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4. A First Contribution on Thermodynamic Analysis and Classification of Geothermal Resources of the Western Carpathians (an Engineering Approach)

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Abstract: Up to date, identified prospective geothermal areas cover 34% of territory of the Slovak Republic. In a contrast to repeatedly reported basic production and wellbore characteristics, geothermal waters and geothermal resources have never been classified by operation or field thermodynamics. The paper gives a brief review on production and field enthalpy distribution, specific exergy and exergy rate capacity of available production and exploration wells, gives a complex hint on thermodynamic quality of geothermal resources by applying the specific exergy index studies, and, provides a brief review on operation parameters of sites currently online by definition of utilization and thermal efficiency and performance indexes such is the sustainable index and thermodynamic improvement potential. In general, geothermal plays of the Western Carpathians are of low quality (SExI < 0.05) and low flow enthalpy (h_{field} < 550 kJ.kg^{-1}) at depths below 1 500 m. There are moderate-enthalpy and moderate-low exergy resources within the Danube Basin Central Depression (Čiližská Radvaň, Topoľovec, Veľký Meder, Topoľníky area), the Košice Basin (the Ďurkov area) and the Upper Nitra Basin (the Koš-Laskár area). If operation and performance indices are stacked, sites of the Tvrdošovce, Čiližská Radvaň, Chalmová, Koš-Laskár, Oravice, Podhájska and Bešeňová appear most adequate for onward development. This must, however, compromise sustainability, technical, social and economical aspects of use.

Key words: classification, geothermal resources, Western Carpathians, exergy, enthalpy, efficiency

4.1. Introduction

Geothermal energy is reported as renewable and sustainable. Natural renewability of geothermal resources is well held by reversibility in its thermodynamics at natural conditions and equilibrium between a source and its surroundings. Yet the sustainability is an artificial aspect of utilization of geothermal resources (Axelsson et al., 2004), requiring account on a certain irreversibilities in its exploitation and processing (Ozgener et al., 2007). A praxis has shown the temperature alone may be of use in particular description of natural conditions in which geothermal resources exist, however, lacks consistency in targeting quality of resources for use (Lee, 2001). Indeed, while temperature is not a conservative attribute and is destructed, e.g. during invasion of geothermal waters into shallower positions, enthalpy remains conserved in a reactive system or, at least, responses much slower (Fournier & Truesdell, 1974).

Geothermal resources have been classified by wellhead temperature (e.g. Franko, 1985; Fendek et al., 2011) or heat flow density – geothermic activity (Čermák & Hurtig, 1979). Still, numerous well established classification schemes, e.g. by play-type (Moeck, 2014; Moeck & Beardsmore, 2014), geothermal resource reporting method (Badgett et al., 2016; Garchar et al., 2016) or exergy (Lee, 1996, 2001) are missing in national source evaluation and analysis concepts.

A systematic exploration and research of geothermal resources dates for almost five decades in Slovakia. Recently, 27 prospective areas have been reported currently, covering 34% of a national territory with a total installed capacity of 149 MWt summarized at 56 sites online (Fendek & Fendeková, 2015). Amongst them, recreational sector owes a fair majority with 87.7 MWt (59%) ahead of agriculture (27.3 MWt / ≈ 18%), individual space (16.6 MWt / ≈ 11%) and district (16.2 MWt / ≈ 11%) heating, or ground heat pumps installations (1.6 MWt). In total, this represents roughly 39% of gross thermal installed capacity within all perspective areas or 2.2% of the total thermal potential. At the national energy mix, heat production from geothermal resources contributed with 5% (2 185 TJ) on total heat generation in 2014. According to Directive 2009/28/EC of the European Parliament and the Council on the promotion of use of energy from renewable sources, the country is called to increase a share of renewables up to 14% on a primary energy mix. Geothermal resources are identified amongst those of the greatest reliance in achieving the goal. With a term drawn in, an onward research and development in geothermal energy should then call on a definition of most perspective areas for high demand installations, identification of sites available for production improvements and sites of potential enough to increase utilization efficiency of current heat generation (e.g. by introducing cascade systems, optimization etc.).

Obviously, a desired increase in utilization of geothermal resources requires initiation of systematic, thermodynamic approach in evaluation and classification of geothermal waters and sites. The submission provides a first systematic overview on thermodynamics and geothermal waters quality in a region of the Western Carpathians.

4.2. REVIEW ON REGIONAL HYDROGEOTHERMICS

Current geological settings of the Western Carpathians owe to multiple folding and thrusting evolution through the Palaeozoic – Recent. A crystalline basement was formed through the Variscan orogeny achieving a crustal-nappe arrangement. Triassic carbonates-dominated sequences, deposited in variously differentiated promontories, underwent a nappe-thrusting in Early to Mid Cretaceous. In Palaeocene – Eocene, siliciclastics-dominates succession deposited onto broken and weathered pre-Tertiary relief. Through the Oligocene – Recent period, several episodes of tectonic dissegmentation and formation of intramountain depressions occurred as well as deep Neogene sedimentary basins were formed, intruded with volcanites. Carpathian depressions and basins are, in addition, covered with Quaternary accumulations of minor fresh-water carbonates occurrence.

4.2.1. Geothermal field and geothermic activity

Geological settings and global tectonic position, which is a reflection on geodynamic evolution, define anisotropy in distribution of a geothermal field of the Western Carpathians. In vertical distribution, (Franko et al., 1986) concluded the geothermal field and heat propagation up to ≈ 3,000 m is disturbed by morphology, water circulation and lithology, whilst at greater depths, the geothermal field is controlled at asthenosphere upwelling and crustal thinning or thickening tendency. A standardized mean heat flow density for the Western Carpathians has been calculated for 82 +/- 20 $mW.m^{-2}$, that characterizes a moderate to fairly increased geothermic activity. The heat flux (Fig. 4.1) increases (≈ 125 $mW.m^{-2}$) along Neogene volcanic propagation and thinned crust based basins. The activity distinctly decreases (50 – 85 $mW.m^{-2}$) at uplifted neotectonic blocks, intramountain depressions away of neovolcanic activities and areas of intense crustal thickening (Franko & Melioris, 2000). Compared to world average at 1,000 m (30 $°C.km^{-1}$), the geothermic gradient is quite increased in the Western Carpathians (38 $°C.km^{-1}$).

4.2.2. Geothermal play-types characteristics

A geothermal play-type is a model of how much a number of geological factors may generate recoverable geothermal resource at a specific structural position and certain geological setting (Moeck, 2014). By that, the play-type refers to drilling conditions, economics, resource characteristics, etc.

Let us neglect some concerns in basic systematics, confusing between geothermal fields and structures in identification of perspective areas, for a moment. Majority of localities refer to conduction-dominated, intracratonic basin (intramountain depressions) and foreland basin (Neogene sedimentary basins) plays (Moeck & Beardsmore, 2014). Intracratonic plays typically associate fault plane bound springs structures (e.g. Turiec depression), deep lateral leakage systems (e.g. Liptov Basin), basin constriction systems (e.g. Piešťany embayment) and bedrock high (e.g. Levoča Basin – W and S part) systems (Brook et al., 1987; Hochstein, 1988; Walker et al., 2005; Williams et al., 2008). Occurrence of reservoirs is controlled by existence of open fault tectonics and typical stratification of at least two Mesozoic nappe series beneath the Inner Western Carpathian Palaeogene (IWCP) or sedimentary Neogene fill. In Mesozoic formations, main aquifers are found in Mid Triassic carbonates. For Tertiary horizons, reservoirs associate with conglomerates and carbonates of the basal Borové Formation (IWCP) or sands and sandstones in Neogene, respectively. Geochemistry of geothermal waters varies due to longevity and depth of circulation, as they usually record carbonatogenic, transient and sulphatogenic, less (hydro)silicatogenic type. Degraded marinogenic waters are rather rare.

Foreland basin plays (Danube Basin Central Depression, Košice Basin, Vienna Basin) associate stratified sedimentary reservoir (Nathenson & Muffler, 1978) and bedrock (Williams et al., 2008) systems in major, however, towards peripheries, local fault plane-bound springs and lateral leakage systems (Brook et al., 1978) occur individually. Deep reservoirs in Mesozoic sequences (obviously Triassic) are often assumed only. Most of wells hit rather upper resources in Neogene sands and sandstones. Alike in previous, structures are usually semi-open or semi-closed and closed, respectively. Geochemistry of waters varies by reservoir depth, lithology and hydrogeological character of a system; however, marinogenic brines and degraded-marinogenic types are well documented.

Yet the Levoča Basin in its north-eastern part and the Humenné Ridge are affine to orogenic (basin) plays (Moeck – Beardsmore, 2014) owing stratified sedimentary reservoir systems (Williams et al., 2008) character. Reservoirs are rather buried deep in Triassic carbonates of various depths beneath flysch-type Palaeogene sequences, impermeable in essence. Geothermal waters are of silicatogenic to carbonatogenic or marinogenic-degraded types with obviously high TDS. Complexity in tectonics and vertical arrangement gives them a frequent semi-closed or closed character with minor recharge.

Some questions arise on a geothermal-play definition for Central Slovakian Neogene volcanites and the Beša--Čičarovce structure. In the first Neogene volcanites, deep-rooted magma channels intrude sedimentary Triassic to Neogene sequences, where majority of documented reservoirs occur; existence of geothermal resources in volcanoclastics is just rare yet. Even of apparently increased heat flow, we rather classify them as conduction-dominated intracratonic basin plays (Moeck, 2014), gaining stratified sedimentary reservoir to lateral leaking systems character (Nathenson & Muffler, 1978; Williams et al., 2008). Accumulation and flow of geothermal waters is controlled by open tectonics and superposition of caprock in Neogene volcanosedimentary complexes. This is a control of hydrogeological regime as well. The chemistry reflects actual host lithology and filtration characteristics, usually acquiring carbonatogenic to sulphatogenic, lesser (hydro)silicatogenic type.

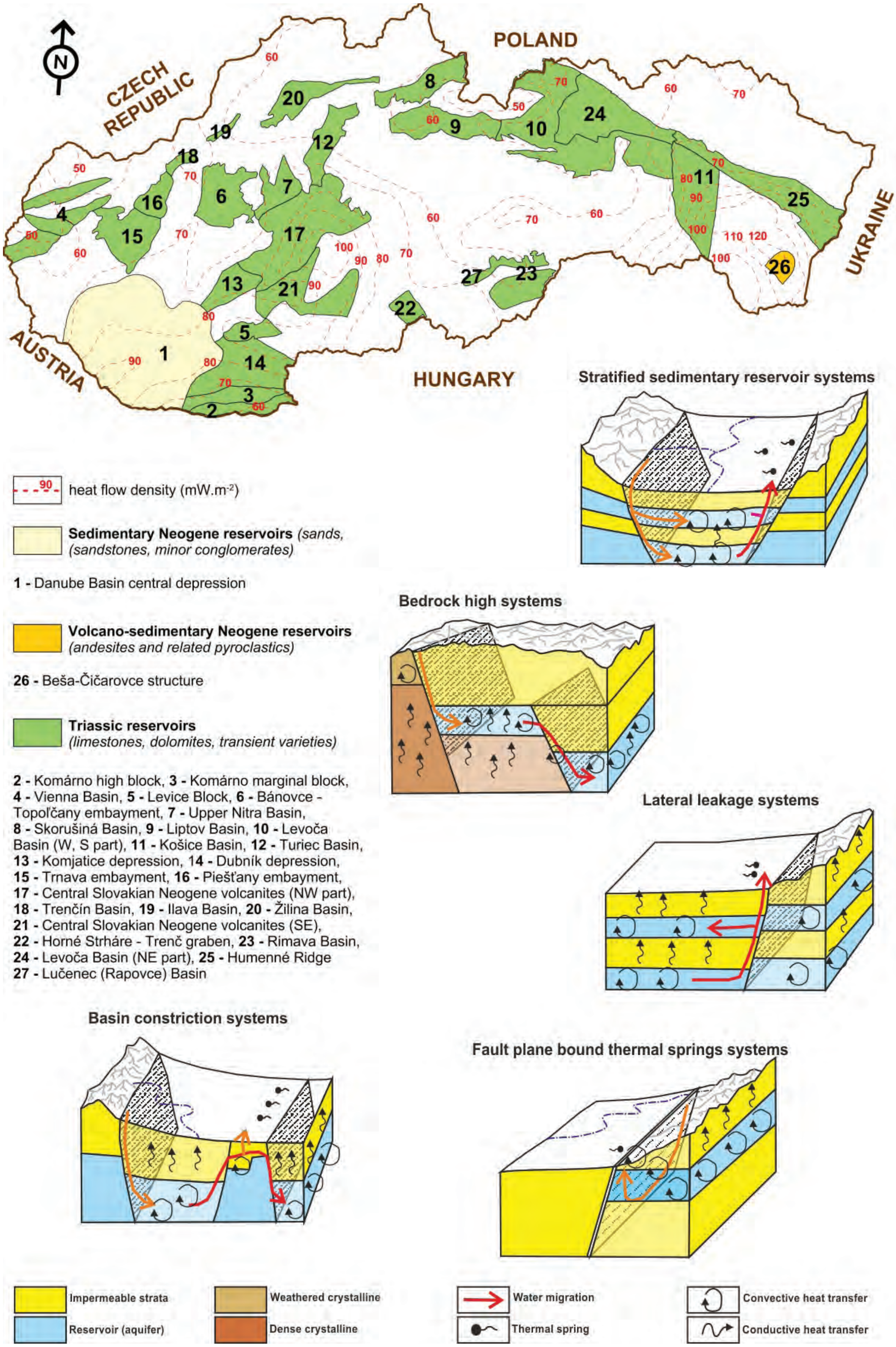

Fig. 4.1 Geothermal resources of Slovakia: prospective geothermal areas, heat flow density map and generalized play-type conceptions in regional conditions on reservoir stratigraphy background.

The Beša-Čičarovce structure represents a deep buried Neogene volcano in Neogene sedimentary fill of the Eastern Slovakian Basin, documented by geophysics and increased heat flow density at a surface. Occurrence of reservoirs is expected in Neogene andesites and related pyroclastics, thus the geothermal structure should be classified as conduction-dominated, foreland basin play (Moeck & Beardsmore, 2014) of stratified regional sedimentary reservoir character (Nathenson & Muffler, 1978). However, as there is a geothermal resource in volcanic products, the structure could be approached as convection-dominated, intrusive magmatic play-type (Moeck, 2014). At whatever position, we expect the structure to preserve a semi-closed or closed character, associating geothermal waters of marinogenic to degraded-marinogenic origin at high dissolved solids content.

4.3. APPROACH

4.3.1. A concept of thermodynamic quality

In natural conditions, the renewability of a geothermal resource, at least in terms of heat and mass delivery, links well with thermodynamic equilibrium, assuming the source is a closed or pseudo-steady-state system. According to the 1st Law of Thermodynamics, energy in natural systems is a conservative measure (1; subchapter 4.3.3.), thus the total energy balance applies, later described by a flow enthalpy (2) once either kinetic and potential energies, a heat and work transfers are neglected (Ozgener et al., 2005) due to equality.

The geothermal resource behaves no more as a (pseudo) closed system under artificial production and cannot be described by the energy balance as each change in initial thermodynamic conditions destructs achieved equilibrium. This is asserted by application of 2nd Law of Thermodynamics that accounts on entropy (thermodynamic disorder) creation (3). Then, the measure of energy available for any artificial conversion (e.g. work, heat delivery) is denoted as exergy (4), which is reciprocal to entropy generation, rather consumed or destroyed instead of being conserved, due to irreversibilities in real processes (Ozgener et al., 2007). For a given geothermal water at a specified flow rate and temperature, the specific exergy (4) transforms to a flow exergy or exergy rate (5) consequently balanced (6).

A problem of definition points

Both (4) and (5) require identification of appropriate definition points. Because of artificial use, the definition point s.s. refers to thermodynamic conditions at a wellhead or inlet into a conversion system, as this is a first stage the fluid is available to perform any work or heat delivery (DiPippo, 2005). Yet numerous studies accent a variation in exergy (and derived efficiencies) with a reference point (e.g. Ozgener et al., 2006; Utlu & Hepbasli, 2008; Kecebas, 2013). The dead-state s.s. addresses an environment of a source at zero working potential, that is unable to undergo any spontaneous change as it is in a complex equilibrium (Bodvarsson & Edgers, 1972; Bodvarsson, 1974). For realistic conditions, the reference state is often termed a restricted-dead-state (Lee, 1996), defined at sink or ambient p-T conditions.

Conversion efficiencies and potential

By the 1st Law of Thermodynamics, the energy efficiency (η – eta) defines how much of a heat conveyed is transformed into a heat production at a conversion stage (7) and sights on energy emission reductions regardless of its quality and origin. The 2nd Law of Thermodynamics screens irreversibilities in conversion processes (8) by exergy efficiency (ε – epsilon) or defines a quality rate the source is ready to deliver (Dincer & Rosen, 2013).

Apparently, the maximum exergy efficiency is achieved by minimizing differences between an input and output. An exergetic improvement potential is as follows (9). A rate of sustainability becomes proportional to efficiency in a conversion system (Gungor et al., 2011) or available energy the source can deliver to the process operated at current state (10).

4.3.2. A concept of thermodynamic classification and analysis

There are several classifications of geothermal resources by enthalpy (Bodvarsson, 1964; Nicholson, 1993; Axelsson & Gunlaugsson, 2000) basically defining low enthalpy fluids of up to 1,000 $kJ.kg^{-1}$ corresponding to 150 – 190 ˚C, depending on p-T, density and steam fraction saturation conditions. These grades are rather convenient with natural (initial) state conditions.

In reservoir engineering and geothermal field research and prospection, thermodynamic studies are conducted applying exergy and specific exergy index analysis in:

a) exergoeconomics, environmental and sustainability studies (Lozano & Valero, 1993; Bilgen & Sarikaya, 2015);
b) optimization of geothermal power plants (DiPippo, 2004) and heat production installations (Ozgener et al., 2007), including heat pumps (Soltani et al., 2015);
c) evaluation of geothermal fields (Quijano, 2000; Lee, 2001); and
d) classification of geothermal resources (Etemoglu & Can, 2007; Barbacki, 2012).

SExI – the specific exergy index

Enthalpy itself cannot be used to describe qualitative properties of a fluid exploited for energy conversion. Thereof the specific exergy index (11) has been introduced (Lee, 1996), relating exergy of a specified fluid to the enthalpy of pure water saturated with steam at 303 °C and 9 MPa. At this setup, the index gives an estimation of real conversion potential of a producing source. For sites with multiple wells or fields, the enthalpy and entropy are rather weighted by a produced mass flow (12-13) to give a site SExI (14). The same procedure is available for time-series analysis and definition of critical utilization scenario.

SExI – classification and mapping

Instead of arbitrary temperature classification guidelines derived off different geothermic conditions (e.g. Muffler & Cataldi, 1978; Hochstein, 1988), the concept of energy quality by SExI parameter refers to real thermodynamics of exploited fluids. In essence, (Lee, 1996, 2001) introduced two baselines. A limit of SExI = 0.5 refers to lowest exergy of saturated steam at p = 0.1 MPa and T = 100 °C, critical for high-scale and efficient direct power production, recorded in moderate-enthalpy to high enthalpy, double-phase or dry-steam fields. A limit of SExI = 0.05 describes a quality of saturated water at T = 100 °C and p = 1 Bar-abs, essential for low-scale, rather indirect (binary) power production or high-duty heat generation, typical for most of low enthalpy, single-phase, liquid-dominated fields. Then, the SExI = 0.2 describes a p-T conditions of double-phase natural systems at p = 20 Bar-abs at enthalpy over 1,000 $kJ.kg^{-1}$ (moderate / high enthalpy fields).

With baselines set, geothermal resources may be classified as follows:

a) low quality (exergy) resources or fields, SExI < 0.05;
b) moderate-low quality (exergy) resources or fields, 0.05 ≤ SExI ≤ 0.2;
c) moderate-high quality (exergy) resources or fields, 0.2 ≤ SExI ≤ 0.5;
d) high quality (exergy) resources or fields SExI > 0.5.

Besides technical quantification, geothermal resources or fields may be mapped using the enthalpy – entropy – pressure Mollier's or exergy – entropy – pressure Rant's diagram

4.3.3. Equations and symbols

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

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

$$s = -\oint (\delta Q / T) \quad (3)$$

$$e = (h - h_0) - T_0 \cdot (s - s_0) \quad (4)$$

$$\dot{E}x = \dot{m}[(h - h_0) - T_0 \cdot (s - s_0)] \quad (5)$$

$$Ex = Ex_{heat} - Ex_{mass-in} - Ex_{mass-out} \quad (6)$$

$$\eta_{th} = \dot{E}_{out} / \dot{E}_{in} \quad (7)$$

$$\varepsilon_{ut} = \dot{E}x_{out} / \dot{E}x_{in} \quad (8)$$

$$IP = (1 - \varepsilon_{ut}) \cdot (\dot{E}x_{in} - \dot{E}x_{in}) \quad (9)$$

$$SI = 1/(1 - \varepsilon_{ut}) \quad (10)$$

$$SExI = (h - 273{,}15 \cdot s)/1192 \quad (11)$$

$$h_{field} = \left(\sum_i^n \dot{m}_{in} \cdot h_{in} \right) / \sum_i^n \dot{m}_{in} \quad (12)$$

$$s_{field} = \left(\sum_i^n \dot{m}_{in} \cdot s_{in} \right) / \sum_i^n \dot{m}_{in} \quad (13)$$

$$SExI_{field} = (h_{field} - 273{,}15 \cdot s_{field})/1192 \quad (14)$$

4.4. THERMODYNAMIC ANALYSIS

Since a systematic research and prospection on geothermal resources was launched in early 70's of the 20th Century, updates on evaluation of hydrogeothermal potential and prospection results have been reported repeatedly (Fendek et al., 1995; Fendek et al., 1999; Remšík, 2012; Fendek & Fendeková, 2010, 2015). Now there is a need to update results of geothermal exploration and research by basic engineering thermodynamics and basic indexes. This is because promotion and increase in geothermal energy use requires general knowledge on geothermal waters quality, recent state of utilization and capacity available at online sites or, at least, on potential left for onward improvements.

We have collected data from exploration and production wells installed in years of 1965 – 2015 (some basic attributes for most of them were already reported in Tab. 1 – Remšík, 2012), at least where essential attributes were available (yield / mass flow, wellhead temperature, total dissolved solids, reservoir stratigraphy, screened depth, geothermal potential, coordinates). Real production parameters (Fendek & Fendeková, 2015; Halás, 2015) have been taken for those wells installed, which report to the Slovak Hydrometeorological Institute as by Act No. 364/2004 Coll. on Water and later amendments. In a consequence, onward calculations may be skewed as much as how intense the uncertainties in reports are.

Together 133 wells were subjected to thermodynamic analysis. Derivation of enthalpy and entropy was carried by the REFPROP 9.0 (NIST), with following setup: reference substance – single compound substance, pure fluid – water (CAS number: 7732-18-5), specified state points – temperature (K) and density ($kg.m^{-3}$). This allows the REFPROP to calculate state points with limits to possible vapour formation and variation in thermodynamic properties by a fluid density according to critical point and reference properties (given by database; Wagner – Pruss, 2002) oscillation under specified ρ-p-T conditions.

4.4.1. Classification by enthalpy

Geothermal resources were documented in stratigraphic horizons dated through the Neogene to Mesozoic at screened (production) base intervals of 49 – 3,330 m. With a temperature varying 20 – 129 °C (293.15 – 402.15 K) at a wellhead and total dissolved solids (TDS) content of 400 – 90,000 $mg.l^{-1}$, the enthalpy of geothermal resources reaches 86 – 924 $kJ.kg^{-1}$. To classify geothermal resources, we have accepted a scheme by (Axelsson & Gunnlaugsson, 2000) with a cut-off level of 1,000 $kJ.kg^{-1}$ for high enthalpy resources, adjusted by an arbitrary value of 550 $kJ.kg^{-1}$ to delineate moderate-enthalpy resources assuming partial vapour fraction volatization at pressure greater than atmospheric (Truesdell & Fournier, 1977).

Stratigraphy criteria

Together 57 wells targeted a geothermal waters reservoir in sedimentary Neogene formations (sands, sandstones, conglomerates, clays) in the Danube Basin

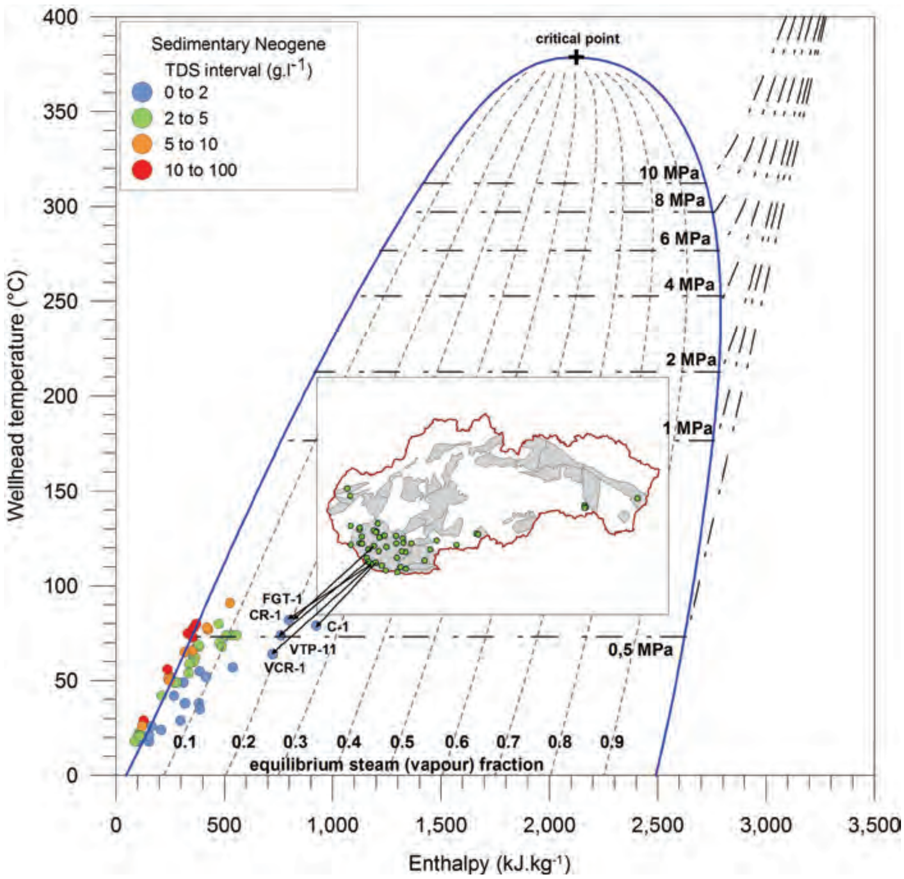

Fig. 4.2 Temperature – enthalpy diagram for geothermal waters of sedimentary Neogene

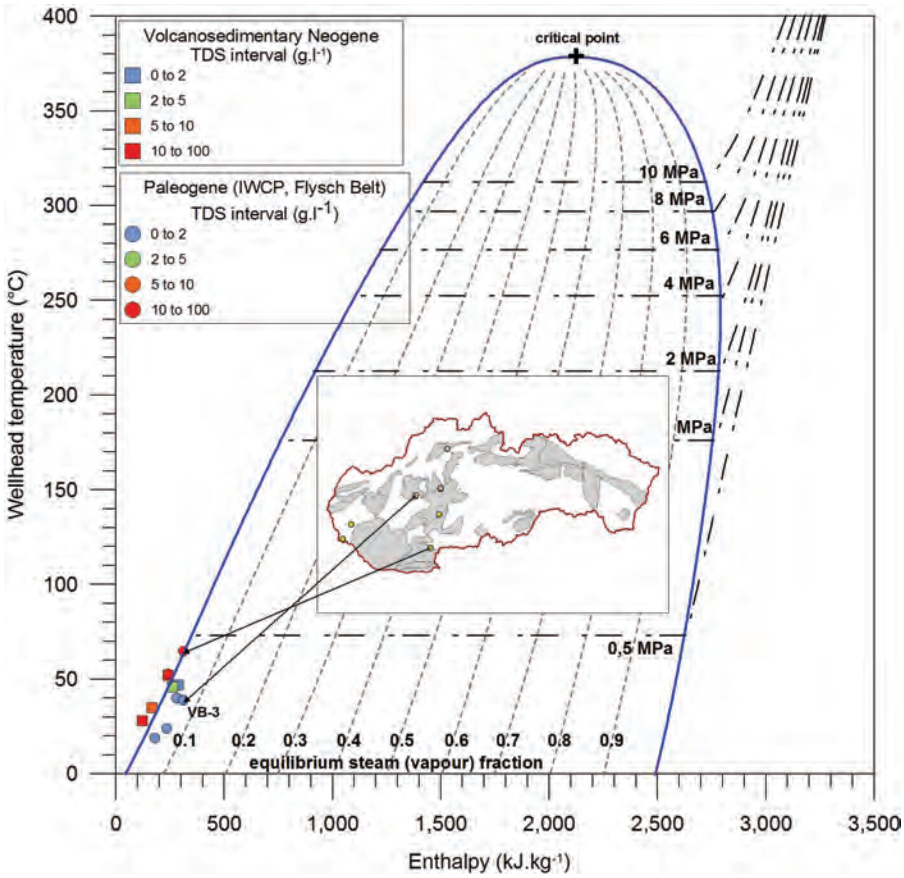

Fig. 4.3 Temperature – enthalpy diagram for geothermal waters of volcano-sedimentary Neogene and Palaeogene (IWCP, Flysch Belt) reservoirs

Central Depression (CDPP), Dubník Depression, Humenné Ridge, Horné Strháre-Trenč Graben, Komjatice Depression, Košice Basin, Komárno Marginal Block, Central Slovakian Neogene volcanites (SE part) and the at depths of 64 – 2,570 m. At the wellhead temperature oscillation between 20 – 91 ˚C (291 – 364 K) the TDS ranges through 400 – 90,000 mg.l^{-1}. The calcula-ted wellhead enthalpy reached h = 86 – 924 kJ.kg^{-1}.

Geothermal waters of the Č-1 Veľký Meder – Čalovo well can be described as of highest enthalpy due combining low TDS and T (h = 924 kJ.kg^{-1}, T_{wh} = 79 ˚C, TDS = 1,100 mg.l^{-1}, b_{perf} = 1,791 m). Moreover, geothermal waters at four wells can be considered of moderate enthalpy (ČR-1, VČR-16, VTP-11 and FGT-1). All are localized within the CDPP (Fig. 4.2, Tab. 4.1). Neogene reservoirs in other perspective areas are definitely of low-enthalpy, moreover, at questionable technological potential because of various TDS and yield.

Unlike for T_{wh} – b_{perf} correlation (R^2 = 0.88), the enthalpy does not necessarily increase with depth of reservoir (R^2 = 0.54) because of variation in TDS (Fig.4.2). At b_{perf} < 500 m and T_{wh} < 30 ˚C, the enthalpy difference is about 100 – 150 kJ.kg^{-1} for TDS = 500 – 12,000 mg.l^{-1}. An enthalpy reduction with TDS increases with depth. At depths of 1,500 – 2,000 m, the TDS = 900 – 90,000 mg.l^{-1}, whereas enthalpy of produced fluid at T_{wh} = 27 – 79 ˚C varies h = 250 – 950 kJ.kg^{-1}. Below 2,000 m, wells produce geothermal fluids at T_{wh} = 50 – 91 ˚C with TDS = 1,100 – 30,000 mg.l^{-1}. Here, highest enthalpies of h = 550 – 750 kJ.kg^{-1} were calculated for geothermal waters of TDS < 2,500 mg.l^{-1}. At the same depth, geothermal waters record lower enthalpies of h = 300 – 425 kJ.kg^{-1} at TDS > 5,000 mg.l^{-1}.

Volcano-sedimentary reservoirs are documented in the CDPP (FGB-1 Chorvátsky Grob, HGB-1 Rusovce), Dubník Depression (HGŽ-3 Želiezovce), and both parts in Central Slovakian Neogene volcanites (HR-1 Banská Štiavnica, R-3 Zlatno). Resources contain low enthalpy geothermal waters of h = 121 – 312 kJ.kg^{-1} at a wellhead temperature in a range of 28 – 69 ˚C and variable TDS content (2,000 – 19,200 mg.l^{-1}). Besides technological problems especially for Na-Cl type waters (e.g. GRP-1, HGB-1), volcano-sedimentary reservoirs are of low enthalpy potential and flow rate, in general.

Geothermal waters of the Levoča Basin (N part) were documented in PL-1 and PL-2 Plavnica wells, associated with Palaeogene sandstones and Triassic carbonates at depths of over 3,000 m, T_{wh} = 53 – 65 ˚C and TDS = 10,000 – 12,300 mg.l^{-1}. This is because of their marinogenic origin. Yet both wells associate well with volatile gases (CO_2, CH_4) causing incidental technical problems. Even of a great depth, both are of low enthalpy, h = 240 – 310 kJ.kg^{-1}. In comparison, MB-3 Malé Bielice and VB-3 Veľké Bielice wells (both within the Bánovce Embayment) produce geothermal waters of T_{wh} = 39 – 40 ˚C at a wellhead enthalpy h = 279 – 310 kJ.kg^{-1} under a production depth of up to 100 m from the IWCP horizons. Yet it is apparent that at a current state of exploration, the IWCP reservoirs contain low enthalpy fluids only.

Triassic geothermal waters were documented at 63 wells from 17 localities. Triassic carbonates are considered the most important reservoir formation in local conditions.

Alike in Neogene formations, temperature – enthalpy correlation in Triassic reservoirs increases (R^2 = 0.78) because of lower TDS content (400 – 31,000 mg.l^{-1}). Indeed, 71% of samples record a dissolved solids content below 5,000 mg.l^{-1}. This is because vast majority of structures are hydrogeologically open and intensively rewashed. Geothermal wells of T_{wh} = 20 – 129 ˚C (293 – 402 K) produce fluids from b_{perf} = 30 – 3,390 m. Marinogenic and degraded brines are observed only with the Košice Basin – Ďurkov area (GTD-1,2,3). Degraded and polygeneous brines were documented within the Levoča Basin – NE Part (L-1 Lipany) and the Komárno Marginal Block (M-1, M-3, GTM-1 Marcelová). In other structures, carbonatogenic to mixed waters prevail. Enthalpy in Triassic carbonates reaches h = 96 – 645 kJ.kg^{-1}. There is not any high enthalpy geothermal resource in Mesozoic strata. Four wells record possibility to produce moderate enthalpy (550 – 800 kJ.kg^{-1}) waters: GTD-1 Ďurkov (617 kJ.kg^{-1}), GTD-2 Ďurkov (645 kJ.kg^{-1}), GTD-3 Ďurkov (601 kJ.kg^{-1}) and Š-1-NB-II Koš (615 kJ.kg^{-1}). Another three wells, RTŠ-1 Kamenná Poruba (430 kJ.kg^{-1}), OZ-2 Oravice (433 kJ.kg^{-1}) and L-1 Lipany (442 kJ.kg^{-1}) produce geothermal water at enthalpy above a boiling point at atmospheric pressure. In general, Triassic geothermal waters may be, with listed exceptions, also considered as low enthalpy (Fig.4. 4).

At depths up to 500 m, geothermal waters from Triassic horizons produce enthalpy higher than those in Neogene reservoirs up to 100 – 250 kJ.kg^{-1}. By thermodynamics, it may be concluded that shallow Triassic reservoirs contain larger energy potential and "enthalpy hunting" approach may become more profitable, especially for low individual heating and small-scale agricultural and industrial heat processing (Fig.4. 5). The situation counters at depths over 1,000 m at even equal TDS content. Up to 2,500 m, highest enthalpies are documented for low TDS (< 5,000 mg.l^{-1}) geothermal waters produced from Pannonian – Pontian sands, this is, however, a general picture with exception of the Ďurkov wells and Š-1-NB-II in the Upper Nitra Basin. However, especially in Neogene horizons, the enthalpy hunting for high energy demand duties (individual or district heating, high demand heat processing for industry and agriculture) must compromise the absolute technical and processing potential of associated waters, where occurrence of mineralized brines (> 10,000 mg.l^{-1}) of (degraded) marinogenic brines increases with depths.

In conclusion, the vertical (stratigraphical) enthalpy distribution is consequent to:

- evasion of geothermal fluids from deep reservoirs into shallow positions and lower TDS content at depths up to 500 m ($h_{Tr2} > h_{Ng}$);
- frequent mixing between several horizons and continuous rewashing of reservoirs in Triassic carbonates due to frequent open hydrogeological regime ($h_{Tr2} < h_{Ng}$);
- association of Neogene reservoirs, especially those in CDPP with crustal thinning and extensive heat flow propagation ($h_{Tr2} < h_{Ng}$);

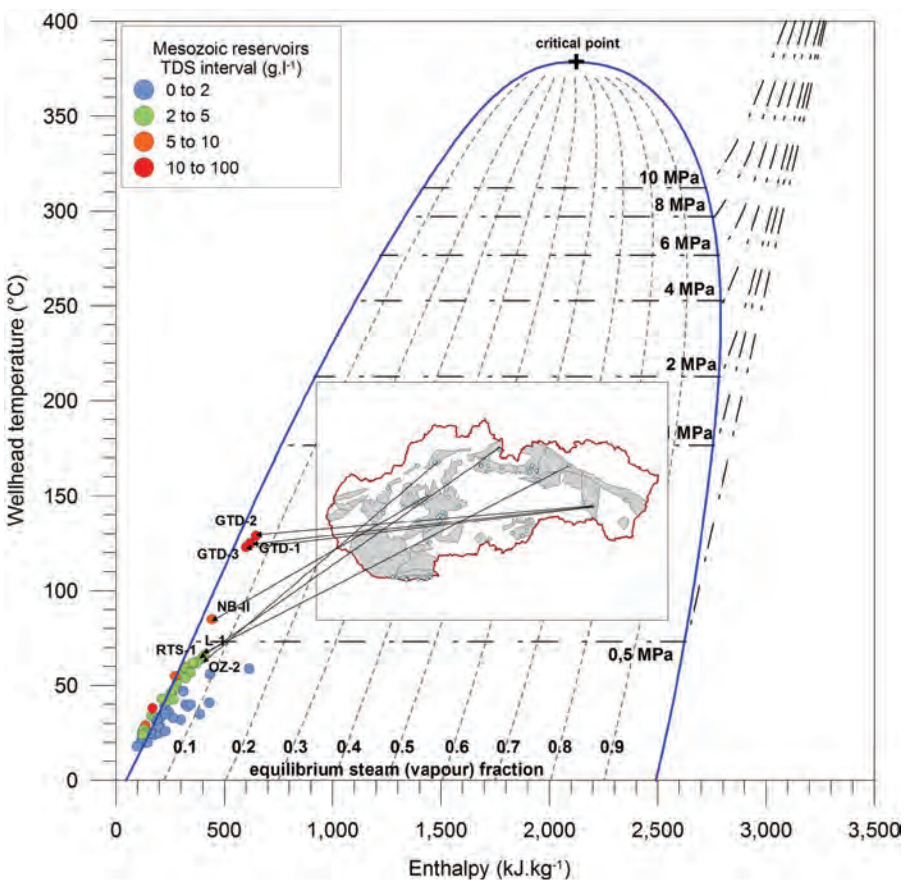

Fig. 4.4 Temperature – enthalpy diagram for geothermal waters of Triassic carbonates.

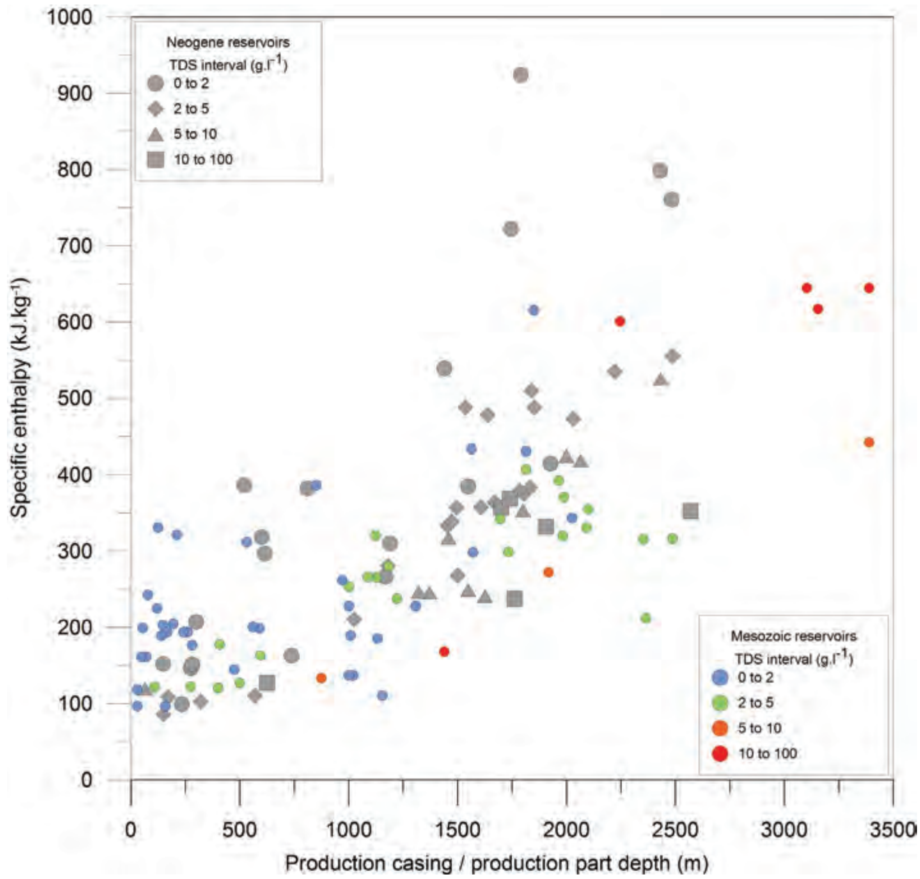

Fig. 4.5 Enthalpy distribution in the Western Carpathians with depth.

- extremely high TDS for marinogenic and degraded-marinogenic saline brines of Neogene at 1,500 – 2,500 mg.l^{-1} ($h_{Tr2} > h_{Ng}$ even at $T_{Tr2} < T_{Ng}$).

Prospective-area criteria

Up to this point, we have evaluated enthalpy conditions at individual wells. Description of identified prospective sites accounts on application of (12) to determine the field enthalpy per each locality. Given results are, however, skewed in some extension by

- productivity of installed wells;
- various TDS content;
- various reservoir depth and heterogeneous hydrogeological regime.

At general conditions, the enthalpy varies h_{field} = 120 – 610 kJ.kg^{-1} (Appendix A). The only area of moderate enthalpy (h_{field} = 610 kJ.kg^{-1}) is the Košice Basin. However, the Vienna Basin, Komjatice depression, Upper Nitra Basin, Turiec Basin, Liptov Basin, both parts of the Levoča Basin, Levice block, Dubník depression and the Skorušiná Basin exceed the average field enthalpy of the Western Carpathians ($h_{field-avg}$ = 281 kJ.kg^{-1}).

To reduce the skewing, we have normalized calculations by excluding wells of b_{perf} < 750 m, Q < 2 l.s^{-1} and TDS > 30 g^{-1}. After normalizing, the enthalpy varies h_{field} = 137 – 620 kJ.kg^{-1} (Appendix A). The Košice Basin appears in general the only area of moderate enthalpy. The Upper Nitra Basin and the Horné Strháre-Trenč Graben record enthalpy over 419 kJ.kg^{-1} for partial vapour formation at atmospheric pressure. The CDPP, Vienna Basin, Levoča Basin (NE), Levice block and the Skorušiná Basin exceed a regional enthalpy average ($h_{field-avg}$ = 328 kJ.kg^{-1}).

4.4.2. Exergy distribution

The enthalpy analysis is rather a qualitative measure of a heat (energy) content stored. Distribution and analysis of exergy is, instead, a study on possible real performance and energy quality potential available and deliverable from a reservoir to the production site. To provide a brief review on a situation in the Western Carpathians, we have examined both, the specific exergy (4) and the flow exergy or the exergy rate (5), understood as a thermodynamic quality contained in the source and a real available energy conveyed, or available for conversion, respectively. By definition, the exergy distribution relies on a specified reference (dead-state) conditions. For following analysis, let us consider the restricted dead-state as representative, defined at a TDS representative to sink temperature at 10 °C (283,15 K).

Specific exergy analysis

By specific exergy, geothermal resources appear monotonous in a thermodynamic quality content of e < 20 kJ.kg^{-1} at depths below 1,500 m. The low quality homogeneity applies for geothermal waters regardless of reservoir stratigraphy and TDS. Deeper, Triassic reservoirs contain the specific exergy above an average (e_{avg} = 20 kJ.kg^{-1}) in the Liptov Basin (FGTB-1 and ZGL-1 Bešeňová), Skorušiná Basin (OZ-2), Levoča Basin (GVL-1 Veľká Lomnica and FGP-1 Stará Lesná), and the Komárno Marginal Block (FGK-1 Komárno). Geothermal wells in the Ďurkov area exceed e > 80 kJ.kg^{-1}, however, at a production depth up to 2,300 – 3,300 m (Appendix B). Geothermal waters of highest quality are distributed within the CDPP. Reservoirs with production depth base of 1,500 – 2,500 m and a wellhead TDS < 5,000 mg.l^{-1} contain a specific exergy e > 40 kJ.kg^{-1}. Geothermal wells in the Čiližská Radvaň, Topoľovec and the Veľký Meder area record highest quality, with specific exergy over 80 kJ.kg^{-1} (Appendix B).

Exergy rate (flow exergy) analysis

The exergy rate (Ex) is amongst criteria in decision making for high-scaled conversion projects or power production optimization, understood as somewhat a quantitative measure in terms of real conversion potential delivery. Obviously, the flow exergy relies significantly on a mass delivery to the definition point. Unlike for enthalpy, the TDS increases then a real amount of energy available by advective supply due to an extensive mass flow.

In gross analysis, the overall exergy rate varies Ex = 1.9 kW (FGS-1) to 200 MW (GTD-3). If wells of Ex < 0.1 MW are excluded, the mean exergy rate at documented wells is calculated for Ex = 8.57 MW in conditions of the Western Carpathians.

In total, 89 wells (Appendix B) record an exergy rate of Ex > 0.1 MW. Highest exergy rate is calculated for the Ďurkov area, where geothermal wells are available at Ex = 169 (GTD-2) – 200 (GTD-3) MW. The greatest score is consequence to combination in high brine flow rate (50 – 65 l.s^{-1}), TDS (30 – 31 g.l^{-1}) and a specific exergy (99 – 113 kJ.kg^{-1}). Sites of Ex > 1 MW are also found in the Podhájska area, Komjatice, Galanta, Horná Potôň, Vrbov, Bešeňová, Šaľa, Topoľníky or Oravice, etc.

Yet this is a thermodynamic quality measure, not a gross power potential, as the water cannot deliver an effective work into a power turbine. If calculated for power potential, recalculations should be done to correct for enthalpy of the vapour fraction and flow rate, turbine efficiency, inlet pressure, etc. In addition, a count on a real available work relies on definition of sink point (e.g. heat exchanger outlet) instead of restricted dead-state. Thus the exergy flow rate can point on perspective wells or sites available for high demand duties.

4.4.3. Specific Exergy Index analysis

The exergy analysis is rather a supportive tool and an engineering approach in analysis of geothermal resources, relying on multiple factors, hard to normalize at a regional scale. The specific exergy index (SExI) is, alike, beneficial in strict identification of definition point conditions, that is, at the wellhead, independent on a reference state. Instead of considering variable reference conditions, the SExI accounts on two independent thermodynamic properties (enthalpy and entropy) at measurable conditions. This makes the SExI a respected classification and decision-making tool gaining global credits (studies conducted in the USA, Iceland, New Zeeland, Japan, Turkey, Poland, Latin America countries, etc.).

SExI field (flow-based) analysis

As we stated in above, classification of prospective areas by enthalpy suffers off the horizontal and vertical variability in attributes of geothermal resources, somehow uprisen by hydrogeological conditions, local hydrogeothermics etc. A representative SExI (14) per field weights enthalpy (12) and entropy (13) by flow rates. In fact, the $SExI_{field}$ accounts then for a weighted average of a certain number of wells (14).

A field SExI analysis must necessarily be skewed by heterogeneity of the perspective areas (Fričovský et al., 2016). The overall SExI = 0.003 – 0.102. Concerning production from reservoirs with b_{perf} < 500, the SExI = 0.003 – 0.018, with highest values calculated for the Komárno High Block and the Central Slovakian Neogene volcanites (SExI = 0,018). This may be an effect of uprising waters into shallow position in Triassic profiles. Some convective / advective heat addition (by ascending geothermal springs or cooling magma channels) cannot be excluded. By example, the Štúrovo area is for a long known of warm springs.

We assume that a cooling effect of reservoir rewashing and recharge ceases at b_{perf} > 1,000 m. Still, by the flow SExI, prospective areas may be evaluated as low quality (Tab. 4.1, Appendix A) up to 1,500 m. At greater depths, the $SExI_{field}$ = 0.018 – 0.102 for the Western Carpathians. The Košice Basin ($SExI_{field}$ = 0.102), Danube Basin Central Depression ($SExI_{field}$ = 0.07) and the Upper Nitra Basin ($SExI_{field}$ = 0.07) record a moderate-low quality score. This is typical for single-phase, liquid-dominated fields in conductive geothermal plays (Fig.4. 6) and corresponds well with heat flow density distribution and additional heat propagation by Neogene volcanism or crustal thinning. This may, however, decrease dramatically towards peripheries of identified localities. Given scores are calculated under given (known) attributes of produced geothermal waters and may vary with exploring of deeper reservoirs or drilling towards centres of geothermal plays where highest temperatures occur typically (Fig.4.7).

From a global perspective, moderate-low quality geothermal fields (Košice Basin, Upper Nitra Basin, Danube Basin Central Depression) record a similar quality to the well utilized low to intermediate enthalpy, single-phase, liquid-dominated systems, where e.g. Fuzhou (SE China) is exploited for large scale agriculture projects and ISH (Pang et al., 2015), the Balcova field (Turkey) supports a largest geothermal district heating system in Turkey (Ozgener et al., 2006), and the Tianjin (Tanggu) field is as well optimized for large scale geothermal district heating use (Axelsson & Dong, 1998). By similarity, it is apparent that at least those three structures could be of a service for district heating supply on a large scale (some projects are already online in the Veľký Meder, Galanta, Šaľa, Sereď).

SExI individual (borehole-based) analysis

For a borehole-based SExI analysis we have substitute individual enthalpy and entropy calculated at a definition point (wellhead) at each well (11). Obtained results are not skewed by weighting inputs with a flow rate.

Tab. 4.1 Review on thermodynamic quality of geothermal resources (field analysis)

Geothermal water body / number		$SExI_{field}$ / quality		$SExI_{field}$ / quality	
< 1.5 km			> 1.5 km		
Danube Basin Central Depression	SK300240PF	0.044-0.045	low	0.049-0.07	moderate
Komárno Marginal Block	SK300020FK	0.018	low	0.018	low
Komárno High Block	SK300010FK	0.05	low	n/a	n/a
Central Slovakian Neogene volcanites – NW part	SK300190FK	0.022-0.033	low	0.033	low
Central Slovakian Neogene volcanites – NE part	SK300200FK	0.02	low	n/a	n/a
Vienna Basin	SK300030FK	n/a	n/a	0.045	low
Trnava embayment	SK300040FK	n/a	n/a	n/a	n/a
Piešťany embayment	SK300050FK	0.004	low	n/a	n/a
Komjatice Depression	SK300180FK	n/a	n/a	0.039	low
Upper Nitra Basin	SK300100FK	0.048	low	0.07	moderate
Trenčín Basin	SK300060FK	n/a	n/a	n/a	n/a
Ilava Basin	SK300070FK	n/a	n/a	n/a	n/a
Žilina Basin	SK300080FK	0.019	low	0.038	low
Topoľčany - Bánovce embayment	SK300090FK	0.023-0.025	low	0.025-0.028	low
Turiec Basin	SK300110FK	0.029	low	n/a	n/a
Skorušina Basin	SK300120FK	0.04-0.046	low	n/a	n/a
Liptov Basin	SK300130FK	0.024-0.032	low	0.024	low
Levoča Basin - W,S part	SK300140FK	0.028	low	0.032	low
Levoča Basin – NE part	SK300150FK	n/a	n/a	0.039	low
Humenné Ridge	SK300160FK	0.006	low	n/a	n/a
Košice Basin	SK300170FK	n/a	n/a	0.102	moderate
Levice Block	SK300210FK	0.037	low	0.04	low
Rimava Basin	SK300220FK	0.008-0.01	low	n/a	n/a
Beša - Čičarovce structure	SK300130FP	n/a	n/a	n/a	n/a
Dubník Depression	SK300250PF	0.032	low	0.034	low
Lučenec - Rakovce Basin	SK300220FK	0.009	low	n/a	n/a
Horné Strháre-Trenč Graben	SK300260FK	0.025	low	n/a	n/a

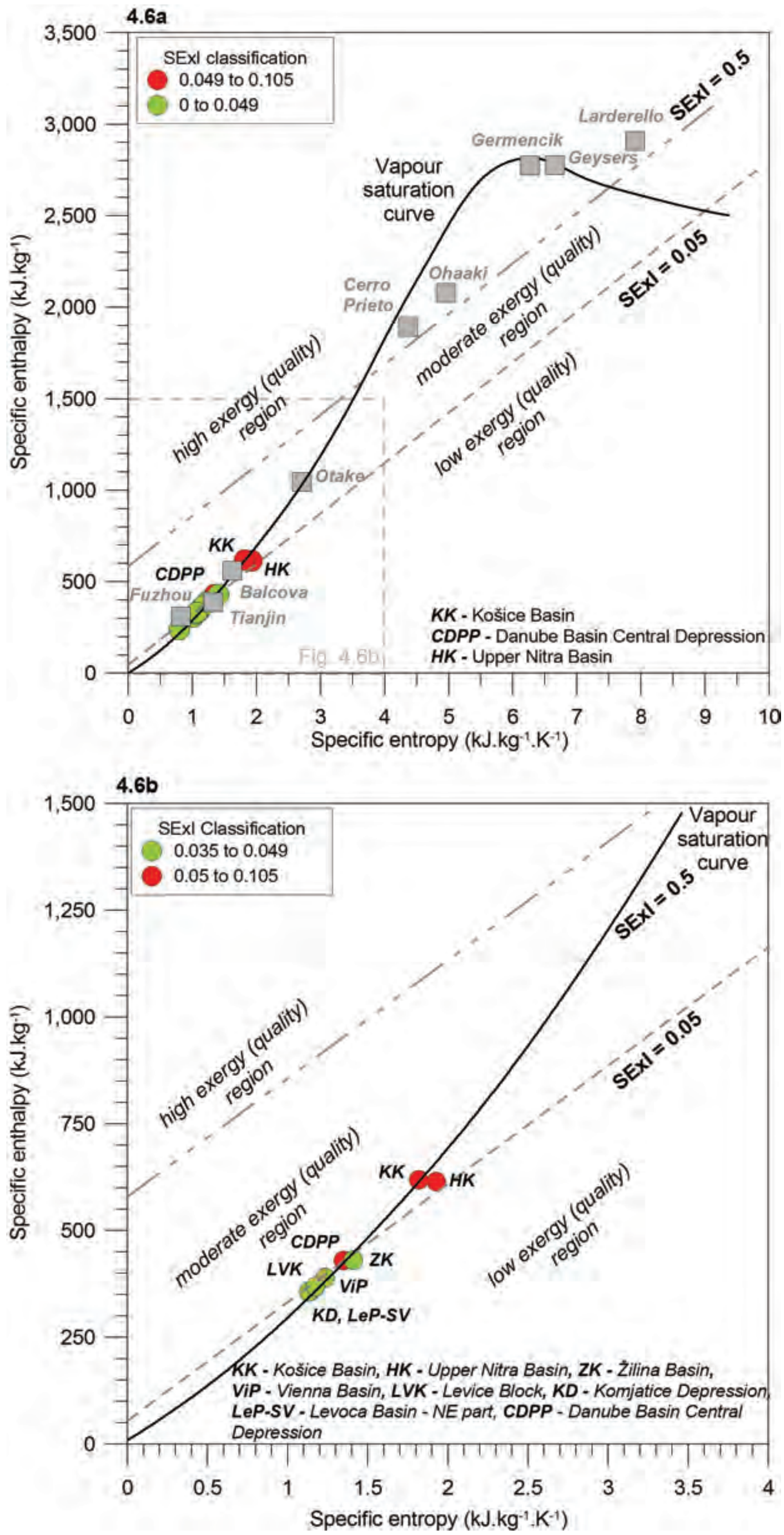

Fig. 4.6 Prospective geothermal localities map on a Mollier's diagram with perspective of global geothermal fields.

The approach is usually used for detailed analysis of geothermal systems or sites operating a single well.

In general, the average SExI is 0.029 as given off the range SExI = 0.0025 – 0.145. Under current state, geothermal resources may then be classified as low to moderate-low exergy. For wells with reservoir production depth of b_{perf} > 500 m, the average SExI = 0.035 at increased minimum limit to SExI = 0.0039.

Together 20 wells counted SExI > 0.05 and reached the moderate quality. Out of these, 13 are located in the Danube Basin Central Depression with the Veľký Meder, Čiližská Radvaň, Topoľovec, Topoľníky, Galanta, Vlčany, Diakovce, Dunajský Klátov or Zemianska Oľča areas (SExI = 0.051 – 0.145). In the Košice Basin, the SExI within the Ďurkov area counts 0.097 to 0.110. The highest SExI in the Upper Nitra Basin is calculated for the Koš

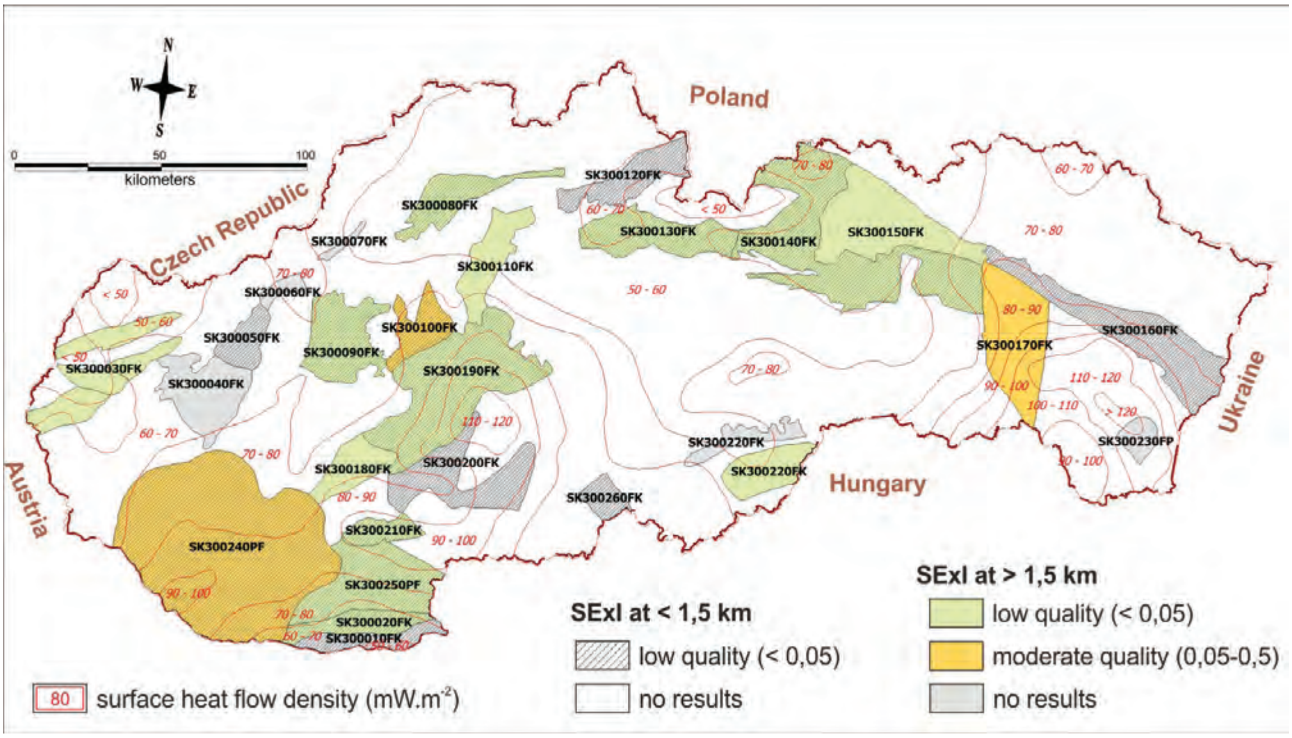

Fig. 4.7 Distribution of thermal waters thermodynamic quality with correlation to the heat flow density map (numerical indicators to geothermal water bodies).

– Laskár area (SExI = 0.074) documented for Š-1-NB-II well. Two other wells, L-1 Lipany (SExI = 0.0557) and RGL-1 Lakšárska Nová Ves (SExI = 0.0501) represent the highest quality for the Levoča Basin (NE part) and the Vienna Basin, respectively (Appendix B).

Evident distinctions between SExI level and reservoir stratigraphy are missing. Out of 57 wells in producing (or documenting) reservoirs in Neogene (SExI = 0.0025 – 0.145), vast majority (42) is up to SExI = 0.0425. The SExI produced from Triassic reservoirs counts 0.00308 (HM-5 Tornaľa) to 0.1107 (GTD-2 Ďurkov), however, 52 out of 62 wells yield the SExI score below 0.035.

A correlation of production part depth (b_{perf}) to the SExI ($R^2 = 0.44$) is questionable at a least. In fact, drilling deeper or producing deeper horizons does not necessarily mean an increase in thermodynamic quality of geothermal waters, which is conform to conclusions for enthalpy distribution in documented wells and reservoirs. Under regional conditions, the relation of SExI with produced temperature is rather exponential ($R^2 = 0.85$) as the enthalpy and entropy are a function of not only a temperature, but a pressure and TDS as well. Then, there is a clear difference between the installed geothermal potential and a quality of a geothermal water (Fig.4.8).

We see now that the individual SExI may be considerably higher than that analysed per geothermal fields or sites. For example, the flow SExI for the CDPP has been calculated for $SExI_{field} = 0.044 – 0.07$, the SExI of individual wells counts SExI > 0,1 for VTP-11 Topoľovec, ČR-1 Čiližská Radvaň and Č-1 Veľký Meder (Čalovo).

In a global perspective, geothermal resources of moderate-low quality (Fig.4. 9) are fairly similar again to those operated e.g. at the Balcova site, supplying a geothermal district heating system through the year, thus may definitely be utilized in high-demand duties.

The SExI alone is not a self-contained indicatory on a potential use. A praxis shows it is better to use the specific exergy index to analyse thermodynamic quality of particular site and then to search for a desired deliverability, according to a project the site should be designed for, or to update a project parameters. Along, a reservoir (site) sustainability and production compromises must be understood. In a meantime, the SExI itself does not account on potential risks associated with utilization of geothermal resources (i.e. the Ďurkov wells are of highest quality, but are known for a huge TDS and calcite to silica rapid scalings).

4.5. OPERATION OVERVIEW

4.5.1. Efficiency

As it was already stated, the Slovak Republic is called to increase a share of “renewables” on a national energy mix, including use of geothermal resources. In fact, the goal can be approached as: a) to search and develop new sites, b) to develop existing sites; and c) to increase an efficiency at existing sites. Under ideal economics, all must come together to maximize the effort. However, at some restricted scale, the easiest way is an increase in overall utilization efficiency. Options ”a“ and ”b“ must, however, compromise a sustainable use of geothermal resources, whilst increase in efficiency is rather an engineering issue on an operator’s side.

Thermal efficiency

The thermal efficiency (η_{th}) is easily understood as a ratio of a heat produced to the heat abstracted (7), thus

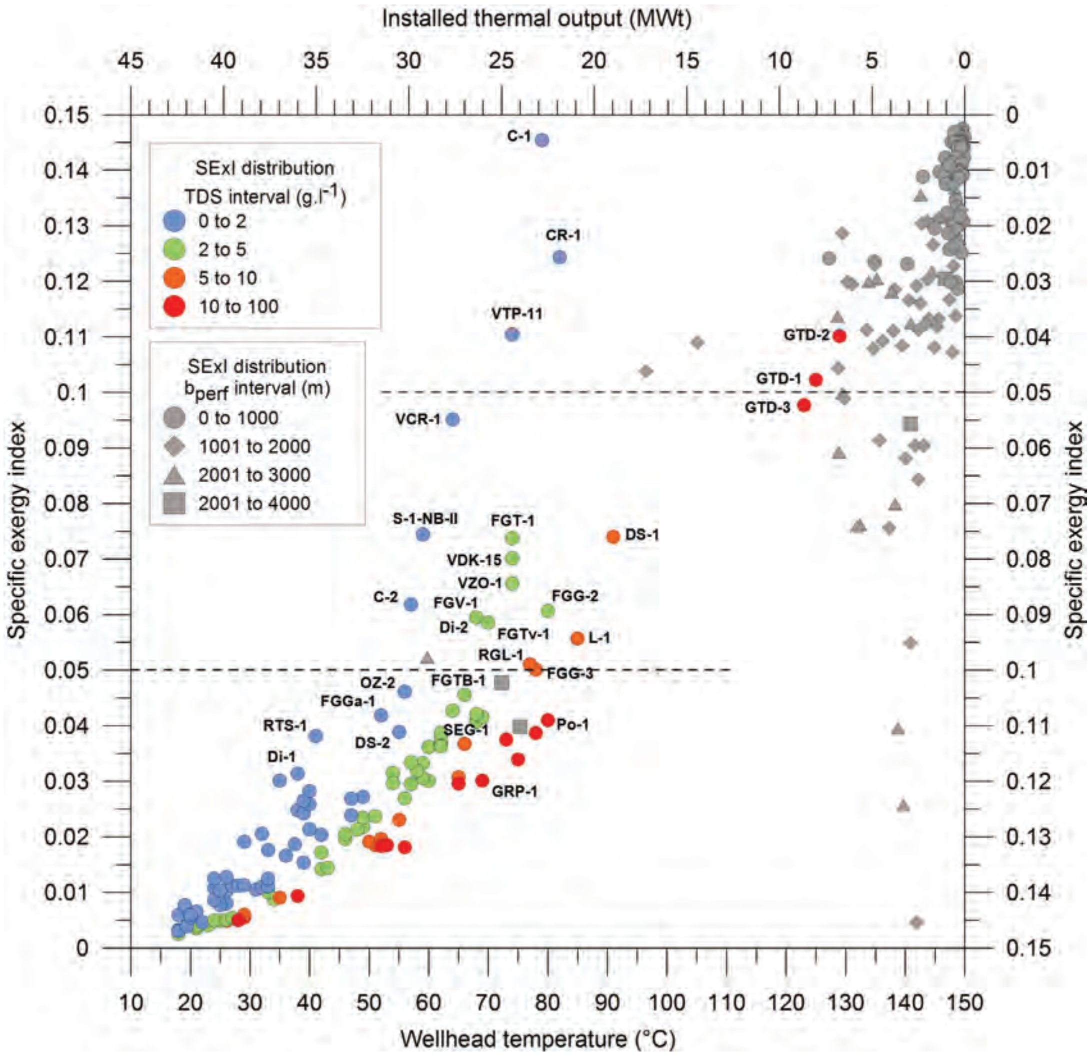

Fig. 4.8 Specific exergy index (SExI) relation to wellhead and installed thermal output

describes how much of a potential is consumed in a heating process (e.g. DiPippo, 2005). The thermal efficiency is amongst most important critical indexes in an engineering analysis of operated sites all along with the capacity factor (actual output in a period of time over an output if operated at a full time), availability factor (actual time of production over a full period of time) and a coefficient of performance (energy output over an electricity energy input to the ground source heat pump).

To provide a brief overview on a performance, we have taken actual reports of thermal output (Fendek & Fendeková, 2015) and compared them to the nameplate output – TTP (Remšík, 2012). The study has been conducted on 60 wells with complete data available.

Surprisingly, 15 wells are used at a full thermal efficiency (η_{th} = 1 or 100%). This is, however, a very unlikely case. At given data, the wells of FBe-1 Bešeňová, HGDS-1 Dolná Strehová, FGG-1 Galanta, BCH-3 Chalmová, FGO-1 Obid and SB-3 Patince are evaluated as of less installed thermal output than the actual output reported. Sites operating wells of BHS-3 Belušské Slatiny, Di-3 Diakovce, G-4 Košice, GN-1 Nesvady, PP-1 Poprad, KMV-1 Sielnica, GTŠ-1 Šaľa, HM-5 Tornaľa and HG-18 Vinice are evaluated to the same TTP as actual output. The high (let's say somehow unrealistic) efficiency may come consequent to erroneous reports or may give some hint of a hazardous use of a geothermal resource.

If we neglect those wells of η_{th} = 1, the thermal efficiency of online wells counts η_{th} = 0.03 – 0.98. With given data, 21 out of 45 wells utilize the resource with η_{th} > 0.75. By purpose, sites utilizing geothermal resource for balneology report a thermal efficiency of η_{th} = 0.03 – 0.98 (average efficiency counts η_{th} = 0.68). If reports are correct, there is a huge potential to increase an use of geothermal waters in the Oravice area (OZ-2: η_{th} = 0.03), Nové Zámky (GNZ-1: η_{th} = 0.08), Veľký Slavkov (VSČ-1: η_{th} = 0.14), Galanta (FGG-3: η_{th} = 0.23), Partizánske (FGTz-1: η_{th} = 0.41) or Šurany (GMŠ-1: η_{th} = 0.08). In agriculture, the thermal efficiency increases towards η_{th} = 0.38 – 0.97, at a mean of η_{th} = 0.71. The high efficiency is by coupling a drying, fish farming and greenhouse-heating with high-demand use, such as individual heating (e.g. TTŠ-1 Turčianske Teplice; η_{th} = 0.92), or recreation purposes (e.g. FGČ-1 Čilistov; η_{th} = 0.97). At individual use for agriculture, the thermal efficiency varies η_{th} = 0,38 – 0,75, at a mean of η_{th} = 0,66. Thermal efficiency of individual space heating (not-cascaded) is about η_{th} = 0.39 – 0.47 off the Koš--Laskár (Š-1-NB-II) and Chalmová (HCH-1). If sources

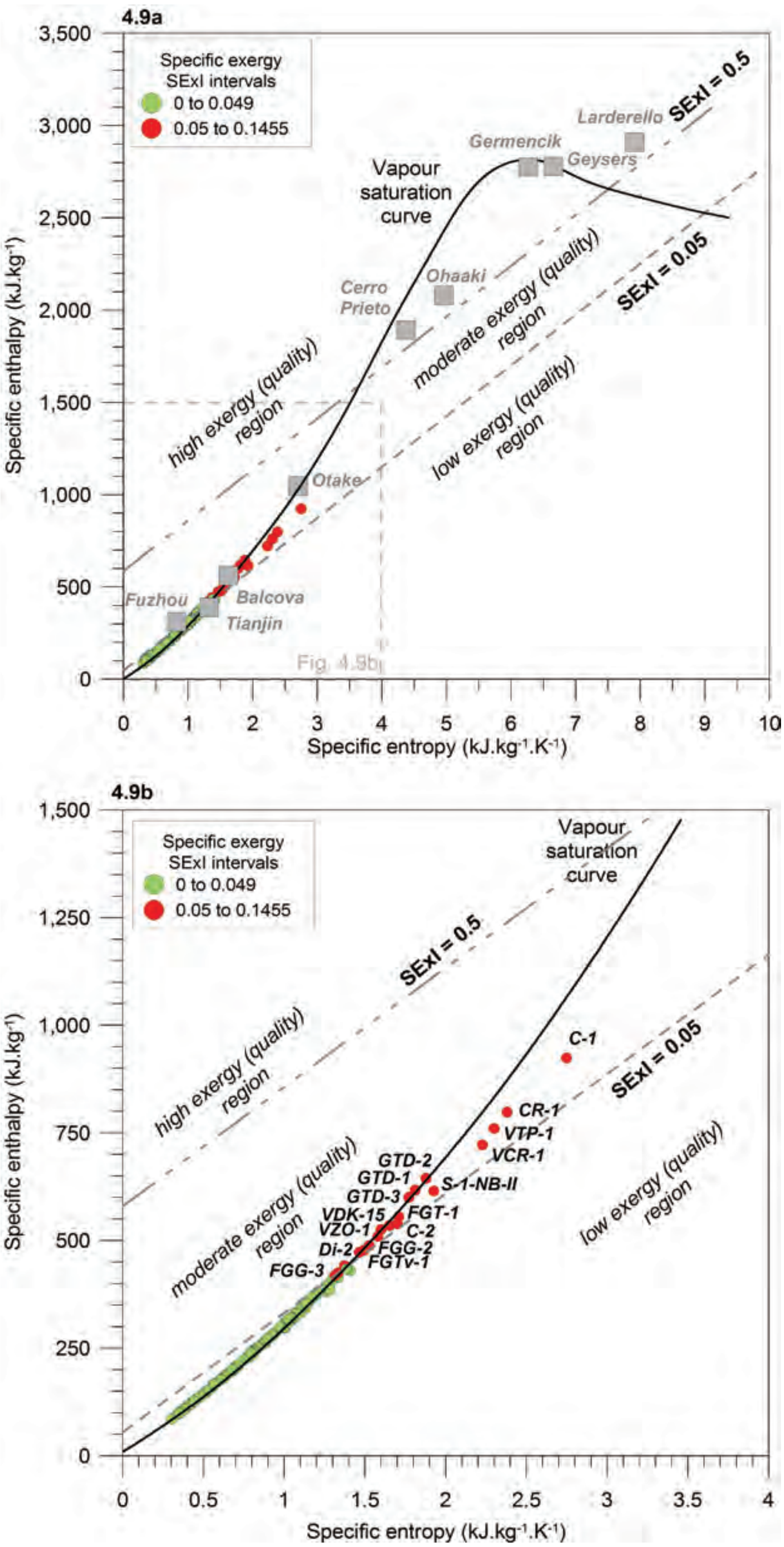

Fig. 4.9 Specific exergy distribution map on a Mollier's diagram in global (up) and detailed (down) perspective

are utilized in cascades, the thermal efficiency rises to $\eta_{th} = 0.03 - 0.95$. We may have pointed to some thermal potential available to increase at Oravice, Koš-Laskár, Chalmová, Vlčany or Bešeňová. Wells implemented into district heating network record a mean thermal efficiency of $\eta_{th} = 0.73 - 0.99$. Wells in Šaľa (GTŠ-1) and Galanta (FGG-1) are reported of $\eta_{th} = 1$, however, this has already been discussed above. A geothermal well of Sereď (SEG-1) operates at $\eta_{th} = 0.98$ in individual setup. Other sites are connected to cascades with recreation and individual space heating.

Thermodynamic (utilization) efficiency

The thermodynamic or utilization efficiency (ε_{ut}) answers rather on how the resource is utilized. With available data, we define the utilization efficiency by relating actually produced exergy rate (Ex_{out}) to the exergy rate available (Ex_{in}) under defined restricted dead-state (8). The produced exergy rate refers to sink conditions (T_{outlet}).

At operated sites, the utilization efficiency varies ε_{ut} = 0.04 – 0.94 with a mean of 0.56. Highest utilization efficiencies have been reached in the Nesvady (ε_{ut} = 0.94), Šaľa (GTŠ-1: ε_{ut} = 0.86) or Sereď (SEG-1: ε_{ut} = 0.86) area, where sink temperatures are of T_{outlet} = 12 – 15 ˚C. An efficiency of wells supplying recreational duties only is ε_{ut} = 0.04 – 0.84, at average of ε_{ut} = 0.49. Sites produced for agriculture record an efficiency of ε_{ut} = 0.42 – 0.94. Apparently, there is some considerable potential to increase in the Tvrdošovce (FGTv-1: ε_{ut} = 0.42) and the Čiližská Radvaň (ČR-1: ε_{ut} = 0.63) areas, where sink temperatures are about T_{outlet} = 20 ˚C and the thermal efficiency is kept below η_{th} = 0.75. Individual space heating as a single network is realized in the Koš-Laskár (ε_{ut} = 0.37) and Chalmová (ε_{ut} = 0.55) only. The Sereď (ε_{ut} = 0.85) and Šaľa (ε_{ut} = 0.86) areas are the only sites where geothermal water supplying a GDHS is not used for other cascaded duties.

We list all efficiencies of utilized geothermal wells in Appendix B. Obviously, both, the utilization (ε_{ut}) and thermal (η_{th}) efficiencies increase with a load or duty. While wells operated for individual purposes reach the annual mean efficiencies of counts η_{th} = 0.08 – 0.98 and ε_{ut} = 0.04 – 0.94, the utilization efficiency of cascaded systems increases, especially for a minimum limit to ε_{ut} = 0.2 – 0.84 with simultaneous increase in thermal efficiency for η_{th} = 0.06 – 0.97.

4.5.2. Improvement potential

Improvement in site operation is a compromise between economics, legal aspects, demand and available potential. Selection of possible sites is usually (amongst basic hydrogeothermal, socio-technical and sustainability studies) grounded by thermal and / or utilization efficiency analysis.

An improvement potential (IP) has been introduced as one of tools to effectively describe limits of operated sites for increasing their productivity. By definition (9), the IP increases with difference between potential (Ex_{in}) and operated (Ex_{out}) exergy. It is then useful in definition of sites where there can be some increase in heat extraction from a source by adopting of new technologies, or sites, where there is still temperature at outlet high enough for improvement. A clear disadvantage of the index is its reliability on initial, restricted dead-state conditions (which is the same problem as for exergy calculation).

We list the IP index of operated wells in Appendix A. By the IP, sites in Dunajská Streda (DS-1: IP = 1.44), Oravice (OZ-2: IP = 0.99), Galanta (FGG-3: IP = 1.09), Bešeňová (FGTB-1: IP = 0.60), Tvrdošovce (FGTv-1: IP = 0.91), or Podhájska (Po-1: IP = 11) appear available for improvement, as η_{th} < 0.70; ε_{ut} < 0.70; T_{outlet} > 25 ˚C. This is, however, an informative parameter requiring detailed exergetic and thermodynamic analysis.

The sustainability index (SI) relates the operation thermodynamics to sustainability (10). The greater is the utilization efficiency, the more energy is actually converted or consumed in a heat production, and, consequently, the less potential for additional "work" is available, increasing the sustainability index. By that, e.g. the Šaľa (FGŠ-1) and Sereď (SEG-1) sites of ε_{ut} > 0.8 and η_{th} > 0.8 give the SI > 7. At these sites, the potential to increase the heat production is significantly lower. In the contrast, the FGG-3 well in Galanta operates at ε_{ut} > 0.7 and η_{th} < 0.5 with SI = 2.55.

4.6. Summary

The territory of the Western Carpathians (Slovakia) has been repeatedly described by temperature or a heat flow distribution. More than 160 exploration and production wells were subjected for temperature or heat flux measurements, tested for a balanced yield or evaluated towards definition of nameplate thermal output (total thermal capacity). Still a general review on explored (and recently available) geothermal resources lacks reports on sustainable reservoir management studies and production thermodynamics.

Geothermal play-types of the Western Carpathians may generally be classified as low-enthalpy where a field enthalpy becomes 137-620 $kJ.kg^{-1}$. The only exception is the Košice Basin, where the field enthalpy in the Ďurkov area consistently exceeds a limit condition of h = 550 $kJ.kg^{-1}$ delineating moderate enthalpy resources. The Danube Basin Central Depression, Vienna Basin, Levoča Basin (NE), Levice Block, Upper Nitra Basin, Horné Strháre-Trenč Graben and the Skorušiná Basin exceed a regional enthalpy average (h_{field} = 328 $kJ.kg^{-1}$). A production enthalpy varies 86 – 924 $kJ.kg^{-1}$. Moderate enthalpy geothermal waters are currently documented in the Ďurkov area, Koš-Laskár, Čiližská Radvaň or Topoľníky, because of sensitivity of enthalpy to TDS possible to skew differences in wellhead temperature. These are the only wells exceeding a specific exergy of e > 70 $kJ.kg^{-1}$ at a regional average of e = 20 $kJ.kg^{-1}$. Under given geothermics and current state of exploration, geothermal plays of the Western Carpathians are all low-quality while reservoir production depth up to 1,500 m. At greater depths, the CDPP, the Košice Basin and the Upper Nitra Basin appear of moderate-low quality, at least within most productive zones. By individual analysis, these sites include 20 wells in total of moderate-low SExI. An onward developing or a search for a new sites should follow an anomaly stacking approach (Cumming, 2009), targeting then shallow Triassic reservoirs for low-duty (recreational) use, whilst Neogene reservoirs at TDS < 2,500 $mg.l^{-1}$ and base at 1,500 – 3,000 m for a high-demand operation in, probably, most profitable scenario. There is, however, a question of deep Triassic reservoirs, available for a high demand use by a natural productivity of carbonates, even at lower thermodynamic quality. In addition, many sites produce geothermal waters from upper Triassic series (e.g. in the Liptov Basin), where existence of deeper, most probably closed reservoirs, cannot be excluded. Extended drilling is, however, a far-long run. Yet drilling deeper does not necessarily comes with higher enthalpy and thermodynamic qualities.

Previously, regional geodynamics, shallow geomorphology and groundwater circulation were concluded as crucial controls on hydrogeothermics of the Western Carpathians (Franko & Melioris, 2000). Reservoir thermodynamics, enthalpy and quality distribution are, moreover, controlled by a TDS content, palaeohydrogeology, formation productivity, and play-type.

By individual analysis, utilization and use indexes (IP, SI, η_{th}, ε_{ut}) increase well where coupled heat production is installed, the more for resources at higher temperature. In regional conditions, the thermal efficiency ranges $\eta_{th} = 0.03 – 0.98$. According to reported data, 21 out of 45 wells were calculated for a thermal efficiency $\eta_{th} > 0.75$. At operated sites, the utilization efficiency is with an interval of $\varepsilon_{ut} = 0.04 – 0.94$ at an average of $\varepsilon_{ut} = 0.56$. Stacking indexes onto (see calculations listed in Appendix B), selection of sites available for production development must then rather be a compromise of: thermal efficiency $\eta_{th} < 0.8$; utilization efficiency $\varepsilon_{ut} < 0.8$; improvement potential IP > 0.5; sustainability index SI < 5; and temperature outlet $T_{outlet} > 20$ ˚C to maintain a gradient between an exhaust and sink conditions. This is, however, only a thermodynamic, or energy potential approach. Obviously, the increase in a heat production at existing sites must simply come with operation economics and investments, demand, technology. Meanwhile, there is (often somewhat) a neglected aspect of reservoir thermal sustainability, which must necessarily be studied, or rather, which principles must simply be adapted into national legislative schemes.

4.4.7. Endnotes

It is a must to accent the conducted study is strictly limited to data available off decades of the research, prospection and development in the country while analysing production thermodynamics (enthalpy, specific exergy, exergy rate, exergy quality), as these are based on previously published input data (wellhead temperature, deliverability, reservoir production part depth, TDS, reservoir stratigraphy), with a last update presented (Remšík, 2012). Obviously, flow (field) analysis results may then vary with new results given by continuous drilling and exploration.

Operation analysis relates to reports given to the Slovak Hydrometeorological Institute as presented on a World Geothermal Congress 2015 (Fendek & Fendeková, 2015). We have already discussed some limitations listed above. Yet the site performance analysis gives an overview on average reported data. A more detailed approach is necessary, as performance indexes vary seasonally, thus a step-by-step time-domain studies must simply come in following. We recommend to use and accept presented data as a baseline.

Geothermal resources of the Western Carpathians may play an indisputable role in a primary energy mix of the country. Even already developed sites provide potential for some increase in a heat generation. There is an enormous potential within the Košice Basin, limited in an interest because of high salinity and scaling potential. By thermodynamic quality, a perspective in geothermal power production restricts to, if any, low-duty binary production only, which is, often, a most challenging problem in socioeconomic issues.

The paper briefly reviews distribution of key thermodynamic parameters of geothermal resources in the Western Carpathians and gives a first approach in analysis of its controls. Authors do believe, that presented thermodynamic database supporting previous characteristics will come profitable in a future R&D in geothermal energy in Slovakia.

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APPENDIX A: THERMODYNAMIC DATABASE - WELLS

Perspective geothermal area	T_{wh}		h_{field} (total)		h_{field} (normalized)		SExI (> 1500 m)		SExI (< 1500 m)	
	°C	class	kJ.kg^{-1}	class	–	class	–	class	–	class
Beša - Čičarovce structure	n/a	low	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Danube Basin Central Depression	28-91	low	398	low	402	low	0.044-0.045	low	0.049-0.07	moderate
Central Slovakian Neogene volcanites - NE	29-57	low	248	low	323	low	0.022-0.033	low	0.033	low
Central Slovakian Neogene volcanites – W,S	25-46	low	157	low	n/a	n/a	0.02	low	n/a	n/a
Dubník Depression	50-75	low	314	low	327	low	0.032	low	0.034	low
Upper Nitra Basin	20-59	low	339	low	446	low	0.048	low	0.07	moderate
Horné Strháre - Trenč Graben	39-35	low	123	low	346	low	0.025	low	n/a	n/a
Humenné Ridge	29-34	low	133	low	n/a	n/a	0.06	low	n/a	n/a
Ilava Basin	22-24	very low	118	low	n/a	n/a	0.005	low	n/a	n/a
Komárno High Block	20-30	very low	253	low	137	low	0.05	low	n/a	n/a
Komárno Marginal Block	42-64	low	241	low	323	low	0.018	low	0.018	low
Komjatice Depression	70-80	low	357	low	n/a	n/a	n/a	n/a	0.039	low
Košice Basin	123-129	moderate	610	moderate	620	moderate	n/a	n/a	0.102	moderate
Levice Block	69-80	low	349	low	350	low	0.037	low	0.04	low
Levoča Basin - NE	31-85	low	356	low	356	low	n/a	n/a	0.039	low
Levoča Basin - W,S	31-62	low	306	low	307	low	0.028	low	0.032	low
Liptov Basin	25-66	low	316	low	326	low	0.024-0.032	low	0.024	low
Lučenec - Rapovce Basin	35-40	low	168	low	168	low	0.009	low	n/a	n/a
Piešťany embayment	20-50	low	190	low	190	low	0.004	low	n/a	n/a
Rimava Basin	20-33	low	120	low	189	low	0.008-0.01	low	n/a	n/a
Skorušiná Basin	28-56	low	392	low	433	low	0.04-0.046	low	n/a	n/a
Topoľčany - Bánovce embayment	20-55	low	259	low	308	low	0.023-0.025	low	0.025-0.028	low
Trenčín Basin	n/a	low	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Trnava embayment	22-24	very low	121	low	121	low	0.05	low	n/a	n/a
Turiec Basin	50-60	low	320	low	320	low	0.029	low	n/a	n/a
Vienna Basin	73-78	low	390	low	390	low	n/a	n/a	0.045	low
Žilina Basin	24-41	low	281	low	305	low	0.019	low	0.038	low

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APPENDIX B: THERMODYNAMIC DATABASE – PERSPECTIVE AREAS

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI (SExI)	η_{th} -	ε_{ut} -	SI -	IP -
Danube Basin Central Depression												
Čilistov, FGČ-1	1,549.00	52.00	Neogene	248.91	0.83	15.90	1.65	0.02	0.97	0.76	4.20	0.09
Čiližská Radvaň, ČR-1	2,430.00	82.00	Neogene	798.57	2.38	125.18	1.20	0.12	0.38	0.64	2.75	0.16
Čiližská Radvaň, VČR-16	1,745.00	64.00	Neogene	721.95	2.23	91.88	1.07	0.10				
Diakovce, Di-1	810.00	38.00	Neogene	382.36	1.26	25.53	0.05	0.03	0.85	0.67	3.03	0.01
Diakovce, Di-2	1,536.00	68.00	Neogene	487.89	1.53	56.48	1.42	0.06	0.79	0.64	2.80	0.18
Diakovce, Di-3	275.00	19.00	Neogene	146.51	0.51	2.64	0.02	*0.01*	1.00	0.39	1.64	0.01
Dunajská Streda, DS-1	2,432.00	91.00	Neogene	525.39	1.60	73.02	7.66	0.07	0.61	0.57	2.30	1.45
Dunajská Streda, DS-2	1,549.00	55.00	Neogene	384.88	1.24	34.76	1.28	0.04	0.83	0.65	2.89	0.15
Dunajský Klátov, VDK-15	2,222.00	74.00	Neogene	534.72	1.65	67.86	2.51	0.07				
Dvory nad Žitavou, FGDŽ-1	1,607.00	62.00	Neogene	357.61	1.15	33.06	0.81	0.04				
Gabčíkovo, FGGa-1	1,926.00	52.00	Neogene	414.63	1.34	37.33	0.41	0.04				
Galanta, FGG-1	1,670.00	62.00	Neogene	363.76	1.17	34.00	1.17	0.04	1.00	0.53	2.13	0.26
Galanta, FGG-2	2,032.00	80.00	Neogene	472.68	1.47	58.51	7.17	0.06	0.85	0.69	3.24	0.68
Galanta, FGG-3	1,999.00	77.00	Neogene	424.57	1.33	48.31	7.13	0.05	0.24	0.61	2.56	1.09
Horná Potôň, FGHP-1	1,804.00	68.00	Neogene	375.23	1.20	37.31	3.51	0.04				
Horná Potôň, VHP-12-R*	1,832.00	68.00	Neogene	383.70	1.22	38.76	3.72	0.04				
Chorvátsky Grob, FGB-1	1,150.00	47.00	Neogene	287.39	0.95	19.78	0.07	0.02				
Chorvátsky Grob, FGB-1/A	299.00	24.00	Neogene	207.19	0.71	6.43	0.01	0.01				
Kráľová pri Senci, FGS-1	570.00	23.00	Neogene	110.41	0.39	1.82	0.00	0.00				
Kráľová pri Senci, FGS-1/A	1,370.00	52.00	Neogene	245.65	0.82	15.49	1.55	0.02				
Lehnice, BL-1	1,455.00	54.00	Neogene	333.61	1.08	27.43	1.40	0.03				
Ňárad (Topoľovec) VTP-11	2,482.00	74.00	Neogene	760.17	2.30	109.43	1.92	0.11				
Nesvady, GN-1	1,494.00	60.00	Neogene	356.92	1.15	32.42	0.25	0.04	1.00	0.94	16.51	0.00
Nové Zámky, GNZ-1	1,473.00	59.00	Neogene	338.80	1.10	29.48	0.42	0.03	0.08	0.85	6.50	0.01
Poľný Kesov, BPK-1	737.00	26.00	Neogene	163.07	0.56	4.71	0.01	0.01				
Poľný Kesov, BPK-2	1,189.00	49.00	Neogene	310.08	1.02	23.02	0.17	0.03				
Rusovce, HGB-1	1,493.00	28.00	Neogene	120.88	0.42	2.51	0.00	0.00				
Senec, BS-1	1,181.00	49.00	Neogene	280.65	0.93	19.45	0.58	0.02	0.61	0.40	16.51	0.00
Sereď, SEG-1	1,800.00	66.00	Neogene	353.26	1.13	33.24	1.36	0.04	0.99	0.86	6.50	0.01

Well, locality	**b_{perf} (m)**	**T_{wh} (°C)**	**Reservoir stratigraphy -**	**h_{wh} $kJ.kg^{-1}$**	**s_{wh} $kJ.kg^{-1}.K^{-1}$**	**e_{wh} $kJ.kg^{-1}$**	**Ex MW**	**SExI (SExI)**	**η_{th} -**	**ε_{ut} -**	**SI -**	**IP -**
Danube Basin Central Depression												
Šaľa, GTŠ-1	1,786	69	Neogene	379.3	1.21	38.25	2.81	0.042	1.00	0.87	7.51	0.050
Šaľa, HTŠ-2	1,169	42	Neogene	266.4	0.89	16.23	0.08	0.020				
Šaľa, HTŠ-3	282	18	Neogene	151.2	0.53	2.54	0.01	0.006				
Šurany, GŠM-1	1,500	49	Neogene	268.0	0.89	17.91	0.19	0.022	0.42	0.22	1.29	0.113
Topoľníky, FGT-1	2,487	74	Neogene	555.2	1.71	71.62	3.62	0.074	0.95	0.83	5.97	0.102
Tvrdošovce, FGTv-1	1,637	70	Neogene	477.8	1.49	55.68	2.78	0.059	0.58	0.43	1.74	0.918
Veľký Meder (Čalovo), Č-1	1,791	79	Neogene	924.1	2.75	146.63	1.61	0.145	0.86	0.73	3.69	0.118
Veľký Meder (Čalovo), Č-2	1,439	57	Neogene	538.8	1.70	57.46	0.94	0.062	0.74	0.60	2.50	0.150
Vlčany, FGV-1	1,852	68	Neogene	487.9	1.53	56.48	1.19	0.060	0.57	0.42	1.72	0.402
Zemianska Oľča, VZO-14	1,839	74	Neogene	509.7	1.58	63.23	1.71	0.066				
Zlaté Klasy – Eliášovce, VZK-10	1,457	65	Neogene	317.4	1.03	27.18	2.82	0.031				
Zlatná na Ostrove, VZO-13	1,625	51	Neogene	241.0	0.80	14.81	0.83	0.019	0.75	0.58	2.36	0.149
Central Slovakian Neogene volcanites – SE part												
Banská Štiavnica, HR-1	829	46	Neogene	261.0	0.87	16.56	0.50	0.021				
Kalinčiakovo, HBV-1	70	25	Triassic	161.1	0.56	4.44	0.11	0.008	0.86	0.31	1.46	0.052
Kalinčiakovo, HBV-2a	49	25	Triassic	161.1	0.56	4.44	0.05	0.008				
Santovka, B-3A	64	26	Neogene	119.4	0.42	2.38	0.21	0.005	0.83	0.31	1.44	0.101
Central Slovakian Neogene volcanites – NW part												
Kremnica, KŠ-1****	531	47	Triassic	311.6	1.02	22.57	0.79	0.027	0.75	0.30	1.44	0.380
Lukavica, LKC-4	851	35	Triassic	386.4	1.28	23.81	0.10	0.030				
Sielnica, KMV-1	407	33	Triassic	177.5	0.61	6.66	0.04	0.010	1.00	0.69	3.18	0.004
Sklené Teplice, ST-4	1,695	57	Triassic	342.4	1.11	29.50	1.23	0.033	0.80	0.67	3.06	0.131
Sklené Teplice, ST-5	1,001	46	Triassic	253.4	0.84	15.69	0.19	0.020				
Topoľčianky, KD-1	500	27	Triassic	127.1	0.44	2.84	0.04	0.005				
Vyhne, H-1	78	36	Triassic	242.5	0.82	12.42	0.07	0.017	0.66	0.44	1.79	0.021
Vyhne, HGV-3	54	29	Triassic	199.3	0.68	7.45	0.04	0.011				
Zlatno, R-3	710	35	Neogene	165.7	0.57	5.91	0.30	0.009				

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} kJ.kg^{-1}	s_{wh} kJ.kg^{-1}.K^{-1}	e_{wh} kJ.kg^{-1}	Ex MW	SExI -	η_{th} -	ε_{ut} -	SI -	IP -
Dubník Depression												
Bruty, VTB-1	1,905	75	Neogene	332.19	1.07	30.57	13.76	0.034				
Svätý Peter, PTG-11	1,321	50	Neogene	246.51	0.82	15.41	0.49	0.019				
Želiezovce, HGŽ-1	234	18	Neogene	99.14	0.35	1.11	0.02	0.003				
Želiezovce, HGŽ-3	900	52	Neogene	239.17	0.80	14.65	0.22	0.018	0.68	0.79	4.82	0.009
Horné Strháre – Trenč Graben												
Dolná Strehová, HGDS-1	615	29	Neogene	296.64	1.00	13.56	0.01	0.019	1	0.70	3.34	0.001
Dolná Strehová, M-4	520	35	Neogene	386.37	1.28	23.81	0.02	0.030				
Slovenské Kľačany, TSK-1	600	38	Neogene	318.56	1.06	19.77	0.03	0.025				
Vinica, HG-18	320	21	Neogene	102.57	0.36	1.42	0.04	0.004	1	0.39	1.64	0.016
Upper Nitra Basin												
Handlová, FGHn-1	430	19	Palaeogene	179.92	0.63	3.67	0.00	0.008				
Handlová, RH-1	1,179	37.5	Palaeozoic	259.70	0.87	14.34	0.23	0.019				
Chalmová, BCH-3	120	39	Triassic	225.00	0.76	11.55	0.11	0.015	1.00	0.54	2.17	0.023
Chalmová, HCH-1	194	33	Triassic	204.75	0.70	8.70	0.15	0.012	0.40	0.55	2.24	0.030
Koš (Laskár), Š-1-NB II	1,851	59	Triassic	615.10	1.93	70.23	1.24	0.074	0.47	0.37	1.59	0.488
Humenné Ridge												
Kaluža, GTH-1	594	34	Triassic	163.07	0.56	5.64	0.05	0.009				
Sobrance, TMS-1	625	29	Neogene	127.37	0.44	2.92	0.14	0.006	0.92	0.56	2.30	0.026
Komárno High Block												
Kravany, FGKr-1	1,021	20	Triassic	136.97	0.48	2.53	0.01	0.005				
Obid, FGO-1	1,000	20	Triassic	136.97	0.48	2.53	0.00	0.005	1.00	0.43	1.75	0.001
Patince, SB-1	160	26	Triassic	194.00	0.67	6.37	0.13	0.010				
Patince, SB-2	146	27	Triassic	202.96	0.69	7.14	0.22	0.011				
Patince, SB-3	167	26	Triassic	194.00	0.67	6.37	0.13	0.010	1.00	0.05	1.05	0.119
Štúrovo, FGŠ-1	210	40	Triassic	321.53	1.06	20.96	1.17	0.026	0.72	0.53	2.11	0.262
Štúrovo, VŠ-1	125	39	Triassic	330.88	1.10	21.39	0.73	0.026				
Virt, vrt JRD	260	26	Triassic	194.00	0.67	6.37	0.03	0.010				
Virt, HVB-1	241	26	Triassic	194.00	0.67	6.37	0.04	0.010	0.72	0.43	1.75	0.015
Virt, vrt VŠE	280	24	Triassic	176.73	0.61	4.99	0.06	0.009	0.99	0.58	2.36	0.011

Well, locality	b_{perf} (m)	T_{wh} (°C)	Reservoir stratigraphy -	h_{wh} $kJ.kg^{-1}$	s_{wh} $kJ.kg^{-1}.K^{-1}$	e_{wh} $kJ.kg^{-1}$	Ex MW	SExI -	η_{th} -	ε_{ut} -	SI -	IP -
Komárno Marginal Block												
Komárno, FGK-1	1,964	64	Triassic	392.91	1.25	39.19	0.38	0.043				
Komárno, M-1	1,221	42	Triassic	237.55	0.79	13.30	0.05	0.017				
Komárno, M-2	1,025	42	Neogene	210.61	0.71	10.56	0.19	0.014				
Komárno, M-3	1,184	51	Triassic	280.18	0.92	19.77	0.31	0.024				
Marcelová, GTM-1	1,761	56	Neogene	237.05	0.79	14.49	7.83	0.018				
Komjatice Depression												
Komjatice, G 1	1,700	78	Neogene	357.29	1.1391	35.513	8.5658	0.0387				
Košice Basin												
Ďurkov, GTD-1	3,155	125	Triassic	616.89	1.81	104.52	175.60	0.102				
Ďurkov, GTD-2***	3,104	129	Triassic	644.49	1.88	113.32	169.99	0.110				
Ďurkov, GTD-3***	2,246	123	Triassic	600.54	1.77	99.53	200.55	0.098				
Košice, G-4	273	26	Triassic	122.18	0.43	2.53	0.06	0.005	1	0.53	2.13	0.012
Šebastovce, KAH-6	149	18	Neogene	86.01	0.30	0.75	0.03	0.003				
Valaliky, KAH-3	171	21	Neogene	108.50	0.38	1.63	0.03	0.004				
Valaliky, KAH-5	148	21	Neogene	152.33	0.53	3.28	0.03	0.007				
Levice Block												
Podhájska, GRP-1*	1,365	69	Triassic	311.60	1.01	26.58	14.29	0.030				
Podhájska, Po-1	1,740	80	Neogene	368.91	1.17	37.93	39.40	0.041	0.71	0.46	1.86	11.344
Levoča Basin – NE part												
Lipany, L-1*****	3,390	85	Triassic	441.62	1.37	53.44	5.02	0.056				
Plavnica, Pl-1	3,360	65	Palaeogene	309.60	1.00	25.93	1.30	0.030				
Plavnica, Pl-2	3,010	53	Palaeogene	240.10	0.80	4.82	0.73	0.018				
Levoča Basin - S, W part												
Arnutovce, HKJ-3	1,133	31	Triassic	185.50	0.63	6.95	0.11	0.010				
Letanovce, HKJ-4	589	25	Triassic	198.68	0.68	6.33	0.03	0.010				
Poprad, PP-1	1,128	48	Triassic	265.32	0.88	17.42	2.99	0.021	1.00	0.80	5.05	0.117
Stará Lesná, FGP-1	2,092	58	Triassic	330.76	1.07	28.07	1.98	0.032				
Veľká Lomnica, GVL-1	2,100	62	Triassic	354.80	1.14	32.63	4.00	0.036				

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Levoča Basin – S, W part												
Veľký Slavkov, VSČ-1	2,353	57	Triassic	315.61	1.03	25.69	2.43	0.030	0.14	0.84	6.12	0.065
Vrbov, Vr-1	1,734	56	Triassic	298.90	0.98	23.13	2.62	0.027	0.64	0.62	2.61	0.384
Vrbov, Vr-2	1,983	59	Triassic	320.38	1.04	26.78	3.53	0.031	0.83	0.84	6.29	0.089
Liptov Basin												
Bešeňová, FBe-1	400	25	Triassic	120.42	0.42	2.39	0.05	0.005	1.00	0.51	2.06	0.011
Bešeňová, FGTB-1	1,814	66	Triassic	407.40	1.29	42.16	4.05	0.046	0.60	0.61	2.57	0.613
Bešeňová, ZGL-1	1,987	62	Triassic	370.73	1.19	35.08	2.84	0.039				
Liptovská Kokava, ZGL-3	2,365	43	Triassic	212.36	0.71	10.85	0.95	0.014				
Liptovský Trnovec, ZGL-2/A	2,486	60	Triassic	316.30	1.03	26.32	3.83	0.030	0.81	0.49	1.96	0.996
Pavčina Lehota, FGL-1	1,570	32	Triassic	298.28	1.00	15.24	0.05	0.021				
Lúčenec Basin/Rapovce structure												
Rapovce, GTL-2	1,439	38	Triassic	167.92	0.57	6.23	0.88	0.009				
Ilava Basin												
Belušské Slatiny, BHS-3	30	22	Triassic	118.55	0.41	2.11	0.02	0.005	1.00	0.46	1.86	0.007
Piešťany embayment												
N. Mesto n. V.-Zel. Voda, GZV-1	1,155	19.4	Triassic	110.46	0.39	1.57	0.02	0.004				
Rimava Basin												
Cakov, BČ-3	874	29	Triassic	133.36	0.46	3.30	0.06	0.006				
Rimavské Janovce, GRS-1	1,008	33	Triassic	189.09	0.64	7.53	0.17	0.011				
Tornaľa, HM-5	158	18	Triassic	96.52	0.34	1.04	0.08	0.003	1.00	0.27	1.37	0.045
Skorušiná Basin												
Oravice, OZ-1	561	28	Triassic	200.29	0.68	7.25	0.20	0.011				
Oravice, OZ-2	1,565	56	Triassic	433.34	1.39	41.94	5.45	0.046	0.03	0.57	2.34	0.992
Topoľčany – Bánovce embayment												
Bánovce n/ Beb., BnB-1	2,025	40	Triassic	343.54	1.13	23.06	0.27	0.028	0.76	0.57	2.32	0.051
Brodzany, HGT-9	139	32	Triassic	188.77	0.64	7.35	0.02	0.011				
Malé Bielice, MB–3	100	40	Palaeogene	279.49	0.93	16.94	0.16	0.021	0.72	0.51	2.04	0.038
Partizánske, FGTz-2	970	33	Triassic	261.81	0.88	12.99	0.11	0.018	0.41	0.73	3.74	0.008
Partizánske, HGTP-1	474	20	Triassic	144.56	0.50	2.79	0.04	0.006				

Well, locality	**b_{perf} (m)**	**T_{wh} (°C)**	**Reservoir stratigraphy -**	**h_{wh} $kJ.kg^{-1}$**	**s_{wh} $kJ.kg^{-1}.K^{-1}$**	**e_{wh} $kJ.kg^{-1}$**	**Ex MW**	**SExI (SExI)**	**η_{th} -**	**ε_{ut} -**	**SI -**	**IP -**
Topoľčany – Bánovce embayment												
Topoľčany, FGTz-1	1,917	55	Triassic	272.01	0.90	19.28	0.23	0.023	0.55	0.31	1.45	0.108
Veľké Bielice, VB-3	90	39	Palaeogene	309.92	1.03	19.43	0.13	0.024	0.60	0.62	2.66	0.018
Trnava embayment												
Koplotovce, KB-1	108	24	Triassic	121.74	0.42	2.39	0.09	0.005				
Turiec Basin												
Turčianske Teplice, TTŠ-1	1,124	54	Triassic	320.67	1.04	25.71	0.80	0.030	0.93	0.74	3.85	0.054
Vienna Basin												
Lakšárska Nová Ves, RGL-1	2,065	78	Neogene	418.55	1.31	47.36	8.05	0.050				
Šaštín-Stráže, RGL-2	2,570	73	Neogene	352.87	1.13	34.21	4.47	0.038				
Žilina Basin												
Kamenná Poruba, RTŠ-1	1,814	41	Triassic	430.56	1.41	32.16	0.22	0.038				
Rajec, RK-22	1,308	26	Triassic	228.02	0.78	8.19	0.09	0.013	0.93	0.21	1.26	0.057
Stráňavy, ŽK-2	550	24	Palaeogene	233.84	0.80	7.68	0.07	0.013	0.65	0.38	1.62	0.026