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Evaluating the South German Molasse Basin's geothermal potential by means of the UNFC 2009 Classification

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ABSTRACT

As geothermal energy is gaining in importance within the global energy system, there are numerous studies concerning the assessment of geothermal potential, although the methodologies used can vary considerably in some cases. Thus, a common framework for the assessment of geothermal resources is crucial for providing comprehensive information to investors, regulators and governments. During the last years, the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) was adapted with respect to geothermal resources for ensuring a uniform and standardized methodology. This paper investigates the application of the UNFC-2009 for evaluating the South German Molasse Basin, which is currently by far the most active region for geothermal projects in Germany. Thus, the work provides a detailed assessment of the geothermal resources of this region. Furthermore, the suitability of the current UNFC-2009 framework is discussed with respect to its application for larger geothermal regions, which are utilized for combined heat and power production.

1. INTRODUCTION

The South German Molasse Basin (SMB) is currently the most active region for geothermal projects in Germany (Eyerer et al., 2017a). The SMB is located in the south of Bavaria and contains attractive hydrothermal resources, which are deep carbonate groundwater aquifers. These aquifers have a thickness between 400 and 600 m and are located in a depth of between 2000 and 5000 mTVD (Flechtner and Aubele, 2019). Currently 22 projects are in operation, while three projects are within drilling or construction phase. The total installed deep geothermal capacity is 322 MW$_{th}$ and 31 MW$_{el}$ (Flechtner and Aubele, 2019; BVG, 2019). This corresponds to 95 % of the thermal and 83 % percent of the total electrical installed geothermal capacities in Germany, which highlights the strong relevance of the SMB within the German geothermal sector (BVG, 2019). While pure heat projects can be already realized with brine temperatures of around 70°C, meaningful power production require a brine temperature of at least 100°C (Eyerer et al., 2017b). The electrical power is generated by a binary power plant, such as the Organic Rankine Cycle (ORC) (Quoilin et al., 2013) or Kalina Cycle (KC) (Dawo et al., 2019).

The utilization of geothermal resources has several advantages. Next to the base load capacity of geothermal power plants, the technology is also beneficial for the combined production of electricity and heat (CHP) (Wieland et al., 2016). Moreover, Heberle et al. (2016) determined an environmental impact of geothermal power plants of 15 - 130 $gCO_{2\text{-}equ}/kWh_{el}$. For the lower values of the range, which are obtained through the application of ORC working fluids with low global warming potential (GWP) such as R1233zd-E or R1224yd-Z (Eyerer et al., 2019a), the environmental impact of geothermal power generation is even lower than for other renewable energy sources such as wind or solar (Turconi et al., 2013). Furthermore, the geothermal power production was and still is strongly supported by the German government through the Renewable Energy Act (EEG), which guarantees currently a fixed feed-in tariff of 25.2 ct/kWh$_{el}$ for 20 years for new geothermal plants (Renewable Energy Act, 2017).

Thus, due to this advantageous characteristic of the technology as well as strong political support, an assessment of the geothermal potential is important with respect to provide up-to-date and comprehensible data for politicians as well as investors. The work by Eyerer et al. (2019b) provides an updated potential assessment of the hydrothermal resources in Germany. It is the first study that assesses the nationwide potential of hydrothermal resources since Paschen et al. (2003). Furthermore, it is the first work, which considers the experience gained by the existing geothermal power plants in Germany for evaluating the technical and economic potential.

However, every assessment of geothermal resources requires the important choice concerning the definition of the potential categories, since there is a wide range of possible classifications concerning their characterization, as discussed in the review by Falcone et al. (2013). The classic approach for fossil resources by defining the categories resources and reserves is only limited applicable to geothermal resources. Rybach (2015) presents five potential definitions for the classification of geothermal resources. He defines the theoretical, technical, economic, sustainable and developed potential. One the one hand, these categories are intuitive and therefor straightforward to interpret also for non-specialist readers. On the other hand, results from different studies cannot easily be compared, since slightly deviating definitions may be applied by different authors due to the lack of clear guidelines.

To face this issue, the development of a clear guideline for the evaluation of geothermal resources was initiated several years ago. The United Nations Framework Classification (UNFC) on fossil energy and mineral reserves and resources 2009, which is an universally accepted evaluation scheme for the categorization of fossil energies and minerals, is currently adapted for the classification of geothermal resources (UNECE, 2016). However, currently the framework is only applied for single projects or smaller regions so far and additional guidelines for the exact execution of the different steps are still under development (Agemar et al., 2018).

The objective of this study is to evaluate the potential of the South German Molasse Basin for combined heat and power generation by means of the UNFC framework. This paper is one of the first studies to apply the new framework to a larger region and was not written by researchers, who contributed to the development process of the guidelines. Therefore, the usage of the UNFC framework is evaluated with respect to its applicability and comprehensibility for researches, which have no knowledge of the development progress and internal discussions of the working group. Additionally, the study compares and discusses the results of the UNFC framework and the study by Eyerer et al. (2017b), who applied the methodology of Rybach (2015).   .

2. THE UNFC-2009 CLASSIFICATION

The UNFC-2009 framework classifies geothermal resources by the application of three axes. These three axes *E*, *F* and *G* represent following fundamental categories:

- **E:** Degree of favourability
- **F:** Maturity of studies
- **G:** Level of confidence

The *E* axis describes the commercial viability of a project considering the social and economic conditions. The feasibility of extraction of the geothermal resources is characterized by the *F* axis. The *G* axis categorises the significant uncertainties affecting the estimated quantities.

The exact specification of the different categories can be found in UNECE (2016). Additionally, a detailed description about the development process as well as the application of the UNFC-2009 is presented by Falcone (2015) and Conti (2017).

The main source for examples for the application of the UNFC-2009 are 14 case studies, published by the UNECE Expert Group on Resource Classification in 2017 (UNECE, 2017). However, most of the case studies are referring to the classification of single projects or smaller fields. The most relevant work for the evaluation of a larger region is the case study "*Dutch Rotliegend Play Area – Nationwide*" (UNECE, 2017) and is therefore applied as a reference work for the following study.

3. INPUT DATA

The following section describes the different steps and input data for the assessment of the potential. This work focuses on the potential of geothermal resources for combined heat and power generation. Therefore, projects and resources with an (expected) brine temperature below 100°C are not considered within the following assessment. In general, the application of the UNFC-2009 may be carried out by a deterministic or probabilistic estimation (see UNECE 2017). Due to the high level of uncertainty concerning the assessment of a large region as well as analogue to the reference case study, this work applies a probabilistic estimate type. If not further stated, a normal distribution is assumed for the input parameters.

In the first step, the actual projects in operation are evaluated. Considering only projects with a brine temperature above 100°C, currently eleven projects are in operation within the SMB. While two of the projects are only producing power and five of them are pure heat projects, four projects are CHP plants.

Table 1 and 2 list the results of the evaluation of the existing plants. For a compact representation, Roman numbers within these tables classify the projects. Table A.1 in the appendix presents the names of the actual projects.

Since these projects are in operation, it is assumed that "*extraction and sale is economic on the basis of current market conditions*", which corresponds to the *E1* definition. However, the subcategory of the *E1* class differs between the heat and power plants. The provision of heat for district heating networks is not supported by any major governmental support. Thus, the thermal power is classified as *E1.1*, as this category represents, that extraction and sale is economic on the basis of current market conditions. The power generation is currently strongly supported by the guaranteed feed-in tariff. Therefore, the power plants are classified as *E1.2*, since the economy of the project is relying on governmental support. Since extraction is currently taking place, all projects are classified as *F.1.1*. In Germany, the entitlement for exploiting a geothermal claim is given for 50 years by authorities (Agemar et al., 2018). Indeed it might be, that either the lifetime of the boreholes or the allowance concerning the water law might reduce the actual lifetime in exceptional individual cases, however it appears reasonable to assume that the remaining period of the claim license can be used to determine the remaining lifetime of the heat projects. Concerning the power generation, a slightly different situation applies due to the guaranteed feed-in tariff for 20 years. Therefore, the categorization with *E1.2* is only valid for this period. Since currently no reliable statements about the economic performance of geothermal power plants can be postulated for ten years or more within the future, the classification changes from E1.2 to *E3* (*"economic viability of extraction cannot be determined due to insufficient information")* after the 20 years of feed-in tariff. The current installed thermal and electrical power is used as the *best* scenario. The *low* and *high* cases represent possible scenarios with 25 % lower and 10 % higher power, respectively. For assessing the full load hours, the average values presented in Eyerer et al. (2017b) are taken into account for the *best* scenario, while 500 h/a more or less are considered for the *low* and *high* case due to the possibility of negative as well as positive developments concerning the plant's reliability.

As described before, the economic operation of the power plants is only ensured for the first 20 years. Thus, after the guaranteed feed-in tariff ends, several scenarios might be possible. Concerning the power generation it might be either, that no power production takes place after the first twenty years as the future market condition would make an operation uneconomic. However, it might also be the case, that operation would be still economical and the power plant operates further on with full or half power. It is also possible that parts or all of the heat flow used to generate electricity may be used to provide additional heat for the district heating network. For the CHP projects is it assumed, that even for the *low* case a certain additional amount of heat is provided to the district heating network due to the expected growth of the networks. The *best* and *high* cases represent the scenarios that half or all of the heat flow is used for power generation, respectively.

Table 1: Listing of resource estimates per project based on installed thermal power and load hour estimates. Class: E1.1; F1.1; G1, 2, 3.

Project	**Power estimate [MW_{th}]**			**Full load hours [h/a]**			**Remaining lifetime [a]**	**Energy estimated over project lifetime [PJ_{th}]**		
	Low	Best	High	Low	Best	High		P90	P50	P10
I_{th}	28.5	38	41.8	1550	2050	2550	38	6.6	10.7	13.9
II_{th}	30	40	44	1550	2050	2550	42	7.7	12.4	16.1
III_{th}	11.6	15.5	17	1550	2050	2550	43	3.1	4.9	6.4
IV_{th}	10,5	14	15.4	1550	2050	2550	43	2.8	4.4	5.8
V_{th}	22.9	30.6	33.6	1550	2050	2550	44	6.2	9.9	12.9
VI_{th}	3	4	4.4	1550	2050	2550	45	0.8	1.3	1.7
VII_{th}	26,25	35	38.5	1550	2050	2550	45	7.3	11.6	15.1
$VIII_{th}$	9	12	13.2	1550	2050	2550	45	2.5	4.0	5.2
IX_{th}	18.3	24.5	26.9	1550	2050	2550	50	5.6	9.0	11.8
							Sum:	42.6	68.3	88.8

I_{th}: Unterhaching; II_{th}: Oberhaching; III_{th}: Pullach; IV_{th}: Waldkraiburg; V_{th}: Kirchweidach; VI_{th}: Sauerlach; VII_{th}: Taufkirchen; $VIII_{th}$: Traunreut; IX_{th}: Holzkirchen

Table 2: Listing of resource estimates per project based on installed electrical power and load hour estimates. Class: E1.2; F1.1; G1, 2, 3.

Project	**Power estimate [MW_{el}]**			**Full load hours [h/a]**			**Remaining lifetime [a]**	**Energy estimated over project lifetime [PJ_{el}]**		
	Low	Best	High	Low	Best	High		P90	P50	P10
I_{el}	4.1	5.5	6.1	6950	7450	7950	10	1.1	1.5	1.6
II_{el}	4.1	5.5	6.1	6950	7450	7950	14	1.6	2.1	2.3
III_{el}	3.2	4.3	4.7	6950	7450	7950	15	1.3	1.7	1.9
IV_{el}	3.8	5	5.5	6950	7450	7950	15	1.5	2.0	2.2
V_{el}	3.2	4,3	4.7	6950	7450	7950	15	1.3	1.7	1.9
VI_{el}	3.0	4.1	4.5	6950	7450	7950	15	1.3	1.6	1.8
							Sum:	8.2	10.7	11.9

I_{el}: Dürnharr; II_{el}; Kirchstockach; III_{el}: Oberhaching; IV_{el}: Sauerlach; V_{el}: Taufkirchen; VI_{el}: Traunreut

It must be noted, that there is an interference between the scenarios, as it is technical not feasible that the high scenario is reached simultaneously for the heat and power generation. This issue is discussed in detail in Chapter 4. The results for the future development of the power plants after the first 20 years of operation are listed in Table 3 and 4. Due to the uncertainty concerning the market conditions, these scenarios are classified as *E3*. On the F axis, they are determined as *F1.3*, since the feasibility of the project is demonstrated by the current operation of the projects.

Next to the existing plants, three further projects are currently within drilling or construction phase. In Holzkirchen, the supply of heat for the district heating network has already started, while the ORC is currently under construction. In Garching a. d. Alz the drilling is completed successfully and the heat and power generation is currently within the planning phase. Within the city of Munich, currently one of the biggest geothermal projects in Europe is within the drilling phase. Six boreholes are planned and the project should provide 50 MW$_{th}$ for the city's district heating network. Currently two boreholes are completed and successful pump tests were carried out. Due to the positive pump tests as well as the ongoing drilling or constructing works, these three projects are defined as *E2*, since '*extraction and sale is expected to become economically viable in the foreseeable future*". Furthermore, since for all three projects successful pump tests were performed, they are classified as *F1.3***.** The results for these projects are listed in Table 5 and 6.

Table 3: Listing of resource estimates per project based on the potential further usage of the existing power plants for heat supply. Class: E3; F1.3; G1, 2, 3.

Project	**Power estimate [MW$_{th}$]**			**Full load hours [h/a]**			**Remaining lifetime [a]**	**Energy estimated over project lifetime [PJ$_{th}$]**		
	Low	Best	High	Low	Best	High		P90	P50	P10
$\mathrm{I}_{\mathrm{el,after20,th}}$	0	27.5	55	0	2050	2550	30	0	6.1	14.4
$\mathrm{II}_{\mathrm{el,after20,th}}$	0	27.5	55	0	2050	2550	30	0	6.1	14.4
$\mathrm{III}_{\mathrm{el,after20,th}}$	5.3	21.5	43	1550	2050	2550	30	1.0	4.8	11.3
$\mathrm{IV}_{\mathrm{el,after20,th}}$	6.2	25	50	1550	2050	2550	30	1.2	5.5	13.1
$\mathrm{V}_{\mathrm{el,after20,th}}$	5.3	21.5	43	1550	2050	2550	30	1.0	4.8	11.3
$\mathrm{VI}_{\mathrm{el,after20,th}}$	6.8	21	41	1550	2050	2550	30	0.9	4.5	10.7
							Sum:	4.1	31.8	75.1

Table 4: Listing of resource estimates per project based on the potential further usage of the existing power plants for power generation. Class: E3; F1.3; G1, 2, 3.

Project	**Power estimate [MW$_{el}$]**			**Full load hours [h/a]**			**Remaining lifetime [a]**	**Energy estimated over project lifetime [PJ$_{el}$]**		
	Low	Best	High	Low	Best	High		P90	P50	P10
$\mathrm{I}_{\mathrm{el,after20,el}}$	0	2.8	5.5	6950	7450	7950	30	0	2.1	5.0
$\mathrm{II}_{\mathrm{el,after20,el}}$	0	2.8	5.5	6950	7450	7950	30	0	2.1	5.0
$\mathrm{III}_{\mathrm{el,after20,el}}$	0	2.1	4.3	6950	7450	7950	30	0	1.6	3.7
$\mathrm{IV}_{\mathrm{el,after20,el}}$	0	2.5	5	6950	7450	7950	30	0	1.9	4.3
$\mathrm{V}_{\mathrm{el,after20,el}}$	0	2.1	4.3	6950	7450	7950	30	0	1.6	3.7
$\mathrm{VI}_{\mathrm{el,after20,el}}$	0	2.1	4.1	6950	7450	7950	30	0	1.5	3.7
			Sum:				**Sum:**	0	10.8	24.7

Table 5: Listing of resource estimates per exploration project based on installed thermal power and load hour estimates. Class: E2; F1.3; G1, 2, 3.

Project	**Power estimate [MW$_{th}$]**			**Full load hours [h/a]**			**Remaining lifetime [a]**	**Energy estimated over project lifetime [PJ$_{th}$]**		
	Low	Best	High	Low	Best	High		P90	P50	P10
$\mathrm{I}_{\mathrm{cons.,th}}$	25	50	62.5	1550	2050	2550	50	7.7	18.4	27.3
$\mathrm{II}_{\mathrm{cons.,th}}$	3.1	6.2	7.8	1550	2050	2550	50	1.0	2.3	3.4
							Sum:	8.6	20.7	30.6

$\mathrm{I}_{\mathrm{cons.,th}}$: München (Sendling); $\mathrm{II}_{\mathrm{cons.,th}}$: Garching a. d. Alz

Table 6: Listing of resource estimates per exploration project based on installed electrical power and load hour estimates. Class: E2; F1.3; G1, 2, 3.

Project	Power estimate [MW$_{el}$]			Full load hours [h/a]			Remaining lifetime [a]	Energy estimated over project lifetime [PJ$_{el}$]		
	Low	Best	High	Low	Best	High		P90	P50	P10
$I_{cons.,el}$	2.5	3.4	3.7	6950	7450	7950	20	1.4	1.8	2.0
$II_{cons.,el}$	2.6	3.5	3.8	6950	7450	7950	20	1.4	1.9	2.1
							Sum:	2.8	3.7	4.1

$I_{cons.,el}$: Holzkirchen; $II_{cons.,el}$: Garching a. d. Alz

Furthermore, also several unsuccessful drillings occurred within the SMB. Most of these projects, such as in Geretsried or Icking, were unsuccessfully due to too low brine flow rate for enabling an economic realization. Therefore, the projects are described by the *E3.3* class, as "*on the basis of realistic assumptions of future market conditions, it is currently considered that there are not reasonable prospects for economic extraction and sale in the foreseeable future*". In addition, due to the non-sufficient constant flow rate, these projects are classified as *F4*, since this categories classifies *"currently non-extractable quantities"*. As the characteristic of the projects are based on results of actual drillings, the level of confidence is high and therefore classified with *G1*. Therefore, the unsuccessful projects are described by *E3.3*, *F4*, *G1*. However, it is unclear whether (and if yes with which numerical value) these projects should be described with a numerical result, since in none of the existing case studies (UNECE, 2017) a project with a *F4* classification occurs. It might be a possible approach, to assume the expected power and full load hours for the calculation. However, this approach seems not meaningful, since it might be that a sufficient high flow rate may be achieved by a sidetrack of the existing borehole, which was however not carried out by the investor due to a too high financial risk. Thus, it is unclear to declare the complete expected resources of these projects with *F4* and *E3.3*, since a sidetrack might change their classification. Due to this lack of clarity concerning the numerical evaluation of unsuccessful projects, they are not represented by numerical results within the final summary of the results in Chapter 4.

In the last step, the potential of the overall resources of the SMB are evaluated. For the SMB, data from the research projects GeoMol are applied (Pfleiderer et al., 2016). The data provide the amount of heat within the geothermal resources per temperature class with a resolution of 5°C steps. Based on this theoretical potential, the amount of recoverable heat is calculated by considering the maximum possible geological extraction factor (Paschen et al., 2003; Eyerer et al., 2019b).

The next step is the assessment of the amount of electricity, which can be generated from the amount of recoverable heat. For this reason, a model function for the net system efficiency is applied, which was obtained based on the operational performance of the real geothermal power plants in Germany (Eyerer et al., 2017b). The model function is visualized in Figure 1.

$$\eta_{el,sys,net} = \frac{P_{el,gross} - P_{aux}}{\dot{m}_{brine}\,(h_{in} - h_{ref})} \qquad [1]$$

The function considers the complete auxiliary demand of the power plant (for the power plant itself as well as for the thermal water pump) and refers the available heat flow of the brine to a reference temperature of 15°C. Therefore, the system efficiency and the amount of recoverable heat are referred to the same ambient temperature and no further adjustments for temperature correction are required (Eyerer et al., 2019b). Since the model function is based on the performance of existing plants, the efficiency can be considered for the *low* case, since it is implausible to assume that future power plants would exhibit lower efficiencies than the current state of the art. For the best and high case, slightly higher efficiencies of 7.5 % and 15 % are assumed.

Furthermore, the model function of the net system efficiency considers the CHP characteristic of most of German geothermal power plants. Based on the average heat-to-power ratio of five, on average for each produced kWh$_{el}$ within a year, five kWh$_{th}$ are provided for district heating, based on the expectation that the future plants may exhibit the same average characteristic as the current CHP projects (Eyerer et al., 2017b).

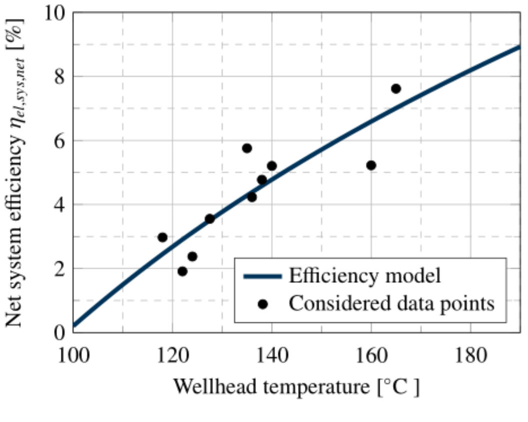

Figure 1: Model function of the net system efficiency based on the performance of operating German geothermal power plants (Eyerer et al., 2019b).

Flechtner and Aubele (2019) investigated the success rate of all geothermal drillings within the SMB. Their results reveal that for depths which are required for ensuring a possible CHP project (by a brine temperature of at least 100°C), 51 % of the drillings are successful, while 31 % of the projects are unsuccessful due to low yields and 18 % fail due to unsolvable drilling problems. Based on these findings, a possibility of discovery of 51 % is assumed for the *best* case, while slightly lower or higher values are chosen for the *low* and *high* case.

The input parameter for the estimation of the SMB's overall resources are summarized in Table 7. Thus, considering the classification analogue to the previous approach, again results for P90, P50 and P10 may be obtained. However, the UNFC-2009 states that potential geothermal energy sources should be classified by the *G4* category. Furthermore, when the category *G4* is used, it shall reflect the best estimate (UNECE, 2017). In addition, the framework specifies, that quantities which are reported in the G4 category are "un-risked" resources. By applying the possibility of discovery, a "risked resource estimate" is obtained.

3. RESULTS AND DISCUSSION

3.1 Results of the UNFC-2009 framework

The results of the previous steps are summarized in Table 8. The layout of the table is based on the layout of the "*Dutch Rotliegend Play Area – Nationwide*" case study. However, this case study considers only potential heat projects. The case study "*Insheim*", which investigates the CHP project within the Upper Rhine Valley in Germany, presents the results for the thermal and power generation in separated tables. However, the Insheim case focuses only one specific project and not on the assessment of a whole region. Therefore, the results are summarized in a table, which is an extension of the layout of the Rotliegend case.

Furthermore, based on the available case studies, it is partly unclear how to deal with the distinction between the electrical gross and net power for the special legal situation in Germany. Since the guaranteed feed-in tariff is paid for the amount of produced gross electricity, the plant operators purchase the electricity for the auxiliary demand from the public grid or from a small gas-fired CHP plant next to the geothermal plant (Eyerer et al., 2017b). For example, within the Insheim case study, the electrical gross power is considered for the calculation. While this might be acceptable from a plant owner's or financial investor's perspective, the focus on the gross power is not meaningful for a holistic evaluation of the resources. When evaluating the possible contribution of the geothermal energy for a region or a whole country (e.g. from a political perspective) it is mainly relevant, what net power this technology can provide. Therefore, when evaluating the potential geothermal resources, only the actual net output may be considered, as it is done within this work (cf. Eq. 1). Due to the described uncertainty, the gross and net power are listed for the assessment of the projects being already in operation or construction, while for the remaining reservoir only the net power is listed.

Table 7: Input parameter for the estimation of the potential geothermal resources of the SMB.

Temperature class [°C]	Recoverable Heat [PJ]	System net efficiency [%]			Possibility of discovery [-]		
		Low	Best	High	Low	Best	High
100 – 105	11,763	0.8%	0.8%	0.9%	0.41	0.51	0.61
105 - 110	13,963	1.4%	1.5%	1.6%	0.41	0.51	0.61
110 - 115	17,438	2.0%	2.1%	2.3%	0.41	0.51	0.61
115 - 120	14,610	2.6%	2.7%	2.9%	0.41	0.51	0.61
120 - 125	11,122	3.1%	3.3%	3.6%	0.41	0.51	0.61
125 - 130	14,689	3.6%	3.9%	4.2%	0.41	0.51	0.61
130 - 135	18,867	4.1%	4.4%	4.7%	0.41	0.51	0.61
135 - 140	27,554	4.6%	5.0%	5.3%	0.41	0.51	0.61
140 - 145	6,424	5.1%	5.5%	5.8%	0.41	0.51	0.61
145 - 150	2,693	5.5%	5.9%	6.4%	0.41	0.51	0.61
150 - 155	1,084	6.0%	6.4%	6.9%	0.41	0.51	0.61
155 - 160	56	6.4%	6.9%	7.3%	0.41	0.51	0.61
160 - 165	63	6.8%	7.3%	7.8%	0.41	0.51	0.61

Table 8: Summarizing results of the UNFC Classification for the SMB.

	Resource estimate			**Risked resource estimate**	
UNFC-2009 classification	**Thermal power [PJ_{th}]**	**Electric power [$PJ_{el.gross}$/$PJ_{el.net}$]**	**Possibility of discovery [%]**	**Thermal power [PJ_{th}]**	**Electric power [$PJ_{el.net}$]**
E1.1.F.1.1.G1+G2	68	-	-	68	-
E1.2.F1.1. G1+G2	-	11 / 6	-	-	6
E2 F1.2 G1+G2	21	4/ 2	-	21	2
E3 F1.3 G1+G2	32	11/ 6	-	32	6
E.3.2. F 3.2 G.4	24,070	- / 4,813	51	12,275	- / 2,455
Total risked resources				12,396	2,469

3.2 Critical discussion of the existing guidelines and interpretability of the UNFC-2009

In general, the UNFC-2009 is a suitable tool for improving the standardization of potential assessments and making results of different studies easily comparable. A clear classification framework may be also especially important for financial investors with respect to evaluate the composition of their portfolio and for institutions such as International Renewable Energy Agency (IRENA) or the International Geothermal Association (IGA) for evaluating the worldwide geothermal potential based on several studies dealing with a specific region or country.

However, as stated by Falcone and Beardsmore (2013) a common assessment and comparison framework is needed not only by investors and researches, but also by governments and consumers. Therefore, there are several possible aspects within the framework of the UNFC-2009, why the current methodology might be unfavourable concerning the latter two target audiences. Firstly, the interpretation might be challenging for readers, which are not familiar with the UNFC-2009 methodology. In comparison to terms such as technical or economic potential (cf. Rybach, 2015), the different classifications of the UNFC-2009 are more complex to understand and interpret. Secondly, when evaluating the potential of geothermal resources of a larger region, more information are necessary since that they are classified as E3.2 (*economic viability of extraction cannot yet be determined due to insufficient information*). Of course, this classification is correct by means of the UNCF-2009. However, from the exemplary perspective of a politician it is still crucial to have at least a very rough estimation about the expected economic performance of the resources, which might be represented by the expected Levelized Costs of Electricity. Based on the current UNFC-2009 framework, assessing highly important questions for decision makers, (such as concerning the potential role of geothermal energy within the future energy system or the necessary political subsidies for enabling economic feasible projects) cannot be answered. Therefore, with the current UNFC-2009 framework, potential assessments focusing on the technical and economic potential, such as for example by Eyerer et al. (2017b) cannot be omitted, as some important questions cannot be addressed with the UNFC alone. Thus, on long term it might be useful to consider the development of additional recommendations concerning these issues. Of course, such a development would require a tremendous effort, but it would provide also highly insightful and comparable information concerning the future role and economic performance of geothermal energy.

Furthermore, against the background of geothermal energy as a renewable energy source, a clear focus should be laid on the issue of sustainability when the potential of a larger region is classified. The extraction of heat from the geothermal resources is counteracted by a certain regeneration due to the geothermal heat flux. If the heat is extracted with the same flux as it is regenerated, the operation of the plant might be endless in theory. However, because of the low regenerative heat flow, this is not technical feasible in praxis, and the brine temperature may decrease over the project lifetime. Once the operation is stopped, the reservoir requires a certain regeneration time to achieve the original brine temperature again. For example, Wenderoth et al. (2005) investigated the regeneration behaviour of a geothermal doublet within the SMB. The results reveal that after end of operation it takes 1,000 years to reach at least 92 % of the original temperature of the reservoir. To face this issue, the work by Eyerer et al. (2017b) assumed a regeneration period of 1,000 years. In order to ensure the utilization of the geothermal resources as a renewable energy source, the exploitation period must be at least equal to the regeneration period. As a consequence, not the complete geothermal resources can be utilized within a short time period such as 50 or 100 years if geothermal energy should still be considered as a renewable energy source. While the issue of ensuring a sustainable utilization of geothermal resources might be not highly important for financial investors, it should be considered in the overall assessment from a political and social perspective. Therefore, a stronger focus on the topic of sustainable utilization appears to be important for enhanced guidelines concerning the UNFC-2009 application for larger regions.

Furthermore, the accurate handling of CHP projects for the utilization of the potential geothermal resources is partly unclear based on the available information and guidelines. Within this work, a constant heat-to-power ratio is assumed as a kind of *best* case, which is considered for the calculation of the *G4* category. The assumption of a constant heat-to-power ratio enables an easy calculation of the *best* case, since it is based on the assumption that the future projects will exhibit the same characteristic as the current CHP projects. However, there are also possible enhanced approaches conceivable. A possible approach would be to assume different probability distribution curves for different temperature ranges, as shown exemplary in Figure 2. In general, such an approach can be incorporated easily within a probabilistic estimation of the UNFC-2009. However, within this step, several uncertainties concerning the exact assumptions and methodology might occur. Therefore, without specified guidelines for the handling of the uncertainty about the characteristic of future CHP projects, it might be that different authors base their calculations on slightly different methodologies.

The same applies partly for the presentation of the results of CHP scenarios. As discussed in the previous chapter, there are several scenarios possible concerning the utilization of the existing geothermal power plants, after the guaranteed feed-in tariff ends. The results in Table 3 and 4 represent the scenarios for increased heat supply for the district heating and the continuous operation of the power plant. However, the *high* cases within both tables cannot be achieved simultaneously. Since the case for the district heating represents that all of the available heat flow from the former power plant is now used for heat supply and the case for the power generation considers a scenario in which the power plant operators at full power also after the first 20 years. Again, there are of course several profound possibilities to present this interference within the results, however this should not be decided individually by the authors, but clearly presented by the UNFC-2009.

4. CONCLUSIONS

This work provides a detailed assessment of the geothermal potential of the South German Molasse Basin, which is one of the most dynamic geothermal regions within Europe. On the one hand, the application of the UNFC-2009 framework enables a clear evaluation of the SMB’s resources and enables also a good comparability with other potential assessments, which were also carried out using the UNFC-2009. On the other hand, several limitations or unclarities of the current UNFC-2009 guidelines are identified with respect to its application for large-scale regions for CHP purposes. Based on these findings, several potential improvements are identified for the case that the UNFC-2009 framework shall become a common instrument for the potential evaluation of larger geothermal resources in the future.

In short, following conclusions and remarks can be postulated:

- The available guidelines as well as case studies provide a profound general insight within the application of the UNFC-2009 framework. Especially when only specific projects and/or pure heat and power utilization are evaluated, the available information provide a sufficient information for a successful implementation of the framework.

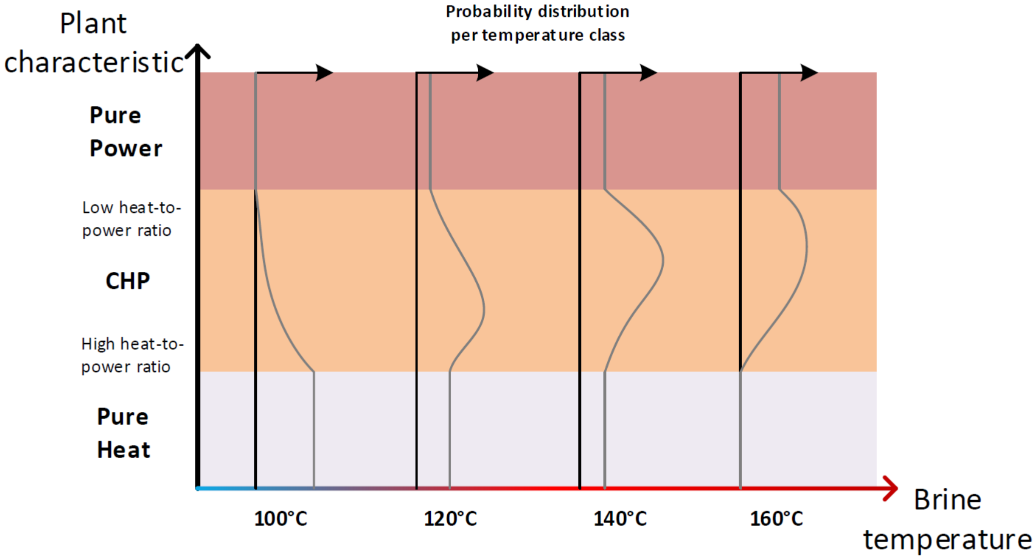

Figure 2: Potential approach for enhanced input parameter for the estimation of the utilization characteristic

- When evaluating large-scale regions, an additional assessment level should be established with respect to the sustainability character of geothermal energy utilization.
- A clearer statement on the handling of gross and net output might be helpful and could lead to improved consistency of further studies.
- A clear explanation of the numerical assessment of unsuccessful projects (*F4* classification) should be included in future case studies.
- Improved guideline concerning the classification of large-scale reservoirs by CHP projects should be provided. Since the provision of official case studies is a valuable tool for researches, an additional case study concerning the CHP utilization of larger regions would increase the certainty of further authors concerning the accuracy of their work.
- A clear statement about the accurate representation of the interference between possible scenarios for CHP utilization within the results should be presented.

REFERENCES

Agemar, T., Weber, J., Moeck, I. S., 2018. Assessment and public reporting of geothermal resources in germany: Review and outlook. Energies 11 (2).

BVG (German Geothermal Association), 2019. Geothermie in Zahlen (Statistics of the current installed geothermal projects). URL: https://www.geothermie.de/geothermie/geothermie-in-zahlen.html

Conti, P. 2017. Application of UNFC-2009 to Geothermal Energy Resources: Presented by Paolo Conti on behalf of the Task Force Application UNFC-2009 to Renewable Energy and the IGA Resources and Reserves Committee.

Dawo, F., Wieland, C., Spliethoff, H., 2019. Kalina power plant part load modeling: Comparison of different approaches to model part load behavior and validation on real operating data. Energy 174, 625-637.

Eyerer, S., Hofbauer, S., Schiffechner, C., Wieland, C., Spliethoff, H., 2017a. Potenzial der Geothermie im deutschen Energiesystem. BWK Das Energie-Fachmagazin 69 (10), 62–65.

Eyerer, S., Schiffechner, C., Hofbauer, S., Wieland, C., et al., 2017b. Potential der hydrothermalen Geothermie zur Stromerzeugung in Deutschland. Technical report., Lehrstuhl für Energiesysteme. URL: https://mediatum.ub.tum.de/1360572

Eyerer, S., Dawo, F., Kaindl, J., Wieland, C., Spliethoff, H., 2019a. Experimental investigation of modern ORC working fluids R1224yd (Z) and R1233zd (E) as replacements for R245fa. Applied Energy 240, 946-963.

Eyerer, S., Schiffechner, C., Hofbauer, S., Bauer, W., Wieland, C., Spliethoff, H., 2019b. Combined heat and power from hydrothermal geothermal resources in Germany: An assessment of the potential. Submitted to Renewable & Sustainable Energy Reviews.

Falcone, G., Beardsmore, G., 2013. Including Geothermal Energy within a Consistent Framework Classification for Renewable and Non-Renewable Energy Resources. Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.

Falcone, G., Gnoni, A., Harrison, B., Alimonti, C., 2013. Classification and Reporting Requirements for Geothermal Resources. European Geothermal Congress 2013.

Falcone, G., 2015. Proposal of a consistent framework to integrate geothermal potential classification with energy extraction. Geothermal Energy Science 3 (1), 7–11.

Flechtner F. and Aubele K., 2019: A brief stocktake of the deep geothermal projects in Bavaria, Germany (2018). PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2019.

Heberle, F., Schiffechner, C., Brüggemann, D., 2016. Life cycle assessment of organic rankine cycles for geothermal power generation considering low gwp working fluids. Geothermics 64, 392–400.

Paschen, H., Oertel, D., Grünwald, R., 2003. Möglichkeiten geothermischer Stromerzeugung in Deutschland.

Pfleiderer, S. H., Götzl, G., Bottig, M., Brüstle, A. K., Porpaczy, C., Schreilechner, M., Eichkitz, C., Jud, M., Sachsenhofer, R., Zosseder, K., Casper, S., Goldbrunner, J., Kriegl, C., Kolmer, C., 2016. GeoMol - geologische 3DModellierung des österreichischen Molassebeckens und Anwendungen in der Hydrogeologie und Geothermie im Grenzgebiet von Oberösterreich und Bayern. Abhandlungen der Geologischen Bundesanstalt.

Quoilin, S., Van Den Broek, M., Declaye, S., Dewallef, P., Lemort, V., 2013. Techno-economic survey of organic rankine cycle (orc) systems. Renewable and Sustainable Energy Reviews 22, 168–186.

Rybach, L., 2015. Classification of geothermal resources by potential. Geothermal Energy Science 3 (1), 13–17.

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (lca) of electricity generation technologies: Overview, comparability and limitations. Renewable and sustainable energy reviews 28, 555–565.

UNECE (United Nations Economic Commission for Europe), 2016. Specifications for the application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to Geothermal Energy Resources. United Nations & International Geothermal Association.

UNECE (United Nations Economic Commission for Europe), 2017. Application of the United Nations Framework Classication for Resources (UNFC) to Geothermal Energy Resources -Selected case studies. Energy series no. 51. United Nations, New York and Geneva.

Wenderoth, F., Fritzer, T., Gropius, M., Huber, B., Schubert, A., 2005. Numerische 3D-Modellierung eines geohydrothermalen Dublettenbetriebs im Malmkarst. Tiefe Geothermie Strom und W¨arme 48, 16–21.

Wieland, C., Meinel, D., Eyerer, S., Spliethoff , H., 2016. Innovative CHP concept for ORC and its benefit compared to conventional concepts. Applied Energy 183, 478–490.

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Appendix

Table A.1: Classification of the existing and exploration projects.

Location	Thermal project	Power project
Unterhaching	I_{th}	-
Oberhaching	II_{th}	III_{el}
Pullach	III_{th}	-
Waldkraiburg	IV_{th}	-
Kirchweidach	V_{th}	-
Sauerlach	VI_{th}	IV_{el}
Taufkirchen	VII_{th}	V_{el}
Traunreut	$VIII_{th}$	VI_{el}
Holzkirchen	IX_{th}	$I_{cons.,el}$
Dürnhaar	-	I_{el}
Kirchstockach	-	II_{el}
München (Sendling)	$I_{cons., th}$	-
Garching a. d. Alz	$II_{cons.,th}$	$II_{cons.,el}$