Carpathian conglomerates. The average production zone is about 300 m thick, with low productive horizons occurring deeper in tectonic dolomitic breccia. The main inflow zones of geothermal water are in the depth range of 2100 – 2600 m on the top of Mesozoic dolomites with fissure and karstic permeability.

Based on a well test analysis of GTD 1, 2 and 3 it is possible to say that geothermal water is located in Kosicka kotlina (basin) mostly in dolomites, less in calcites (Tab. 7).

Tab. 7: Geological structure in Kosicka kotlina (numbers are in meters) (Wittenberger & Pinka, 2005)

	Stratigraphy	Geological cutting
	2.3.7	
0 – 16 m	post-tertiary	clays, gravels
16 – 60 m	sarmat, neogene	clay slates, slurries, sandstones
60 – 1865 m	baden, neogene	sandstones, slates
1865 – 2740 m	karpat, neogene	sandstones, slates, conglomerates
2740 – 3600 m	trias	dolomites, dolomitic limestones,

The well parameters taken from the well tests were more promising than was originally expected. Geothermal water temperature at wellhead is 124 – 129 °C. Free flow 56 – 65 l/s, dynamic pressure on wellhead 0,97 – 2,2 MPa, and the degassing point at depths of 750 – 1146 m.

Geothermal water has high TDS (total dissolved solids) content with remarkable sodium–chloride type. From a genetic point of view it is halogenic water that probably originated from meteoric water infiltrating through the salt–bearing formation of Carpathian into the Mesozoic collector. The geothermal structure is the confined one utilizable only by reinjection. Thermodynamic modeling shows the possibility of scaling, predominantly by carbonates. There is also the possibility of high corrosion, which implies the necessity of inhibitor usage, pressure maintenance (2,1 – 2,2 MPa) and other precautions.

There were several projects done assuming total heat output for 100 MWt. To complete the whole project requires at least 7 production and 7 reinjection wells. The model is calculated for 30 years of operation with various production and reinjection flow rates. To avoid improper technology implementation the long term semi–operational test will be performed. The ratio of gas / water, production pressure drop, temperature drop in reservoir, chemical composition, reinjection pressure, scaling and corrosion equilibrium will be investigated (Wittenberger & Pinka, 2005) .

The investigation conducted from 1998 – 1999 in the Durkov geothermal structure showed the presence of a geothermal reservoir with heat potential of at least 100 MWt. This structure is located about 15 km east from Kosice, the second largest town in Slovakia and the geothermal heat should supply about 60 000 flats in Kosice. This project was discussed for a couple of years and a considerable amount of money was invested in drilling, but to reach the final project realization it would be necessary to wait a little bit longer.

Smaller towns and villages under which lie geothermal reservoirs would benefit from utilizing that energy (Bidovca, Svinica, Ďurd’ošík, Olšovany etc.).

The establishment of a municipal heating system with geothermal energy utilization, from an area with the best potential in Europe, is still highly possible in Kosice (Vranovska, Benovsky, Drozd, Halas, & Vana, 2000).

Currently three geothermal wells – GTD1, 2 and 3 – in the Durkov location are closed at the wellhead by a safety ball valve with closing flange to which a production cross with all necessary armatures is planned to be installed. Wellheads are also covered by safety steel casings which can be locked to save wells from bad weather conditions and also from damage by people.

Several projects were conducted over the period of time since the basic investigation and survey drilling were done. Most of them are related to the utilization of geothermal water for distinct heating purposes but there was also an idea to utilize small geothermal power plants to produce electricity and heat together from these low temperature geothermal sources.

So far the idea of producing electricity has not been developed as much as the idea for district heating. Projects were done by foreign companies but also by the Slovak government. The process of preparation is time-consuming and capital-investive. Survey drillings were done, the capacity of the sources was recorded and the circle of arranging all necessary permissions was started.

One of the latest project planned was to set up 5 -6 geothermal duplets 2 – 3 km deep. Part of this plan was also to build geothermal centers and transport geothermal water by caliduct owned by the company TEK0 (Heating station Kosice). Surveys showed good parameters with which to utilize these sources not only for district heating purposes but also for possible electricity production (Podhorská, 2008). This project is to be completed in 2010.

From well tests it is visible that Kosice basin lies in a low temperature geothermal fluid area. The utilization of low-to-medium temperature fluid is basically focused on direct use in fishing, balneological baths, as heating for greenhouses and in agriculture. Considerable progress was also made in generating electricity from low-to-medium temperature geothermal fluids and from the waste hot waters coming from the separators in water dominated geothermal fields. Improvements were made in binary fluid technology.

2.4 Geothermal power plants

2.4.1 Utilization of low-to-medium geothermal fluids for electricity production

In order to generate electricity from low-to-medium temperature sources and to increase the utilization of thermal resources by recovering waste heat, binary technologies have been developed.

The binary plants utilize a secondary working fluid, usually an organic fluid (typically n-pentane) that has a low boiling point and high vapor pressure at low temperatures, compared with steam. The secondary fluid operates through a conventional Rankine cycle: the geothermal fluid yields heat to the secondary fluid through heat exchangers, in which this fluid is heated and vaporizes; the vapor produced drives a normal axial flow turbine, is then cooled and condensed, and the cycle begins again. When suitable secondary fluids are selected, binary systems can be designed to utilize geothermal fluids in the temperature range of 85 to 170 °C. The upper limit depends on the thermal stability of the organic binary fluid, and the lower limit on the technical-economic factors: below this temperature the size of the heat exchangers required would render the project uneconomical. Apart from low-to-medium temperature geothermal fluids and waste fluids, binary systems can also be utilized where flashing of the geothermal fluids should preferably be avoided (for example, to prevent well scaling). In this case, down-hole pumps can be used to keep the fluids in a pressurized liquid state, and the energy can be extracted from the circulating fluid by means of binary units (Dickson & Fanelli, 2003).

Binary plants are usually constructed in small modular units of a few hundred kWe to a few MWe capacities. These units can be linked up to create power plants of a few tens of megawatts. Their cost depends on a number of factors, but particularly on the temperature of the geothermal fluid produced, which influences the size of the turbine, heat exchangers and cooling system. The total size of the plant has a small effect on the specific cost, as a series of standard modular units is joined together to obtain larger capacities.

Binary plant technology is a very cost-effective and reliable means of converting into electricity the energy available from water-dominated geothermal fields (below 170 °C). A new binary-fluid cycle has recently been developed, called the Kalina cycle, which utilizes a water-ammonia mixture as the working fluid. This fluid is expanded in superheated conditions, through the high-pressure turbine, and then reheated before entering the low-pressure turbine. After the second expansion the saturated vapor moves through a recuperative boiler before being condensed in a water-cooled condenser. The Kalina cycle has 30 to 40% higher thermal efficiency, according to the first law for low temperature heat sources, than other existing geothermal binary power plants (Dickson & Fanelli, 2003).

Small mobile plants, conventional or not, can not only reduce the risk inherent to drilling new wells but also, what is more important, can help in meeting the energy requirements of isolated areas. The standard of living in many communities could be considerably improved where they are able to draw on local sources of energy. Electricity could facilitate many apparently banal, but extremely important operations. The convenience of the small mobile plant is most evident for areas without ready access to conventional fuels, and for communities in which it would be too expensive to connect to the national electric grid (Dickson & Fanelli, 2003).

2.4.2 Binary cycles in geothermal energy utilization

Binary cycle geothermal power plants are the closest in thermodynamic principle to conventional fossil or nuclear plants in the undergoing fluid in an actual closed cycle. The binary system utilizes a secondary working fluid, typically n-pentane or isobutane which, compared with steam, has a low boiling point and high vapor pressure at low temperature. The secondary fluid is operated through a conventional Rankine cycle. By selecting the appropriate working fluid a binary system can be designed to operate with an inlet temperature in the range of 85 to 170 °C (Dickson & Fanelli, 2003). Heat is transferred from the geothermal fluid to the binary cycle through heat exchangers, where the binary fluid (working fluid) is heated and vaporized, being expanded through a turbine to some lower pressure/temperature.

The working fluid, chosen for its appropriate thermodynamic properties, receives heat from the geofluid, evaporates, expands through a prime-mover, condenses and is returned to the evaporator by means of a feedpump (Fig.9).

Currently binary plants are the most widely used types of geothermal power plant with 162 units in operation (in May 2007) generating 373 MW of power in 17 countries. They constitute 32% of all geothermal units in operation but generate only 4% of the total power. Several binary cycles in operation with existing flash-steam plants were added to recover more power from hot waste brine (Dickson & Fanelli, 2003).

In the domain of low-to-medium temperature applications, organic fluids have several special properties which provide them with an advantage over water (steam) and allow a higher cycle efficiency: a low boiling point allows the organic fluids to flash at low temperatures; a high molecular weight and low enthalpy drop allow organic fluids to operate with a lower flow rate and hence the turbo machinery to be simpler; non-condensing characteristics during expansion (steam in part condenses on the turbine blades during expansion, resulting in reduced efficiency if it is not superheated sufficiently, therefore requiring higher temperatures); a low preheat and vaporization energy ratio. Furthermore, geothermal fluids often have a high salt content which causes problems in the design and construction of good quality heat exchangers.

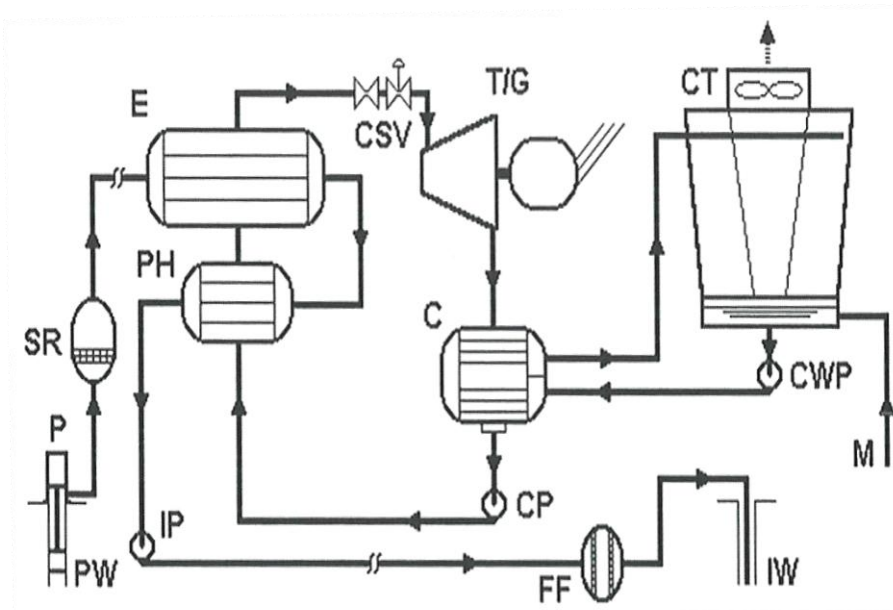


Fig. 9: Schematic diagram of a binary cycle type geothermal plant (DiPippo, 2008)

In its simplest form a binary plant's working flow starts with the production well being fitted with pumps, followed by the sand removers. Typically there are two steps in the heating-boiling process conducted in the preheater and in the evaporator. The geofluid is everywhere kept at a pressure above its flash point for the fluid temperature to prevent the breakout of steam and non-condensable gases that could lead to calcite scaling in the piping.

Kalina binary cycle

The more developed non-organic fluid Rankine cycle at present is the Kalina cycle (Fig. 10), which uses a water-ammonia mixture as a working fluid (85-15 weight %) (Dickson & Fanelli, 2003). This process has the benefit that the boiling point of the mixture increases as the evaporation progresses, which reduces the impact of the pinch-point limitation and therefore permits a higher heat exchange effectiveness to be achieved. The Kalina cycle achieves a thermodynamic efficiency (brine effectiveness) that is approximately 50% greater than that of standard binary Rankine plants (Dickson & Fanelli, 2003).

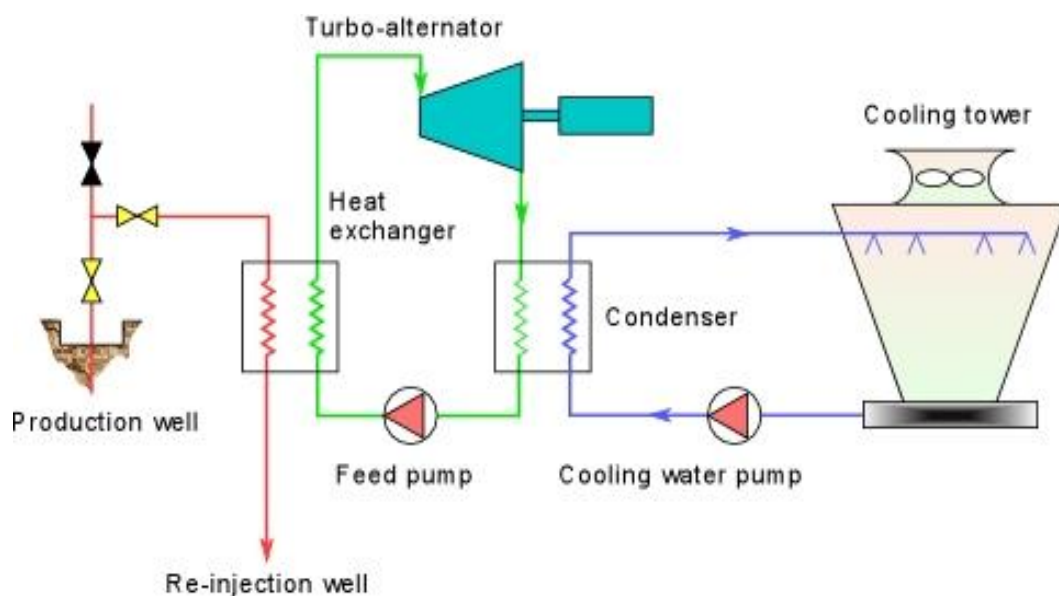


Fig. 10: Schematic diagram of a Kalina Plant cycle (Dickson & Fanelli, 2003)

The hot brine from the geothermal well is used firstly to both superheat and reheat the working fluid and then to evaporate and preheat it before being reinjected into the ground.

The features that distinguish the Kalina cycles (there are several versions) from other binary cycles are (Dickson & Fanelli, 2003):

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

Kalina cycles show an improved thermodynamic performance of heat exchangers by reducing the irreversibilities associated with heat transfer across a finite temperature difference.

The heaters are arranged so that a better match is maintained between the brine and the mixture at the cold end of the heat transfer process.

A possible difficulty for the Kalina cycle is maintaining very tight pinch-point temperature differences in the heat exchangers. There are also relatively large temperature differences at the start and at the end of the condensing process.

Traditionally, binary plants have been small units varying in size from a few hundred kilowatts to several megawatts. The cost-effectiveness of these small developments is supported by their modular construction, which facilitates short manufacturing and installation times. Larger developments of 10 to 50 MW can be achieved by bringing a number of modular units together in a common development (Dickson & Fanelli, 2003).

With wells that do not flow spontaneously, or where it is advantageous to prevent flashing of the geothermal fluid (to prevent well calciting for example), down-hole pumps can be used to keep the fluid in a pressurized liquid state. Binary units can be used to extract energy from the circulating fluid.

Heat exchangers are required to heat and evaporate the binary fluid, as well as to de-superheat and condense it during the heat rejection phase of the cycle. Conventional heat exchangers are of the shell-and-tube or plate type. They are physically large and form a great portion of the cost of binary plants. One of the major disadvantages of hydro-carbons and refrigerants, used as binary fluids, is that they have poor heat transfer characteristics. Scaling often compromises the heat transfer performance of heat exchangers, which in some cases can make certain development strategies impractical. Scale reduces the heat transfer and hydraulic performance of conventional surface heat exchangers, and also gives rise to higher maintenance costs and reduced plant utilization. Research and state-of-the-art techniques have been directed toward direct contact (mixing) heat exchangers, which are very efficient and much smaller than conventional shell-and-tube types but their operation causes some difficulties (need to have primary and secondary fluids at the same pressure, solubility of geothermal fluid in the binary fluid, cost and benefits have not been clearly defined) (Dickson & Fanelli, 2003).

3 MODELING AND ANALYSIS OF SMALL GEOTHERMAL BINARY POWER PLANTS

3.1 Programs used during the modeling

3.1.1 EES - Engineering Equation Solver

Currently there are many programs which can help to solve sometimes very difficult thermodynamical calculations. One of the simplest is EES (acronym for Engineering Equation Solver).

The basic function provided by EES is the solution of a set of algebraic equations. EES can also solve differential equations, equations with complex variables, do optimization, provide linear and non-linear regression, generate publication-quality plots, simplify uncertainty analyses and provide animations.

There are two major differences between EES and existing numerical equation-solving programs. First, EES automatically identifies and groups equations that must be solved simultaneously. This feature simplifies the process for the user and ensures that the solver will always operate at optimum efficiency. Second, EES provides many built-in mathematical and thermophysical property functions useful for engineering calculations. The steam tables are implemented in such a way that any thermodynamic property can be obtained from a built-in function call in terms of any two other properties. A similar capability is provided for most organic refrigerants, ammonia, methane, carbon dioxide and many other fluids. Air tables are built-in, as are psychrometric functions and JANAF table data for many common gases. Transport properties are also provided for most of these substances.

The library of mathematical and thermophysical property functions in EES is extensive, but it is not possible to anticipate every user's need. EES allows the user to enter his or her own functional relationships in three ways. First, a facility for entering and interpolating tabular data is provided so that tabular data can be directly used in the solution of the equation set. Second, the EES language supports user-written Functions and Procedures similar to those in Pascal and FORTRAN. EES also provides support for user-written routines, which are self-contained EES programs that can be accessed by other EES programs. The Functions, Procedures, Subprograms and Modules can be saved as library files which are automatically read in when EES is started. Third, external functions and procedures, written in a high-level language such as Pascal, C or FORTRAN, can be dynamically-linked into EES using the dynamic link library capability incorporated into the Windows operating system. These three methods of adding functional relationships provide very powerful means of extending the capabilities of EES.

EES is particularly useful for design problems in which the effects of one or more parameters need to be determined. The program provides this capability with its Parametric Table, which is similar to a spreadsheet. The user identifies the variables that are independent by entering their values in the table cells. EES will calculate the values of the dependent variables in the table. The relationship of the variables in the table can then be displayed in publication-quality plots. EES also provides the capability to propagate the uncertainty of experimental data to provide uncertainty estimates of calculated variables. With EES it is no more difficult to do design problems than it is to solve a problem for a fixed set of independent variables.

EES offers the advantages of a simple set of intuitive commands that a novice can quickly learn to use for solving any algebraic problems. However, the capabilities of this program are

extensive and useful to an expert as well. The large data bank of thermodynamic and transport properties built into EES is helpful in solving problems in thermodynamics, fluid mechanics, and heat transfer.

EES can be used for many engineering applications; it is ideally suited for instruction in mechanical engineering courses and for the practicing engineer faced with the need for solving practical problems.

Interesting practical problems that may have implicit solutions, such as those involving both thermodynamic and heat transfer considerations, are often not assigned because of their mathematical complexity. EES allows the user to concentrate more on design by freeing him or her from mundane chores.

3.1.2 REFPROP

REFPROP is an acronym for REference fluid PROPERTIES. This program, developed by the National Institute of Standards and Technology (NIST) provides tables and plots of the thermodynamic and transport properties of industrially important fluids and their mixtures with an emphasis on refrigerants and hydrocarbons.

REFPROP is based on the most accurate pure fluid and mixture currently available. It implements three models of thermodynamic properties of pure fluids: equations of state explicit in Helmholtz energy, the modified Benedict-Webb-Rubin equation of state, and an extended corresponding states (ECS) model. Mixture calculations employ a model that applies mixing rules to the Helmholtz energy of the mixture components; it uses a departure function to account for the departure from ideal mixing. Viscosity and thermal conductivity are modeled with either fluid-specific correlations, an ECS method, or in some cases the friction theory method.

REFPROP was used in this modeling to determine all necessary water and working fluid properties in case EES cannot do it.

The first properties to be searched in REFPROP were properties of geothermal water at wellhead pressures and temperatures. It was necessary to look at the definition of the brine to know if we were dealing with a one phase (water based) inlet or a two phase (water-steam) inlet.

REFPROP helped to determine, in these models, if we were working with subcooled geothermal water (see Modeling of Organic Rankine cycle).

Knowing the input parameters and that we were working with liquid phase input, our process was able to start with calculations using the EES program.

3.2 Modeling of small geothermal power plants in Eastern Slovakian conditions - Durkov area.

3.2.1 Basic hydraulic, geochemical and technological parameters in Durkov area.

Investigation wells GTD-1, GTD-2 and GTD-3 are located in Durkov geothermal structure and proved the existence of a geothermal water reservoir. The Durkov geothermal structure is called the depression of a Neogene basement where Mesozoic dolomites occur at depths of 2000 m and more and their thickness is at least 1000 m. All three geothermal wells were drilled from one place. All the wells were drilled through Neogene rocks and the geothermal reservoir was found on the top of Mesozoic dolomites just below Neogene Carpathian conglomerates. The main inflow zone, located on (Fendek M. , 1998) top of Mesozoic rocks, is a fractured and karstic one. The evaluation of the well test data resulted in reservoir characteristics calculations. The hydraulic parameters of GTD-1 from well test – $T = 2,089 \cdot 10^{-4} \text{ m}^2/\text{s}$, $k_f = 4,471 \cdot 10^{-7} \text{ m/s}$ (Fendek M. , 1998). The effective thickness of the collector was appointed to 467 m according to flowmeter measurements. For a long term discharging flowrate of 56 kg/s it was suggested with an expected depression 0,97 MPa (Fendek M. , 1998). The degassing point was appointed to 750 m depth.

In reality two well tests on GTD-2 were conducted – the first one just after well completion, the second one a half-year later. During the first test the wellhead temperature was 124 °C, dynamic wellhead pressure was 0,2 MPa(1,4MPa) and a free flowrate of 70 kg/s was reached. The hydraulic parameters of GTD-2 were calculated from the first test – for production $T = 8,16 \cdot 10^{-5} \text{ m}^2/\text{s}$, $k_f = 9,44 \cdot 10^{-8} \text{ m/s}$, for built up $T = 1,34 \cdot 10^{-4} \text{ m}^2/\text{s}$, $k_f = 1,55 \cdot 10^{-7} \text{ m/s}$. The degassing point was appointed to depth 1070 – 1100 m TVD (Giese, 1998). After production on GTD-2, injection into GTD-1 was done with a flowrate of 50 kg/s, $t = 15 \text{ °C}$ and 0 MPa on well head. After half a year (March 1999) a one-week production test on GTD-2 was performed with the continual injection into GTD- 1. The preliminary experiences were confirmed and 50 kg/s of 48 °C geothermal water was injected with 0 MPa wellhead pressure on GTD-1. Free flow in the longer period from GTD- 2 showed an increase of the wellhead temperature up to 129 °C with flow rate 50 kg/s and wellhead pressure 1,4 MPa.

The chemical composition of the water, which is almost the same as the one in GTD-3, and the increase in wellhead temperature compared to the first well test showed that tests after well completion were too short for reaching the real reservoir conditions. During the test downhole pressure interference measurements with GTD-1 and 3 were performed, and they showed very good communication between GTD-1 and GTD-3, GTD- 3 and GTD-2 and poorer interference between GTD-1 and GTD-2. It seems that the transmissivity from GTD-3 towards the other wells is almost the same. The data interpretations were very difficult because of continuous production and reinjection; the hydraulic characteristics are summarized in Tab. 8 (Jetel, 1999).

Tab. 8: Hydraulic properties of Mesozoic dolomites from well test in March 1999 (Jetel, 1999)

WELL	T (m ² /s)
GTD - 1	$(2,1 \div 5,7) \cdot 10^{-4}$
GTD - 2	$1,6 \cdot 10^{-4} - 8,2 \cdot 10^{-3}$
GTD - 3	$6,3 \cdot 10^{-3} - 3,4 \cdot 10^{-4}$
GTD-1 – GTD-2	$(1,3 \div 3,9) \cdot 10^{-3}$
GTD-1 – GTD-3	$3 \cdot 10^{-3} - 2 \cdot 10^{-2}$
GTD-3 – GTD-1	$8,4 \cdot 10^{-3}$
GTD-3 – GTD-2	$(4,2 \div 8,4) \cdot 10^{-3}$

A preliminary test was performed on GTD-3. This confirmed a powerful inflow zone in karstic dolomites in contact with Neogene basement about 55 m thick. Later on the well test was conducted in one step free discharging with flowrate 65 kg/s. The temperature at wellhead reached 123 °C, dynamic wellhead pressure was 2,2 MPa. Maximum free flow could reach about 140 kg/s. The degassing point was appointed to depth 1146 – 1195 m TVD. Hydraulic characteristics for production $T = 3,41 \cdot 10^{-4}$ m²/s, $k_f = 8,5 \cdot 10^{-6}$ m/s (Giese, 1999). During the well test downhole pressure interference (2000 m TVD) was recorded. Pressure fall-off on GTD-1 was performed within 10 minutes after the opening of GTD-3 and the pressure difference reached 30 kPa. Where the degassing points of the wells are too deep, the utilization of submersible pumps is considered. Heat output of each well is about 15 MW.

From a geochemical point of view the hydrogeothermal structure Durkov is a complicated system – water-steam-solid phase. TDS value in both wells ranges from 29 g/l to 32 g/l. The biggest differences are in its Ca, Mg, SO₄ and HCO₃ content. The chemical composition of water is a remarkable Na-Cl type with low content of Na-HCO₃. In chemical analyses of the condensate curiously high contents of non-volatile components, mainly Fe, Mn, Na, occurred. On the other site the condensate is enriched by volatile components, mainly NH₄ (concentration is three times higher). The cause of this content distribution is not clear; Fe and Mn are probably enriched by the corrosion of the inner part of the testing equipment. The lowest total content of solids in geothermal water occurs in condensate, but Fe is an exception. Ca and Mg content in solid phase is highest in samples taken after the gas separator, where equilibrium is caused by CO₂ degassing and the carbonates of Ca and Mg precipitate into solid phase. The same dependence can be observed in Sr behavior, which has similar chemical properties. The content of SiO₂ is similar in sampling before and after the separator, but the solid form of SiO₂ does not occur in the condensate. Compared with other geothermal sources in Slovakia, there are interesting amounts of arsenic (20 to 50 mg.l⁻¹), boron (about 1000 mg.l⁻¹ as HBO₂), lithium, bromides (16.9 - 20 mg/l) and iodides (10 - 14 mg-/l).

On the basis of isotopic analyses of oxygen in sulphate the reservoir temperature for GTD-1 is estimated to be between 159–165 °C. For water from GTD-2 the calculated reservoir temperature is 140–148 °C, for GTD-3 151–158 °C (Mizutani & Rafter, 1969).

From a genetic point of view of geothermal water we suppose that it is halogenic water, which probably originated from meteoric water infiltrating through the salt-bearing formation of Carpathian into the Mesozoic collector.

The following arguments support this opinion (Bodis, Michalko, & Rapant, 1999):

- Remarkable sodium-chloride type of geothermal water
- Very low value or lack of Na-HCO₃ component. It means that water was not degraded by infiltration, which is confirmed by values of the coefficient HCO₃/Cl in the range 0,057 – 0,079.
- The value of the coefficient Cl/Br is higher than 1000, which represents the ratio present in ocean water
- The molar ratio Cl/Na in geothermal water corresponds to the stoichiometric solubility of this mineral
- Geothermal water has low content of biogene elements, mainly iodine
- The isotopic composition of d18O and dD of geothermal water is very similar, in the case of downhole samples it is almost identical (d18O: -0,36 to 1,31 ‰, dD : -49,3 to – 50,10 ‰). The isotopic composition excludes the sea as the origin of the geothermal water. For geothermal water in carbonates, in medium temperatures (150 °C) there is a transfer, of isotopic composition, of oxygen towards the higher content of a heavier isotope because of water-rock interaction. The isotopic composition of hydrogen does not change, mainly in chloride type water. In this case as meteoric water we consider the content of dD to be about 50 ‰.

The physical and chemical properties of GTD-2 and GTD-3 wells, which are intended for production, are almost identical. They are characterized by their increased mineralization, which consists especially of higher amounts of chlorides (16.6 - 17.1 g.l⁻¹), sodium (10.85 - 11.78 g.l⁻¹), HCO₃ - (1653 – 2135 g.l⁻¹), sulphates and potassium. Typically the high content of dissolved gas varies from 12.7 to 17 m³ of gas per m³ of water, 98% of which is CO₂ (in one sample from GTD-3 even 21 m³.m⁻³). The calcium carbonate system is very sensitive to the changes of pressure (and consequent degassing) and temperature. The calcium content ranges within 320 - 413 mg.l⁻¹ (downhole sample). The results of the chemical equilibrium model computations revealed that under partial degassing, when the pH rises to more than 5.57 at GTD-3 wellhead (pCO₂ 2.2 MPa, 125 °C), the water tends to form scaling. For instance, free Ca²⁺ ions are supersaturated at the GTD-3 wellhead, compared with the relevant equilibrium concentration of 61 mg.l⁻¹ at pH 6.4 (pCO₂ 0.373 MPa, 125 °C) and when degassed more severely (pH 7.0 or higher) the free Ca²⁺ ions (scale forming) supersaturation reaches 173 mg.l⁻¹(pCO₂ 0.079 MPa, 70 °C). On the other hand, when the water is kept under pressure high enough to maintain a sufficient amount of CO₂ that is dissolved, serious corrosion takes place due to the increased contents of Cl⁻, SO₄²⁻, NH₄⁺, CO₂-HCO₃ - etc. The partial CO₂ pressure required to maintain the calcium ions in the solution reaches app. 2.1- 2.2 MPa for GTD-2 and GTD-3 wells (Drozd & Vika, 1998). The wellhead pressure at GTD-3 under free outflow conditions is 2.2 MPa, which is enough; but at GTD-2 well the pressure is only 1.7 - 1.8 MPa, i.e. a submersible pump will be needed to raise the pressure at the wellhead and consequently in the heat exchanger system. As an example, in Tab.9 the results of the calcium-carbonate system model calculation are given, where delta Ca means supersaturation (+) or undersaturation (-) of the geothermal water by free Ca²⁺ ions with respect to the equilibrium state. These results were confirmed by coupon check (Bodis, Michalko, & Rapant, 1999).

Tab. 9: The chemistry of calcium in GTD-3 water (not degassed, resp. very little) (Bodis, Michalko, & Rapant, 1999)

Temp. (°C)	Press. [MPa]	Condition	cCa ²⁺ equil. (mg.l ⁻¹)	delta Ca ²⁺ (mg/l)	part.pressure of CO ₂ [MPa]	cCO ₂ (mg.l ⁻¹)	pH
131.8	19.55	aquifer 2400m	75.4	-0.19	2.541	9421	5.49
129.9	12	casing 1300m	72.5	0.3	2.515	9397	5.51
125	2.2	wellhead	76.2	0.2	2.2	8460	5.57
110	2	cooling	120.4	-8.7	2.073	8593	5.50
100	2	cooling	151.6	-12.6	1.843	8152	5.50
90	2	cooling	202.0	-38.2	1.602	7672	5.50
80	2	cooling	235.4	-45.0	1.421	7416	5.50
70	2	cooling	270.3	-47.9	1.232	7234	5.50
60	2	cooling	315.4	-62.2	1.087	7290	5.50

During the hydrodynamic test the steel coupons (plates) were mounted at the wellhead, behind the gas separator and at the discharge from the system. At GTD-3 the scaling occurred during the hydrodynamic test only between the separators and at the wellhead; and in the outflow from the system corrosion was observed, which can be explained by high pressure at the wellhead. The corrosion rate reached around 5 mm.y⁻¹, the scaling rate was 0.9 mm. day⁻¹ (GTD-2). The analyses of scale deposits proved that the scaling consists mainly of CaCO₃, with small amounts of SiO₂ and FeCO₃. Under different conditions (partial degassing and correspondingly higher pH, lower temperatures), except for the calcite, the water is also supersaturated by caolinite, quartz, dolomite and strontianite, which will co-precipitate. The heavy metals concentrate in scaling (e.g. as in sandy deposits from tanks). With respect to these results the treatment of water by an inhibitor will be necessary for its long-term utilization, except, as a matter of course, in the event of careful handling of pressure and other auxiliary precautions. The inhibitor will protect against scaling and corrosion. The best solution is the dosage of an inhibitor downhole at the aquifer to protect the whole system - both the casings and heat exchangers with pipelines (Drozd & Vika, 1998). The dosage of inhibitor will also enable the use of lower pressures in the heating system. The summary of basic parameters from Durkov geothermal area is shown in Tab. 10.

Tab. 10: Summary of basic parameters from Durkov geothermal area (Wittenberger & Pinka, 2005).

Parameter	GTD 1	GTD 2	GTD 3
Q [l.s-1] flow	56	50	65
Qmax [l.s-1] maximum flow	66	70	120
T head [°C] wellhead temperature	125	129	126
T bottom [°C] well bottom temperature	144	154	131
P head [MPa] wellhead pressure	0,92	0,2	2,2
P bottom [MPa] well bottom pressure	29,3	27,4	21,9
H [m] depth of the drill	3210	3250	2252

3.3 Modeling of Organic Rankine cycle

The simple case of a binary cycle is shown in Fig. 11. Modeling and analysis of the basic Organic Rankine cycle will take a place here.

The Organic Rankine cycle utilizes a secondary working fluid which, compared with steam, has a low boiling point and high vapor pressure at low temperatures.

The basic Organic Rankine cycle consists of 3 basic components: a heat exchanger, a turbine and a condenser with cooling tower.

The working fluid is preheated and evaporated in the heat exchanger, where the heating medium is brine from a geothermal source. The resulting saturated vapor enters the turbine and expands. After expansion in the turbine cooling and condensing of the working fluid takes place in the condenser. From the condenser the working fluid is pumped back into the heat exchanger. The working fluid is in a closed loop system, which is heated up by brine to evaporate and then cooled to condense by cooling water coming from the cooling tower, which is also the part of the power plant.

The cycle has a subcritical boiler pressure and we are assuming the working fluid to be ISOBUTANE. Pressure losses in all heat exchangers and piping will be assumed negligible (DiPippo, 2008).

The cycle specifications are as follows

- brine inlet temperature
- brine inlet flow (flow from wellhead)
- brine pressure at wellhead

At the very beginning it is important to build and to draw the most basic and simple binary Organic Rankine Cycle (Fig. 11).

Basic components of this model are the heat exchanger with preheater and evaporator (point 6), the turbine with generator (points 1-2), the condenser with cooling tower (point 3) and the feedpump (points 4-5).

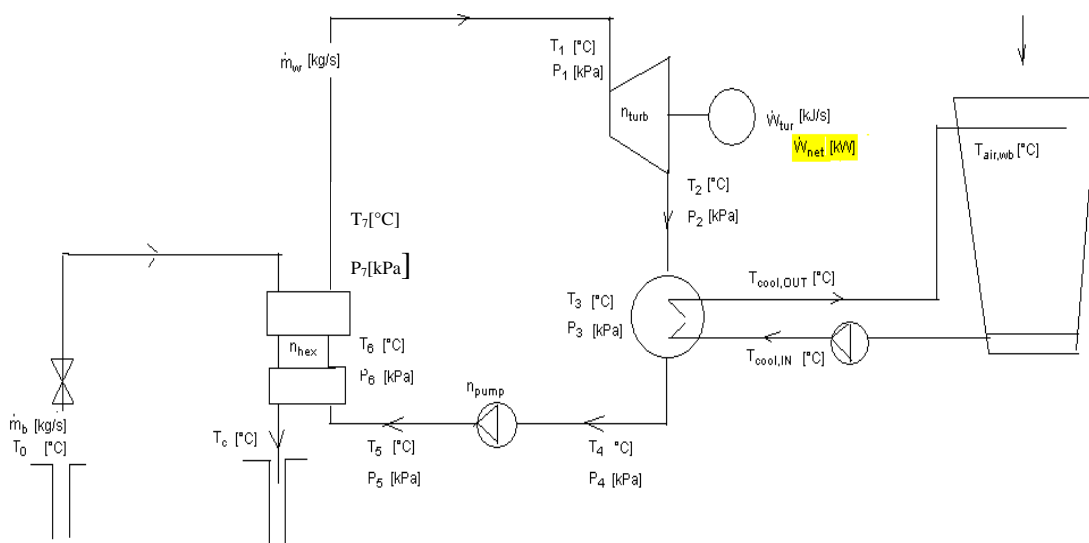


Fig. 11: Basic binary Organic Rankine cycle scheme (source: EES)

To understand the thermodynamic processes in the ORC plant, the use of two important diagrams is necessary – a pressure-enthalpy diagram and a temperature-entropy diagram Fig12.

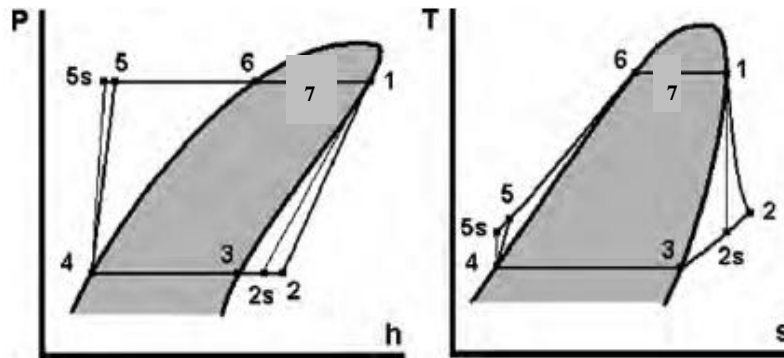


Fig. 12: Pressure-enthalpy and temperature-entropy diagrams for ORC cycle (DiPippo, 2008)

In point 1 saturated isobutane vapor enters the turbine where it expands and produces work, which is changed to electric power in the generator. In point 2 saturated isobutane vapor after turbine expansion is shown, which has lowered pressure and decreased temperature. The vapor with constant pressure enters the condenser. Point 3 corresponds with the condensing point of the working fluid (isobutane). The vapor is cooled with cooling water from the air cooled cooling tower and changed to saturated liquid working fluid. Saturated isobutane liquid is again returned to the cycle after condensing (point 4) by being pumped back (point 5) to the heat exchanger. Preheating and evaporating of the working fluid takes place in point 6 and the whole cycle is repeated.

Looking at the diagrams it is clear that we must determine the enthalpy values for the isobutene at the six state points in the cycle using EES to determine all necessary parameters and to find the power plant output, which is, for the purpose of this study, the most interesting parameter.

By modeling, the highest possible power output from the turbine is found and the net production of the modeled power plant is calculated. By changing the pressure in the heat exchanger this study will show how this heat exchanger pressure influences all of the cycle parameters and will optimize the model to the most feasible parameters. The goal is to find the highest power output from the power plant.

Using EES together with REFPROP it is easy to estimate all the needed parameters. REFPROP helps to determine whether the geothermal water is a one phase or two phase mixture. With inlet parameters (temperature and pressure) REFPROP defines the geothermal source as subcooled, which means that the brine is in a liquid state during the whole heat transfer process (see Tab.11).

Tab. 11: Output of calculations of specific state point of geothermal water in REFPROP

Temperature [°C]	Pressure [kPa]	Density [kg/m ³]	Enthalpy [kJ/kg]	Entropy [kJ/kg.K]	Quality [kg/kg]
125,00	920,00	939,37	525,55	1,5809	Subcooled
129,00	1400,0	936,27	542,89	1,6230	Subcooled
126,00	2200,0	939,20	530,68	1,5904	Subcooled

Input parameters for Organic Rankine cycle modeling in the EES program

Input parameters for EES are given from known well test analysis:

GTD-1

Twell1=125 [°C]

Pwell1=920 [kPa]

mwell1=56 [kg/s]

GTD-2

Twell2=129 [°C]

Pwell2=1400 [kPa]

mwell2=50 [kg/s]

GTD-3

Twell3=126 [°C]

Pwell3=2200 [kPa]

mwell3=65 [kg/s]

Looking at diagrams for this process it is possible to make a couple of assumptions which can help when making the calculations.

From the P-h diagram it is clear that the turbine inlet pressure (point 1) is equal to the outlet temperature from the heat exchanger (point 6) and also the temperature after the feedpump (isoenthalpic) (point 5_s) and the non-isoenthalpic temperature after the feedpump (point 5) right before entering the heat exchanger.

$$P[1]=P[6]=P_{5s}=P[5]$$

Equal pressures can also be found in the lower pressure part of the P-h diagram. The pressure after the turbine (point 2) is equal to the pressure of the isentropic turbine expansion (point 2_s), to the pressure in the condenser (point 3) and the pressure after the condenser (point 4). It is apparent that isobaric condensing is occurring.

$$P[2]=P_{2s}=P[3]=P[4]$$

Looking at the T-s diagram equal temperatures can be seen in points 1 and 7. Point 1 is the turbine inlet temperature and point 7 is the temperature in the heat exchanger, which is divided between the preheater and the evaporator. Point 7 is the state of the working fluid after the evaporation process.

$$T[1]=T[7]$$

The same temperatures are also in the condenser, There were equal pressures here as well.

$$T[3]=T[4]$$

Looking at the T_s diagram it is also possible to make assumptions about entropies. It will later be necessary to estimate the parameters of the turbine and feedpump using isentropic changes in the turbine and feedpump. Then we can write:

$$s[1]=s_{2s}$$

$$s[4]=s_{5s}$$

Knowing all of the input geothermal brine parameters we can step by step calculate all enthalpies in the cycle, work of the turbine, condensing temperature, working fluid flow, pump work, heat exchanger parameters and also one of the most important parameters – the geothermal water outlet temperature.

Turbine analysis

Turbine analysis is the first step in the cycle analysis. (See scheme - point 1).

Turbine work, which produces electricity in the generator, is the main and most interesting parameter to find. It is important to know that in this part of the power plant we are already working with a different fluid (not geothermal brine) which is called working fluid. In this model the working fluid is Isobutane. Basic chemical and thermodynamical properties of Isobutane are shown in Tab.12.

Tab. 12: Basic chemical and thermodynamical properties of ISOBUTANE (working fluid (Pocket Guide to Chemical Hazards, 2005))

Parameter	3.3.1
Molecular formula	C ₄ H ₁₀
Molar mass	58, 12 g/mol
Density	2,15 kg/m ₃ gas; 593,4 kg/m ₃ liquid
Melting point	- 159,6 °C
Boiling point	-11,7 °C
Solubility in water	insoluble
Appearance	colorless gas
EU classification	highly flammable
Autoignition temperature	460 °C

Isobutane, also known as methylpropane or 2-methylpropane, is an alkane, isomeric with butane. Recent concerns with the depletion of the ozone layer by freon gases have led to the increased use of isobutane as a gas for refrigeration systems, especially in domestic refrigerators and freezers, and as a propellant in aerosol sprays. When used as a refrigerant (Pocket Guide to Chemical Hazards, 2005) or a propellant, isobutane is also known as R-600a. Some portable camp stoves use a mixture of isobutane with propane, usually 80:20. Isobutane is used as a feedstock in the petrochemical industry, for example in the synthesis of iso-octane.

To come to a conclusion based on which of the two modeled small geothermal power plants is producing more electricity it is necessary to calculate turbine work, which is given by the equation:

$$W_t = m_{wf} \cdot (h[1] - h[2]) = m_{wf} \cdot \eta_{tur} \cdot (h[1] - h_{2s})$$

$h[1]$enthalpy of the working fluid (isobutane) as function of temperature $T[1]$ and quality of the isobutane which is equal to 1 (saturated vapor quality).

h_{2s}isentropic enthalpy of the working fluid after the turbine as a function of the P_{2s} and s_{2s} (pressure and entropy in point 2_s).

The equation for determining the efficiency of the turbine helps to define enthalpy in point 2 by knowing the efficiency of the turbine, which is usually given by the producer of the turbine. In this case the turbine efficiency was stated to be $\eta = 0,75$. The efficiency of the small gas turbines is usually in a range of 70-80% (DiPippo, 2008).

$$\eta_{tur} = (h[1] - h[2]) / (h[1] - h_{2s})$$

It is necessary to take into consideration the parasitic electricity losses in the cycle. Parasitic losses are losses from electricity production used by the power plant itself. Generated electricity is decreased by the electricity used to run the feedpumps, cooling tower fan and pumps on the geothermal source's wellhead. In this model, to simplify the calculations, only parasitic losses in the feedpump are assumed, the cooling tower fan and pumps on the wellheads are not taken into consideration (they can be added later to the model). Parasitic losses usually take up 10% from the electricity produced in the cycle. Electric power produced in the turbine, which is lowered by parasitic losses, is called net power. Net power is the total electric power produced by the power plant which can be sent to a network for use.

$$W_{net} = W_{tur} - W_{par}$$

$$W_{par} = W_{pump}$$

Power production from the turbine is a function of inlet and outlet pressures and temperatures and also the efficiency of the turbine.

Condenser analysis

Working fluid which expanded in turbine is condensed in the condenser. The condenser is a heat exchanger working with two fluids. It uses cooling water from the air cooling tower to decrease the temperature of the working fluid and to condense it (to change phase of the working fluid from vapor to liquid state).

An analysis of the condenser requires the use of another thermodynamic diagram. The temperature-heat transfer (T-q) diagram shows the total amount of heat that passes from the turbine to the cooling water in order to cool down and condense the working fluid.

Heat rejected from the working fluid to the cooling water in the condenser is calculated using enthalpies of inlet and outlet parameters of the working fluid in the condenser:

$$Q_c = m_{wf} * (h[2] - h[4])$$

$h[2]$turbine input enthalpy which was defined in the turbine analysis

$h[4]$condenser outlet enthalpy as a function of $T[4]=T[3]$ and quality of isobutane, in this point equal to 1

The temperature of the inlet cooling water is found from the cooling tower properties. From weather data it is possible to find the average temperature for given place – in this case the exploited area is close to Kosice town, which has weather data in an international weather database (Energy Efficiency and Renewable Energy -Building Technologies Program - Weather Data, 2008).

The average yearly temperature measured as a dry bulb temperature is 9 °C. As long as dry bulb temperature is being discussed, the relative humidity of the air, which has influence over the inlet condenser cooling water temperature, must be taken into account. EES has a function for the calculation of wet bulb temperature using dry bulb temperature as an input variable and which also includes the relative humidity. It is necessary to add 3-4 degrees, which will increase the temperature at the bottom in the cooling tower, to the inlet cooling water. In the calculation of the wet bulb temperature the atmospheric pressure in the cooling tower is assumed.

$$T_{air_wb} = \text{WetBulb}(\text{AirH}_2\text{O}; r=rh_1; T=T_{air_db}; P=P1)$$

The outlet temperature of the cooling water is calculated from the inlet cooling temperature, which is increased by raising the temperature of the cooling water in the condenser:

$$T_{\text{cool_OUT}}=T_{\text{cool_IN}}+T_{\text{delta}}$$

$T_{\text{delta}}=12$ [°C] usual increase of inlet water temperature in the condenser caused by heat transfer between the cooling water and the working fluid.

The relationship between the mass flow of the working fluid and the mass flow of the cooling water is given by mass balance equations. Mass balance equations help to find the mass flow of the working fluid and also the condensation temperature.

Cooling water mass flow calculation:

$$m_{\text{dot_cw}}*c_{p_w}*(T_{\text{cool_OUT}}-T_{\text{cool_IN}})=m_{\text{dot_wf}}*(h[2]-h[4])$$

Condensing temperature determination:

$$m_{\text{dot_cw}}*c_{p_w}*(T_{\text{cond}}-T_{\text{cool_IN}})=m_{\text{dot_wf}}*(h[3]-h[4])$$

Knowing the assumed pinch point temperature (5 °C), it is possible to calculate the condensing temperature of the working fluid as follows:

$$T[3]=T_{\text{cond}}+T_{\text{pp}}$$

Looking at T-q diagram it is necessary to define six temperatures to properly describe the process of heat transfer in the condenser. After the condenser analysis we know the temperatures of the cooling water inlet and outlet and also the inlet and outlet temperatures of the working fluid passing through the condenser. Temperature T[3] is important for the estimation of condensing temperature of the working fluid, which divides the condenser into two parts – the cooler and condenser.

Feed pump analysis

The working fluid is pumped from the condenser to the heat exchanger by means of a feedpump. The analysis of the feedpump is based on known inlet and calculated outlet parameters in this point of the cycle (point 4-5 at Fig. 11).

The work of the feedpump is calculated as follows:

$$W_{\text{dot_pump}}=m_{\text{dot_wf}}*(h[5]-h[4])$$

h[4].....condenser output enthalpy (defined in condenser analysis)

h[5].....enthalpy after the feedpump, calculated from pump efficiency

$$n_{\text{pump}} = (h_{5s} - h[4]) / (h[5] - h[4])$$

h_{5s}isentropic feedpump outlet enthalpy as a function of P_{5s} and s_{5s} , which is equal to $s[4]$ as a function of $T[4]$ and quality equal to 0.

Pump efficiency is assumed to be 0,75. The efficiency of the feedpump is dependent on the outlet pressure from the condenser and from the pressure required in the next step of the cycle, which is the heat exchanger. The pump parameters can also be set by the producers of the feedpumps for binary cycles. All the parts of power plants are also dependent on the cost demand on a power plant.

Compressed working fluid, which increases the pressure in the feedpump, produces heat energy, which causes the outlet temperature to increase slightly.

The outlet temperature is calculated as a function of $P[5]$ and enthalpy in this point $h[5]$:

$$T[5] = \text{Temperature (Isobutane; } P=P[5]; h=h[5])$$

Feedpump work is counted as a parasitic loss in a power plant because it demands power in order to run.

Heat exchanger analysis

The analysis of the heat exchanger is probably the most difficult part of modeling small geothermal power plants. It is necessary to divide heat exchanger into the preheating and evaporating parts.

In the heat exchanger the heat is transferred from one fluid to another and it is necessary to thermodynamically describe the heat transfer processes.

It is assumed that the heat exchanger is well-insulated so that all the heat transfer is between the brine and the working fluid- isobutane. It is also assumed that the flow is steady, and the differences in the entering and leaving potential energy and kinetic energy are negligible.

The heat exchanger's function is demonstrated in the temperature-heat transfer, or T-q, diagram (Fig.13).

The abscissa represents the total amount of heat that is passed from the brine to the working fluid. It can be shown either as a percent or in heat units (for example kJ/kg of working fluid).

The preheater provides sufficient heat to raise the working fluid to its boiling point (in the figure, state in point 6). The evaporation occurs from 6-1 along an isotherm for a pure working fluid. The place in the heat exchanger where the brine and the working fluid experience the minimum temperature difference is called the pinch-point, and the value of that difference is designated the pinch-point temperature difference ΔT_{pp} (DiPippo, 2008)

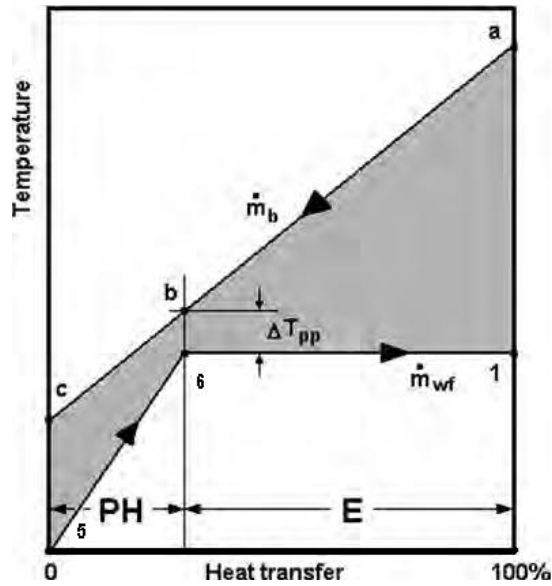


Fig. 13: Temperature-heat transfer diagram for ORC preheater and evaporator (DiPippo, 2008).

From the diagram, point 5 is compressed liquid, the outlet from the feedpump. State 6 is a saturated liquid at the boiler pressure. State 1 is saturated vapor, the same as the turbine inlet condition. The preheater and evaporator are analyzed separately as two heat exchangers.

Heat exchanger efficiency was set to be 95%. Heat exchangers have efficiency close to 99%; the loss of 1% is caused by losses from the surface of the heat exchanger.

Dividing the heat exchanger into the preheater and the evaporator encourages thinking about each of these parts separately.

The parameters after the preheater can easily be found by knowing the pressure and temperature at this point $P[6]$ and the pressure after the preheater, which is equal to the higher pressure, which can be varied straight in the diagram; and quality at this point is equal 0:

$$T[6]=\text{Temperature}(\text{Isobutane};P=P[6];x=x[6])$$

$$h[6]=h_{\text{bubble}}$$

The enthalpy of the bubble point is a function of pressure and quality equal to 0 at the given point (point6).

Evaporator analysis

After the preheater the working fluid goes to the evaporator, where the preheated working fluid changes its phase to saturated vapor. The parameters of the working fluid after the evaporator – vaporizer are found as follows:

$$T_a = T[0]$$

$T[0]$...temperature of the brine from the geothermal wells which are defined as a function of initial pressure and enthalpy of the geothermal fluid.

$$T[0] = \text{Temperature}(\text{water}; P = P[0]; h = h[0])$$

$P[0]$ was stated to be the highest pressure found on the wellheads. It is used due to the possibility of corrosion, which was mentioned in the chapter 1.7.1.

Only well GTD-3 has the required pressure. The other two wells need to have the pump to keep the required pressure on the wellhead.

Inlet geothermal water enthalpy is a function of enthalpies in each well and their mass flow rates:

$$h[0] = (h_{\text{well}[1]} * m_{\text{dot_well}[1]} + h_{\text{well}[2]} * m_{\text{dot_well}[2]} + h_{\text{well}[3]} * m_{\text{dot_well}[3]}) / m_{\text{dot_b}}$$

Enthalpies on the wellheads are functions of pressure and temperature on each wellhead.

The mass flow of the geothermal brine is the sum of the mass flow of each well:

$$m_{\text{dot_b}} = m_{\text{dot_well}[1]} + m_{\text{dot_well}[2]} + m_{\text{dot_well}[3]}$$

Specific heat capacity of the geothermal water as a function of initial temperature and pressure:

$$cp_b = Cp(\text{water}; T = T[0]; P = P[0])$$

The parameters of the evaporator can easily be found knowing that the pressure at this point (point 7) is the same as the pressure at the beginning of the heat exchanger and after the preheater. Pressure is kept equal through all heat exchanger processes.

$$P[7] = P_{\text{high}}$$

Enthalpy at this point (point 7) is a function of pressure and quality, which is equal to 0:

$$h[7]=\text{Enthalpy}(\text{Isobutane};P=P[7];x=x[7])$$

The vaporizer on its own is characterized by mass balance equations of both parts of the heat exchanger.

Preheater mass balance equation:

$$m_{\text{dot}_b} \cdot c_{p_b} \cdot (T_b - T_c) = m_{\text{dot}_{wf}} \cdot (h[6] - h[5])$$

- this equation helps to find the temperature of the brine after the heat exchanger T_c , which can be re-injected or used further in district heating.

Evaporator mass balance equation:

$$m_{\text{dot}_b} \cdot c_{p_b} \cdot (T_a - T_b) = m_{\text{dot}_{wf}} \cdot (h[1] - h[6])$$

- in this equation the only unknown is the mass of the working fluid $m_{\text{dot}_{wf}}$, which can be determined from this equation

The parameters on the right side of the mass balance equations were calculated earlier in this chapter.

Enthalpy $h[6]$ is a function of $P[6]$ and quality at this point is equal to 0. Temperature at this point was also estimated as a function of pressure $P[6]$ and quality $x=0$.

The brine inlet temperature in each well is always known. The brine inlet temperature is calculated as a function of $P[0]$ and $h[0]$. Brine inlet temperature is $T[0]=T_a$, which gives us the point on the T-q diagram.

The pinch-point temperature difference is generally known from the manufacturer's specifications, this allows T_b to be found from the known value for $T[6]$.

$$T_b = T[6] + T_{pp}$$

Temperature of the brine after it passed the heat exchanger and gives all possible heat energy T_c is calculated from the preheater mass balance equation.

Pressure at the top of the wellhead should be 2,2MPa due to the danger of corrosion processes which were mentioned in chapter 1.7.1. Pressure at the wellheads will require installing pumps to maintain the required pressure. Initial pressure was therefore stated to 2,2 MPa.

3.3.2 Analysis of Organic Rankine cycle modeling results

The aim of this model is to find the highest possible power output from the cycle, knowing the inlet parameters from the wellhead in the given area - Durkov.

In the parametric table (Tab.13) output of the power plant in total net power is shown depending on heat exchanger inlet pressure, which is changed straight in the diagram.

Tab. 13: Parametric table of modeled ORC - Relation between changing heat exchanger inlet pressure and power output (source: EES.)

P[6] [kPa]	T[6] [°C]	T_c [°C]	T_cond [°C]	W_dot_tur [kJ/s]	W_dot_net [kW]
405	30,05	35,01	25	8,161	7,881
683,1	49,92	42,64	24,61	2738	2617
961,2	64,46	50,93	24,33	3903	3696
1239	76,16	59,65	24,12	4318	4055
1517	86,06	68,8	23,96	4281	3987
1796	94,69	78,42	23,85	3926	3627
2074	102,4	88,65	23,77	3317	3039
2352	109,3	99,71	23,73	2478	2252
2630	115,6	112	23,73	1397	1258
2908	121,4	126,4	23,78	5,642	5,031

From the parametric table it is visible that the highest possible power output from the modeled Organic Rankine cycle binary power plant is reached using inlet heat exchanger pressure 1239 kPa; produced power is then approximately 4 MWe.

By increasing the pressure inlet to the heat exchanger the temperature in the heat exchanger is also increased. Increased pressure and temperature in the heat exchanger inlet causes the mass flow of the working fluid to slightly decrease (Tab.14). By decreasing the mass flow of the working fluid, increased pressure and temperature the heat transfer in heat exchanger is lowered, which again causes the increase of the brine outlet temperature. The higher the brine's temperature upon its return to the reinjection well the higher the possibility of corrosion. Corrosive reactions occur faster due to the higher temperature.

After the use of geothermal water in the power plant the brine outlet temperature is still hot enough to be used in district heating systems with preheating by other heat sources (gas or coal preheating). The temperature which is required for district heating is 80 °C. Our outlet temperature is 60 °C so it should be preheated by at least 20 °C. The highest possible heating temperature limitation is 100 °C. Preheating would increase the initial cost of the power plant, but on the other hand geothermal source can be utilized for power production and also for heating purposes.

The problem with utilizing Durkov geothermal water in district heating is also its high chemical content, which can cause corrosion in the pipelines. Cleaning of the geothermal outlet water would also increase the initial and maintenance cost of the power plant. It is also

possible to use fresh, heated water for district heating with outlet brine temperature – to implement another heat exchanger to utilize as much energy as possible from the geothermal source.

Tab. 14: Parametric table of changing output temperatures and mass flow of the working fluid with changing inlet heat exchanger pressure.(source: EES)

P[6] [kPa]	T[6] [°C]	T_c [°C]	m_dot_wf [kg/s]
405	30,05	26,44	205,7
683,1	49,92	35,4	174,3
961,2	64,46	44,74	149,3
1239	76,15	54,37	127,3
1517	86,05	64,36	106,9
1796	94,71	74,83	87,17
2074	102,4	85,87	67,59
2352	109,3	97,76	47,35
2630	115,6	111	25,45
2908	121,4	126,4	0,09955

Changing the heat exchanger inlet pressure has an influence on the whole cycle. Not only does it act on the mass flow of the working fluid and by that on the heat transfer in the heat exchanger but also on the work and power output of the turbine. Turbine work is a function of inlet pressure and temperature. The higher the pressure and temperature of the inlet turbine parameters, the higher the power production from the turbine is. The limiting factor of the turbines is material resistance in turbine itself. The high parameters of the turbines require more resistant material for the turbine and especially for its blades. Other issues of binary power plant turbines are working fluid parameters. The turbine has to be made from material that does not react with the working fluid. A turbine made from more resistant materials means an increase in the initial cost of the power plant.

In the scheme (Fig.14) all input and output data shown were calculated using the EES program and according to written procedure.

Input data are highlighted with green and main output – net power output is highlighted in yellow. Input data is possible to change and to study all changes related with the change of one parameter.

Efficiencies of the turbine, heat exchanger and pump are possible to change according to the real efficiencies of the used devices.

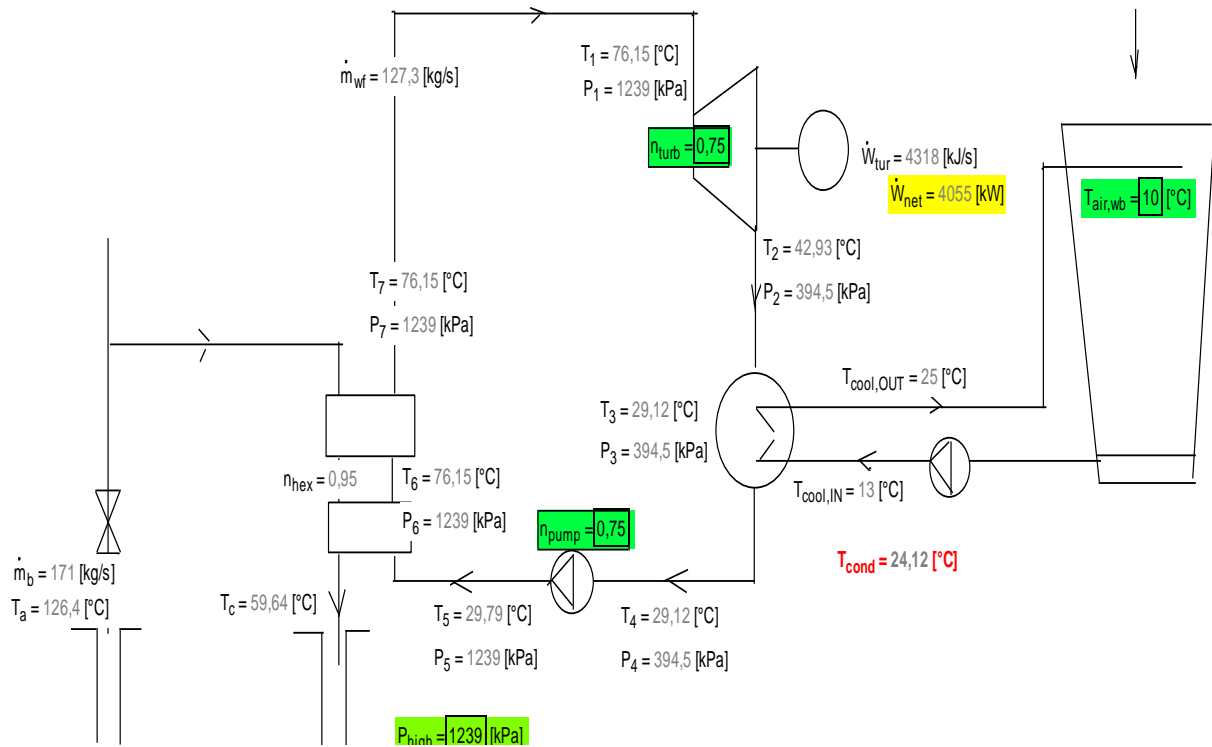


Fig. 14: Organic Rankine cycle with input and output parameters with higher reached power output (source: EES)

The most important part of the whole cycle is the air cooling tower, which ensures cool water for condenser. The temperature of the water that enters the condenser is dependent on wet bulb temperature, which is calculated from the dry bulb temperature of the air. Values of dry bulb air temperatures change with the weather throughout the year. When making the calculations it is good to estimate the average yearly dry bulb air temperature obtained from weather data, which are available on the internet (Energy Efficiency and Renewable Energy - Building Technologies Program - Weather Data, 2008). For Kosice region the yearly average dry bulb air temperature is 9 °C. Calculations showed that, taking into the consideration the relative humidity in this region, the yearly average wet bulb temperature is 10 °C. Wet bulb temperature can easily be changed straight in diagram.

Changing the temperature in the cooling tower also changes the condensing temperature in the condenser. Parametric table (Tab. 15) is set to calculate the change of the condensing temperature by changing the wet bulb air temperature in the cooling tower. Wet bulb temperatures are set according to the monthly average dry bulb temperatures recalculated to wet bulb temperatures. From the table it is possible to notice how power output also changes with changing temperature in the cooling tower. The lower the temperature in the cooling tower, the higher the power output is from the cycle due to better heat transfer in the heat exchanger. The condensing temperature has an influence on the whole cycle. From this it is clearly visible that all the processes in the cycle are related and by changing one parameter the parameters in the whole cycle change.

Tab. 15: Parametric table of ORC cycle – change of cooling air temperatures in relation with condensing temperature and total (net) power output (source: EES)

Months in year	T _{air_wb} [°C]	T _{cond} [°C]	T[3] [°C]	T _{cool_IN} [°C]	T _{cool_OUT} [°C]	W _{dot_tur} [kJ/s]	W _{dot_net} [kW]
January	-2,3	11,68	16,68	0,7	12,7	5722	5429
February	-1,2	12,79	17,79	1,8	13,8	5592	5301
March	4,1	18,15	23,15	7,1	19,1	4977	4699
April	9,6	23,71	28,71	12,6	24,6	4362	4098
May	15,1	29,29	34,29	18,1	30,1	3768	3521
June	17,9	32,13	37,13	20,9	32,9	3474	3237
July	19,3	33,55	38,55	22,3	34,3	3330	3098
August	19,5	33,75	38,75	22,5	34,5	3309	3078
September	14,7	28,88	33,88	17,7	29,7	3811	3562
October	9,6	23,71	28,71	12,6	24,6	4362	4098
November	3,4	17,44	22,44	6,4	18,4	5057	4777
December	-1,7	12,29	17,29	1,3	13,3	5651	5359

In Fig. 15 a plot of temperature and heat transfer from heat exchanger is shown. The blue line shows geothermal water slowly decreasing in temperature and the red line shows the preheated and later evaporated working fluid line. A break in the line divides the heat exchanger into the preheating and evaporating parts. Basically, the diagram can be read as a map of the processes in the heat exchanger. The working fluid (blue line) from the pump enters the heat exchanger and the geothermal water (red line) slowly increases the temperature of the working fluid. Increasing the temperature of the working fluid causes a decrease in the geothermal water temperature. The closer both lines are to each other the better the heat transfer in the condenser (heat exchanger).

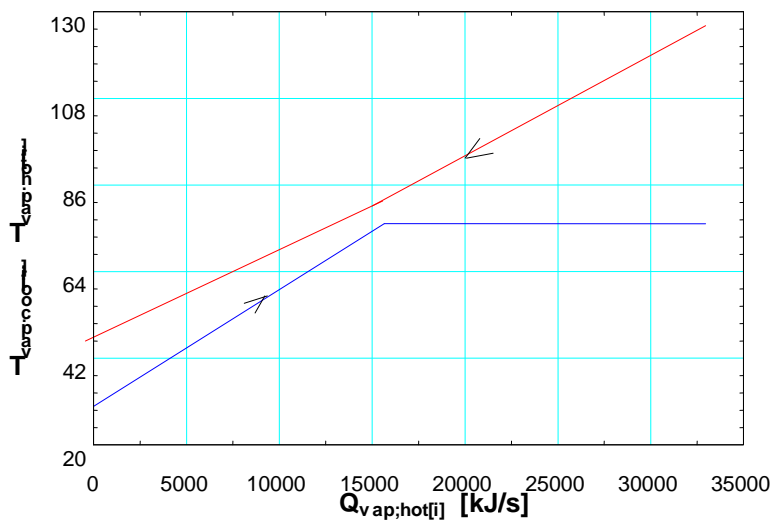


Fig. 15: Plot of temperature and heat transfer relation from condenser (source: EES)

3.4 Modeling of Kalina binary cycle

A simple model of a Kalina binary power plant is shown in Fig. 16.

The Kalina binary cycle is based on the same principle as the Organic Rankine cycle but with different working fluid. In the Kalina cycle, a mixture of ammonia and water is used as the working fluid in different ratios of ammonia and water.

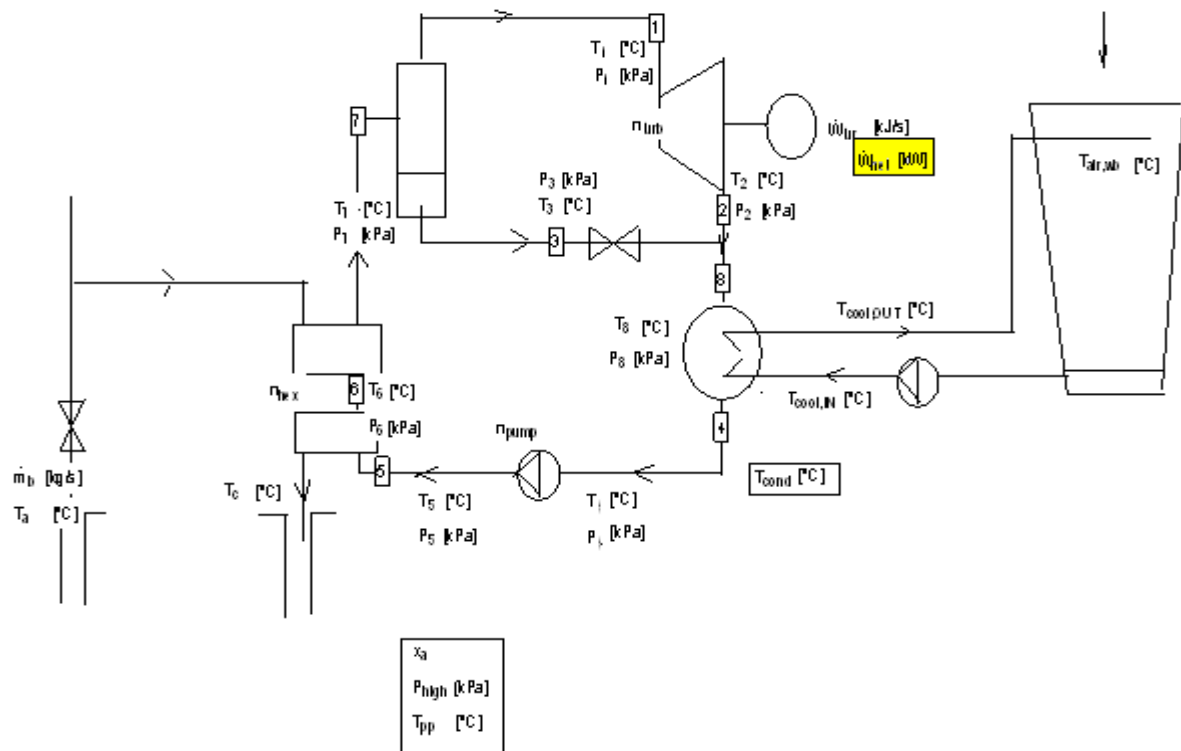


Fig. 16: Basic Kalina binary power plant scheme (source: EES)

The model is built from the same devices as an Organic Rankine cycle, but the separator is placed between the heat exchanger and the turbine to separate (mechanically) the mixture of ammonia vapor and water, which was already chemically separated by preheating and evaporating in the heat exchanger. Ammonia saturated vapor enters the turbine and water, rich with ammonia from the lower part of the separator, enters the condenser after lowering the pressure by the throttle. Exhaust of ammonia vapor from the turbine outlet is then again mixed with water from the separator. Water from the separator is sprayed into the condenser containing the ammonia vapor.

The ammonia-water mixture has specific parameters which significantly increase the efficiency of the cycle by decreasing entropy generation and thermodynamic losses by allowing lower temperature differences between the hot source and working fluid. The ammonia mixture has different boiling and condensation temperatures and therefore the increase of entropy in the heat exchanger decreases. Ammonia has, compared to water, lower boiling and condensation point temperatures and ammonia is more volatile than water. Ammonia starts to evaporate first and its concentration in the mixture decreases, which causes an increase of the mixture's boiling point temperature. Efficiency increases thanks to a smaller difference between the hot source and the working fluid (Holoubek, 2005).

Kalina cycle modeling in EES program

At the beginning of the calculation stage, the basic ammonia-water mixture parameters are specified by functions which are in the EES program and are called CALL codes. Call codes enable the user to specify the parameters of the mixture. The NH3H2O procedure provides the thermodynamic properties of ammonia-water mixtures in subcooled, saturated and superheated conditions. The procedure is called from EES by the statement:

```
CALL NH3H2O(Code,In1,In2,In3: T,P,x,h,s,u,v,q)
```

The 4 parameters to the left of the colon are inputs to the procedure; the eight values to the right are outputs whose values are set by the NH3H2O procedure. The NH3H2O routine operates in SI units with T=[K], P=[bar], x=[ammonia mass fraction], h=[kJ/kg], s=[kJ/kg-K], u=[kJ/kg], v=[m³/kg], and q=[vapor mass fraction].

For saturated states, $0 \leq q \leq 1$. Subcooled states are indicated with $q = -0.01$; superheated states have $q = 1.01$.

Input parameters for Kalina modeling in EES program

In the Kalina model we are working with the same input parameters, which are temperature, pressure and mass flow from each wellhead and were determined from well tests.

"GTD-1"	GTD-2"	"GTD-3"
T_well[1]=125 [°C]	T_well[2]=129 [°C]	T_well[3]=126 [°C]
P_well[1]=920 [kPa]	P_well[2]=1400 [kPa]	P_well[3]=2200 [kPa]
m_dot_well[1]=56[kg/s]	m_dot_well[2]=50 [kg/s]	m_dot_well[3]=65 [kg/s]

Input temperature is calculated as a function of input geothermal water pressure and enthalpy of all wells:

$T_a = \text{Temperature}(\text{water}; P = P_a; h = h_a)$

$P_a = 2200$ [kPa] highest pressure on wellhead; required due to corrosion problems

$h_a = (h_{\text{well}[1]} * m_{\text{dot_well}[1]} + h_{\text{well}[2]} * m_{\text{dot_well}[2]} + h_{\text{well}[3]} * m_{\text{dot_well}[3]}) / m_{\text{dot_b}}$

Enthalpy is the function of each geothermal water enthalpy and mass flow from each well. Brine mass flow is a sum of all wells' mass flow.

Modeling a Kalina cycle in EES has a different order of equations but the description of the model's calculations will be done in same order as it was in the case of the Organic Rankine cycle modeling.

Separator analysis

The separator is a vertical vessel into which a liquid and vapor mixture is separated by gravity. Liquid falls to the bottom by gravity and vapor leaves the separator at the top of the vessel with high (design) velocity, which minimizes the entrainment of any liquid droplets in the vapor

Assuming that the outlet temperature of the ammonia vapor from separator is also the inlet temperature to the turbine and the pressure in the separator is the same as the turbine input, the process of separation is isobaric and isothermal.

$$T[7]=T[1]$$

$$P[1]=P_high$$

The quality of the ammonia vapor is calculated using one of the previously define Call functions. The quality of the ammonia mixture is define by temperature $T[1]$ and pressure $P[1]$.

$$x[1]=NH3_strength_128(T[1];P[1];1)$$

Enthalpy and entropy of the separated ammonia vapor are functions define in CALL code by pressure $P[1]$ and quality $x=1$

The separator outlet liquid – water rich in ammonia – has the same temperature and pressure as in the separator:

$$T[3]=T[7]$$

$$P[3]=P_high$$

Enthalpy is determine by CALL function as a function of pressure $P[3]$ and quality which is defined by CALL code as a function of temperature $T[3]$ and pressure $P[3]$:

$$x[3]=NH3_strength_128(T[3];P[3];0)$$

The separator analysis is based on separator mass balance equations that are common in all types of heat exchangers:

ammonia mass balance:

$$m_dot_wf*x[6]=m_dot_1*x[1]+m_dot_3*x[3]$$

water mass balance:

$$m_dot_wf*(1-x[6])=m_dot_1*(1-x[1])+m_dot_3*(1-x[3])$$

Ammonia vapor separated from water in the separator goes to the turbine where it expands and produces electric power through the generator.

Turbine analysis

Turbine outlet power is define by the equation:

$$W_{\dot{\text{tur}}}=(m_{\dot{1}}*0,75)*w_{\text{tur}}$$
$$w_{\text{tur}}=h[1]-h[2]$$

where $m_{\dot{1}}$ is the mass flow of ammonia vapor as an inlet to the turbine, enthalpy $h[1]$ was previously defined in the separator analysis and enthalpy $h[2]$ is calculated from turbine efficiency equation:

$$n_{\text{turb}}=(h[1]-h[2])/(h[1]-h_{2s})$$
$$h_{2s}=\text{Enthalpy}_{235}(P[2];x[2];s[1])$$

Temperature after the turbine is define as a condensing temperature and as a function of pressure in point $P[2]$ which is equal to pressure after the condenser, quality equal to quality in point 1 and enthalpy $h[2]$

Power production, which is lower because of electric losses from the power plant itself, is given by the equation:

$$W_{\dot{\text{net}}}=W_{\dot{\text{tur}}}-W_{\dot{\text{loss}}}$$
$$W_{\dot{\text{loss}}}=W_{\dot{\text{pump}}}$$

In this case we are assuming only losses taken from feedpump operation.

Condenser analysis

The condenser is a place where exhaust ammonia vapor is mixed with water from the bottom of the separator, which is also rich in ammonia content.

The condenser's entry point is a place where all the mixing happens. Water from the separator is sprayed into the ammonia exhaust to ensure good mixing of both substances.

Mixing is defined by the mass balance equation:

$$m_{\text{dot_wf}}*h[8]=m_{\text{dot_1}}*h[2]+m_{\text{dot_3}}*h[3]$$

where pressure is equal to the pressure after condensing (condensing pressure) and quality is equal to the quality of the ammonia itself.

These two parameters are important in estimating the condensing temperature of the mixture at the mixing point:

$$T[8]=\text{Cond_Temperature}_{234}(P[2];x[2];h[2])$$

Condenser bottom parameters are given by the condensing temperature and condensing pressure as a function of temperature and quality at this point:

$$P[4]=\text{Cond_Pressure}_{138}(T[4];x[4];0)$$

$$h[4]=\text{Enthalpy}_{238}(P[4];x[4];0)$$

$$x[4]=x_a$$

$$T[4]=T_{\text{cond}}$$

Mixed working fluid as the mixture of ammonia and water leaves the condenser and, through the feedpump, is passed to the heat exchanger.

Feedpump analysis

Feedpump inlet parameters were calculated as the bottom part of the condenser in the condenser analysis.

The analysis of the feedpump outlet parameters is based on the calculation of the turbine work, which is later considered to be a parasitic loss in cycle power output calculations:

$$W_{\text{dot_pump}}=m_{\text{dot_wf}}*(h[5]-h[4])$$

Enthalpy $h[4]$ was previously defined in the condenser analysis. Enthalpy $h[5]$ can be found as a sum of the enthalpy $h[4]$ and pressure difference in the feedpump:

$$dh_{\text{pump}}=(P[5]-P[4])*Volume_{238}(P[4];x[4];0)/n_{\text{pump}}$$

n_{pump} is pump efficiency, which is one of the input variables in diagram. Volume function is function defined by CALL code in EES, knowing the pressure $P[4]$ and quality of the working fluid in this point of cycle which is equal to ammonia quality:

$$P[5]=P_{\text{high}}$$

$$x[5]=x_{\text{a}}$$

Enthalpy $h[5]$ is calculated as follow:

$$h[5]=h[4]+dh_{\text{pump}}$$

Temperature in this point is also the temperature which enters the heat exchanger late:

$$T[5]=Cond_Temperature_{234}(P[5];x[5];h[5])$$

The working fluid enters the heat exchanger after leaving the feedpump, where it is first preheated and then evaporated.

Heat exchanger analysis

Temperature in the heat exchanger after the preheater is calculated using the CALL function for ammonia-water mixture working fluid:

$$T_{\text{bubble}}=Temperature_{238}(P[6];x[6];0)$$

$$T[6]=T_{\text{bubble}}$$

Pressure $P[6]$ is the pressure from the input variable in the diagram. By changing this pressure we can easily see changing parameters in all cycles. This pressure influences the heat transferred in the heat exchanger:

$$P[6]=P_{\text{high}}$$

Enthalpy in this point is also calculated using the CALL function. Enthalpy is given by pressure and quality in the preheater, where bubbling of the working fluid is initiated and slow evaporation begins its process:

$$h[6]=h_bubble=Enthalpy_238(P[6];x[6];0)$$

Pressure after the evaporator stays the same through all of the heat exchanger processes and the quality of the working fluid is the quality of the ammonia mixture:

$$P[7]=P_high$$

$$x[7]=x_a$$

These two parameters help to determine the enthalpy of the vaporized mixture and temperature at this point in the heat exchanger:

$$h[7]=Enthalpy_123(T[7];P[7];x[7])$$

$$T[7]=T_a-T_pp$$

The vaporizer analysis is based on mass balance equations to determine all necessary parameters:

calculation of T_c (brine outflow temperature)

$$m_dot_b*cp_b*(T_b-T_c)=m_dot_wf*(h[6]-h[5])$$

calculation of m_dot_wf

$$m_dot_b*cp_b*(T_a-T_b)=m_dot_wf*(h[7]-h[6])$$

3.4.1 Analysis of Kalina cycle modeling results

Similarly to the Organic Rankine cycle, in the Kalina cycle the total net power output is investigated to find out which of the modeled cycles is more effective and more feasible.

The parametric table from the EES program shows how the inlet heat exchanger pressure changes the power output (Tab. 16), which is similar to how it was done in ORC model. By changing the pressure in the heat exchanger the inlet temperature in this point increases. Due to increased pressure and temperature, the power output from the turbine increases. The higher the turbine inlet pressure and temperature, the higher the power produced from turbine by the generator. Turbine input is limited by material resistance in the turbine. High pressure and temperature causes more stress to the material in the turbine, which in turn can possibly cause damage. High input parameters are not the only thing that can cause problems with the turbine in the Kalina cycle. The Kalina cycle's working fluid is an ammonia and water mixture that usually has a high content of ammonia (ratio ammonia: water usually 70:30). The Kalina cycle requires a special turbine material composition that will not react with ammonia vapor entering turbine in very high pressure and temperature. In some cases a titanium turbine was used in the Kalina cycle.

Tab. 16: Parametric table of Kalina cycle – change of inlet heat exchanger pressure in relation with cycle power output.(source: EES)

x_a	P[6] [kPa]	T[6] [°C]	T_c [°C]	W_dot_tur [kJ/s]	W_dot_net [kW]
0,7	670	24,95	28,56	716,7	709
0,7	1234	45,98	43,74	3265	3214
0,7	1799	60,77	54,43	4625	4532
0,7	2363	72,53	63,3	5334	5201
0,7	2928	82,48	71,17	5642	5475
0,7	3492	91,22	78,46	5686	5489
0,7	4057	99,1	85,4	5535	5314
0,7	4621	106,3	92,14	5273	5033
0,7	5186	113,1	98,84	4900	4647
0,7	5750	119,4	105,6	4425	4167

The first column in the parametric table shows the quality of ammonia in the mixture. In the modeled Kalina cycle the ratio ammonia-water was first set to 70:30. The table shows the influence of changing the heat exchanger inlet pressure using 70% ammonia in the mixture. By changing the quality of the ammonia in the mixture the parameters in the cycle change. By increasing the ratio of ammonia in the mixture the power output increases and all the parameters in the cycle show higher values. An increase in the amount of ammonia results in a more saturated ammonia vapor being evaporated and later expanded in the turbine, which is directly related to the power output of the power plant.

A change in the pressure inlet to the heat exchange has a similar impact to the cycle as it does in the Organic Rankine cycle. Increased pressure in the heat exchanger causes the heat exchanger's temperature to rise due to the decreased mass flow of the working fluid (Tab.17). The lowered mass flow of the working fluid causes heat transfer degradation. Worse heat transfer in the heat exchanger increases the geothermal water outlet temperature, which can be utilized after the heat exchanger in district heating because of having a sufficient amount of heat power. A temperature of 80°C for the outlet geothermal water is suitable for district heating without any preheating needed. The problem related to the utilization of geothermal water in district heating is the high content of minerals in the water that can possibly cause corrosion in the pipelines. Before water enters the pipelines it is necessary to reduce the amount of minerals in the water. Water maintenance increases the initial and operational cost of the built power plant. On the other hand, the Kalina cycle produces more electric power and it is possible to utilize "waste" water for district heating without preheating.

Tab. 17: Parametric table of Kalina cycle – changing mass flow of working fluid with inlet heat exchanger pressure P[6].(source: EES)

x_a	P[6] [kPa]	T[6] [°C]	T_c [°C]	m_dot_wf [kg/s]
0,7	670	24,95	28,56	36,97
0,7	1234	45,97	43,73	42,21
0,7	1799	60,77	54,43	42,41
0,7	2363	72,52	63,29	41,27
0,7	2928	82,48	71,17	39,61
0,7	3492	91,22	78,46	37,67
0,7	4057	99,1	85,4	35,54
0,7	4621	106,3	92,14	33,24
0,7	5186	113,1	98,84	30,73
0,7	5750	119,4	105,6	27,92

The highest power output for the modeled Kalina cycle using ammonia quality equal to 70% of the mixture was reached using heat exchanger inlet pressure 3492 kPa. Power output from the cycle was approximately 5,5 MWe.

Compared to ORC pressure, the Kalina's pressure in the heat exchanger is almost three times higher. High pressure and temperature in the heat exchanger increases the pressure and temperature in the turbine inlet and, together with this power output, in the whole cycle.

Higher pressure in Kalina cycle gives 1 MWe more power output compared to the Organic Rankine cycle, and also gives sufficient outlet brine temperature for district heating utilization.

High parameters in the Kalina cycle mean stronger and more resistant materials. The ORC works with lower parameters. The Kalina increases pumping requirements with high pressure and more resistance, therefore it requires expensive materials, especially in the turbine.

Cooling in the Kalina cycle is based on the same principle as in the ORC. The air cooling tower ensures cooling water to the condensing process. By changing weather conditions, dry bulb air temperature changes. When using dry air temperature it is necessary to recalculate the temperature in the cooling tower to wet bulb temperature, taking into consideration the relative air humidity. The parameters for the cooling tower are the same as if they were set in the ORC. Average dry bulb air temperature was calculated from weather data for 9 °C in Kosice region. Recalculating the dry air temperature to wet bulb temperature gives 10 °C in the cooling tower.

By changing the cooling tower temperature, the temperature in the condenser also changes and influences all of the cycle parameters (Tab. 18). Lowering the wet bulb temperature means increasing the power output from the cycle. Power increases due to higher heat transfer in the heat exchanger and condenser.

Tab. 18: Parametric table of Kalina cycle – relation between change of wet bulb air temperature and power output (source: EES).

T _{air_wb} [°C]	T _{cond} [°C]	T _{cool_IN} [°C]	T _{cool_OUT} [°C]	T _{pinch_condenser} [°C]	m _{dot_cw} [kg/s]	W _{dot_tur} [kJ/s]	W _{dot_net} [kW]
-2,3	7	0,7	7	6,3	1283	6785	6578
-1,2	8	1,8	8	6,2	1299	6691	6486
4,1	13	7,1	13	5,9	1340	6230	6028
9,6	18	12,6	18	5,4	1436	5776	5579
15,1	24	18,1	24	5,9	1284	5240	5049
17,9	27	20,9	27	6,1	1227	4975	4788
19,3	28	22,3	28	5,7	1308	4888	4701
19,5	28	22,5	28	5,5	1355	4888	4701
14,7	24	17,7	24	6,3	1202	5240	5049
9,6	18	12,6	18	5,4	1436	5776	5579
3,4	12	6,4	12	5,6	1417	6322	6120
-1,7	7	1,3	7	5,7	1418	6785	6578

The plot for the heat exchanger from the Kalina binary geothermal power plant is shown in Fig. 17. The plot shows heat transfer between the geothermal source and working fluid in the Kalina cycle. Basically, the closer the lines are to each other, the better the heat transport and the higher the outlet working fluid temperatures that are reached, which directly influence the turbine and cycle power output. The mixture of ammonia and water changes phase in the boiling and condensing processes over a temperature range, rather than at a fixed temperature as with a pure fluid. This property of mixing working fluids has the effect of reducing irreversibilities in the cycle and improving plant performance. Besides that the temperature of the geothermal fluid is still high enough for district heating utilization. A possible difficulty for the Kalina cycle, one that is common to all cycles that strive for high efficiency, is maintaining very tight pinch-point temperature differences in the heat exchanger.

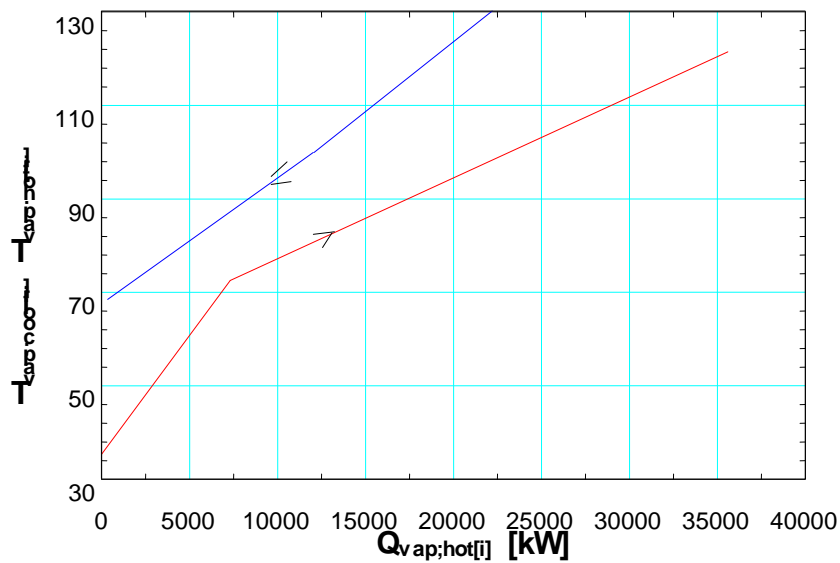


Fig. 17: Plot of Kalina cycle heat exchanger temperature-heat transfer diagram (source: EES)

The scheme in Fig. 18 shows all input parameters that can be changed and all output parameters that were calculated using the previously define EES code.

Input parameters can easily be changed and all process recalculated using new parameters. Efficiencies of the heat exchanger, turbine and pump were set to the same values as they were in the ORC in order to have the same parameters in both models for better comparison. The quality of the ammonia-water mixture is also stated. The amount of ammonia in the mixture is 70%.

The cooling tower's changing wet bulb temperature influences the condensing temperature of the working fluid, which was shown in Tab. 21.

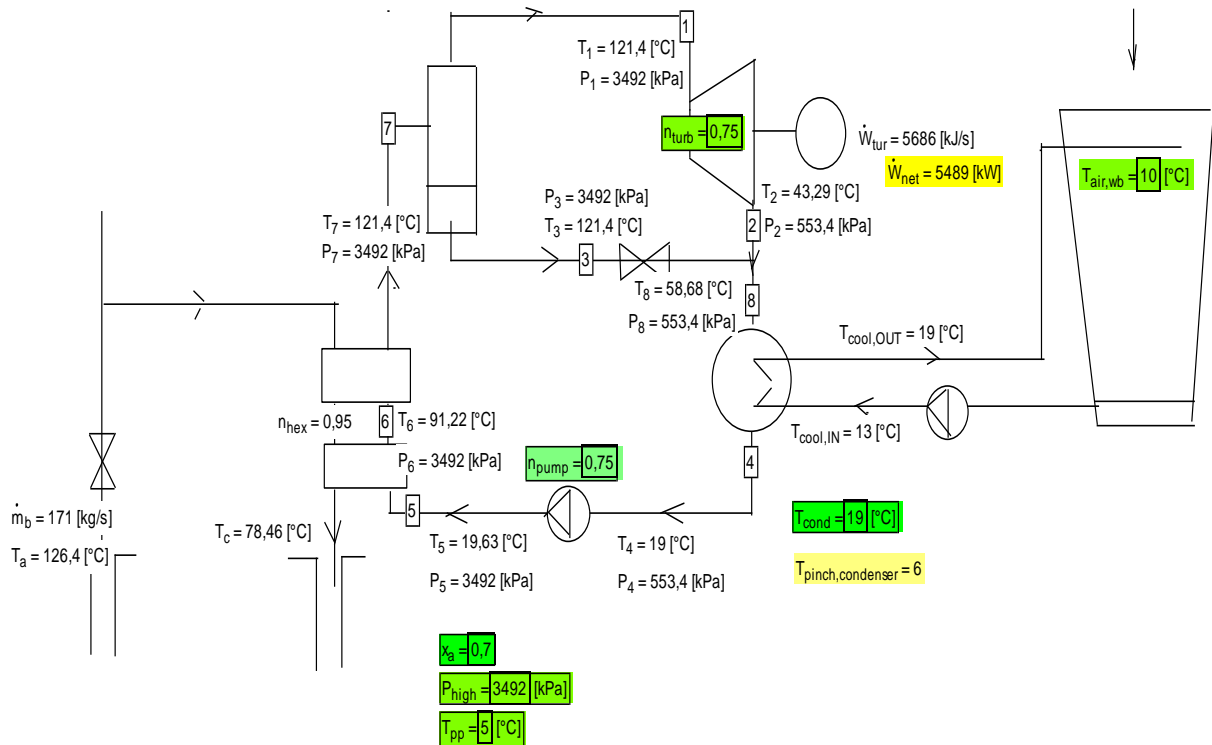


Fig. 18: Scheme of Kalina cycle with input and output parameters.(source: EES)

Having the same conditions that were in the Organic Rankine cycle modeling, the Kalina cycle has higher power output and generally higher parameters in the cycle. These high values are achieved by specific ammonia-water mixture properties. The ammonia mixture boiling and condensing processes are under different temperatures. As it was mentioned before, the condensing and boiling process phase changes occur over a range of temperatures rather than at a fixed temperature as for pure fluids.

The difference in the ammonia-water mixture condensing properties causes the condensing temperature of the Kalina to be 10 °C lower than in the ORC. The condensation curve for Kalina is not a straight line and there is no specific pinch point difference point (in the model the pinch point is at the condensate outflow temperature). It is situated on the curve, and this results in a low condensation temperature. In the ORC the condensation curve is a horizontal line, with a relatively small superheat part and the pinch point is close to the temperature of the inflow into the condenser.

Low condensing temperature and low boiling temperatures are the main advantages of the Kalina working fluid ammonia-water mixture.

The difference between the Kalina and Organic Rankine cycle is 1MWe power more produced by Kalina. Besides the higher power output, the high and still utilizable temperature of the geothermal source outlet temperature is an important indicator in the feasibility evaluation of both models.

3.5 Comparison of the modeled Organic Rankine cycle and Kalina cycle.

A basic feasibility study of the Organic Rankine cycle and the Kalina cycle using data obtained from Eastern Slovakia geothermal source input parameters is conducted in this chapter.

To compare both models the same conditions and parameters were set each model. The same efficiencies of heat exchanger, turbine and pump, which can be changed according to the properties of the supplied devices for possible project realization, were assumed. By changing these parameters it is easy to see changes in the modeled cycles.

Cooling conditions in both models were set by the average yearly dry bulb temperature in this region (Slovakia, Kosice – Durkov), taking into the consideration the relative humidity, and were recalculated to the wet bulb temperature. Later, parametric tables for changing the inlet cooling tower conditions were shown with average monthly wet bulb temperatures. Both models are significantly influenced by cooling tower conditions.

Both models are small geothermal binary plants utilizing a “secondary” working fluid, which takes heat energy from the geothermal fluid in the heat exchanger and utilizes it in the cycle.

The Organic Rankine cycle model working fluid is Isobutane, which is broadly used in binary power plants due to its good chemical and physical properties. Isobutane is also used as a propellant, a solvent and a refrigerant. Its utilization has no large difficulties. The only danger is its flammability. More severe complications can occur in the turbine due to a possible reaction between the isobutane and the material from which the turbine is constructed. The risk of corrosion by the gas in the presence of moisture was investigated but cannot cover all conditions of concentration, temperature, humidity, impurities and aeration. Isobutane shows satisfactory results when used with aluminum, brass, cooper, ferritic steel and stainless steel.

In the Kalina cycle the mixture of ammonia and water in different ratios is utilized. In the modeled Kalina cycle case the ratio of ammonia-water was set at 70:30. Sufficient power output was reached with this ratio. Ammonia is, similarly to isobutane, widely used as a refrigerant in some refrigerators instead of chlorofluorocarbons (freons). As it was mentioned before, the main advantages of an ammonia-water mixture are different boiling and condensing temperatures. Utilization in binary power plants can cause problems due to higher pressure and temperatures when entering the turbine and also a possible reaction between the saturated ammonia rich vapor and the turbine material. Ammonia, compared to isobutane, shows satisfactory results only with aluminum, ferritic and stainless steel. Another danger is the inhalation of ammonia and bodily contact, but on the other hand it is a non-flammable gas.

In both cases it is apparent that working fluid parameters cause some difficulties (mostly in the turbine, which is the most loaded part of the whole cycle). The turbine has to withstand high pressure and temperature and also the chemical composition of the working fluids. It is recommended to utilize different alloys and, in the case of the ammonia mixture, stainless steel. Ammonia rich saturated vapor from the separation process, which takes place in the separator between the heat exchanger and turbine, allows building a smaller and less costly turbine than for a hydrocarbon working fluid (isobutane). The cost, which is reduced depending on the size of the turbine, is again increased by using special and highly resistant materials for its construction.

Looking at the heat exchangers, binary cycles require the binary fluid to be heated, evaporated, cooled and condensed. Conventional heat exchangers (shell-and-tube) are

physically large and make up a large part of initial investments. The main disadvantage of working fluids used in these models (hydrocarbons and refrigerants) is low heat transfer performance, which is even lower from possible scaling. Scaling causes problems not only with heat but also with hydraulic performance that increases the maintenance costs.

Heat transfer in the Kalina is also decreased by higher inlet pressure and temperature, which decreases the mass flow of the working fluid through the heat exchanger. Decreased heat transfer requires a larger surface of the heat exchanger in order to maintain a contact surface between the working and geothermal fluid that is as large as possible. A larger surface naturally increases the initial cost of the whole cycle because the heat exchanger makes up the biggest part of the overall initial cost of the power plants.

The Organic Rankine cycle has better heat transfer in the heat exchanger but still lower power output due to the lower output parameters of the working fluid after the heat exchanger. Lower initial investment in the heat exchanger must be reconsidered knowing that power output from ORC is, in these conditions, almost 1,5 MWe lower than in Kalina which is 26% higher output.

Thermal efficiency in both modeled power plants, which is the ratio of net power output and heat input to the cycle, can be slightly increased by the utilization of regeneration, which is basically the internal exchange of heat within the cycle. The gas still leaves the turbine at a relatively high temperature. The regenerator is used to preheat the working fluid before the heat exchanger by using the heat from the exhaust turbine gas of the working fluid. Regeneration involves the installation of the heat exchanger (recuperator) through which the turbine exhaust gases pass.

The use of a regenerator can increase the cycle's thermal efficiency. However, the relative high cost of such a regenerator is a disincentive to its use. A regenerator can improve the efficiency of the gas turbines by 5-6%. However, use of a regenerator reduces specific power output as a result of additional pressure losses in the regenerator.

Another limiting factor for regeneration is, in most cases, silica scaling risk, which is increased as the brine temperature drops.

Heat transfer in the heat exchanger directly influences the outlet geothermal water temperature and its future utilization for possible reinjection. It is necessary to reconsider whether it is possible to utilize the heat potential in the outlet brine or it is better to return it back to the geothermal reservoir by reinjection. Both cases can cause difficulties.

In the studied case of the Durkov geothermal area the mineralization of geothermal water is high and reinjection can cause difficulties related with scaling and corrosion on the wellhead of the reinjection wells and on the way down to the reservoir. On the other hand, the utilization of outlet brine temperature requires not only a necessary cleaning treatment of the water before entering the pipelines but also, in the case of the Organic Rankine Cycle, preheating in order to reach the required district heating supply temperature. These special treatments naturally increase the initial and maintenance costs of the power plant. To name all possible problems with the brine outlet temperature it is also necessary to mention that the Durkov geothermal area is a reservoir with limited water inflow, where the heat in the field is not the limiting factor, but the water in the field is scarce or limited by precipitation or underground water flow into the reservoir.

The question still remains as to which of the two modeled binary plants is worth building or is even feasible to build. The one with low power output, low initial cost but high maintenance cost due to the preheating of geothermal outlet water before entering the district

heating system? Or the one with higher power output but high initial cost due to more specific and resistant materials?

Looking at the power output of both power plants we can calculate how many houses can be supplied with each power plant. The calculation is based on annual household consumption of electricity, which is 4200 kWh.

A simple calculation can be done. Our Kalina cycle produces approximately 5 MW of electric power. To calculate how much power would be needed to obtain a running Kalina power plant for 365 days and 24 hours per day a simple equation comes up:

$$5 M \rightarrow 5000 kW * 24 \frac{hours}{day} * 365 \frac{days}{year} = 43,8.10^6 kWh$$

Knowing that annual household consumption of electricity is around 4200 kWh we can calculate how many houses can be supplied by our Kalina geothermal power plant:

$$\frac{43,8.10^6 kWh}{4200 kWh} \doteq 10\,429 houses$$

After calculating the electric consumption demand we can also calculate heat demand for a district heating system if it is decided to utilize the hot outlet geothermal water for this purpose.

A similar calculation can be done for the Organic Rankine cycle. Knowing that ORC produces, with the given parameters, approximately 4 MW we can calculate the yearly production of an ORC:

$$4 M \rightarrow 4000 kW * 24 \frac{hours}{day} * 365 \frac{days}{year} = 35,04.10^6 kWh$$

Assuming annual household electricity consumption is the same as in the Kalina calculations we can find the approximate number of houses possible to supply with the modeled ORC power electric output:

$$\frac{35,04.10^6 kWh}{4200 kWh} \doteq 8\,343 houses$$

Knowing that hot geothermal outlet water from the ORC has to be preheated from 60 °C to 80 °C before entering the district heating system, we can say that the Kalina cycle seems more feasible based on these calculations.

Looking at both cycles from an engineering point of view, the Kalina seems more feasible in terms of power output and other utilization. Utilizing Kalina for power production with lower energy consumption from the geothermal source but with higher power output and possible geothermal outlet water utilization in district heating looks more promising compared to the Organic Rankine cycle.

Visibly lower power output from quite a high energy consumption from the well geothermal water and the requirement for preheating and cleaning makes the ORC unattractive for investors.

It is also important to look at the price of the electricity in Slovakia and, according to this, reconsider the decision. In 2006 the price for electricity was €12,4 cents per kWh (Austrian

Energy Agency, 2003). Based on this knowledge and also knowing the yearly power output from both power plants a simple calculation can be again done to know what would be the reached profit:

Kalina cycle:

$$43,8 \cdot 10^6 kWh * € 12,4 = € 543 120 000/year$$

ORC:

$$35,04 \cdot 10^6 kWh * € 12,4 = € 434 496 000/year$$

The main cost the calculations are concerned with is the cost for electricity produced from traditional power plants (coal, gas source). From the annual benefits for electricity production it is visible that the difference between the two modeled power plants is not vast, but the initial investments in both cases are high.

Even though the investments into the geothermal power plants are high and the produced power is comparable with the traditional coal or gas power plants it is important to take into consideration the advantages of geothermal power utilization. Looking at the environmental issues related with traditional power plants small geothermal binary power plants are the most benign of all power plants.

The only impact on the environment takes place at the heat reinjection side of the power plant. If the geofluid is pumped from the reservoir and returns entirely to the reservoir after passing through the heat exchanger, the potentially harmful geofluid never sees daylight. The working fluid is in a closed loop system so it never comes into chemical or physical contact with the environment.

The only possible form of pollution from a binary plant might be thermal pollution, the amount of heat that must be reinjected from the cycle. All types of geothermal power plants discharge more waste heat per unit of power output than other thermal power plants. In the case of the binary plant, the amount of thermal power that needs to be absorbed by the surroundings is about nine times the useful power delivered by the plant. This effect can be minimized by utilizing the waste heat of geothermal water temperature in the district heating system or for heating greenhouses or preheating in the other cycles (secondary cycle) (DiPippo, 2008).

4 CONCLUSIONS

Models of small geothermal power plants were made as a part of this thesis to make a comparison of power outputs from two types of power plants.

Organic Rankine cycle and Kalina cycle are so-called binary cycles utilizing secondary fluid for obtaining heat energy through a heat exchanger from a geothermal source. The models are based on the parameters of the wells in the Durkov geothermal area in Eastern Slovakia. To make a proper comparison the same cycle parameters were set for each cycle in the model. The difference between the ORC and Kalina cycle is in the working fluid. Organic Rankine cycle utilizes Isobutane as a working fluid in a closed loop. Kalina has specific parameters due to its mixture of ammonia and water.

By changing the inlet heat exchanger pressure, changes in each point of the cycles were studied and evaluated. Changing the heat exchanger inlet working fluid pressure has a significant influence on the whole cycle, but most of all on the power output.

To evaluate both models from a thermodynamical point of view would be very easy. Obviously the Kalina cycle has higher power output by utilizing less energy from the geothermal source. A hot geothermal outlet temperature can also be further utilized for district heating.

ORC has, compared to the Kalina cycle, a lower power output and takes more energy from the hot geothermal source. Outlet geothermal water can be further used in district heating, but only with additional preheating to increase the temperature from 60 °C to 80 °C, which is the required temperature for district heating systems. The difference between ORC and Kalina in terms of power output is 1 MWe. Kalina is able to produce, in the stated conditions, 5 MWe power and ORC approximately 4 MWe power.

The models were constructed without possible regeneration, which could in both cases (but mostly in ORC cycle) increase the power output. Regeneration may be added to the model but it would have to be recalculated. The aim of this work was to build simple models based on inlet parameters from geothermal sources and several simplifications were used. Regeneration would have a similar function as the heat exchanger. It would extract the remaining thermal energy from the working fluid and utilize more of this energy in the cycle itself. The effect of regeneration would be more visible in the ORC cycle in that it could increase the power output by about 1 MWe.

Looking at both cycles from an investment and cost demand point of view it is hard to decide which of the modeled geothermal binary power plants is more feasible. The inlet temperature of the geothermal fluid has a significant effect on the cost of binary power plants. The inlet temperature influences the size of the turbine, the heat exchangers and the cooling tower required for a given power output, and these sizes have a dominant effect on the capital cost of the unit. Inlet temperatures in these models are quite low and because of this high power outputs cannot be expected, but using binary power plants helps to increase the power output even though the study was conducted with low geothermal source utilization in mind.

Concerning the capital cost for the power plants, more expensive and specific materials must be taken into account, which increases the capital cost. Also, the cost of maintenance is part of the investment that must be considered in a feasibility study.

The modeled power plants are able to produce sufficient amounts of electric power for smaller towns by using the geothermal water for heating and possibly for cooling purposes. It is just a question for investors as to which of the modeled binary plants is more cost effective

for them. Should they choose the one with higher capital cost but higher power output and utilization of hot geothermal water without any additional customization (Kalina)? Or is less cost demanding power plant with lower power output and additional customization of geothermal water for heating purposes (Organic Rankine Cycle) a better option?

From a thermodynamic point of view the decision is easier. Looking at the cycles' input parameters and output power production it is easy to determine which of the modeled geothermal power plants is more effective.

Another question which remains open to debate is if the possible investors will invest in a power plant that has been operating all over the world for more than 30 years or if they will put their trust into the system which is still under the development.

Looking at the numbers of energy input and power output in the modeled systems the answer is clear. From a thermodynamical point of view Kalina cycle is a more suitable small geothermal power plant to build in the Eastern Slovakian conditions present in the Durkov area.

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