

Engineering Approach in Classification of Geothermal Resources of the Slovak Republic (Western Carpathians)

Branislav Fričovský¹, Radovan Černák¹, Daniel Marcin¹, Katarína Benková¹, Anton Remšík, Marián Fendek²

¹ State geological institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic

² Department of Hydrogeology, Faculty of Natural Sciences, Comenius University in Bratislava, Slovak Republic

branislav.fricovsky@geology.sk

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ABSTRACT

The specific exergy index (engineering) approach is introduced to map and classify geothermal resources of the Slovak Republic, both for geothermal water bodies and individual wells. At depths over 500 – 1000 m, the effect of geothermal field destruction by cooling ceases progressively. The Central Danube Depression (SE_{ExI} = 0,07), Horná Nitra Basin (SE_{ExI} = 0,07) and the Košice Depression (SE_{ExI} = 0,102) appear most adequate for high heat delivery demand projects, yet there is still some challenge to improve thermodynamic efficiency on existing district heating systems. Because of complexity of GWBs, we recommend individual sites studies instead.

1. INTRODUCTION

For years, sources of geothermal energy have been classified by reservoir / wellhead temperature in Slovakia, with limits set arbitrary, lacking wide agreement in general, referencing to classification schemes already introduced worldwide. With time, upturn in (not only on a national scale) geothermal resources prospection and utilization shown poor indicatory of temperature itself onto evaluation of usable, heat and power generation potential of geothermal systems. To answer irreversibility of thermodynamic processes in artificial use of geothermal sources, requiring at least two independent thermodynamic properties, the engineering concept based on the specific exergy has been introduced (Lee, 1996). Owing to geological and geodynamic evolution, the territory of the Slovak Republic is fairly rich in geothermal resources. The most actual data (Fendek & Fendeková, 2015) summarize 27 identified perspective geothermal areas (geothermal fields) covering 16 750 km², which counts 34 % of the territory of the Slovak Republic. Meanwhile, total online direct use reached 149 MWt (proven reserves) out of 6 653 MWt (probable reserves).

2. BACKGROUND

2.1 Geothermal energy in Slovakia as of 2014 / 2015

An onset of research and prospection on geothermal resources in Slovakia dates back to late 70-thies of 20th Century. Exploration documented 26 perspective geothermal areas (fields) as to 2005 (Fendek & Fendeková, 2005), with online geothermal heat production of 88 MWt. In 2010, reported number of geothermal fields increased by one and online heat production capacity grown rapidly towards 164 MWt (Fendek & Fendeková, 2010). However, a period of 2010 – 2015 recorded all but growth, as operating capacity dropped down to 149 MWt and only 6 new geothermal wells have been put online (Fendek & Fendeková, 2015). Actual country update presented at WGC2015 reports 56 localities with some use of geothermal energy. Recreational purposes are fairly prevailing in installed capacity (87,7 MWt), as due to a majority of low temperature wells. Individual and district space heating are about equal (16,6 and 16,2 MWt). Fish farming, greenhouse heating and GHP share the most of the rest of installed capacity (Fendek & Fendeková, 2015).

2.2 The Western Carpathians – brief review on geology

The Western Carpathians record geological settings continuously formed through the Variscan and Alpine orogeny. In its essence, the WCs are distinguished into the Outer Western Carpathians comprising Tertiary marine-siliciclastics dominated foreland (in Poland) and the Flysch Belt typical in marginal non-flysch sequences (in Poland) and typical flysch-type successions (Hroudá et al., 2009) at the NW and NE margins of the country (Fig. 1). Tectonically dissegmented and folded Klippen Belt of Jurassic – Early Cretaceous carbonates dominated core and Late Cretaceous – Early Miocene mostly siliciclastic, shelf to deep-marine provenienced pseudo-flysch envelope (Plašienka et al., 2012). The Inner Western Carpathians represent a belt of Paleozoic crystalline (metamorphites, magmatites) and thin-skinned Mesozoic nappes beneath autochthonously deposited Inner Western Carpathian Paleogene (IWCP), intruded with Neogene volcanic or covered with sedimentary (marine to continental) Neogene formations and exclusively continental Quaternary cover.

Mesozoic nappes are organized into several superpositioned units. Usually, a vertical profile composes of Early Triassic siliciclastics (aquiclude), Mid Triassic carbonates (aquifer) and Late Triassic shales and pelitic carbonates (aquitard). Succession of Jurassic to Mid Cretaceous, numerous duplexed organogene to pelitic limestones, shales and marlstones forms a thick aquitard in the Tatricum Envelope (Fig. 1) and Križna Nappe unit only. Atop, the basal, Borové Formation of the IWCP of detritic carbonates, breccias and conglomerates, less sandstones form a thin aquiferous zone beneath claystones-dominated Hutý Formation and flysch-type Zuberec Formation (Franko et al., 1995). Sedimentary Neogene is typical in numerous vertical alterations of sandstones (sands) and conglomerates (gravels) with claystones, marlstones and siltstones and their unconsolidated varieties (Biely et al., 1996).

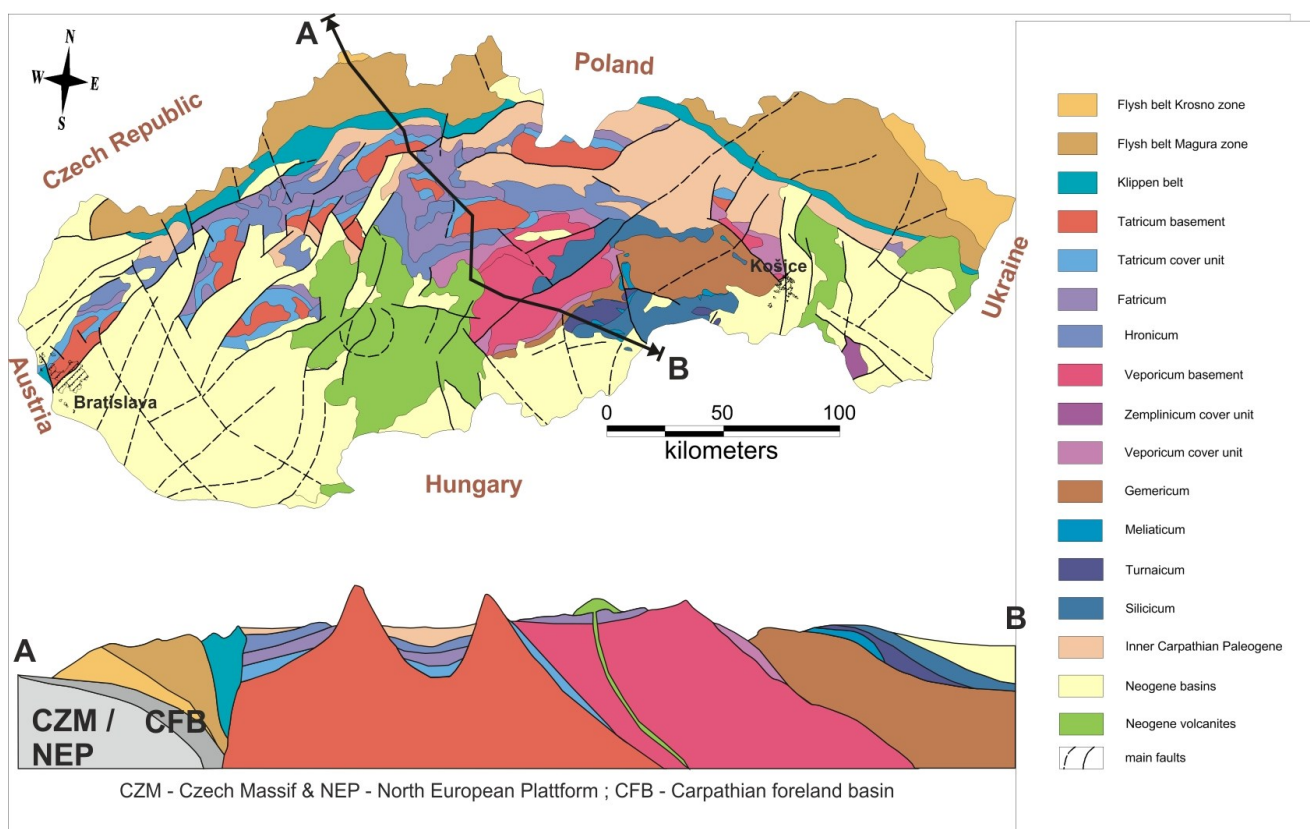


Figure 1: Geotectonic scheme and generalized cross-section across the Western Carpathians

2.3 The Western Carpathians – hydrogeothermics

Geological evolution and vertical structure allows catalogization of the Western Carpathians' hydrogeothermal structures as conduction-dominated, intracratonic basin plays and orogenic / foreland basin plays (Moeck & Beardsmore, 2014), and convection-dominated, intrusive magmatic play (Moeck et al., 2015) respectively (the Beša-Čičarovce structure). Because of a nappe-folded character of intramountain depressions and thick sedimentary cover of Neogene basins, hydrogeothermal structures express structural analogy to stratified reservoir sedimentary systems and basin constriction systems (described in Nathenson & Muffler, 1975; Hochstein, 1988). The Outer Western Carpathians do not govern conditions supporting formation of geothermal systems (Franko et al., 1995).

Hydrogeological regime of geothermal structures depends on local play type and geological settings. Salinity of thermal waters then reflects circulation duration and depth. Open hydrogeothermal structures usually contain low ($< 5 \text{ g.l}^{-1}$) to medium ($< 10 \text{ mg.l}^{-1}$) mineralized carbonatogene (Ca-HCO_3 , Ca-Mg-HCO_3) and (hydro)silicatogene (Na-Ca-HCO_3 , Ca-Na-HCO_3 , Na-HCO_3) waters in shallow and carbonatogene, hydrosilicatogene and sulphatogene (Ca-SO_4) to transient ($\text{Ca-Mg-HCO}_3\text{-SO}_4$, $\text{Ca-Mg-SO}_4\text{-HCO}_3$) in intermediate and deep circulation, where salinity increases to $< 35 \text{ mg.l}^{-1}$. Of course, mixed waters may occur. Semi-open and semi-closed thermal waters are usually medium to highly mineralized ($10 - 35 \text{ mg.l}^{-1}$), including polygenetic type (e.g. marinogene degraded). Saline brines, marinogene waters (Na-Cl) and polygenetic types of deep regime are typical for semi-closed to closed structures of very high TDS $> 35 \text{ mg.l}^{-1}$ (Franko & Melioris, 2000; Černák et al., 2014).

Neotectonic activity controls distribution of heat flow propagation in the Western Carpathians, which varies roughly $40 - 122 \text{ mW.m}^{-2}$, with a mean of $82 \pm 20 \text{ mW.m}^{-2}$. Highest geothermic activity of $80 - 122 \text{ mW.m}^{-2}$ is distributed within Neogene volcanics (Central Neovolcanites, Slanské vrchy Mts.) and crustal thinning / thermal relaxation influenced basins (Eastern Slovakian Basin, Danube Basin), whilst heat flow density propagation within intramountain depression scatters of $50 - 85 \text{ mW.m}^{-2}$. A mean geothermal gradient is estimated to $39 \text{ }^\circ\text{C.km}^{-1}$ (Franko et al., 1995). Wellhead temperature of sampled waters extends from $20 \text{ }^\circ\text{C}$ to $130 \text{ }^\circ\text{C}$ with a yield of $1,5 - 100 \text{ l.s}^{-1}$. The depth of screened reservoir intervals through all the 27 identified geothermal is located at $11 - 3400 \text{ m.b.s.l.}$, exploiting Mesozoic (limestones, dolomites and transient varieties), Paleogene (breccia, conglomerates, detritic carbonates, sandstones) and Neogene (sandstones, sands, gravels, conglomerates, andesites and pyroclastics) reservoirs (Černák et al., 2014).

3. THEORETICAL CONCEPT

Geothermal resources are natural phenomena as long as they are in reservoir environment. Under theoretical considerations, renewability of geothermal resources is documented amongst hundreds of springs conveying a heat and mass for decades (or centuries) without any signs of decline (Rybach et al., 2000). By thermodynamics, the renewability means equilibrium of the source with its

environment, so that the mass and energy lost is simultaneously replaced, for every process that takes part is reversible. Utilization of geothermal sources is, however, an artificial problem of certain irreversibility, regardless of it is in heat or power generation (Ozgener et al., 2007). Utilized water is then no more closed, but open thermodynamic system, so must be described by at least two independent thermodynamic properties (Lee, 1996).

3.1 Concept of exergy

According to 1st Law of Thermodynamics, the energy is a conservative measure (1), which can be simplified to a terms of flow enthalpy (2) once either kinetic and potential energies, and heat and work transfers are neglected. The 2nd Law of Thermodynamics, however, asserts the qualitative parameter of energy, an amount which can be extracted as a useful work from its source (Hepbasli, 2008), termed exergy (3). This is why a concept of available work was proposed by means of thermal power plants assessment (DiPippo, 1984).

In operation of geothermal projects, only physical exergy is considered, assuming changes in kinetic and potential exergies at a negligible rate and no chemical reactions within the system, transforming (3) into (4), defining the specific exergy (5) and exergy rate (6) for the geothermal fluid flow system (Ozgener et al., 2005). The rate of exergy consumption (5-6) is then proportional to a rate of entropy or thermodynamic disorder generation.

At least two stages are required in thermodynamic analysis. In analysis of engineering potential of geothermal projects or sites, it is convenient to allocate a definition point to the wellhead, as this is a first stage where the geofluid can perform some useful work. For a sink conditions, the ambient temperature appears most adequate, even it changes fast in time (Lee, 2001).

3.2 Specific exergy index (SExI)

Because of irreversibility, each open thermodynamic system requires at least two independent thermodynamic properties for a proper definition and analysis. The specific exergy index (7) accounts a thermodynamic state of the fluid to the enthalpy of pure water saturated with steam at $P = 9$ MPa and $T = 303$ °C. Enthalpy (8) and entropy (9) of a brine per production well are calculated as weighted average (Lee, 1996). To map a SExI for the entire geothermal field, enthalpy and entropy are taken as weighted average as well (Quijano, 2000).

3.3 SExI – mapping and classification principles

Thermodynamic (engineering) studies of geothermal fields can be applied to: i) analysis of heat and power plant or heat and power systems performance (e.g. DiPippo, 1984); ii) evaluation of geothermal fields by exergy (e.g. Quijano, 2000); and iii) to classify geothermal resources (e.g. Barbacki, 2012).

Limits for classification are based on thermodynamics of saturated steam and water. The $SExI = 0,5$ refers to the lowest exergy of steam for direct electricity generation, thus to a saturated steam at $P = 0,1$ MPa and $T = 100$ °C. The $SExI = 0,05$ defines a state of saturated thermal water ($T = 100$ °C) at atmospheric pressure, which is the absolute for direct use (Lee, 2001).

High quality wells and fields then yield $SExI > 0,5$ meaning they are available for power production (high duty conversion). Low quality fields and wells fall below the $SExI = 0,05$, and are definitely not suitable for indirect use, conveying too low potential for conversion. Medium quality sources then record $SExI = 0,05 - 0,5$. In mapping a quality of geothermal fields and resources, flow enthalpies and entropies are plotted against onto the Mollier's and Rant's diagram (Lee, 1996).

3.4 Governing equations and symbols

$$\dot{Q} + \sum \dot{m}_{in} \cdot h_{in} = \dot{W} + \sum \dot{m}_{out} \cdot h_{out} \quad (1)$$

$$\sum \dot{m}_{in} \cdot h_{in} = \sum \dot{m}_{out} \cdot h_{out} \quad (2)$$

$$E_x = E_x^{PH} + E_x^{KN} + E_x^{PT} + E_x^{CH} \quad (3)$$

$$E_{x,heat} - E_{x,work} + E_{x,mass,in} - E_{x,mass,out} = E_{x,dest} \quad (4)$$

$$e = (h - h_0) - T_0 \cdot (s - s_0) \quad (5)$$

$$E_x = \dot{m} \cdot [(h - h_0) - T_0 \cdot (s - s_0)] \quad (6)$$

$$SExI = \frac{h - 273,16 \cdot s}{1192} \rightarrow SExI_{field} = \frac{h_{field} - 273,15 \cdot s_{field}}{1192} \quad (7)$$

$$h_{field} = \frac{\sum_{i=1}^n m_{wi} \cdot h_{wi}}{m_{wi}} \quad (8)$$

$$s_{field} = \frac{\sum_{i=1}^n m_{wi} \cdot s_{wi}}{m_{wi}} \quad (9)$$

Thermodynamic symbols			Superscripts / subscripts	
Symbol	description	Unit	Symbol	description
e	specific exergy	kJ.kg^{-1}	dest	destruction
Ex	exergy	kJ	in	inflow, input
Ex •	exergy rate	kW	KN	kinetic
h	specific enthalpy	kJ.kg^{-1}	out	outflow, output
m •	mass flow rate	kg.s^{-1}	PH	physical
Q	heat transfer rate	kW	PT	potential
s	specific entropy	$\text{kJ.kg}^{-1}.\text{K}^{-1}$	res	reservoir
W	work rate	kW	0	dead-state, reference

4. RESULTS AND DISCUSSION

4.1 Procedure

The aim of this submission is to provide an initial approach on classification of geothermal resources of the Western Carpathians (Slovakia) by their thermodynamic quality. To meet the goal, we collected data from 132 exploration and geothermal wells, with, for at least, documented wellhead and base temperature ($T_{wh} > 20 \text{ }^\circ\text{C}$), tested pumping or overflow rates, geochemistry of fluids, proven or estimated thermal output and screened stratigraphy. Not all of these are recently in operation, neither every geothermal well installation provides sufficient data for analysis. Unfortunately, quality of available data varies, thus not every documented perspective geothermal area is represented by a well, thus it is not analyzed. By a contrast, some areas include a huge number of representative installations. A robust uncertainty of a study is variable screening length of boreholes. Some systems may then be sufficiently analyzed to the first reservoir horizon only, lacking data of deeper aquiferous bodies.

We used a REFPROP v9.1 (by NIST) to calculate specified state points of a pure fluid – thermal water, as a single compound substance. Enthalpy and entropy of a substance, substituted into (7) to calculate the SE_{ExI} by flow enthalpy (8) and flow entropy (9) per geothermal water body (GWB) or perspective area (PGA) were derived of the wellhead temperature and thermal water density. Flow rates were taken as of proven yield per each well.

Analysis of geothermal resources associated with “geothermal perspective areas” has been established well in a national scheme, as these strongly reflected definition of geothermal field commonly used worldwide. A nomenclature changed since the Directive 2000/60/EC of the European Parliament and Council, The Water Framework Directive has been adopted into national legislative. Henceforth, geothermal resources are supposedly evaluated with reference to 27 geothermal water bodies, as an independent group out of 101 groundwater bodies catalogued under newest schematization (Kullman jr. et al., 2005)..

4.2 Engineering (SE_{ExI}) classification

The Western Carpathians (WC) record low to moderate geothermic activity (Franko et al., 1995), typical for basin play types ($40 - 122 \text{ mW.m}^{-2}$), defining single phase (thermal water) reservoir media sampled in production and exploration wells. Deep reservoirs of temperature greater than $T_{res} > 50 \text{ }^\circ\text{C}$ occupy horizons below 1000 – 1500 m, due to a mean geothermic gradient $\approx 39 \text{ }^\circ\text{C.km}^{-1}$.

4.2.1 Spatial distribution

In overall analysis, the calculated specific exergy index per each GWB reaches $\text{SE}_{ExI} = 0,003 - 0,102$. Given score reflects vertical and horizontal anisotropy in distribution of temperature and hydrogeothermal characteristics of WC’s reservoirs, more distinct to compare than characteristics obtained off temperature comparisons.

In shallow depths up to 500 m, the score demonstrates low thermodynamic quality of GWBs at $\text{SE}_{ExI} = 0,003 - 0,018$. The highest SE_{ExI} score for the GWBs is calculated for the Komárno High Block (KVK; $\text{SE}_{ExI} = 0,018$), Central Slovak Neovolcanites – NW part (SN-SZ; $\text{SE}_{ExI} = 0,018$) and Topoľčany – Bánovce Embayment (TZaBK; $\text{SE}_{ExI} = 0,014$). Out of 132 wells, only 30 of them reached some thermal water ($T > 20 \text{ }^\circ\text{C}$) accumulation up to this depth, with wellhead temperature of $T = 20 - 40 \text{ }^\circ\text{C}$. Thermodynamic quality of sampled waters per well varies between $\text{SE}_{ExI} = 0,0025 - 0,026$. Apparently, highest score is reached in wells nearby the Stúrovo area – Komárno High Block ($\text{SE}_{ExI} = 0,025 - 0,026$). The geothermal water associates with elevated Mid Triassic carbonates covered with Neogene

siliciclastics. The entire area is for a long known by thermal springs and used widely for recreational purposes. At the Topoľčany – Bánovce Embayment, we calculated the high score for Veľké Bielice area ($SE_{\text{ExI}} = 0,024$). A same “rising spring” model can be applied to the Horná Nitra Basin – BCH-1 ($SE_{\text{ExI}} = 0,012$) and HCH-3 ($SE_{\text{ExI}} = 0,015$) in the Chalmová area. To some confidence, at shallow depths up to 500 m, an increase in the SE_{ExI} in a magnitude of an order tends to reflect zones of elevated Mesozoic carbonates associated with upflow and natural discharge zones of deeper geothermal systems. Yet most of these structures are heated additionally with some convection by upwelling springs, and higher SE_{ExI} score owes somehow to the enthalpy preservation (unlike temperature, the enthalpy of a system is fairly conservative with the mixing system). Negative SE_{ExI} correlation with density gives some more proof towards the spring association model on an anomaly explanation. Where there is a monotonous conductive field, along with no additional heat support (e.g. crustal stretching / thinning or thermal relaxation), the SE_{ExI} sets at a lowest score.

Together 82 wells sampled thermal waters out of reservoirs at depths greater than 500 m. The mean (flow) $SE_{\text{ExI}} = 0,004 - 0,102$ for geothermal water bodies increases negligibly along a low region. A score of $SE_{\text{ExI}} < 0,01$ is hereby due to skewing of results in the Komárno High Block (KVK; $SE_{\text{ExI}} = 0,005$), the Piešťany Embayment (PEZ; $SE_{\text{ExI}} = 0,004$), the Humenné ridge (HCH; $SE_{\text{ExI}} = 0,006$) and the Rimava Basin (RiK; $SE_{\text{ExI}} = 0,009$). There is, however, only one well within a 1000 – 1500 m of depth interval (Č-2 Veľký Meder, Čalovo in Central Danube Depression) where thermal waters record a moderate quality with $SE_{\text{ExI}} = 0,061$. By the flow enthalpy, geothermal water bodies can be classified as low quality.

A cooling effect on reservoir environment by fast downflow circulation regimes, especially in a region of intramountain depressions hosting aquifers in Mesozoic carbonates, ceases with depth over 1000 – 1500 m. Still by the mean (flow) SE_{ExI} per GWB, these are generally classified as low quality. At depths between 1500 – 2000 m, 8 wells exceed the $SE_{\text{ExI}} = 0,05$, out of which 7 are with the Central Danube Depression ($SE_{\text{ExI}} = 0,05 - 0,145$) and 1 is with the Horná Nitra Depression (Š-1-NB-II; $SE_{\text{ExI}} = 0,074$). All of these are currently installed online for individual and district heating or recreational / agricultural purposes. Below 2000 m, the flow (mean) specific exergy index per GWB increases to $SE_{\text{ExI}} = 0,024 - 0,102$, calculated from 7 GWBs where deep geothermal or structural (exploration) wells (20 / 132) sampled thermal waters of $T = 40 - 129$ °C at a wellhead. However, only the Central Danube Depression (CDPP; $SE_{\text{ExI}} = 0,07$) and the Košice Depression (KK; $SE_{\text{ExI}} = 0,102$) may be classified of moderate quality. In total, 11 wells reached the moderate quality score per well, of which only 5 are currently being utilized for heating (FGG-2 Galanta) agriculture and recreational purposes.

Thermodynamic quality of geothermal resources of the Western Carpathians reflects to several influencing factors at depths over 1000 m. In total, 20 geothermal wells yielded a $SE_{\text{ExI}} > 0,05$. The Central Danube Depression (CDPP) involves 14 moderate quality wells, out of which only 1 well (Č-2) hits reservoirs at depths less than 1500 m. All installations screened bearing horizons in Neogene sands and sandstones. Highest SE_{ExI} is estimated for central and southern part with moderate correlation of temperature with depth ($R^2 = 0,62$). Obviously, inhomogeneous vertical temperature and fluid thermodynamics distribution may then be resultant to an effect of Neogene ALCAPA crustal thinning and passive volcanism propagation, supporting additional heat transfer into reservoir formations at various depths. There is a contrast to the CDPP documented in L-1 Lipany well associated with the Levoča Basin – NE part, screening deepest reservoir at ≈ 3400 m and the score of $SE_{\text{ExI}} = 0,055$. Clearly, the moderate quality is a consequence of depth along a monotonous conductive heat transfer along a vertical, flysch sequences and its Mesozoic underbed. In the Košice Depression, geothermal wells in the Ďurkov area (GTD-1 to GTD-3) hit Mesozoic Mid Triassic carbonates of the Veporicum Megaunit at depths of 2000 – 3200 m, all recording moderate quality thermal waters ($SE_{\text{ExI}} = 0,09 - 0,11$). Along with a burial depth, vertical temperature and gradient distribution give some evidence on local Neogene areal volcanism propagation continuously through additional heat source supply.

4.2.2 Geothermal water bodies classification

Geothermal sources of the Western Carpathians (Slovakia) are conventionally classified by wellhead (Tab. 1) and reservoir temperature with a reference to (Franko et al., 1986). Temperature itself, however, gives a low outline of usable potential conveyed by a reservoir. Apparently, introduction of an engineering approach helps better resolution on qualitative parameters of geothermal sources. Up to 1500 m, all geothermal water bodies can be classified as low quality resources. However, the Central Danube Depression, Komárno High Block, Horná Nitra Basin and Skorušiná Basin approach a moderate quality. Out of 27 GWBs, only the Central Danube Depression, Horná Nitra Basin and the Košice Basin can be classified as moderate quality at depths over 1500 m (Fig. 2 - 3).

4.2.3 Individual resources classification

In fact, such a scheme is all but representative and a primary evaluation gives it only a local, general review importance. This is because defined GWBs include usually one or more hydrogeothermal structures of various geothermic and hydrogeological regime, mostly because of tectonics or vertical stratification, involving reservoir positions in different tectonic units. This is e.g. a case of the Liptov Basin (typical intramountain, basin-constriction system, where depressed structures horizontally alterate elevated systems). Geothermal wells with $SE_{\text{ExI}} > 0,05$ (moderate quality) are listed in Table 2. The table also includes geothermal wells used for geothermal district heating with $SE_{\text{ExI}} < 0,05$ (Fig. 4).

Obviously, the most perspective area appears nearby towns of Veľký Meder (VM-GDHS), Galanta (GA-GDHS), and the Ďurkov village. In the Veľký Meder, a mean boiler plant output is about 15 000 MWh of which which geothermal delivery counts up to 62 % due to seasonal load. Geothermal wells wells Č-1 ($SE_{\text{ExI}} = 0,145$) and Č-2 ($SE_{\text{ExI}} = 0,061$) give a mean net output of 1,76 MWt. We calculated the thermodynamic efficiency of the district heating system for $\epsilon = 0,72$ defining the sustainability index for $SI = 3,57$. According to (Halás, 2015), a complete reinstallation of the VMGDHS, after which both wells will be replaced by a single well.

Table 2: Geothermal water bodies: comparison of wellhead temperatures and SExI for reservoirs deeper than 500 m.

Geothermal water body	GWB code	T_{wh} (°C)	Class	SExI		Quality	SExI	
		(°C)		< 1,5 km	> 1,5 km		Quality	
Central Danube Depression	SK300240PF	28-91	low	0,044-0,045	low	0,049-0,07	moderate	
Komárno Marginal Block	SK300020FK	42-64	low	0,018	low	0,018	low	
Komárno High Block	SK300010FK	20-30	low	0,05	low	n/a	n/a	
Central Slovakian Neovolcanics - NW	SK300190FK	29-57	low	0,022-0,033	low	0,033	low	
Central Slovakian Neovolcanites - NE	SK300200FK	25-46	low	0,02	low	n/a	n/a	
Viena Basin	SK300030FK	73-78	low	n/a	n/a	0,045	low	
Trnava Embayment	SK300040FK	n/a	low	n/a	n/a	n/a	n/a	
Piešťany Embayment	SK300050FK	20-50	low	0,004	low	n/a	n/a	
Komjatice Depression	SK300180FK	70-80	low	n/a	n/a	0,039	low	
Horná Nitra Basin	SK300100FK	20-59	low	0,048	low	0,07	moderate	
Trenčín Basin	SK300060FK	n/a	low	n/a	n/a	n/a	n/a	
Ilava Basin	SK300070FK	n/a	low	n/a	n/a	n/a	n/a	
Žilina Basin	SK300080FK	24-41	low	0,019	low	0,038	low	
Topoľčany - Bánovce Embayment	SK300090FK	20-55	low	0,023-0,025	low	0,025-0,028	low	
Turiec Basin	SK300110FK	50-60	low	0,029	low	n/a	n/a	
Skorušina Basin	SK300120FK	28-56	low	0,04-0,046	low	n/a	n/a	
Liptov Basin	SK300130FK	25-66	low	0,024-0,032	low	0,024	low	
Levoča Basin - W,S	SK300140FK	31-62	low	0,028	low	0,032	low	
Levoča Basin - NE	SK300150FK	53-85	low	n/a	n/a	0,039	low	
Humenné Ridge	SK300160FK	29-34	low	0,006	low	n/a	n/a	
Košice Basin	SK300170FK	123-129	moderate	n/a	n/a	0,102	moderate	
Levice Block	SK300210FK	69-80	low	0,037	low	0,04	low	
Rimava Depression	SK300220FK	20-33	low	0,008-0,01	low	n/a	n/a	
Beša - Čičarovce structure	SK300130FP	n/a	low	n/a	n/a	n/a	n/a	
Dubník Depression	SK300250PF	50-75	low	0,032	low	0,034	low	
Lúčenec - Rakovce Basin	SK300220FK	35-40	low	0,009	low	n/a	n/a	
Horné Strháre Grabben	SK300260FK	39-35	low	0,025	low	n/a	n/a	

* classification by wellhead temperature (Franko et al., 1986): low temperature ($T_{wh} < 120$ °C), moderate temperature ($T_{wh} = 120 - 150$ °C), high temperature ($T_{wh} > 150$ °C). In GWB code: FK – fissure-karst permeability, PF – porous-fissure permeability, FP – fissure-porous permeability.

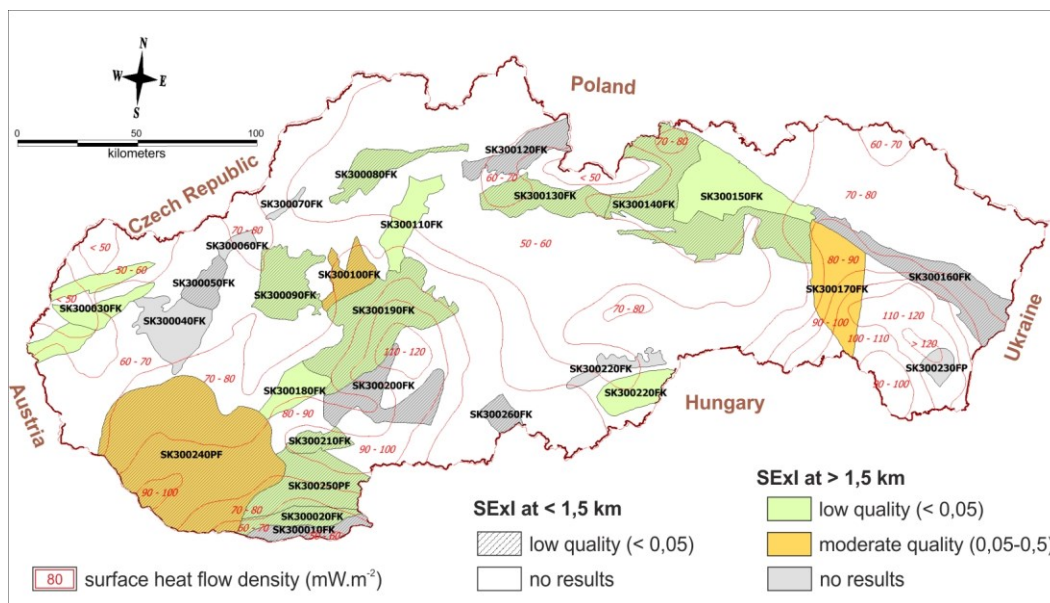


Figure 2: SExI distribution in GWBs at a surface heat flow area map

The GA-GDHS has been commenced in 1996. Two geothermal wells, FGG-2 (SExI = 0,0607) and FGG-3 (SExI = 0,051) provide a base heat output of 8,37 MWt. Use of thermodynamic approach estimates the thermodynamic efficiency of the system for $\varepsilon = 0,78$ and SI = 4,68. In 2015 (Halás, 2015) reported the system as grounded towards peak-loads and backup by natural gas boilers with 13,1 MWt of installed capacity, increasing operational and seasonal safety of the entire system.

The Šaľa geothermal district heating system (SA-GDHS) has been put online in 2011. In fact, the system is hybrid, including natural gas boilers with installed capacity of 20,7 MWt. Recently, (Halás, 2015) evaluated the system as overdesigned, as massive thermal insulation of apartments cut the heat consumption in the area. With a current heat output of 1,45 MWt, the efficiency drops rapidly to $\varepsilon = 0,54$ and the SI = 2,2.

The Sered' geothermal district heating system (SE-GDHS) has been operated since 2012 after completion of SEG-1 well to couple natural gas boilers of 8,7 MWt. The desired output off the geothermal heat exchanger is designed for 1,1 MWt (Halás, 2015). At a first approach, the efficiency counts fairly $\varepsilon = 0,86$ and the SI = 7,35.

The Ďurkov area is identified as the most perspective structure in the Western Carpathians, most probably the only suitable for power production. Three geothermal wells are installed since 1998 – 1999 and proven able to provide at least 100 MW of thermal output (Vranovská et al., 1999). Under such conditions, the system exploited by GTD-1 (SExI = 0,102), GTD-2 (SExI = 0,110) and GTD-3 (SExI = 0,097) is considered to operate the district heating system under $\varepsilon = 0,59$ (SI = 2,45), still capable for low scale binary power production. Because of closed hydrogeological character and highly mineralized brines content (up to 30 – 31 g.l⁻¹), implementation of reinjections is the ultimate condition to provide sustainable operation.

Apparently, moderate quality wells (Tab. 2) are currently used as a source for agricultural, recreational and individual heating purposes. The Lipany (L-1) well served as exploration well for oil and gas, however, it is not utilized because of high chloride / sulphate content, what is also a case of RGL-1 Lakšárska Nová Ves installation. There are, however, more installations around Slovakia used for individual space heating of low exergetic quality (in towns of Senec, Diakovce, Topoľníky, Komárno, Chalmová, Kováčová, Oravice, Rajecké Teplice, Bešeňová, Liptovský Trnovec, Poprad, Podhájska, Štúrovo, Nováky, and Vyšné Ružbachy). Exergy efficiency and sustainable index (potential) is an object of ongoing studies.

Table 2: SExI score and utilization status of wells with moderate quality, Western Carpathians (Slovakia)

<i>Geothermal well / locality</i>	<i>GWB</i>	<i>Stratigraphy / lithology</i>	<i>Yield</i> (l . s ⁻¹)	<i>Twh</i> (°C)	<i>b/perf</i> (m)	<i>SExI</i> <i>wellhead</i>	<i>In use</i>	<i>Utilization</i>
Veľký Meder (Čalovo), Č-1	SK300240PF	Ng / sands	10	79	1791	0,1454131	yes	DH
Čiližská Radvaň, ČR-1	SK300240PF	Ng / sands	6	82	2430	0,1243317	yes	A
Ňárád (Topoľovec) VTP-11	SK300240PF	Ng / sands	14,6	74	2482	0,1104498	yes	A
Ďurkov, GTD-2***	SK300170FK	Tr 2 / carbonates	50	129	3104	0,1101775	no	-
Ďurkov, GTD-1	SK300170FK	Tr 2 / carbonates	56	125	3155	0,1022395	no	-
Ďurkov, GTD-3***	SK300170FK	Tr 2 / carbonates	65	123	2246	0,0977124	no	-
Čiližská Radvaň, VČR-16	SK300240PF	Ng / sands	14,5	64	1745	0,0951148	no	-
Koš (Laskár), Š-1-NB II	SK300100FK	Tr 2 / carbonates	22	59	1851	0,0744301	yes	IH
Dunajská Streda, DS-1	SK300240PF	Ng / sands	15,2	91	2432	0,074037	yes	A
Topoľníky, FGT-1	SK300240PF	Ng / sands	23	74	2487	0,0737857	yes	R, A
Dunajský Klátov, VDK-15	SK300240PF	Ng / sands	15,4	74	2222	0,0701311	no	-
Zemianska Oľča, VZO-14	SK300240PF	Ng / sands	10	74	1839	0,0656469	no	-
Veľký Meder (Čalovo), Č-2	SK300240PF	Ng / sands	18,2	57	1439	0,0618376	yes	DH
Galanta, FGG-2	SK300240PF	Ng / sands	25	80	2032	0,060731	yes	DH, R
Vlčany, FGV-1	SK300240PF	Ng / sands	10	68	1852	0,0595351	yes	IH, A
Diakovce, Di-2	SK300240PF	Ng / sands	12	68	1536	0,0595351	yes	IH, R
Tvrdošovce, FGTv-1	SK300240PF	Ng / sands	20	70	1637	0,0585953	yes	R, A
Lipany, L-1****	SK300150FK	Tr 2 / carbonates	10	85	3390	0,0557109	no	-
Galanta, FGG-3	SK300240PF	Ng / sands	25	77	1999	0,0510549	yes	DH, R
Lakšárska N. Ves, RGL-1	SK300030FK	Tr 2 / carbonates	25	78	2065	0,0501066	no	-
Šaľa, GTŠ-1	SK300240PF	Ng / sands	15	69	1786	0,0415653	yes	DH
Sered', SEG-1	SK300240PF	Ng / sands	66	66	1800	0,0367425	yes	DH

* Stratigraphy / lithology: Tr2 – Mid Triassic, Ng – neogene; Utilization: DH – district heating, IH – individual space heating, A – agriculture, R - recreation

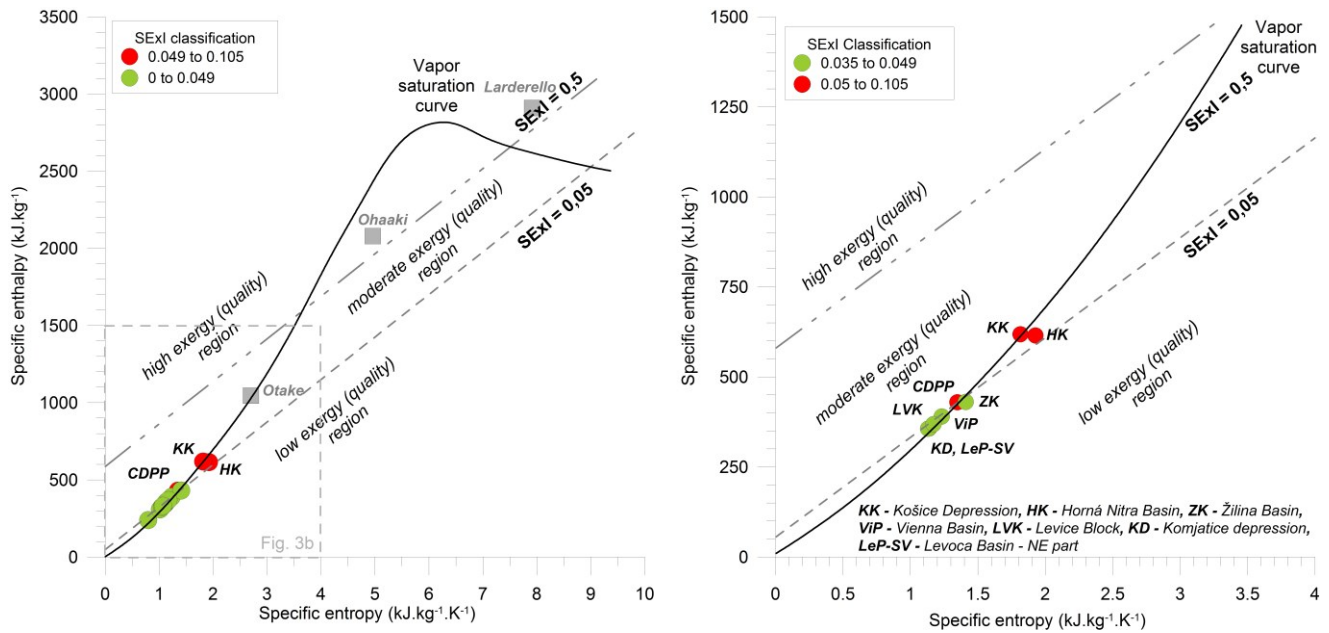


Figure 3: Most perspective GWBs on the Mollier’s diagram

5. CONCLUSIONS

Owing to geological evolution and, essentially, neotectonic regime, the geothermal field of the Western Carpathians, Slovakia, is utterly heterogeneous in vertical and horizontal direction. Temperature, geothermal activity and thermodynamic quality of associated geothermal waters is controlled by reservoir position, heat flow anomalies association (e.g. crustal thinning, cooling of deep volcanic centers, vertical interflow between stratified reservoirs) and dissolved solids content.

It seems the effect of cooling by shallow and fast filtration ceases at depths up to 1500 m. Considering reservoirs up to 1000 m, geothermal water bodies are of low quality, not suitable for any high duty operation. For reservoirs at depths below 1000 m, the Central Danube Depression, the Horná Nitra Basin and the Košice Depression appear able to support high energy duty demands (Tab. 1). Out of 132 analyzed wells, only 20 reached a region of moderate quality – Tab. 2, Fig. 5 (SEI = 0,05 – 0,145). Then, instead of classifying GWBs as solid systems towards completion of national scheme, we recommend detailed analysis by hydrogeothermal structures or sites (such as by group of installed wells providing source for a certain project).

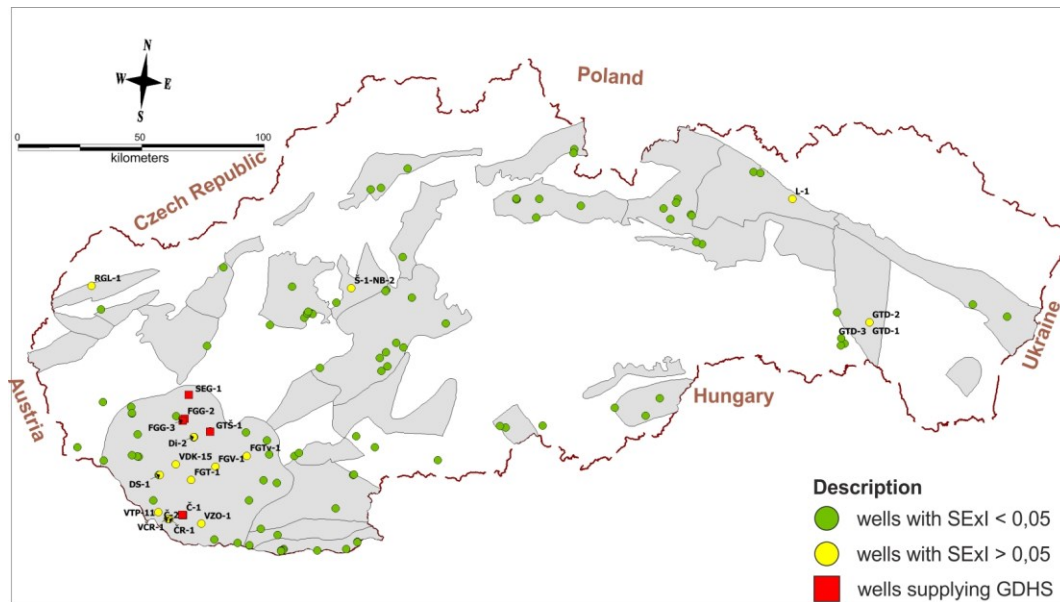


Figure 4: Location of most perspective wells and high duty (district heating) systems in Slovakia

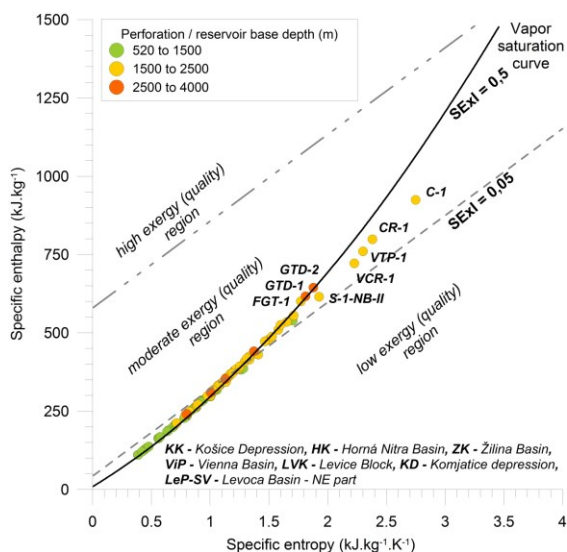


Figure 5: Mapping geothermal wells on Mollier's diagram (perforation / reservoir base depth > 500 m)

Under the Directive 2009/28/EC of the European Parliament and of the Council, the Slovak Republic is obliged to ensure 14 % share of RES on the final energy. The geothermal energy is amongst most perspective in the country, obviously for a heat generation. Exergy analysis of most perspective wells shown their capacity is fairly consumed for heating. We do not exclude currently unidentified sources adequate for geothermal power production, however, under current state-of-art, the Ďurkov area appears the only structure suitable only.

Knowledge on energy efficiency by engineering approach is then a reliable tool to determine most perspective sites for geothermal development. Besides sites used recently for DHS, the research and evaluation activities should focus on increasing efficiency where moderate or sub-moderate resources of capacity enough are utilized for small scale agriculture or recreational only by introducing cascades or individual heating. After years of obstructions, a country must prompt on developing the Ďurkov area meanwhile.

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