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Report on the numerical modelling at the Vienna Basin pilot area model; Step 2: Scenario modelling

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5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

5.3.1 Map series of the scenario models results and regional zoning planes

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1 Preamble

This report is a revised and extended version of chapter 6 of the "Report on the numerical modelling at the Vienna Basin pilot area model". It provides more details on the methodology and the complete results of the scenario modelling.

The here discussed modelling is focussed on:

- The detailed scenario modelling at the most promising trans-boundary structure at the Hydrogeothermal Play "VB04 Juvavic Nappe System", the so called "Wetterstein Dolomite" reservoir.

2 Introduction

The Wetterstein-Dolomite geothermal reservoir has been figured out to be the most promising trans-boundary geothermal reservoir in the Vienna Basin pilot area. Because of the high salinity of the thermal waters of this aquifer the trapped thermal water is not suited for balneological purposes. Hence, the only possible utilisation can be a pure energy usage, realized by a doublet installation with complete reinjection of the thermally deployed brine. As this Hydrogeothermal Play has not been used for geothermal use yet, the scenario modelling is focusing und possible future near-boundary utilization schemes.

The main objectives of the detailed scenario modelling are represented by:

- Analyses of the hydraulic influence of (i) fault systems and (ii) the geometrical shape of the reservoir on the coupled hydraulic and thermal conditions of different doublet-use scenarios, represented by different locations and operational settings.
- Estimation of the technically extractable amount of heat by assuming several hydrogeothermal doublets.

The area of interest shows a lateral extension of about 15 km x 3 km, striking approximately along a SE-NW direction. The river March and the Austro-Slovakian boarder crosses the body right in the middle in N-S direction. On the Austrian side, large parts of the watersides of the river March are protected by "Natura 2000 - European Nature Reserve". Hence no surface hydrogeothermal installations, such as wells or heating facilities are considered to be legally allowed in this area. In opposite "Záhorie Protected Landscape area" is situated on the Slovakian side along the river Morava / March. Despite of this fact, the location of the Slovakian hydrogeothermal doublets has been set within this protection area nearby the village of Visoká pri Morave. This was done in order to investigate possible trans-boundary hydraulic flow and thermal influences at the reservoir.

On the Austrian side of the reservoir three abandoned hydrocarbon wells (SCH-T1, SCH-1 and BG-4) could possibly be used (re-entry) for geothermal usage and supply the Gänserndorf / Strasshof area (approx. 20.000 inhabitants) with energy (heat and electric power). At least the above mentioned drillings have proofed the evidence of thermal water at the investigated reservoir (see also Table 1). On the Slovakian side we considered the Zohor – Láb – Záhorská Ves triangle containing about 10.000 inhabitants as a plausible area for geothermal supply of heat.

Table 1: Depth interval and maximum observed temperatures at DST tests for the Wetterstein-Dolomite geothermal plays, observed at Austrian hydrocarbon exploration wells.

Well	Drilled Depth Interval (m b.s)	Maximum observed temperature (degC)
SCH-T1	2985 - 3508	121
SCH-1	3042 - 4005	128
BG-4	2784 - 2842	92

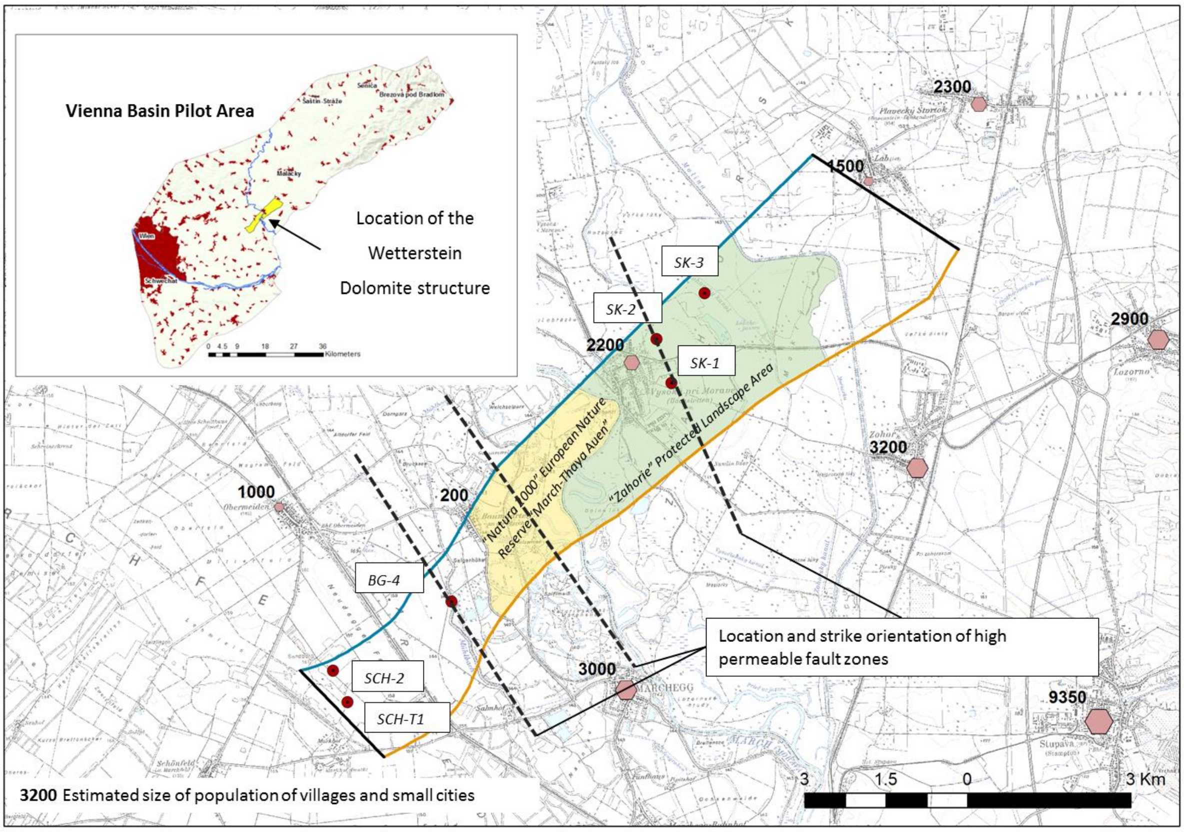


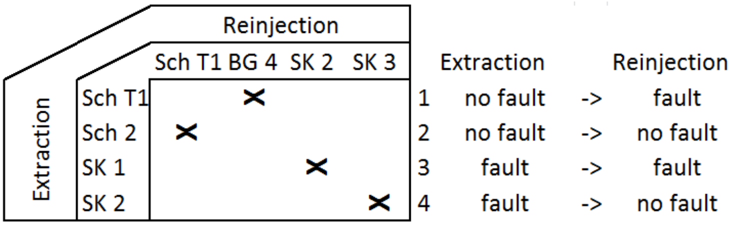
Figure 1: Outline of the scenario model „Schoenfeld-Láb“. The red dots show possible well locations, the size of the hexagons display the population of the bigger settlements in the vicinity of the hydrogeothermal play ‘Wetterstein-Dolomite’.

3 Model setup

The scenario modelling is carried out using the Finite Element subsurface Flow Simulation software FeFlow™. The model setup in FeFlow™ works as follows: The geometry is defined in two dimensions only – the so-called "Supermesh". Afterwards it is translated into a triangular mesh. In the third step this triangular mesh is then extruded multiple times to produce a three-dimensional geometry consisting of various prisms. In general there are two different approaches to fulfil this task: The more common way is to start with a horizontal plain and extrude the geometry in the z-direction. In this case the geometry of the Wetterstein-Dolomite Hydrogeothermal Play implies a vertical approach, where the geometry is defined as cross-section and then extruded horizontally. Since the reservoirs longitudinal extension is oriented SW-NE it was necessary to use a local model-coordinate system that is rotated by 45° from UTM. To avoid round-off errors of the solver, the origin of the local coordinate system is shifted by 5350 km towards north. The model consists of 90 sub-vertical slices with a maximum distance of around 150 metres. The minimum mesh size around the wells is about 10 metres. The "in-slice" resolution ranges from approx. 3 metres around the well-screens up to about 250 metres at the boundaries of the model. The fault zones are approximated by high-permeability zones of a lateral thickness of 50 metres.

3.1 Well setup

Two of the three selected wells on the Austrian side of the model-block drilled the Wetterstein-Dolomite complex at a tectonically undisturbed position, while one well hits a known fault zone. Since there is no information about fault systems on the Slovakian part of the Aquifer, one exemplary fault is assumed, where two of the three hypothetic wells are located. Hence all different 'fault'- 'no fault scenarios' have been considered by combination of different wells in terms of geothermal doublets. The applied matrix of combination is shown in (Figure 2). Previous studies have shown that a geothermal exploitation can only be economically viable with a minimum yield of 100 l/s, a production temperature of at least 100 to 120 ° C and (regarding the investment costs and return of investment) the drilling depth. In order to fulfil these "rule of thumb" criteria, the depth of the well screens is ranging between 3 and 4 km and the yield is assumed constant (100 l/s). To include the fractured character of the reservoir, the well screens are realised using five point sources/sinks each (see chapter 5)



		Reinjection			
		Sch T1	BG 4	SK 2	SK 3
Extraction	Sch T1		×		
	Sch 2	×			
	SK 1			×	
	SK 2				×

	Extraction		Reinjection
1	no fault	->	fault
2	no fault	->	no fault
3	fault	->	fault
4	fault	->	no fault

Figure 2: Compilation of the considered doublets.

3.2 Simplifications and modifications

Since the two SCH – wells are located very close to the model boundary they were displaced about 300 m towards northeast to reduce effects produced by the model-boundary (no flow and fixed temperature boundary conditions). Furthermore the wells SCH-T1 and BG-4 are set on the same slice, so only one refinement is necessary for both wells. The same approach was applied to the hypothetical wells Slovak 2 and 3. The wells Slovak 1 & 2 as well as SCH T1 & T2 are dislocated (shifted) in a way that only one lateral refinement is necessary for two wells (see Figure 3).

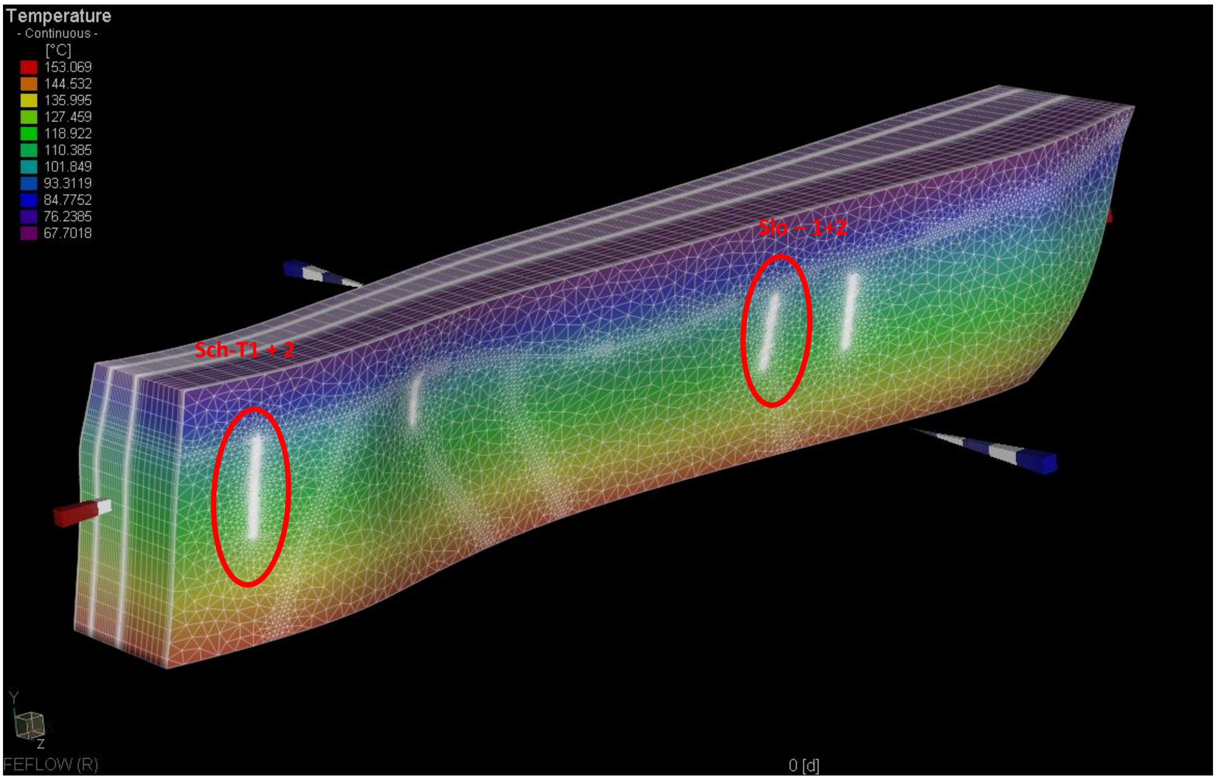


Figure 3: 3D Feflow-model of the Wetterstein-Dolomite hydrogeothermal play used for scenario modelling.

4 Material properties

The thermal parameters can be adopted from the steady-state model of the pilot area. In addition flow properties have to be added to the model. In this context the following assumptions have been applied: The Wetterstein Dolomite is a typical fractured reservoir. Hence, the flow behaviour is, strictly speaking non-Darcy. A common approximation for fractured reservoirs is the tensor form of the Darcy equation, where it is possible to incorporate the conductivity as anisotropic values. Log interpretations done in previous studies indicate a main fracture orientation of the Wetterstein Dolomite of 110/70 (strike/dip-Notation) towards North-Northeast.

Inside the fault zones crossing the Aquifer the conductivity is expected to be elevated. No exchange between the Neogene Sediments and the Dolomite is expected, so a very small conductivity is assigned for the sedimentary layers above. There is an evidence for an approximately 50 metres thick layer of Breccia at the base of the Neogene.

Table 2: Material properties

Properties (matrix) / Units	Thermal		Fluid Flow	
	Conductivity $[W/m \cdot K]$	Capacity $[kJ/m^3 \cdot K]$	Porosity [%]	Permeability $[mD]$
Neogene Sediments	3.2	1734	20	0.01
Base Conglomerate				0.01/100*
Dolomite	3.42	2666	4.2	100/10**
Faults				100/200*

*: Different scenarios | **: Anisotropy

5 Boundary conditions

Since there is no natural flow occurring in the considered aquifer, all boundaries can be considered as “no flow boundaries”. The hydraulic head has to be set at some nodes at the top as reference and of course at the well nodes a “Well BC” has to be set. To take the fact into account, that the fractures are not evenly distributed, not the whole well screen is activated as “Well BC”. Instead the Well boundary condition has only been applied on five nodes per well (see also Figure 4). If a well screen is hitting a fault zone, the activated nodes are placed inside that fault zone, otherwise they are distributed randomly over the screen. The reinjection temperature is assumed at 50 °C and applied as constant Temperature BC at the points of reinjection.

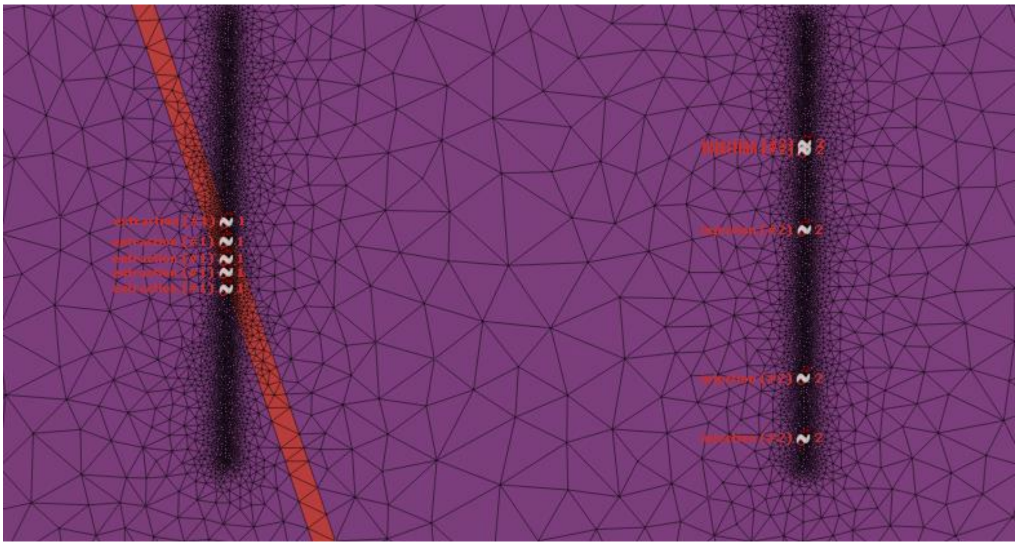


Figure 4: Distribution of the “Well BC” at the screens of the wells SK-2 and SK-3. Red: fault zone

6 Description of scenarios

At each modelling run two doublets - one on the Austrian and one on the Slovakian side of the reservoir - are simulated at a time, so basically two runs are sufficient to simulate the combinations described in chaper 3.1. Doublette [1] and [3] (see also Figure **2**) were considered in 'scenario 1' and the doublettes [2] and [4] in 'scenario 2'. Additionally, the influence of a 50 metres thick layer of Breccia at the base of the neogene Sediments was surveyed in 'scenario 3'.

As no hydrogeothermal utilization has been developed yet for this Hydrogeothermal Play, the applied scenario modelling is focussing on the coupled hydraulic – thermal influence of the anisotropic shape of the reservoir (low ratio of lateral- to the longitudinal extension of the reservoir) and assumed high permeable discrete fault zones, which may act as flow channels for the injected cold water. In addition hydrocarbon drillings in the vicinity and partly within the Hydrogeothermal Play itself show the evidence of a high hydraulically conductive porous aquifer at the lowermost 50 meters of the Neogene deposits, which are directly overlaying the target reservoir. This assumed porous sedimentary layer would lead to an coupled hydraulic – thermal interflow between the wells of the doublet, which may be different to the fault related interflow. As the fault related interflow acts as a discrete flow channel, the porous layer interflow may act as a volume related interflow, which may lead to a later but smoother thermal breakthrough at the production well of a doublet. In contrast a channel related interflow is, in the worst case (both wells are located at the same conductive fault zone), expected to lead to a short thermal breakthrough time and an massif decrease of the temperature at the production well.

Table 3: Overview on the investigated scenarios

Scenario	Involved Doublets	Description
1	Austria: Sch2 (P) – BG4 (I) Slovakia: SK1 (P) – SK2 (I)	**High influence of fault zone**: At the Austrian doublet the injection well is located at the fault zone, which may lead to a fast propagation of the cold water plume. In contrast it also may reduce the technical effort of the water injection. At the Slovakian side both wells are influenced by a high permeable fault zone, which may strongly enhance both hydraulic and thermal short-cuts.
2	Austria: Sch2 (P) – Sch (I) Slovakia: SK2 (P) – SK3 (I)	**Moderate influence of fault zone**: Both wells of the Austrian doublet are located at tectonically undisturbed positions of the reservoir, which may on one hand lead to enhanced hydraulic resistivity at the wells but on the other hand inhibits thermal short-cuts. At the Slovakian doublet the production well is located within a high permeable fault zone. As the injection well is located at an assumed tectonically undisturbed position of the reservoir, the thermal breakthrough may be inhibited on the one hand, but the effort in order to inject the used water may be raised on the other hand.

3	Austria: SchT1 (P) – Sch 2(I) Slovakia: SK2 (P) – SK3 (I)	**<u>Influence of high permeable porous layer</u>**: Existence of a highly conductive layer at the lowermost 50 meters of the Neogene sedimentary deposits upon the reservoir, which may lead to thermal shortcuts. Additionally, the well screens on the Austrian side are set directly underneath the brecciated high permeability layer to demonstrate a quick thermal breakthrough.

P... Production well, I... Injection well

It is also making a difference which of the two wells of a doublet is located at the fault zone. There are 3 different schemes, which can be distinguished:

i. <u>Both wells are located within the fault zone</u>: Strong directive, channel like interflow between the two wells of the doublet leding to a fast and massive attenuation of the temperature at the production well. From a hydraulic point of view the efforts for production and injection of thermal water (pumping effort) is reduced due to lowered hydraulic transfer resistance between the screen of the wells and the reservoir. This situation was assumed at the Slowakian doublet at scenario 1.

ii. <u>The injection well is located within the fault zone</u>: From a technical point of view the reinjection of (thermal) water is more sensitive to hydraulic and technical failures and more likely to be non-successful than the production of water (e.g. scaling due to temperature changes of the used thermal water). Therefore the hydraulic transfer resistance between the screen of the well and the reservoir should be as low as possible. This in turn is a strong argument for placing an injection well within a high permeable fault zone. From a thermodynamic point of view a channeled water interflow at the reservoir may lead to two different effects: (1) Shortened thermal breakthrough periods due to reduced heat-transfer surfaces between the flow channels (bearing cold injected water) and the surrounding hot rock matrix. (2) In contrast cold water has a higher density than hot water and therefore is tending to sink towards the deeper parts of the hydraulically connected reservoir due to gravitational forces. As a consequence of this, hot water is displaced to shallower parts of the reservoir, which may lead to a rise of the water temperature in the production well. This scheme is represented at the Austrian doublet in scenario 1.

iii. <u>The production well is located within the fault zone</u>: As described above the technical and consequently economic gain of placing the production well in a fault zone is less than placing the injection well in the fault zone. On the other hand, the risk of enhanced or interflow leading to uncontrolled or hardly predictable changes of the temperature at the production well is lower than at scheme 2. This scheme is represented at the Slovakian

Taking into account all possible effects and transport phenomena described at the three different schemes, it can be summarized, that scheme (ii) is assumed to be the preferred doublet scheme of a geothermal doublet located in a fault zone affected reservoir.

7 Results

7.1 Temperature history of production

Apart from the possible yield, that is considered (and consequently presumed) at a constant value of 100 l/s, the production temperature is the most crucial factor for the economic viability of a geothermal installation.

The susbequent Figure 5 shows the results of the coupled thermal – hydraulic scenario modelling in terms of the predicted water temperature at the production wells of the Austrian as well as the Slowakian doublet for an overall time period of 100 years.

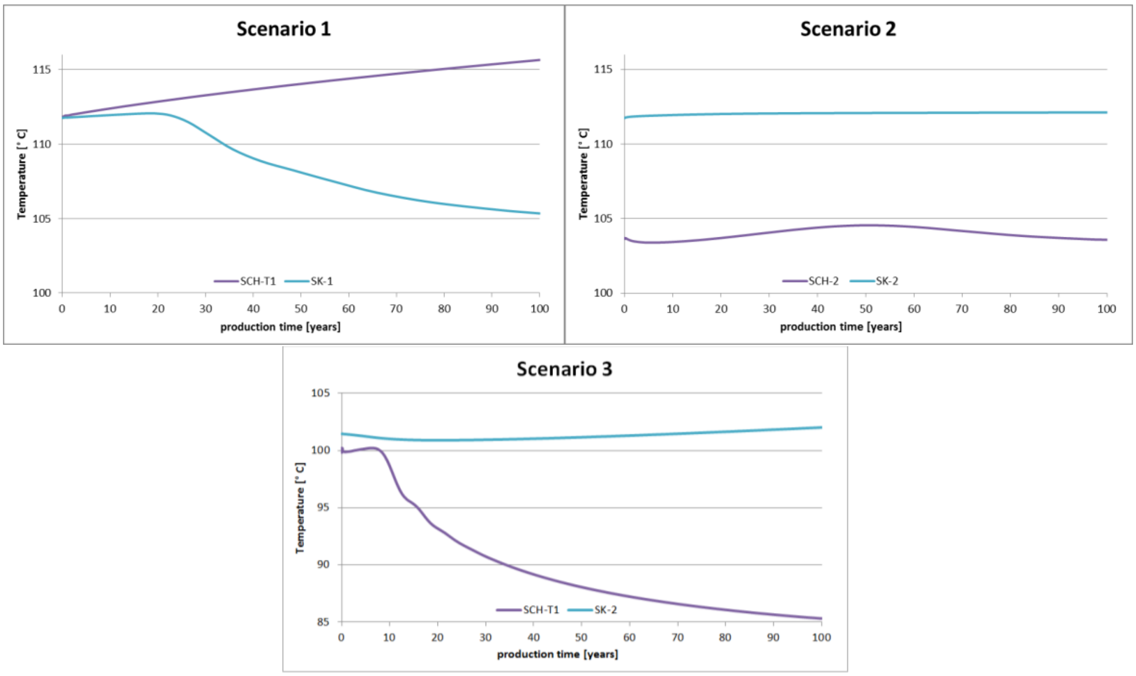


Figure 5: Time series showing the predicted temperature at the production wells of the Austrian and Slowakian doublets.

Scenario 1, which has been labeled as highly influenced by a high permeable fault zone, is showing significant changes due to convective heat transport within the assumed high permeable fault zones. The temperature at the production well of the Austrian well is continuously rising during the production period of 100 years. As described at scheme (ii) in the previous chapter this temperature rise is related to hot thermal water from the deeper parts of the reservoir, which has been replaced by sinking injected cold water. In contrast the thermal evolution of the production well at the Slovakian doublet is smoothly falling after an operational period of approximately 25 years due to enhanced interflow during the fault zones, where both wells are located. This scenario is presenting scheme (ii) described in the previous chapter.

Scenario 2 is represented by minor influences on both the Austrian and Slovakian doublets. While at the Austrian doublet both wells are located at tectonically undisturbed parts of the carbonate reservoir (lack of high conductive fault zones), only the production well of the Slovakian doublet is located within the fault zone. The interflow between the wells of the Austrian doublet is dominated by anisotropic volume flow through a moderate conductive reservoir. Therefore no thermal breakthrough has been observed for an operational period of 100 years at a well distance of approximately 1 kilometer. The temperature history at the Slovakian production well shows a slight temporally confined temperature-rise, which is assumed to be related to upstream of thermal water from deeper parts of the reservoir due to pressure decrease as a consequence of water production. It can be summarized, that both doublets simulated at scenario 2 (low influence of fault zone) are leading to stable temperature conditions at the production well.

Scenario 3 is investigating the influence of a highly conductive porous sedimentary layer on the top of the fractured basement. Such basal breccia and conglomerates, which are hydraulically connected to the fractured basement below, are widely spread over the Vienna Basin. In order to investigate a so called worst case scenario the wells of the Austrian doublet have been set in tectonically undisturbed locations within the Wetterstein Dolomite structure. Therefore the resulting flow paths are forced to pass the overlaying conductive porous layer. In contrast to the situation at the Austrian doublet the production well of the Slovakian well has been set on a highly conductive fault zone. The modelling results show a strong interference between the injection and the production well of the Austrian doublet. After a time period of approximately 10 years there is a massive temperature decline observed at the production well of almost 15°C as the cold water plume is preferentially passing the highly porous sedimentary layer at the top of the reservoir. In that case the Austrian doublet would fail. In contrast the production well of the Slovakian doublet does not show any interference, although the injected cold water plume also passes the highly conductive sedimentary layer above the reservoir. This is due to the fact, that the water pathways associated to the production well are preferably located within the highly conductive fault zone. This in turn reduces the pressure gradient within the overlaying, highly conductive porous layer and inhibits the propagation of the cold plume.

7.2 Temperature slices at depths of reinjection

To evaluate the thermal anomaly caused by geothermal exploitation, Figure **6** shows the lateral extent of the thermal plumes of the different scenarios. This can be used to estimate the maximum number of possible doublets.

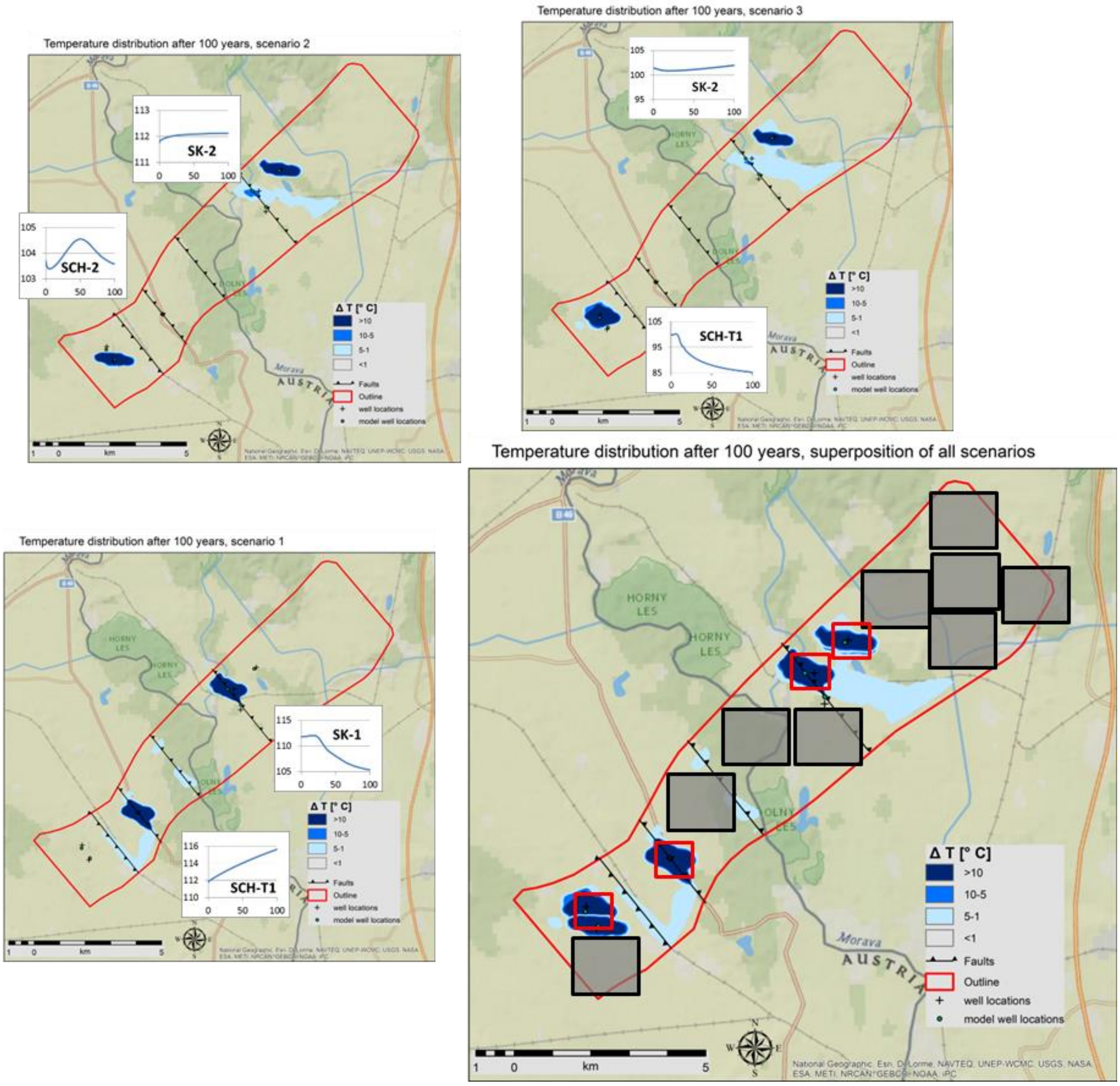
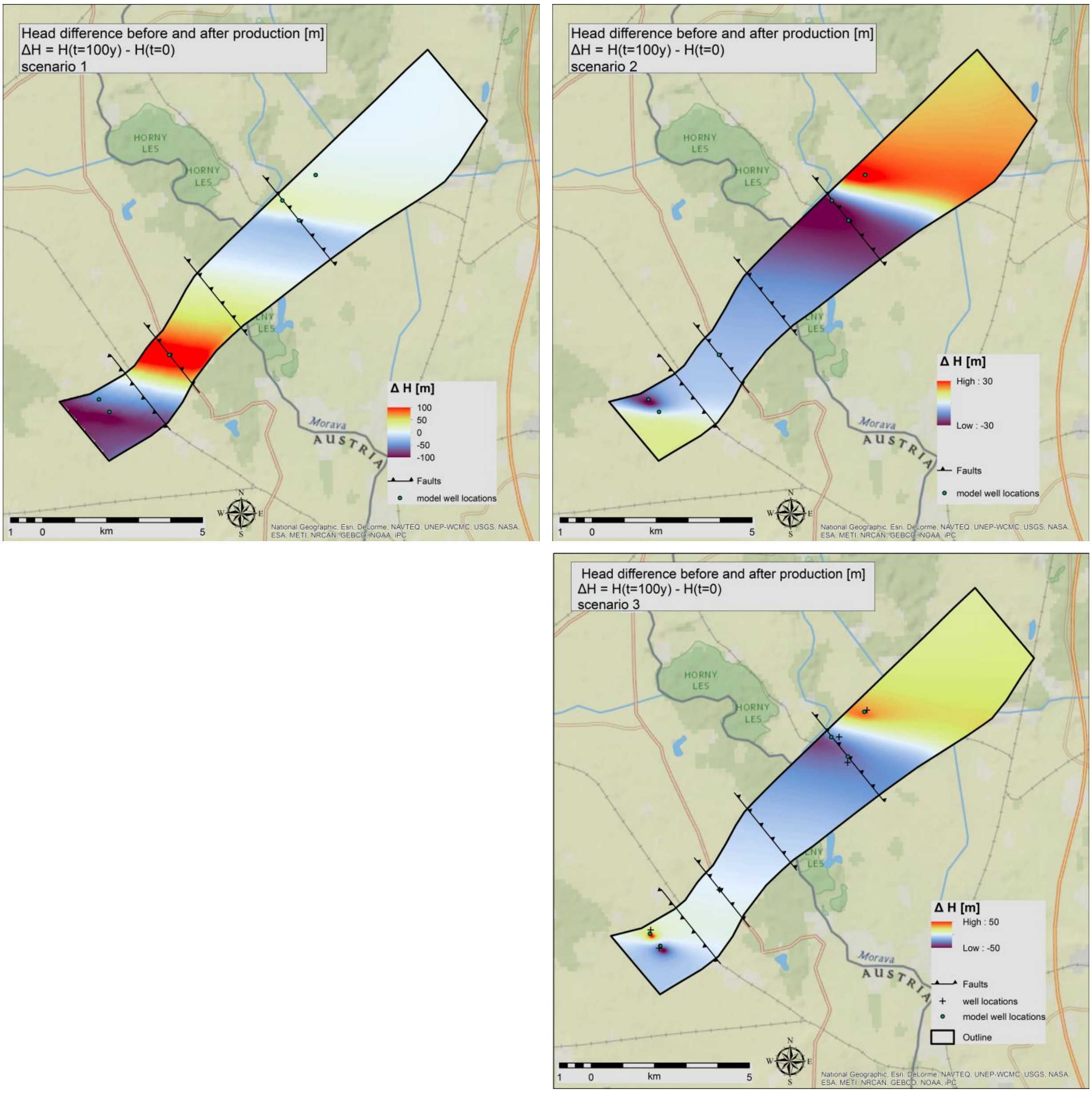


Figure 6: Temperature distribution at the depths of maximal plume at the reinjections. The overlain diagrams show the temperature evolution of the produced water.

7.3 Hydraulic head distribution at base of Neogene

For estimation of far field effects of a geothermal exploitation the head distribution can be evaluated. While the effect on the temperature field is spatially limited, the pressure distribution is affected over the whole reservoir. For all these simulations the transition to the Neogene is assumed to be perfectly sealed. If this is not the case, it could be possible that waters from structural higher levels penetrate the reservoir or vice versa.



Head difference before and after production [m]
ΔH = H(t=100y) - H(t=0)
scenario 1

Head difference before and after production [m]
ΔH = H(t=100y) - H(t=0)
scenario 2

Head difference before and after production [m]
ΔH = H(t=100y) - H(t=0)
scenario 3

National Geographic, Esri, DeLorme, NAVTEQ, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC

Figure 7: Head differences at the base of the Neogene sediments.

8 Hydrogeothermal Resource Assessment

8.1 Summary

As there are still no major hydrogeothermal utilizations in the Vienna Basin pilot area, activities have focused on a harmonized assessment of possible resources. Following the Canadian Geothermal Code for Public Reporting published by the Canadian Geothermal Energy Association (Deibert 2010) the following steps have been performed:

- Identification and description of relevant Hydrogeothermal Plays
- Selection of technical schemes of hydrogeothermal utilization for resource assessment
- Calculation of the stored Heat in Place
- Calculation of Inferred Resources
- Calculation of Measured Resources
- Evaluation of limitations and estimation of Probable Reserves.

All calculations have been performed using 2D Grids, which have been derived from the previous achieved geological and numerical 3D models for the Vienna Basin Pilot Area.

The assessment of the above mentioned different levels of hydrogeothermal resources have been performed for **5 different Hydrogeothermal Plays** (subsurface structures with high chances of thermal water) assuming 3 different technical utilization schemes (balneological use, heat supply and electric power generation combined with heat supply).

The assessed hydrogeothermal potential, the so called **Heat in Place**, varies between **78 GW** and **1,646 GW** assuming an operational lifetime of 50 years. This has to be understood as the maximum, theoretically available amount of heat stored in the subsurface, which cannot be extracted in practice.

The next level of resource assessment is represented by the so called **Inferred Resources**, which can be seen as an estimation of the technical extractable amount of heat at a low level of resolution and confidence. Assuming a systematic extraction of the heat stored by various doublets (multiplet scheme) the assessed Inferred Resources vary between **1.6 GW** and **161 GW**, which in turn corresponds to an heat recovery factor (amount of technical extractable Heat in Place) at a max of 10%.

Considering economic constraints the Inferred Resources correspond to the so **called Probable Reserves**. By allowing a maximum distance between hydrogeothermal doublets and settlement areas of 1,000 meters, we have calculated the Probable Reserves for the heat supply scheme, which is at a level of **49 GW**.

The **Measured Resources** show a high level of confidence provided by direct measurement at wells. We have calculated the Measured Resources based on water inflow on Austrian hydrocarbon exploration wells. The assessed Measured Resources, which can be seen as the already proven resources, vary between **0.06 GW** and **1.6 GW**.

In order to summarize the existing hydrogeothermal resources of 5 identified Hydrogeothermal Plays in the Vienna Basin for heat supply have been estimated in the range of at least (already

proven) 1.6 GW_{Th} and at a max of 161 GW_{Th} (in case of a systematic exploitation of heat based on doublets).

8.2 Overview on the identified Hydrogeothermal Plays

Following the terminology of the Canadian Geothermal Code for Public Reporting a Hydrogeothermal Play is defined as a subsurface volume, at which heat can be technically extracted by the means of trapped natural thermal water. For the Vienna Basin Pilot Area Hydrogeothermal Plays have been delineated by major geological structures in terms of geological strata as well as tectonic nappes, which are supposed to bear at least one or more thermal water reservoirs. The spatial as well as geological resolution is limited by the regional scale of the established geological 3D model for the pilot area. That means it has not been distinguished yet between hydraulic conductive rock units or regions within a selected Hydrogeothermal Play (aquifers) and less or none conductive zones (aquitards).

Apart from hydrogeological considerations the selection of relevant Hydrogeothermal Plays was influenced by the expected temperature level (average temperature above 50°C) as well as by aspects concerning the intensity of hydrocarbon production in order to avoid utilization conflicts between hydrogeothermal utilization and hydrocarbon - above all crude oil - production.

Table 4: Overview on the identified Hydrogeothermal Plays

ID	Title	Type	Age and Lithology
VB 01	Aderklaa Conglomerate	Porous sedimentary layer (Neogene Basin filling)	Middle Miocene (Lower Badenian), conglomerates
VB 02	Deltafront Sediments	Porous sedimentary layer (Neogene basin filling)	Lower Miocene (Eggenburgian - Ottnangian), sandstones and sands
VB 03	Tirolic Nappe System	Fractured carbonates (basement)	Upper – Middle Triassic (Norian – Ladinian), dolomites
VB 04	Juvavic Nappe System	Fractured carbonates (basement)	Middle Triassic (Anisian – Ladinian), dolomites, limestones
VB 05	Central Alpine & Tatric Carbonates	Fractured carbonates (basement)	Middle Triassic (Anisian – Ladinian), dolomites

The vertical and geographical location of the identified Hydrogeothermal Plays is shown in the figures below. The identified Plays cover the major part of the pilot area and are partly overlapping. They are partly outcropping to the surface (especially VB 05) and reach maximum depths of more than 10.000 meters below surface. The uppermost part of the sedimentary basin filling of the Vienna Basin has been excluded due to still ongoing hydrocarbon production, moderate reservoir temperatures and reduced chances of wide spread reservoirs.

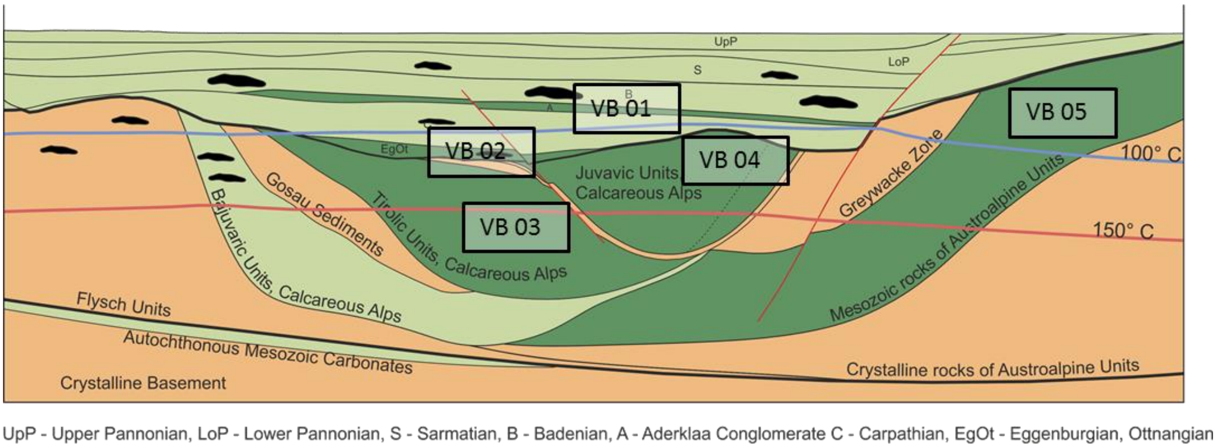


Figure 8: Schematic hydrogeological cross-section through the Vienna Basin Pilot Area showing the location of the identified Hydrogeothermal Plays: Dark green colored areas outline geological units with high chances of thermal water; light green areas represent units with reduced chances of wide spread reservoirs; red colored areas out

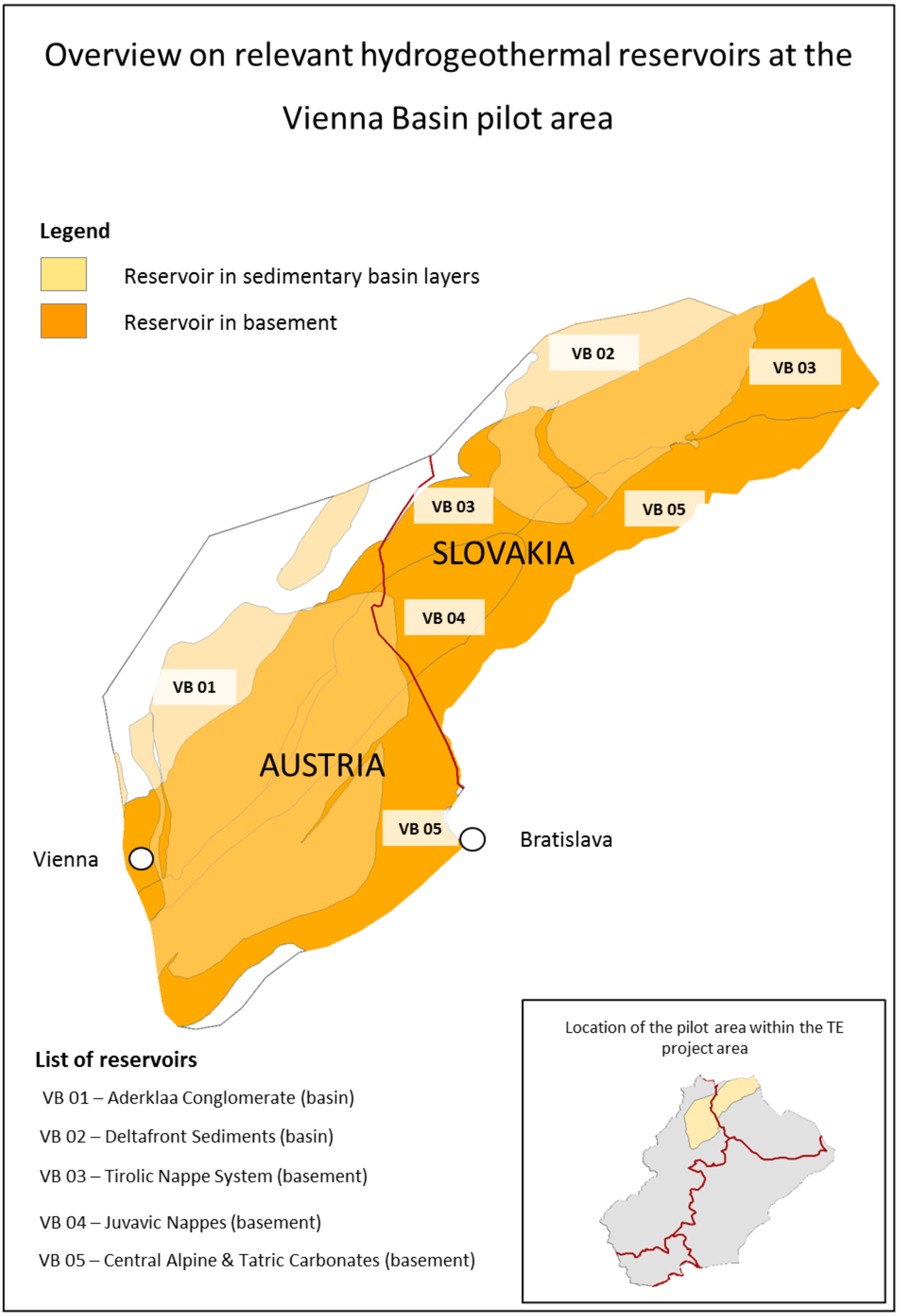


Figure 9: Location of the identified Hydrogeothermal Plays at the Vienna Basin Pilot Area

The geometrical settings of the identified Hydrogeothermal Plays have been derived from an achieved geological 3D model covering the entire pilot area. The calculated rock volumes represent gross parameters also including not resolved zones of non-water bearing rocks within the Hydrogeothermal Plays. In the context of Transenergy the “Gross Aquifer Volume” represents the estimated volume of fluid filled, hydraulically connected pore space including fractures, which were derived by combining the “Gross Volume” and the average hydraulically effective porosity.

The Hydrogeothermal Plays located at the basement rocks of the Vienna Basin (VB 03 – VB 05) show great maximum depths of up to more than 10,000 meters below surface, which are currently not applicable from a technical and economic point of view.

Table 5: Geometrical parameters of the identified Hydrogeothermal Plays

ID	Title	Average Thickness	Maximum Depth	Gross Volume	Gross Aquifer Volume
		m	m.b.s	km³	km³
VB 01	Aderklaa Conglomerate	747	4,470	248.728	37.309
VB 02	Deltafront Sediments	666	4,880	123.657	21.269
VB 03	Tirolic Nappe System	6,624	9,080	4,495.399	265.229
VB 04	Juvavic Nappe System	4,634	7,410	900.403	30.614
VB 05	Central Alpine & Tatric Carbonates	6,359	10,750	3,219.976	103.039

m.b.s. meters below surface

In order to calculated the hydrogeothermal resources thermal- as well as hydraulic rock parameters had to be estimated for the identified Hydrogeothermal Plays. The below listed data have been derived from measurements achieved by the involved Geological Surveys as well as from archive data stored at the surveys. As the assessment of resources is performed at a regional scale and only a few data were available for some Hydrogeothermal Play, we have chosen to only use uniform values for each Hydrogeothermal Play, which were represented by average values. Local variations of the rock properties within the Hydrogeothermal Plays could not be considered.

The Volumetric Heat Capacity is governing the heat transfer between the hydrogeothermal reservoir (Play) and the geothermal doublet (production- and injection well). The hydraulic conductivity and respectively the transmissivity (combination of hydraulic conductivity and the thickness of a reservoir) are in turn governing the flow rate of thermal water and pressure change, respectively, between the reservoir and the doublet.

Table 6: Thermal and hydraulic parameters used for the assessment of hydrogeothermal resources

ID	Title	Volumetric Heat Capacity[1]	Hydraulic Conductivity	Transmissivity
		MJ / (m³ x K)	10^{-6} m/s	10^{-3} m²/s
VB 01	Aderklaa Conglomerate	3.137	1.63	0.32
VB 02	Deltafront Sediments	2.735	1.96	0.36
VB 03	Tirolic Nappe System	3.019	0.52	1.16
VB 04	Juvavic Nappe System	2.812	0.52	1.01
VB 05	Central Alpine & Tatric Carbonates	2.565	0.52	1.01

[1] Bulk value of the fluid filled rock volume

8.3 Description of the selected hydrogeothermal utilizations schemes

The assessment of hydrogeothermal resources is strongly depending on the assumed utilization scenario. The governing parameters are given by: (1) The minimum required temperature of the thermal water, (2) the thermal efficiency of the utilization (discharge or reinjection temperature) and (3) the type of utilization (single well use or doublet well use). From an ecologic and economic point of view a doublet-well utilization consisting of a production well (water extraction) and a reinjection well is more favorable than a single-well use, as the pressure at the reservoir can be preserved by injection of cooled down water as well as the fact, that critical waters may not be discharged to rivers or creeks. It has to be pointed out, that balneologically used thermal water is not allowed to be re-injected to the reservoir for hygienic reasons.

We have selected 3 different schemes, which are representing the most common utilization schemes:

Table 7: Overview of the utilization schemes selected for hydrogeothermal resource assessment

ID	Title	Required minimum temperature	Reference temperature (discharge, re-injection)	Type of scheme	Constraints
		°C	°C	-	-
1	**Balneology** (energetic use of water for local heating)	30	10*	Single Well	None
2	**Heat Supply** (district heating as well as individual heating)	40	25	Doublet (2 wells)	Maximum flow rate 100 l/s or max. drawdown of 100 meters**
3	**Electric Power Generation** (combined with heat supply)	105	55	Doublet (2 wells)	Maximum flow rate 200 l/s or max. drawdown of 200 meters**

* Equals the surface temperature as the extracted thermal water will not be re-injected to the subsurface, therefore a high efficiency is presumed for the energetic use of the trapped thermal water (e.g. heating of spa facilities).

** Maximum drawdown of the water table at the production well, estimated by correlation to the transmissivity of the Hydrogeothermal Play at a specific location

For all chosen schemes an operational period of 50 years at an annual full load was assumed.

8.4 Results

Assessment of Heat in Place

The term “Heat in Place” describes the amount of heat stored within a specific rock volume. It represents a theoretical quantity describing the thermal potential reflecting the surface volume, the temperature conditions as well as the thermal rock parameters. In practice it is not possible from a technical point of view to extract the entire amount of heat stored in a subsurface volume. However, the term Heat in Place confines the (theoretically) available maximum amount of heat. The Heat in Place was calculated for every Hydrogeothermal Play with respect to the above described utilization schemes.

The table below shows the estimated reservoir temperatures at the identified Hydrogeothermal Plays, derived from a steady state pure conductive 3D model covering the entire pilot area. The estimated great reservoir temperatures at the deep buried sections of the Hydrogeothermal are of course not proven, as these sections have not been drilled yet.

Table 8: Calculated reservoir temperatures of the selected Hydrogeothermal Plays, derived from numerical 3D modelling (steady state conductive model)

ID	Title	Average temperature	Maximum temperature	Observed maximum temperature[1]
		°C	°C	°C
VB 01	Aderklaa Conglomerate	80	114	100
VB 02	Deltafront Sediments	58	155	85
VB 03	Tirolic Nappe System	118	239	165
VB 04	Juvavic Nappe System	129	193	128
VB 05	Central Alpine & Tatric Units	134	282	73

[1] Data only for Austrian wells available

The calculated Heat in Place is shown in the table below.

Table 9: Calculated Heat in Place associated to the identified Hydrogeothermal Plays

ID	Title	Heat in Place ($MW_{Th, 50 years}$)		
		Balneological scheme	Heat Supply scheme	Electric power generation scheme
VB 01	Aderklaa Conglomerate	5,449	28,794	454

VB 02	Deltafront Sediments	1,153	7,422	1,289
VB 03	Tirolic Nappe System	52,998	858,027	587,344
VB 04	Juvavic Nappe System	6,533	194,102	122,013
VB 05	Central Alpine & Tatric Units	12,628	557,686	380,336
	TOTAL SUM	**78,760**	**1,646,031**	**1,091,436**

Please note that the above shown hypothetical thermal capacities cannot be entirely used by any technical means! The above shown potential may be interpreted as a physical limitation: For example, it is not possible to extract thermal power in the range of more than 450 MW_{Th} (approx. 5 MW electric power) at the Aderklaa Conglomerate by any technical measures.

Assessment of Inferred Resources

The term "Inferred Resources" estimates the technical extractable amount of heat at a quite low level of resolution and confidence tending to overestimate the "real resources". However, this term gives a by far better estimate of existing technical limits than the so called Heat in Place. It is also suitable to use the Inferred Resources in order to compare the relevance of different Hydrogeothermal Plays at different technical utilization schemes. At Transenergy we have chosen the following approach in order to calculate the Inferred Resources:

Based on the modelled geometry and temperature conditions as well as based on the derived thermal as well as hydraulic reservoir parameters for the identified Hydrogeothermal Plays we have assumed to put one individual hydrogeothermal doublet (1 production well + 1 injection well) at one square kilometer at the surface area confined by an individual Hydrogeothermal Play. Doing so, the entire area will be systematically developed by numerous doublets, which lead to so called "multiplet (multi-doublet) scheme". For the assumed technical scheme 1 (balneological use) a similar approach has been used assuming one single well at an area of one square kilometer. By correlating the maximum allowed drawdown at the production well of an individual doublet to the estimated transmissivity at a specific location, the maximum yield (extraction rate = injection rate of the used thermal water) can be calculated. In order to avoid unrealistic yield the maximum yield of an individual doublet was limited to 100 l/s. Finally, the thermal power of an individual doublet at a specific cell of 1 km² was calculated for the estimated average temperature and the maximum allowed yield at the specific location. Of course the above mentioned minimum criteria associated to the different utilization schemes will be considered for each location. The total amount of inferred resources will be calculated by summing up the thermal power of the individual doublets for all cells, which fulfill the minimum temperature requirement.

Table 10: Inferred Resources calculated for the identified Hydrogeothermal Plays at the Vienna Basin pilot area.

ID	**Title**	**Inferred Resources (MW_{Th})**		
		Balneological scheme	Heat Supply scheme	Electric power generation scheme
VB 01	Aderklaa Conglomerate	636	14,285	229
VB 02	Deltafront Sediments	199	4,455	835

VB 03	Tirolic Nappe System	459	66,624	46,242
VB 04	Juvavic Nappe System	72	15,567	10,945
VB 05	Central Alpine & Tatric Units	264	60,547	41,756
	TOTAL SUM	**1,630**	**161,478**	**100,007**

Except for the balneological scheme, the calculated Inferred Resources are representing only approximately 10% of the calculated Heat in Place. Of course those Hydrogeothermal Play, which are affected by great depths and reservoir temperatures, respectively, show by far higher Inferred Resources than the Hydrogeothermal Plays located at the Neogene Basin fillings (limited thickness and depth). It has to be kept in mind, that the Inferred Resources do not consider any economic constraints, such like maximum drilling depths.

Assessment of Measured Resources

Measured Resources are representing a high level of confidence by applying data from direct measurements in deep drillings. We have calculated the Measured Resources based temperature data measured in hydrocarbon exploration wells. Doing so only those cells have been considered, where exploration wells have been drilled using the above described workflow for the different utilization schemes. All considered hydrocarbon wells have shown significant inflow of thermal water. In addition the temperature measurements have been directly applied on the inflowing water. Therefore the calculated Measured Resources can be seen as proven resources.

Table 11: Inferred Resources calculated for the identified Hydrogeothermal Plays at the Vienna Basin pilot area.

ID	Title	Measured Resources (MW$_{Th}$)		
		Balneological scheme	Heat supply scheme	Electric power generation scheme
VB 01	Aderklaa Conglomerate	6	114	0
VB 02	Deltafront Sediments	1	28	0
VB 03	Tirolic Nappe System	36	1,007	349
VB 04	Juvavic Nappe System	10	461	102
VB 05	Central Alpine & Tatric Units	5	20	0
	TOTAL SUM	**60**	**1,630**	**450**

The Measured Resources are representing only a very small share of the Inferred Resources (less than 1%). Furthermore only Austrian wells could be considered in the estimation as there were no data available from Slovakia. In addition it has to be considered, that hydrocarbon wells have been drilled for the exploration of oil and gas, not for thermal water. Therefore Measured Resources are in general underestimating the true resources. However, it can be summarized that around 1.6 GW$_{Th}$ are already proven considering the Heat supply scheme and 450 MW$_{Th}$ (corresponding to around 30 - 40 MW$_{El}$) are proven for the Electric power generation scheme.

Estimation of Probable Reserves

The term Reserves describes both the technical as well as economical extractable amount of heat stored in the subsurface. Probable Reserves correspond to Inferred Resources by outlining the share, which can be developed in an economically feasible way. There are various economic constraints controlling the feasibility of hydrogeothermal utilizations. Most of them are very site specific and are difficult to generalize (e.g. the load profile of local users). However general constraints are given by the maximum drilling depth and the distance to existing settlement zones. In order to give a rough estimation about Probable Reserves we have considered the limitations given by the distance to existing settlement areas. By assuming a maximum distance of 1,000 meters to settlements the Probable Reserves have been assessed for the heat supply utilization scheme.

Table 12: Probable Reserves calculated for the identified Hydrogeothermal Plays considering the heat supply utilization scheme.

ID	Title	Probable Reserves (MW_{Th})
		Heat supply scheme
VB 01	Aderklaa Conglomerate	816
VB 02	Deltafront Sediments	87
VB 03	Tirolic Nappe System	22,688
VB 04	Juvavic Nappe System	5,292
VB 05	Central Alpine & Tatric Units	20,391
	TOTAL SUM	**49,273**

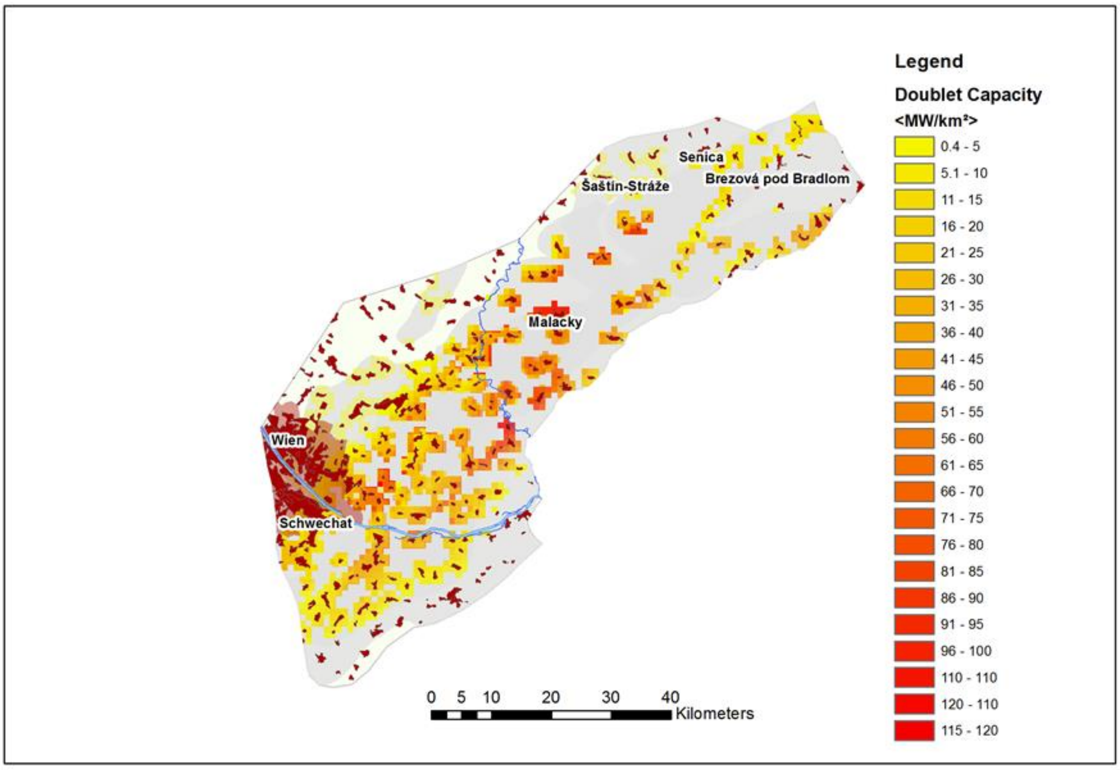


Figure 10: Probable Reserves: Hydrogeothermal doublet capacity per km² combined for all investigated Hydrogeothermal Plays. Settlement Areas: Eurosat©, Corrine Landcover (2006)

Considering a maximum distance of 1.000 meters the estimated Probable Reserves associated to the heat supply scheme are in the range of 49 GW_{Th}. The resulting hot spots for hydrogeothermal heat supply are located at the surrounding of the capital city Vienna and at the Austrian – Slovakian border region between Malacky and Schoenkirchen / Aderklaa.

9 Summary and Conclusions

An easy, though reasonable, approach to assess an estimate exploitable amount of energy from a reservoir is to estimate the number of possible doublets. Multiplication of power of one doublet times the number of doublets yields the exploitable Heat in Place.

The results of the different scenario modelling studies can be used for the assignment of hydrogeothermal claims (zone assigned to single hydrogeothermal doublet utilizations). As shown in Figure 6 in terms of black and grey colored rectangles in total 9 hydrogeothermal doublets could be installed in the outlined Wetterstein Dolomite structure irrespective of natural reserve zones. The average installed power of the modelled doublets is around 25 MW_{Th}, therefore the total sum of all installed doublets would be in the range of around 230 MW_{Th}. This result is now compared with the outcomes of the regionals scale resource assessment in term of the so called Inferred Resources (per square kilometer) considering the electric power generation multiplet scheme.

The comparison is shown in Figure 6 in terms of red colored squares of one km² as well as in the below shown Figure 11:

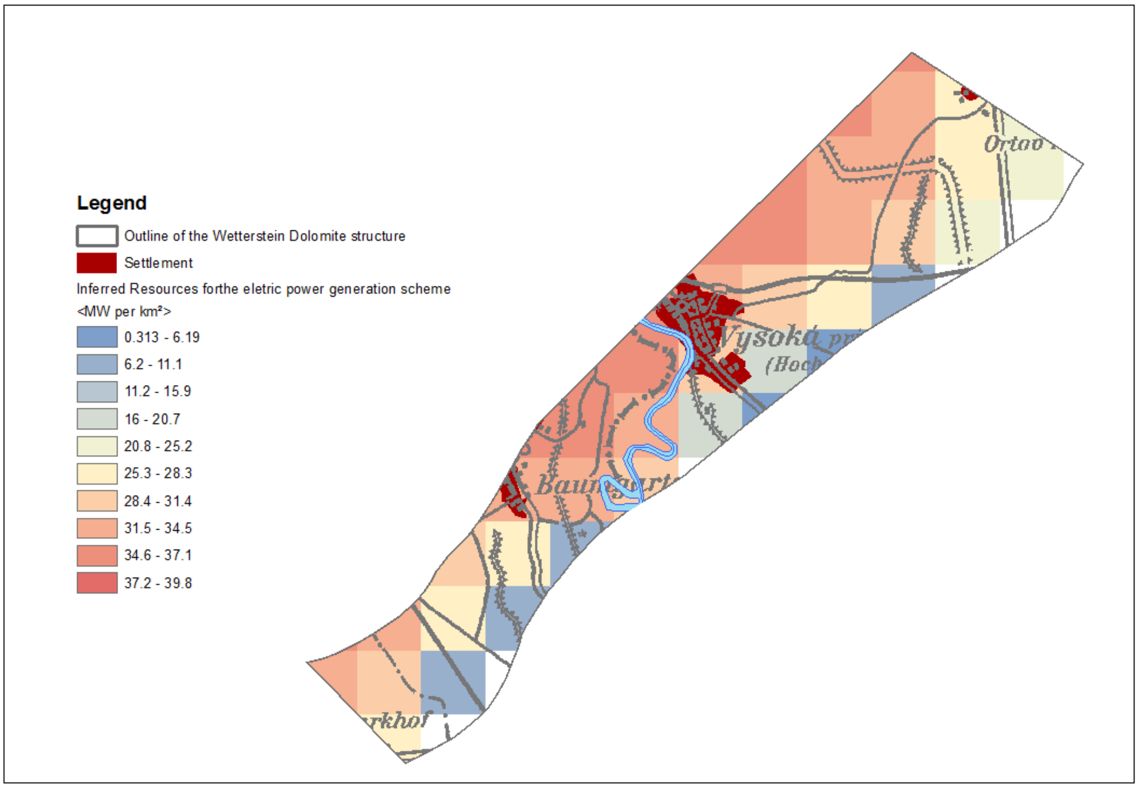


Figure 11: Calculated Inferred Resources based on the multiplet scheme considering the technical utilization scheme "electric power production", which has been cut out at the outlines of the Wetterstein Dolomite structure.

The estimated hydrogeothermal capacities per square kilometer are varying between 9.6 MW_{Th} and 35.9 MW_{Th}. The average installed capacity of 29.3 MW_{Th} is fitting quite well to the average thermal power derived by the scenario modelling studies. By summing up all cells, which are entirely covered by the Wetterstein Dolomite structure the total Inferred Resources are in the range of 470 MW_{Th}, which is about 2 times larger than the total available resources derived from the detailed modelling studies. The reason for this is given by a too optimistic assumption considering the needed space of a single hydrogeothermal doublet in the raster based estimation of Inferred Resources. As shown by the red colored squares at figure 3, the modelled cold water plume exceeded the assumed one square kilometer area for a single hydrogeothermal doublet.

Taking a look at the temperature distributions and the hydraulic conditions at the reservoir a multiplet scheme consting of maximum 10 to 15 doublets, which are jointly controlled, could be most efficient way to develop the reservoir. Depending on the attainable energy price it would be possible to exploit deeper levels (> 4000 m) of the reservoir and/or apply more elaborate exploitation schemes (e.g. multiplet arrays or EGS). Taking these possibilities into account, up to 25 % of the total Heat in Place could be exploitable. As Table X shows different calculation scenarios.

Table 13: Energy balance of possible doublettes. [*]: Statistics Austria, Energy demand of 2011, multiplied by 100 (http://www.statistik.at/web_de/statistiken/energie_und_umwelt/energie/energiebilanzen/)

		T_ref	Energy		%
HiP_total		50 [° C]	5,338	TWh	100
1 doublet, 25 MW, 100 years		50 [° C]	22	TWh	0.4
number of doublets	x5		110	TWh	2.1
	x15		220	TWh	4.1
	x15		330	TWh	6.2
including deeper levels or EGS	x2		220	TWh	4.1
			439	TWh	8.2
			659	TWh	12.3
both	x4		439	TWh	8.2
			879	TWh	16.5
			1,318	TWh	24.7
for comparison: primary energy demand of Vienna in 100 years [*]			4,430	TWh	

References

DEIBERT L., TOOHEY, B. (eds.), 2010, *The Canadian Geothermal Code for Public Report-ing. Reporting of Results, Geothermal Resources and Geothermal Reserves – 2010 Edition*. Canadian Geothermal Association (CanGEA). Calgary, Alberta.