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Geothermal Energy Utilization In Slovakia: First Insights From Sustainability Perspective

Branislav Fričovský[1], Ladislav Vizi[2], Daniel Marcin[1], Radovan Černák[1], Veronika Blanárová[3], Zuzana Ujjobbágyová[4], Dušan Bodiš[1], Katarína Benková[1], Ondrej Pelech[1] and Klement Fordinál[1],

[1] Dionýz Štúr State institute of Geology, Mlynská dolina 1, 817 04 Bratislava, Slovak Republic

[2] Dionýz Štúr State institute of Geology, Regional branch Košice, Jesenského 8, 040 01 Košice, Slovak Republic

[3] Directorate of Geology and Natural Resources, Ministry of Environment of the Slovak Republic, Bukurešťská 4, 811 04 Bratislava, Slovak Republic

[4] VIA IURIS, Holubyho 37, 902 01 Pezinok, Slovak Republic

branislav.fricovsky@geology.sk and daniel.marcin@geology.sk

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ABSTRACT

Production of geothermal energy is regulated through multiple legal tools, as is the Act No. 569/2007 Coll. (Act on Geology), Act no. 364/2004 Coll. (Act on Water) or Act No. 538/2005 Coll. (the Spa Act); rather with only a little relation to enactments of some effect on promotion of renewables contribution in primary energy generation (e.g. the Act No. 309/2009 Coll.) and their market (e.g. Act No. 521/2012 Coll., Act No. 609/2007 Coll., Act No. 555/2005 Coll. etc.). Although geothermal energy is repeatedly denoted renewable or sustainable energy resource within these texts, there is no legal form controlling energy and thermal potential balance aspects in sustainable use of the resource.

This paper represents tentative results of geothermal reserves booking carried individually on recently delineated geothermal water bodies (GWBs) according to mandatories provided in EU Directive No. 2006/60/ES – the Water Framework Directive (WFD) applying Monte Carlo simulation individually to the USGS volume method combined with recovery factor R_0 definition. The latter combines production efficiency and effective reservoir volume principles on a unified time scale, i.e. t_{prod} = 40 years and t_{prod} = 100 years, with a unified reference temperature of T_{ref} = 15 °C for GWBs without reinjection and T_{inj} = 40 °C for GWBs with considerable reinjection. Then, the concept of resource capacity ratio with several modifications has been used to track GWBs where prolonged production may be questionable, and to assess sustainable thermal potential.

For 31 GWBs, probable reserves are assessed for R_{pb} = 6,716 MWth and R_{pb} = 2,686 MWth respectively, considering short- and long-term balance. For t_{prod} = 40 years, GWBs may be operated at a current mean yearly thermal output (P_{th} = 67.6 MWth). Sustainability is, however, differentiated whether prolonging the production period towards 100 years, or increasing thermal output up to installed capacity at 3 to 10 GWBs respectively. At recent installed capacity (229 MWth), there is likely 1,187 MWth (t_{prod} = 100 years) or 2,750 MWth (t_{prod} = 40 years) developable, if not compromising sustainability of thermal production ($P_{th(S)}$), resulting in the total sustainable thermal potential of $P_{th(S*)}$ = 1,416 MWth and $P_{th(S*)}$ = 2,979 MWth respectively. In fact, the potential is mainly in closed systems of complicated reservoir chemistry, involving reinjection considerations.

1. INTRODUCTION

Utilization of geothermal energy in Slovakia dates back far beyond the Medieval Age. Historical bills document several resorts in 17th to 18th Century utilizing thermal springs, however, the first official reference on a well completed to tap a geothermal water is of 1899 in Kováčová spas, serving the nobility. A complex research, prospection and use of geothermal energy has been underway since the 70's, responding to global concerns on fossil fuel economics.

Any recent enactment answers a question of sustainable reservoir management, when concerning the energy aspect of produced resource. Indeed, the Act No. 569/2007 Coll. (Act on geology) with later amendments obligates execution of 21-days long pumping test to estimate flowrates and hydraulic parameters when reaching for withdrawals provisions. The Technical Standard No. STN 73 6614 (Test of groundwater resources) recommends generation of at least three drawdown stages during the test, including 1 sample each in no longer than a 14 days interval, including periodic monitoring of temperature. Each withdrawal provision is issued by Commission on Groundwater resources and reserves classification by the Ministry of Environment of the Slovak Republic, licensed for 10 years. Prolongation requires, however, regime (now continuous) flowrate measurements, pressure and head logs, including at least two sampling analysis from the previous period, if the operator does not apply for an increase in yield. Following the repeatedly amended Act No. 364/2004 Coll. (Act on water), the operator is obliged to pay for geothermal water withdrawals (Fendek & Fendeková, 2015), not for the energy extraction itself. Obviously, monitoring breakthrough or reservoir changes compromising a concept of sustainable reservoir management for geothermal waters is legislatively vague.

Utilization of geothermal waters in spas with curative effects on a human health is, however, regulated separately. The Act No. 538/2005 Coll. (the Spa Act) entitles the Inspectorate of Spas and springs (ISS) by the Ministry of Health of the Slovak Republic to issue provisions on groundwater withdrawals, individually upscaling objections on qualitative monitoring of produced resource (Božiková & Bodiš, 2016). Moreover, automatized monitoring with direct connection to a general database is already in operation, administered by the ISS. A risk on reservoir depletion is, meanwhile, reduced with extensive protective zones, restricting any other drilling and groundwater production. It is apparent that thermal waters produced in spas are subjected to at least a few regulations meeting principles of sustainable geothermal production management.

2. APPROACH

2.1 Geothermal water bodies: recent delineation and brief characteristics

The entire concept of geothermal water bodies (GWBs) has been introduced to a national scheme with transition towards EU Water Framework Directive (WFD) objections. In recent years 27 geothermal prospective areas have been identified– GPAs (Franko et al., 1995) including their margins (Kullman ml. et al., 2005). As such, these were later adopted in the last Country Update (CU) for Slovakia by Fendek and Fendeková (2015), assessing 6,233 MWth of probable geothermal reserves. The WFD introduction, including new wells, however, leads to: 1) increase in proven reserves for the country – 453 MWth; 2) increase in installed capacity from 136 MWth in 2015 to 229 MWth in 2017 / 2018 while adding new wells into a national geothermal database; 3) redefinition and enlistment of previous and new GWBs; and 4) questioning previous hydrogeothermal assessments carried out on a different scale, using the concept and specifications of GPAs.

According to official submission to the Ministry of Environment of the Slovak Republic, 31 recently defined GWBs cover 36 % of the entire territory (17 638 km^2). A mean geothermal gradient for Slovakia is 30 °C.km^{-1}, while the surface heat flow density varies 50-120 mW.m^{-2} with a mean of 82.1 ± 20 mW.m^{-2} (Bodiš et al., 2018), with local maxima observed along Neogene volcanic mountains and basins (Marcin et al., 2014; Majcin et al., 2017), the latter is a consequence of crustal thinning, a less to vanishing Neogene volcanic activity and distribution of radiogene isotopes in crust. Geotectonic position, deep geological structure (e.g. Schmid et al., 2008, Plašienka, 2018), regional hydrogeothermics (Fendek et al., 1999) and major heat sources (Franko & Melioris, 1999) identify hydrogeothermal systems associated within the GWBs as conduction-dominated orogenic belt / foreland basin play types (Moeck, 2014). The Beša – Čičarovce structure as a part of the Trebišov Depression appears repeatedly as the only exception, possibly classified as the magmatic intrusion type (Moeck & Beardsmore, 2014). Sampled reservoir temperatures reach 25 up to 150 °C (e.g. Vranovská et al., 2015), however, targeted reservoir strata may contain fluids at 180 °C – e.g. in the Košická kotlina Basin and the Ďurkov depression geothermal structure (Fričovský et al., 2018). Reservoir media are, thus, geothermal waters at various degrees of saturation with a gaseous phase and low to moderate-low thermodynamic quality (Fričovský et al., 2016a).

2.2 Booking geothermal reserves

Through last decades, multiple regional hydrogeothermal evaluations on GPAs have been carried. A sound inconsistency has continuously increased, introducing different methods of probable reserves assessment (i.e. heat flux balance for open and USGS volume method for closed systems) or production period scaling (i.e. 30 to 40 years). In calculations, inputs have been usually given arbitrary or set as mean values. No regionally scaled geothermal reserves booking has been performed.

With transition towards a concept of GWBs, there is a need to reassess and unify concept of probable reserves. For such, we turn towards the USGS volume method (1), appropriate for early stages of reservoir evaluation (Sanyal, 2007). The method computes total thermal energy stored in the reservoir H_T as a sum of a heat stored in the rock H_R and associated reservoir fluid H_W (Muffler & Cataldi, 1978), be it a single-phase geothermal water in conditions of geothermal systems of Slovakia, given by area (A), reservoir thickness (Δz), estimated porosity (ϕ), gradient between a reservoir and reference state (T_{res} - T_{ref}) and fluid / matrix properties:

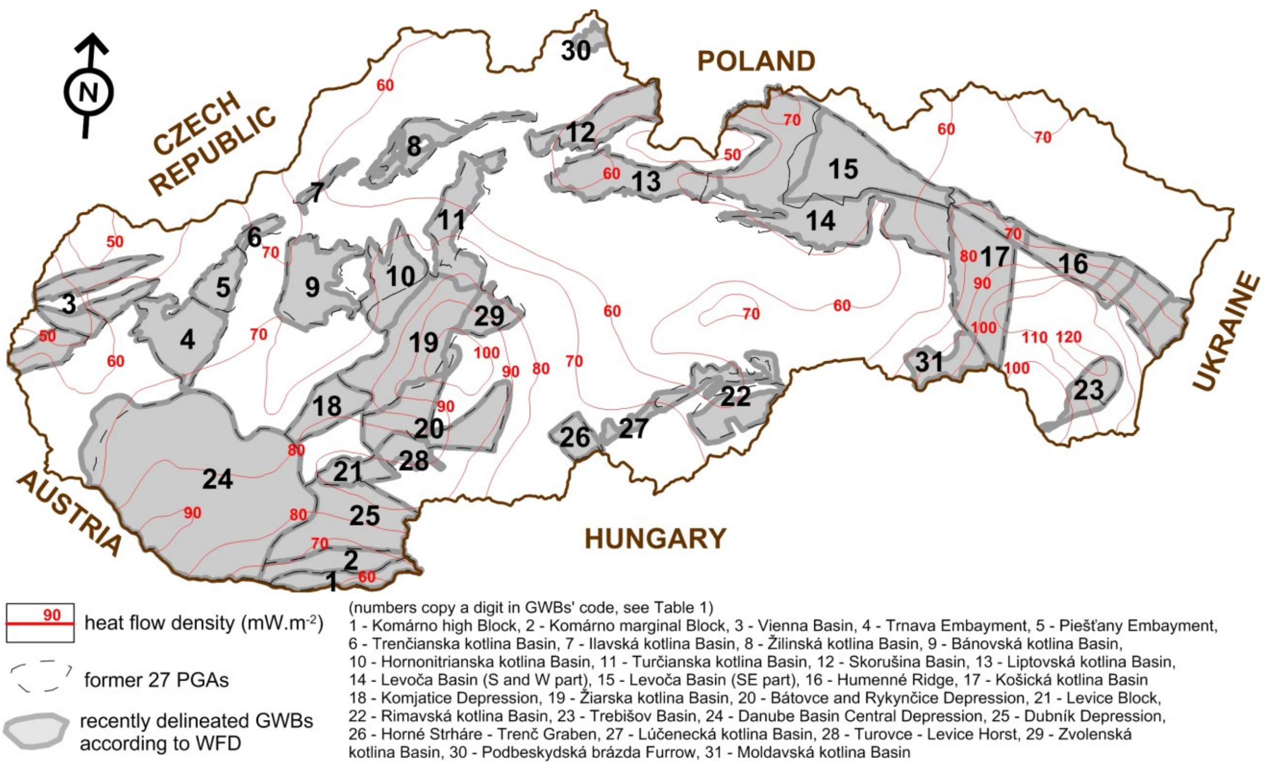

Figure 1: Geothermal Water Bodies in Slovakia: recent delineation and geothermic activity

$$H_T = A.\Delta z.\left[\phi.\rho_w.c_w + (1-\phi).\rho_r.c_r\right].\left(T_{res} - T_{ref}\right) \quad (1)$$

Equation (1) sums not only heat in the reservoir fluid and matrix, but also a heat accumulated and in flow through the reservoir (Axelsson et al., 2005). Apparent simplicity of the method yields, however, a risk of overestimates on a scale of multiples to folds (Grant, 2014) arising when only "representative", i.e. sampled values, are invoked. A critical weakness of the volume method is, then, definition of the recoverable heat (in place) H_0, the part of a heat that can be reasonably exploited (2):

$$H_0 = R_0.H_T \quad (2).$$

Selection of recovery factor R_0 derivation method is of crucial impact on the H_0 assessment, yielding variations by a fold to an order. The energy production efficiency (η_{prod}) approach (3) introduced by Ungemach et al. (2005, 2007, 2009) measures thermal energy produced (Q_{prod}) during a designed period of time (t_{prod}) over that stored in the reservoir ($A.\Delta z$), where γ_f and γ_a stand for thermal capacity of a fluid and reservoir respectively. The R_0 is assessed through a gradient between production ($T_{res} - T_{ref}$) and natural ($T_{res} - T_s$) conditions, using an ambient temperature T_s (4). As designed for doublet production, the method has been applied in GWBs where reinjection is required or recommended due to the absence of natural recharge or geothermal water chemistry:

$$\eta_{prod} = \frac{Q_{prod}}{A.\Delta z}.\frac{\gamma_f}{\gamma_a}.t_{prod} \quad (3)$$

$$R_0 = \eta_{prod}.\frac{T_{res} - T_{ref}}{T_{res} - T_s} \quad (4).$$

The reservoir volume method (e.g. Sanyal & Buttler, 2005) relates coverage of prospective area A_e (e.g. given by heat flux anomaly extension) of the evaluated system over its total territory A_t, including recharge zones where drilling and production of geothermal waters is less plausible. Similarly, the total reservoir thickness Δz represents a maximum thickness of the reservoir, while the effective thickness Δz_e stands for a minimum thickness of the inflow zone (5) and where ϕ is porosity:

$$\varphi_L = \frac{V_e}{V} = \frac{A_e.\Delta z_e.\phi}{A_t.\Delta z_t.\phi} \quad (5).$$

A recoverable energy proportion R_0 (Sanyal & Buttler, 2005; Williams, 2007, 2014) is then given through a ratio of the acceptable rate of reservoir cooling (typically no more than 10 %) and initial thermal gradient (6), i.e. initial reservoir temperature ($T_{r,i}$) to ambient temperature (T_s). Theory beyond this concept allows its use for geothermal water bodies of open hydrogeological character, where natural reservoir recharge realizes at peripheries, usually connected to surrounding hydrogeological massifs.

$$R_0 = \varphi_L \frac{0,9.T_{r,i}}{T_{r,i} - T_s} \quad (6).$$

Approaching the national-scaled booking using a standardized H_T evaluation method and accounting principal distinctions between GWBs in groundwater quality and quantity through individually adjusted R_0 assessment methods appears, at least in an initial stage, more reasonable, than use of two completely different principles.

Geothermal reserves booking application follows the McKelvey's scheme (Muffler & Cataldi, 1978) consequently modified (Clotworthy et al., 2006; Falcone et al., 2013) to address geothermal reserves and resources. Balancing is set for a unified (here desired) period of production, i.e. 40 years (most of initially assessed GPAs) and 100 years to reflect a minimum period of long-term production considered in a concept of sustainable geothermal production (Axelsson et al., 2001). For the purpose of the study, we herein refer to only booking of probable – R_{pb} and proven – R_{pv} reserves, as presented in Sanyal and Sarmiento (2005). Basic formulations according to the cited paper are listed in Table 1, using mode (Md) and respective percentiles (P10, P50, P90) of H_0.

2.3 Modifying the reserve capacity ratio concept

The reserve capacity ratio approach (7) is based on a balance evaluation between the accessible energy stored in reservoir (R_{pb}) and energy available for extraction under designed (R_{pv}) or realistic (P_{th}) conditions. In an original work (Bjarnadottir, 2010), the reserve capacity ratio $r_{cap} = R_{cap} / R_{pb}$ accounts on the reserve capacity $R_{cap} = R_{pb} - R_{pv}$ value over the probable reserves, applied to classify 5 states of reservoir production ranging from sustainable to exploitative. As such, it provides a ratio of energy left in the reservoir at a given certainty level compared to that accessible, accenting the sustainability issue.

Original definition of the reserve capacity ratio, allows introduction of two intuitive concepts. Relating the actual thermal output P_{th} per individual GWB to the booked probable reserves at a corresponding reliability scale (7) yields an assessment of actual sustainability of production – $r_{cap(U)}$. The P_{th} is upscaled as based on the recent country update report submitted to WGC2020 (Fričovský et al., 2020). When installed capacity is substituted $P_{th,inst}$, the analogous procedure provides a rate of event potential to prove without compromising a sustainable production in relation to estimated reserves; may that be a sustainably developable potential – $r_{cap(S)}$ (8). To classify both, we use a 4-scaled classification scheme (e.g. Fričovský et al., 2019). Classification criteria for both, the $r_{cap(U)}$ and $r_{cap(S)}$ are listed in Table 2:

$$r_{cap(U)} = \frac{R_{cap}}{R_{pb}} = \frac{R_{pb} - P_{th}}{R_{pb}} \quad (7)$$

$$r_{cap(S)} = \frac{P_{th(r_{cap(U)}=0.5)} - P_{th,inst}}{P_{th(r_{cap(U)}=0.5)}} \quad (8).$$

Table 1: Review on concept of geothermal reserves and resources booking. Modified after: Sanyal and Sarmiento (2005).

Class	Definition	Computation
Geothermal resources	Energy accumulated in the reservoir, accessible for near-future economical and legal extraction, less than 100 years	$RS_T = \frac{\mathrm{P10}(H_T) - \mathrm{P10}(H_0)}{t_{prod}}$
Inferred reserves	Part of energy and a resource accumulated in the reservoir that is soundly indicated by analogy with other geothermal systems at comparable conditions, however, susceptible to a robust re-evaluation when additional exploration is carried	$R_{\inf} = \frac{\mathrm{P10}(H_0) - \mathrm{Md}(H_0)}{t_{prod}}$ if $\mathrm{Md}(H_0) < \mathrm{P50}(H_0)$ $R_{\inf} = \frac{\mathrm{P10}(H_0) - \mathrm{P50}(H_0)}{t_{prod}}$ if $\mathrm{Md}(H_0) > \mathrm{P50}(H_0)$
Probable reserves	Part of energy and a resource accumulated in the reservoir that is indicated by both, the direct and indirect manifestations, and relevant results from geophysical, geochemical and numerical modeling. A change of re-evaluation with additional exploration carried is significantly less than that by inferred reserves.	$R_{pb} = \frac{\mathrm{Md}(H_0) - \mathrm{P90}(H_0)}{t_{prod}}$ if $\mathrm{Md}(H_0) < \mathrm{P50}(H_0)$ $R_{pb} = \frac{\mathrm{P50}(H_0) - \mathrm{P90}(H_0)}{t_{prod}}$ if $\mathrm{Md}(H_0) > \mathrm{P50}(H_0)$
Proven reserves	Part of energy and a resource accumulated in the reservoir that is successfully proven and sampled through realized wells. Proven reserves represent installed or online capacity of geothermal fields. Probability of re-calibration after carrying another stages of exploration is relatively weak.	$R_{pv} = \frac{\mathrm{P90}(H_0)}{t_{prod}}$

Table 2: Reserve capacity ratio approach: modified sustainable production (U) and developable potential (S) scheme.

Sustainability of production			Sustainably developable potential		
Class	Definition	$r_{cap(U)}$ range	Class	Definition	$r_{cap(S)}$ range
Intense reservoir depletion	Massive overexploitation of the system. The P_{th} exceeds probable reserves at a high risk of collapse.	$r_{cap(U)} < 0$	No developable capacity	Recent nameplate capacity at a particular GWB exceeds the sustainable reserve capacity, no other development is recommended.	$r_{cap(S)} < 0$
Reservoir depletion	Overexploitation of the system. Up to all of the probable reserves are utilized, increasing a risk of a collapse. No capacity for increased production.	$r_{cap(U)} = 0 - 0.5$	Uncertain developable capacity	Nameplate capacity is close to the sustainable reserve capacity, any development at a site may probably compromise a rate of sustainable production.	$r_{cap(S)} = 0 - 0.5$
Sustainable production	Sustainable use of the system. Up to a half of probable reserves are utilized. A system is capable to operate for a desired production period with only a weak risk of collapse.	$r_{cap(U)} = 0.5 - 0.75$	Limited developable sustainable capacity	Sustainable capacity is higher than actual installed output. Up to a half of a recent capacity may be installed, posing only a weak risk on sustainable production, or production may be considered safe for prolonged period.	$r_{cap(S)} = 0.5 - 0.75$
Well sustainable production	Sustainable use of the system. A system may be left for prolonged production or there is a potential for doubling geothermal production at a site	$r_{cap(U)} > 0.75$	Well developable sustainable capacity	Installed capacity may increase twice not compromising sustainable production, or the design period is likely to prolong twice without significant risks on geothermal resource qualitative sustainability.	$r_{cap(S)} > 0.75$

3. INSIGHTS ON GEOTHERMAL PRODUCTION SUSTAINABILITY – TENTATIVE RESULTS

3.1 Booking geothermal reserves – preliminary results

The booking has been carried on a national scheme. Because of a short-place, we will not deliver review on instant formulation of inputs per GWB. When compared to previous hydrogeothermal assessments, booking unifies the designed period of production for every GWB, and sets the reference temperature to 15 °C for systems not requiring reinjection and 40 °C for the rest. To note, reinjection is considered at GWBs where chemistry of geothermal waters restrains disposal into surface recipients after cooling to a reference temperature or where closed hydrogeological system limits natural recharge.

Use of Monte Carlo simulation in USGS volume method application on all 31 GWBs yields a cumulative total heat potential of $H_{T(P50)}$ = 227 EJ and $H_{T(P90)}$ = 72 EJ respectively. Introducing the recovery factor calculated individually for each GWB, the total heat in place for GWBs at a given level of confidence are $H_{0(P50)}$ = 12.4 EJ, $H_{0(Md)}$ = 6.4 EJ and $H_{0(P90)}$ = 3.9 EJ. The recovery factor varied R_0 = 0.02 – 0.11. Based on selected methods, there has been higher R_0 calculated for systems with reinjection. The discrepancy is due to a large difference between the effective and total reservoir volume, restrained based on local heat flux / temperature highs, accessibility and vertical reservoir stratification in open-type systems.

Previous works assessed probable reserves for 27 PGAs as 6,233 MWth (e.g. Remšík, 2012). The number may, however, be questioned, because total areal coverage of GWBs increased, including new ones; studies used different reference temperatures at same conditions without reasonable scaling. The balanced period varied and typically only mean values have been substituted into equations. Balancing equations listed in Table 1 for t_{prod} = 40 years and t_{prod} = 100 years yields cumulative probable reserves assessed for all 31 GWBs equal to R_{pb} = 6,716 MWth and R_{pb} = 2,686 MWth respectively, at a 50 % confidence level according to the IDF. This counts for an 8 % increase in probable reserves compared to previous assessments. That may be reasonable because of change in methodology, unified balancing, increased total areal coverage of GWBs, etc. Some contribution, however, may be subjected to a level of probability the booking scheme defines assessment of probable reserves. Obviously, where $H_{0(PX)}/t_{prod} > R_{pb}$, the IDF curve is soundly skewed left, and the Md < P50. A Monte Carlo simulation has, thus, reflected disproportion between total and effective reservoir volume, or temperature distribution. A fact that simulated $R_{pb} + H_{0(P90)}/t_{prod}$ for t_{prod} = 40 years is always greater than R_{pv} referred in the WGC2020 CU increases reliability of the carried simulation, as exactly proven thermal capacity does not exceed the assumed thermal potential, however close some estimates come.

Table 3: Tentative geothermal reserves booking. Results from Monte Carlo simulations.

GWB name	R_{pb} (GPAs)$^{++}$	R_{pb} (t_{prod} = 40 yrs)	R_{pb} (t_{prod} = 100 yrs)	R_{pv} **
	MWth	MWth	MWth	MWth
Komárno high Block $^{+}$	9.7	5.6	2.3	19.21
Komárno marginal Block	227.5	266	106.4	3.13
Vienna Basin *	511	557.5	223	9.5
Trnava Embayment $^{+}$	33.5	116.5	46.6	0.55
Piešťany Embayment $^{+}$	10.5	28	11.2	19.4
Trenčianska kotlina Basin $^{+}$	4.6	3.4	1.4	0
Ilavská kotlina Basin $^{+}$	1.1	5.2	2.1	2.92
Žilinská kotlina Basin $^{+}$	13.2	12.1	4.8	6.28
Bánovská kotlina Basin $^{+}$	12.5	43.6	17.4	5.26
Hornonitrianska kotlina Basin $^{+}$	29.12	76.5	30.6	14.27
Turčianska kotlina Basin $^{+}$	22.5	79.4	31.8	10.77
Skorušina Basin $^{+}$	24	81.9	32.8	18.29
Liptovská kotlina Basin $^{+}$	34.6	132.5	53	26.26
Levoča Basin (W and S part) $^{+}$	75.4	202.8	81.1	35.16
Levoča Basin (NE part) $^{+}$	1316	786.9	314.7	16.18
Humenné Ridge *	750.5	588.4	235.3	0.66
Košická kotlina Basin *	1276.4	877.8	351.1	78.22
Komjatice Depression *	392.6	190.8	76.3	2.5
Žiarska kotlina Basin $^{+}$	n/a	171.3	68.5	10.49
Bátovce and Rykynčice Depression $^{+}$	n/a	16.5	6.6	1.62
Levice Block *	126	63.4	25.4	20.74
Rimavská kotlina Basin $^{+}$	21	48.9	19.6	1.76
Trebišov Basin *	n/a	702.6	281	2.1
Danube Basin Central Depression $^{+}$	150	194.1	77.6	106.8
Dubník Depression *	808.3	1359.2	543.7	3.7
Horné Strháre – Trenč Graben $^{+}$	6.2	8.4	3.4	1.82
Lúčenecká kotlina Basin $^{+}$	n/a	1.2	0.5	1.04
Turovce – Levice Horst $^{+}$	n/a	9.1	3.6	3.95
Zvolenská kotlina Basin $^{+}$	n/a	10	4	13.88
Podbeskydská brázda Furrow $^{+}$	n/a	5.3	2.1	0.06
Moldavská kotlina Basin $^{+}$	n/a	71.2	28.5	0.66

* use of reinjection systems is recommended (T_{inj} = 40 °C); $^{+}$ open geothermal systems (T_{ref} = 15 °C); $^{++}$ comparable where GWB corresponds to GPA (neglecting change in areal coverage; Remšík, 2012), ** R_{pv} in CU for WGC2020 (Fričovský et al., 2020)

3.2 Current geothermal energy use in Slovakia

The most recent CU for Slovakia presented at the WGC2020 (Fričovský et al., 2020) reports 236 wells proving 437 MWth of geothermal reserves at a Q = 2,716 $l.s^{-1}$ referenced to T_{ref} = 15 °C, including wells utilized in spas with curative effect on human health administered by the ISS (many of these went absent in previous CUs; e.g. Fendek and Fendeková, 2015). According to available data (geothermal database; reports to the Slovak Hydrometeorological Institute provided by producers), 114 wells were operated, i.e. 48 % of all at 74 sites. The overall installed capacity has been calculated for 229 MWth (52 % of proven reserves), with cumulative yearly mean thermal output of 67 MWth produced from 16.7 .10^6 m^3 of geothermal fluids at a mean yield of 570 $l.s^{-1}$. Some geothermal installation is available at 24 of 31 GWBs.

3.3 Short-term considerations: t_{prod} = 40 years

According to (7), recent geothermal energy utilization may be considered somewhat sustainable (Table 4) as the $r_{cap(U)} = 0.59 – 0.99$ for each of GWB when balanced for t_{prod} = 40 years. Balancing reserve capacity ratio to the total GWB shows that even for GWBs with multiple installations and a real thermal output higher than 5 MWth there is a weak risk of compromising sustainable use of the available potential (e.g. Piešťany Embayment), or production appears available for prolonging or doubling due to $r_{cap(U)} > 0.75$ (e.g. the Liptov Basin, Levoča Basin – W and S part or Danube Basin Central Depression - DBCD) while maintaining the desired t_{prod} = 40 years. The situation differs considering operation at a full (nameplate) capacity ($r_{cap(U)}^*$), substituting installed output $P_{th,inst}$ into (7) instead of that actual (P_{th}). Although the majority of GWBs fits the sustainable class, production longevity might appear questionable for some ($r_{cap(U)}^* < 0.5$). An example is the Piešťany Embayment (PEM) with the most famous spa resort in the country, and where a new recreation site is set to launch in the near future, almost next-door to that already existing. A negative $r_{cap(U)}^*$ calculated for the Komárno High Block (KHB) is also considerable, as the GWB associates transboundary aquifer with Hungary, opting for a cautious operation management, all the more the recharge zone located in Magas – Gerecsei Mts. (Hungary). However, the KHB is recently subjected to a joint hydrogeothermal evaluation along with the Komárno marginal block, so that new data supporting a conceptual site model entering the USGS-based geothermal reserves booking may slightly modify the estimate.

Obviously, the $r_{cap(U)}^*$ correlates well with the $r_{cap(S)}$ – see (8) for definition. Where sustainability at nameplate production is compromised ($r_{cap(U)}^* < 0.5$), there is uncertainty, or rather no capacity developable under sustainable conditions at a given booking confidence ($r_{cap(S)} < 0.5$), and so that $P_{th}^+ = 0$ as quantification of potential available for sustainable development. Therefore, at sites, where $r_{cap(S)}$ merges to zero, any further development shall be considered. Instead, focus shall be paid to GWBs with $r_{cap(S)}$ greater than 0.75, where even corrections in booking and probabilistic assessment will not change the potential instantly.

Table 4: Reserve capacity ratio approach: balances for t_{prod} = 40 years.

GWB name	R_{pv}	P_{th}	$P_{th,inst}$	$P_{th(rcap=0.5)}$	$r_{cap(U)}$	$r_{cap(U)}^*$	$r_{cap(S)}$	P_{th}^+
	MWth	MWth	MWth	MWth	-	-	-	MWth
Komárno high Block	19.21	2.16	16.4	2.8	0.61	-1.93	-4.86	0
Komárno marginal Block	3.13	0	0	133	n/a	n/a	n/a	n/a
Vienna Basin	9.5	0	0	278.75	n/a	n/a	n/a	n/a
Trnava Embayment	0.55	0.06	0.55	58.25	0.99	0.99	0.99	57.7
Piešťany Embayment	19.4	11.4	14.94	14	0.59	0.47	-0.07	0
Trenčianska kotlina Basin	0	0	0	1.7	n/a	n/a	n/a	n/a
Ilavská kotlina Basin	2.92	1.35	2.01	2.6	0.74	0.61	0.23	0.59
Žilinská kotlina Basin	6.28	0.68	3.2	6.05	0.94	0.74	0.47	2.85
Bánovská kotlina Basin	5.26	0.59	3.04	21.8	0.99	0.93	0.86	18.76
Hornonitrianska kotlina Basin	14.27	2.96	10	38.25	0.96	0.87	0.74	28.25
Turčianska kotlina Basin	10.77	0.73	1.53	39.7	0.99	0.98	0.96	38.17
Skorušina Basin	18.29	0.71	17.2	40.95	0.99	0.79	0.58	23.75
Liptovská kotlina Basin	26.26	7.63	20.12	66.25	0.94	0.85	0.7	46.13
Levoča Basin (W and S part)	35.16	9.32	24.84	101.4	0.95	0.88	0.76	76.56
Levoča Basin (NE part)	16.18	0	0	393.45	n/a	n/a	n/a	n/a
Humenné Ridge	0.66	0.2	0.41	294.2	0.99	0.99	0.99	293.79
Košická kotlina Basin	78.22	0	0	438.9	n/a	n/a	n/a	n/a
Komjatice Depression	2.5	0	0	95.4	n/a	n/a	n/a	n/a
Žiarska kotlina Basin	10.49	2.36	8.68	85.65	0.99	0.95	0.9	76.97
Bátovce and Rykynčice Depression	1.62	0	0	8.25	n/a	n/a	n/a	n/a
Levice Block	20.74	1.61	14.42	31.7	0.97	0.77	0.55	17.28
Rimavská kotlina Basin	1.76	0.37	1.01	24.45	0.99	0.98	0.96	23.44
Trebišov Basin	2.1	0.41	0.58	351.3	0.99	0.99	0.99	350.72
Danube Basin Central Depression	106.8	21.17	79.49	97.05	0.89	0.59	0.18	17.56
Dubník Depression	3.7	2.09	2.4	679.6	0.99	0.99	0.99	677.2
Horné Strháre – Trenč Graben	1.82	0.28	0.59	4.2	0.97	0.93	0.86	3.61
Lúčenecká kotlina Basin	1.04	0.26	1.04	0.6	0.78	0.13	-0.73	0
Turovce – Levice Horst	3.95	0.45	2.74	4.55	0.95	0.7	0.4	1.81
Zvolenská kotlina Basin	13.88	0.84	4.2	5	0.92	0.58	0.16	0.8
Podbeskydská brázda Furrow	0.06	0	0	2.65	n/a	n/a	n/a	n/a
Moldavská kotlina Basin	0.66	0	0	35.6	n/a	n/a	n/a	n/a

* $P_{th}^+ = P_{th(rcap=0.5)} – P_{th}$ (MWth)

3.4 Long-term considerations: t_{prod} = 100 years

Considerable credits have been addressed to the sustainable geothermal utilization definition (Axelsson et al., 2001), providing a sound debate on how renewability of a resource and sustainability of its use differ (Axelsson et al., 2004, 2005). In Slovakia, the geothermal energy is repeatedly credited as sustainable or renewable, both still usually mixed together. Legislation recognizes them both, yet little attention is paid to their evaluation. However, in an attempt to tentatively assess thermal potential of geothermal resources on a long-term scale, we subjected the booking scheme towards prolonged balanced period t_{prod} = 100 years. As discussed in Axelsson (2011), it appears a compromise between what the reasonable time scale for predicting societal development is and whatever sustainable development (e.g. Chichilniski, 1997; Nel & Cooper, 2009) means. Obviously, prolonging the production period used to balance the renewable heat in place H_0 means the R_{pb} and R_{cap} will drop and so $R_{pv(rcap=0.5)}$ will work, decreasing $r_{cap(U)}$, $r_{cap(U)}^*$, $r_{cap(S)}$, P_{th}^+ and $P_{th(S)}$ ($P_{th(S)} = P_{th}^+ + P_{th}^{++}$) subsequently (Table 5).

When focused on current yearly mean thermal output of wells producing in GWBs, long-term sustainability appears questionable ($r_{cap(U)}$ = 0 to 0.5) or compromised ($r_{cap(U)}$ < 0) for the KHB, previously discussed PEM, Ilavská kotlina Basin (IKB) and the Lúčenecká kotlina Basin. Low $r_{cap(U)}$ = 0.36 at IKB is for the foreseeable future an issue for consideration, and the score may change with upscaling the conceptual model and booking. Some focus is even more important as geothermal waters are also produced for curative spas and fishery. In terms of resource quality preservation, negative $r_{cap(U)}$ for PEM is negligible, with questionable longevity of intense resource production, for the Piešťany Spa and so for the planned project at the site.

The number of GWBs where long-term sustainability and the reserve capacity aspect is limited or questionable increases in the study when a nameplate capacity of existing wells is included. Together 10 of 22 GWBs reach $r_{cap(U)}^*$ < 0.5 (Table 5). Amongst, the Žilinská kotlina Basin involves 3 different sites including 1 curative spa and 3 recreation resorts and the Zvolenská kotlina Basin, where 2 important spas are located. Indeed, these are of more interest for preservation. If producing at a nameplate capacity, the DBCD containing a highest number of sites (25), including those for individual (5) and district heating (4), recreation (6) and greenhousing (10) is at $r_{cap(U)}^*$ = -0.02, so that the long-term intense operation turns questionable. Here we point out that the H_0/t_{prod} for the DBCD is even greater than previously assumed, i.e. R_{pb} = 194 MWth compared to R_{pb} = 150 by Remšík (2012).

As based on the concept above, the rate of sustainability according to $r_{cap(U)}^*$ drops also for the Levice Block with the Podhájska resort, operated as only using reinjection in the country, producing marinogene geothermal waters for heating and pools. Although, comparison to previous assessment (Remšík, 2012) shows drop by a half in R_{pb} using the MC simulation (Tab. 3). The Skorušiná basin, a transboundary aquifer with Poland, may also be questioned in sustainability considering operation at full capacity.

Table 5: Reserve capacity ratio approach: balances for t_{prod} = 100 years.

GWB name	R_{pv}	P_{th}	$P_{th,inst}$	$P_{th(rcap=0.5)}$	$r_{cap(U)}$	$r_{cap(U)}^*$	$r_{cap(S)}$	P_{th}^+
	MWth	MWth	MWth	MWth	-	-	-	MWth
Komárno high Block	19.21	2.16	16.4	1.15	0.06	-6.13	-13.26	0
Komárno marginal Block	3.13	0	0	53.2	n/a	n/a	n/a	n/a
Vienna Basin	9.5	0	0	111.5	n/a	n/a	n/a	n/a
Trnava Embayment	0.55	0.06	0.55	23.3	0.99	0.99	0.98	22.75
Piešťany Embayment	19.4	11.4	14.94	5.6	-0.02	-0.33	-1.67	0
Trenčianska kotlina Basin	0	0	0	0.7	n/a	n/a	n/a	n/a
Ilavská kotlina Basin	2.92	1.35	2.01	1.05	0.36	0.04	-0.91	0
Žilinská kotlina Basin	6.28	0.68	3.2	2.4	0.86	0.33	-0.33	0
Bánovská kotlina Basin	5.26	0.59	3.04	8.7	0.97	0.83	0.65	5.66
Hornonitrianska kotlina Basin	14.27	2.96	10	15.3	0.9	0.67	0.35	5.3
Turčianska kotlina Basin	10.77	0.73	1.53	15.9	0.98	0.95	0.9	14.37
Skorušina Basin	18.29	0.71	17.2	16.4	0.98	0.48	-0.05	0
Liptovská kotlina Basin	26.26	7.63	20.12	26.5	0.86	0.62	0.24	6.38
Levoča Basin (W and S part)	35.16	9.32	24.84	40.55	0.89	0.69	0.39	15.71
Levoča Basin (NE part)	16.18	0	0	157.35	n/a	n/a	n/a	n/a
Humenné Ridge	0.66	0.2	0.41	117.65	0.99	0.99	0.99	117.24
Košická kotlina Basin	78.22	0	0	175.55	n/a	n/a	n/a	n/a
Komjatice Depression	2.5	0	0	38.15	n/a	n/a	n/a	n/a
Žiarska kotlina Basin	10.49	2.36	8.68	34.25	0.97	0.87	0.75	25.57
Bátovce and Rykynčice Depression	1.62	0	0	3.3	n/a	n/a	n/a	n/a
Levice Block	20.74	1.61	14.42	12.7	0.94	0.43	-0.14	0
Rimavská kotlina Basin	1.76	0.37	1.01	9.8	0.98	0.95	0.9	8.79
Trebišov Basin	2.1	0.41	0.58	140.5	0.99	0.99	0.99	139.92
Danube Basin Central Depression	106.8	21.17	79.49	38.8	0.73	-0.02	-1.05	0
Dubník Depression	3.7	2.09	2.4	271.85	0.99	0.99	0.99	269.45
Horné Strháre – Trenč Graben	1.82	0.28	0.59	1.7	0.92	0.83	0.65	1.11
Lúčenecká kotlina Basin	1.04	0.26	1.04	0.25	0.48	-1.08	-3.16	0
Turovce – Levice Horst	3.95	0.45	2.74	1.8	0.88	0.24	-0.52	0
Zvolenská kotlina Basin	13.88	0.84	4.2	2	0.79	-0.05	-1.1	0
Podbeskydská brázda Furrow	0.06	0	0	1.05	n/a	n/a	n/a	n/a
Moldavská kotlina Basin	0.66	0	0	14.25	n/a	n/a	n/a	0

3.5 Estimate on sustainable potential for development

After (8), the proportion of potential developable under sustainable conditions with given reserve capacity may be estimated, yielding the $r_{cap(S)}$. There is a weak or no potential for development where $r_{cap(U)}^*$ is less than 0.5, as even a full operation at installed capacity may compromise longevity of the resource production (in terms of energy). More realistic quantification of the potential, is, thus, found combining the $P_{th}^+ = P_{th(rcap=0.5)} - P_{th}$ for GWBs already produced with $P_{th}^{++} = 0.5xR_{pb}$ for systems, where production is not yet opened. This is because $P_{th(rcap = 0.5)} = 0.5xR_{pb}$ from (7). After substitution, the sustainable potential for development may be tentatively assessed as $P_{th(S)} = P_{th}^+ + P_{th}^{++}$, with the limiting factor of $r_{cap(U)}^* \geq 0.5$. Both are listed in Tables 4 to 5 above at a given production longevity balance. Because the P_{th}^+ is based on installed capacity assumed to operate, the total sustainable potential can then be formulated as $P_{th(S^*)} = P_{th,inst} + P_{th(S)}$. We do, however, keep in mind this is only a rough estimate, based on balancing available data from still reconstructed geothermal database and geothermal reserves booking at its preliminary stage.

For the short-term considerations, where t_{prod} = 40 years, the estimate of sustainable potential for development is $P_{th(S)}$ = 2,750 MWth at a critical level of $r_{cap(U)*}$ =0.5. The number, thus, represents thermal potential that can be proven and installed through the entire country (at existing GWBs) without compromising reserves balance in the system during production. As long as installed capacity is $P_{th,inst}$ = 229 MWth, the sustainable thermal energy potential of geothermal waters associated with 31 GWBs in Slovakia is estimated $P_{th(S^*)}$ = 2,979 MWth, still balanced to t_{prod} = 40 years. Increase in the desired period of production towards the concept of sustainable geothermal production (following the energy aspect again), so that the t_{prod} = 100 years, causes an obvious decrease in both, the potential for development and sustainable potential, as the balanced capacity drops. According to data available in Table 5, subtracting those of $r_{cap(U)}^* < 0.5$, the $P_{th(S)}$ = 1,187 MWth. Adding $P_{th,inst}$ = 229 MWth yields $P_{th(S^*)}$ = 1,416 MWth available to be produced during the t_{prod} = 100 years at a weak risk of thermal (energy) reservoir depletion. Again, this is a tentative assumption, as for the short-term period.

Read from Table 4 to 5, the potential for development is distributed unevenly in the country. Whether for a short-term or a long-term production, the vast majority of $P_{th(S)}$ associates with systems assumed to produce using reinjection, such is the Vienna Basin (not produced), NE part of the Levoča Basin (soon to got installed with 1 site), the Humenné Ridge (1 site under production), Trebišov Basin (1 site) and the Dubník Depression (1 site) – depicted on Figure 3. Indeed, these represent 79 % (t_{prod} = 40 years) to 82 % (t_{prod} = 100 years) of potential likely not compromising sustainability. Listed systems do, however, relate to zones of crustal thinning in the Western Carpathians (Slovakia) that increases local geothermic activity; ceasing thermal increment from volcanism in Neogene; and/or associate reservoirs related to great depths, high content of radioactive elements, low permeability, including reservoir fluids of high T.D.S. or high scaling/corrosion potential, so that an extensive production may be challenging. Although quantification of P_{th}^+ or P_{th}^{++} points on GWBs a research and prospection in the country should focus on, more attention would be, realistically, paid to GWBs where production of geothermal waters is already proven high and safe according to recent state of monitoring, such are systems in Mesozoic (Mid Triassic) carbonates containing reservoir media of acceptable chemistry, nevertheless of considerably lower temperature.

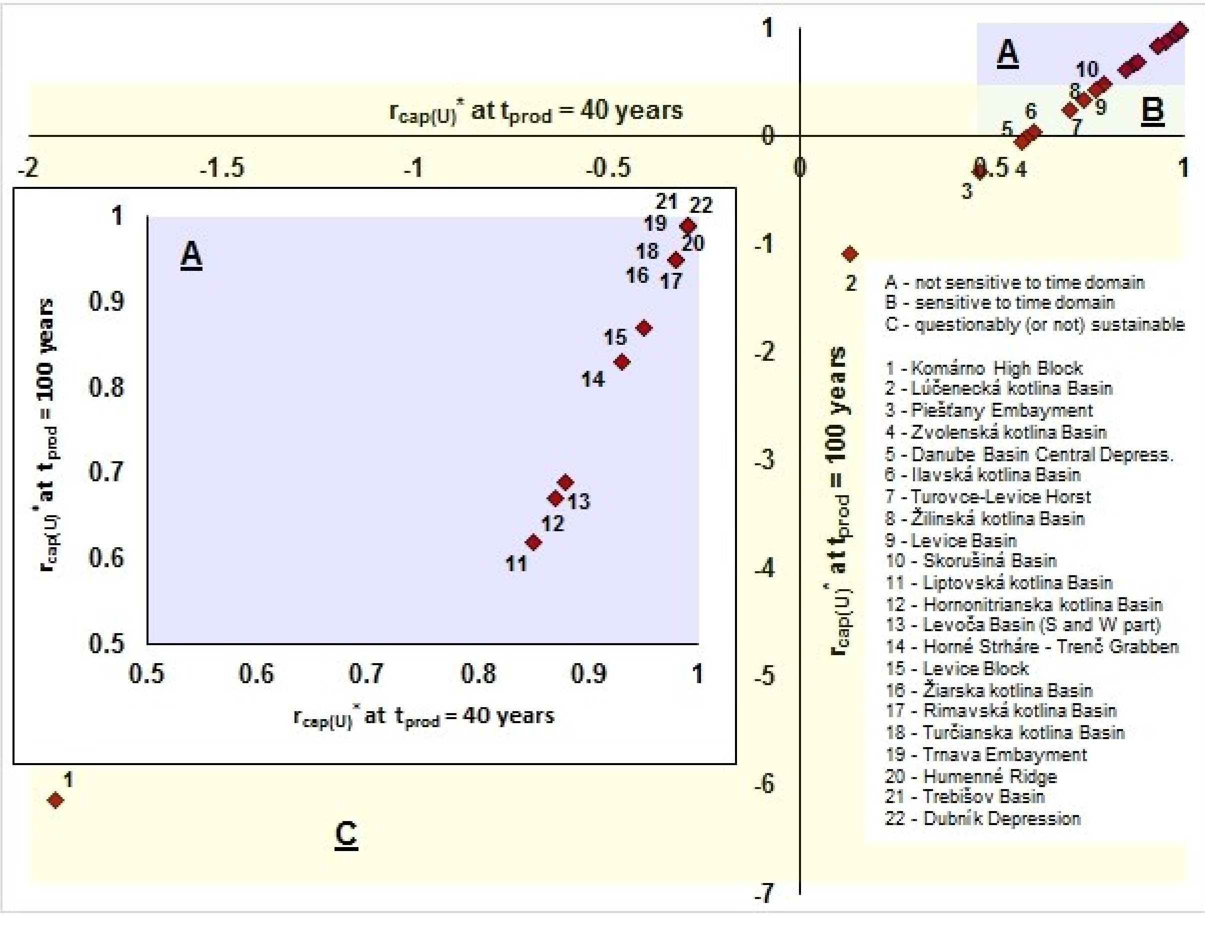

Figure 2: Sustainability classification map of GWBs in Slovakia.

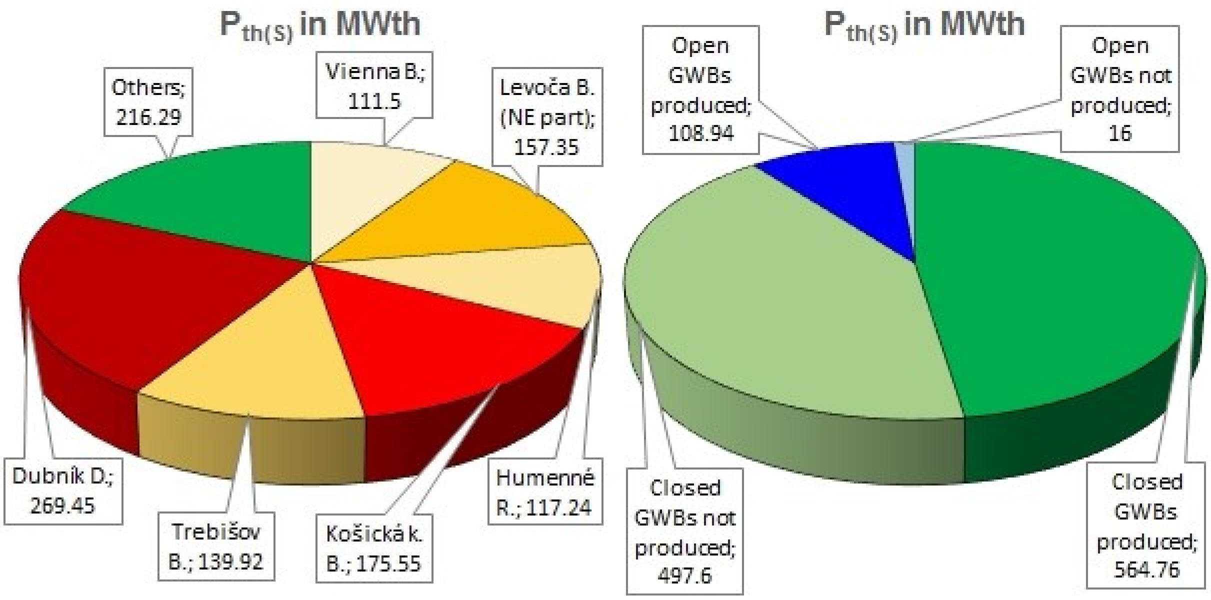

Figure 3: Sustainably developable potential Pth(S) pie-chart for GWBs in Slovakia at different classification criteria.

4. DISCUSSION AND COMMENTS

4.1 Key legal controls on sustainability, renewable energy resources and geothermal energy in Slovakia

The entire concept of sustainable development (SD) and its application into a praxis has some legal support on a national scheme, whatever questionable in its effectiveness it is. Principally, three major aspects prevail in the SD enacting: general support of renewable energy sources (RES) in introduction to a primary energy mix; financial support for energy generation; efficiency and savings related to RES and emissions reduction.

The principal document is the Act No. 309/2009 Coll. On promotion of RES and high efficiency energy production, as an ancillary to the EU Directive No. 2009/28/ES, however, it is limited to the definition of renewables and supplementary actions, including subsidies towards energy production. The situation on the electricity market including RES is enacted through the Act. No. 251/2012 Coll. (Act on energy economics) as later amended. The concept of national economic interest introduced therein specifies advancing renewables and cogeneration in delivery to the grid, however, no controls on efficiency and sustainable use of RES are implemented. This includes taxes reduction regulated through Act No. 609/2007 Coll. On Excise taxes from electricity, coal and natural gas, as long as there is a sound proof on electricity generation from renewables. This act lists the geothermal energy amongst resources supported for electricity generation in Slovakia, however, there is no plant in operation today, with a fair skepticism towards a near future. The energy demand, consumption and efficiency aspect of sustainable development is approached in Act. No. 555/2005 Coll. On Energy efficiency of buildings, introducing a concept of zero energy demand constructions, again with legislatively defined financial supports. According to that, each new construction approved after December 31st 2020 is obligated to meet the goal. Shallow geothermal energy is, however, mentioned only in brief, as an energy source promoted to supply the constructions. A scheme on emissions limit marketing is regulated through the Call. No. 414/2012 Coll. On emissions limits and trading, the plan is to allocate 30 % of Environmental Fund turnoffs from trading with emissions for financial support of RES implementation, carbon savings, GHG mitigation and fossil fuels replacement.

Geothermal energy itself takes a minor part in relevant regulations, mentioned generally in terms of electricity production or heat generation for individual or space heating only. Some legal control on exploration, production and utilization is fairly dispersed in Geological Act, Act on Water, with several notes also included in the Mining Act (Act No. 44/1988 Coll. On Use and protection of mineral resources). At least quality and quantity of mineral and thermal-mineral waters with curative effects on a human health is regulated through the Spa Act. However, whatever aspect is discussed therein, quotes on renewable and sustainable approach are missing, when referring to the long-term sustainability and renewability of the resource and thermal potential accessible in the reservoir. Indeed, manual, operator- / producer- managed reporting of yield rates at sites with gauges is easy to evade in true numbers, moreover, it does not solve any problem on long-term heat flux, temperature, quality and heat content stability, and the topic is not investigated, neither during exploration, nor through the production stage.

Therefore, there is a need to modify national legislation and consecutive enactment towards the concept of sustainable and renewable use of geothermal resources in a country, including the recent shortcomings commented on above. A consensus on energy resource use and its protection towards longevity of production, is necessary for State Authorities, such is the Ministry of Environment of Slovak Republic, Ministry of Economy and Ministry of Health; as well as between the state and typically private investors (operators, producers etc.). Otherwise, the situation is unlikely to change.

4.2 Comments to recent study

A combination of Monte Carlo simulation (MSC) applied to USGS volume method and R_0 specification for individual GWB has been tentatively carried out as the national geothermal scheme transits towards the EU Water Framework Directive, and used as a key input for initial $r_{cap(U)}$, and derived r_{cap}-based analysis, including the assessment of sustainable potential for development ($P_{th(S)}$ and sustainable geothermal potential ($P_{th(S^*)}$).

Although working with best available data for MCS, the booking itself carries some uncertainties, as with many GWBs, a lack of relevant data (e.g. structural and reservoir geometry, porosity, permeability, vertical temperature distribution) required use of "best guess" approximates and use of analogy concept. For this case, we rather do not consider results of booking as finished, as numbers may somewhat vary. Therefore, some changes can occur in the future. Developing more precise conceptual models for GWBs providing data entering the MCS and instant changes in classification of sustainability using the rcap concept are rather unlikely.

All the analysis has been carried as balanced to the entire GWB energy content. Most of GWBs, however, contain several hydrogeothermal structures at various degree of connectivity, such is the Liptovská kotlina Basin (e.g. Remšík et al., 2005; Fričovský et al., 2016b), S and W part of the Levoča Basin (Blanárová et al., 2017), Rimavská kotlina Basin etc. Thus, we also expect that the for GWBs where low connectivity will recall partial dissection to structures, presented estimates of r_{cap} and derived parameters will change. Some example is the Ďurkov hydrogeothermal structure, a part of the Košice basin, with questionable connectivity to the entire GWB, or at least with some neighboring systems, such is the Bidovce depression, assessing only 49 MWth (e.g. Fričovský et al., 2019) as sustainable thermal potential for a desired period of production t_{prod} = 100 years, however, balanced to $T_{inj} = T_{ref}$ = 65 °C (reasonable temperature for reinjection at local conditions).

Comments on several GWBs where longevity of production at current or nameplate thermal capacity appears questionable are based on $r_{cap(U)}$, $r_{cap(U^*)}$ and $r_{cap(S)}$, so that they are effected by the overall uncertainty in reserves balancing. Consequently, they provide a recommendatory accent on increasing interest to involved sites and GWBs instead of instantly predicting potential shut-downs or other absolute negative forecasts.

5. CONCLUSIONS

The geothermal energy in Slovakia is recently utilized at 74 sites, with 114 wells providing geothermal waters in 22 of 31 geothermal water bodies, where cumulative deliverability of 16.7 x10^6 m^3 in 2017 (last available data for Country Update) contributed to production of 1,987 TJ of heat at an installed capacity of 229.4 MWth and a mean yearly thermal output of 67.7 MWth, including wells operated in a supply thermal waters with curative effects on human health.

A systematic research and prospection of geothermal energy was launched in the 70's, answering global fuel concerns. Initially, 27 geothermal prospective areas (GPAs) were identified with cumulative probable reserves assessed for 6,233 MWth (e.g. Remšík, 2012; Marcin et al., 2014; Fendek & Fendeková, 2015; Bodiš et al., 2018). Little concern was paid to resource balance and longevity aspects of geothermal energy production, simply reflecting lack of legal regulations. Numerous schemes cover the entire sector of renewables or geothermal (groundwater) production, relating to deliverability only.

With a transition towards the geothermal water bodies concept (GWBs) following the Directive No. 2006/60/EC (Water Framework Directive, WFD), the Country Update for Slovakia submitted to WGC2020 (Fričovský et al., 2020) reports proven reserves of 437 MWth. Besides formal affairs, the WFD introduction required review of numerous GPAs and delineation of new GWBs. However, as conceptual models changed the previous probable reserves assessment became incommensurate to the new scheme.

The presented study provides tentative results of both the application of modified reserve capacity ratio concept (originally introduced by Bjarnadottir in 2010), and the initial stage of geothermal reserves booking; as based on data available for recently delineated GWBs in the prior assessment of sustainable potential for development in the country and sustainable geothermal potential. Geothermal reserves in Slovakia booked for 31 geothermal water bodies are assessed for 6,716 MWth when balanced for t_{prod} = 40 years or 2,686 MWth considering the prolonged period of t_{prod} = 100 years, turning to a minimum sustainable period according to the formulation of sustainable geothermal production concept (Axelsson et al., 2001, 2004, 2005). This represents, however, results of tentative booking, though subjected to a corresponding confidence according to the booking scheme (Sanyal & Sarmiento, 2005; Sanyal & Buttler, 2005) and there is an obvious probability that accessible thermal potential stored in geothermal aquifers may change, adding new GWBs or refining inputs based on future data.

Yet results of balanced booking gave a baseline for reserve capacity ratio derived analysis, evaluating longevity performance for recent thermal output – $r_{cap(U)}$, installed capacity – $r_{cap(U)^*}$ and potential of development in terms of sustainable geothermal production – $r_{cap(S)}$. Then, developable potential $P_{th(S)}$ and sustainable thermal potential $P_{th(S^*)}$ has been assessed, both for t_{prod} = 40 years and t_{prod} = 100 years. For a conservative period of time, production at a recent capacity (cumulative mean yearly thermal output of 67.6 MWth) should not pose any risk on production sustainability, as 22 of 22 GWBs reach $r_{cap(U)} > 0.5$, however, $r_{cap(U)}^* < 0.5$ (not sustainable) for 3/22 when considering thermal production at a nameplate capacity. Extending longevity due to approaching philosophy of "future generations" of the sustainable development concept, the Komárno High Block, Lúčenecká kotlina B., Piešťany Embayment and the Ilavská kotlina B. yield $r_{cap(U)} < 0.5$; produced for recreation and for curative spa resorts respectively. The low $r_{cap(U)}$ score at recent capacity should accent an increased desire to analyze these systems in more details and focus on energy aspects. When related to t_{prod} = 100 years, the $r_{cap(U)}^* < 0.5$ for 10/22 GWBs, with the Danube Basin Central Depression (most developed, including ISH, GDHS, greenhousing sites), Skorušina Basin (transboundary with Poland), Levice Block (recently only site in Podhájska with active reinjection), Zvolenská kotlina B. (historical spa) etc. Instead of an hasty opposition to production we rather recommend detailed hydrogeothermal studies at these GWBs.

According to available data, the total sustainable thermal potential $P_{th(S^*)}$ in Slovakia is now assessed for $P_{th(S^*)}$ = 2,972 MWth and $P_{th(S^*)}$ = 1,416 MWth, the latter for a period of 100 years. However skewed the estimate is with uncertainties, it may represent some baseline on a national scale. However, as long as a legislative scheme will not enact sustainability principles to use with regard to geothermal resources, any transition is unlikely in the country.

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