Supplementary data to

# Potential of Low-Temperature Aquifer Thermal Energy Storage (LT-ATES) in Germany

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## SD1. Hydrogeological and climatic data

Table SD1: Data sets used for the potential study of ATES in Germany.

| | Criterion | Description | Data source | Comments | Resolution or scale |
|---|---|---|---|---|---|
| time-independent | Aquifer productivity | Productivity of groundwater resources in Germany | BGR (2019a) | - | Vector data. Scale of the map originally published in print: 1:1,000,000 |
| time-independent | Iron and manganese contents in groundwater | Areas with increased Fe or Mn contents in the groundwater | BGR (2019b) | - | Vector data. Scale of the map originally published in print: 1:1,000,000 |
| time-independent | Groundwater flow velocity | Mean groundwater velocity | Wendland et al. (1993) | Data available for most areas in Germany with an unconsolidated shallow subsurface. The data set was manually digitized and georeferenced, since no digital version is available. | 3 km × 3 km. Scale of the map originally published in print: 1:3,500,000 |
| time-dependent | Daily surface temperatures | WettReg2010 data set with daily surface temperatures (1961 - 2100) for 383 climate stations in Germany | Kreienkamp et al. (2010) | Basis for calculating heating and cooling degree days. | Limited by the number of weather stations used for interpolation (383). Digital terrain model used in cokriging: 1 km × 1 km |

## SD2. Digital terrain model of Germany

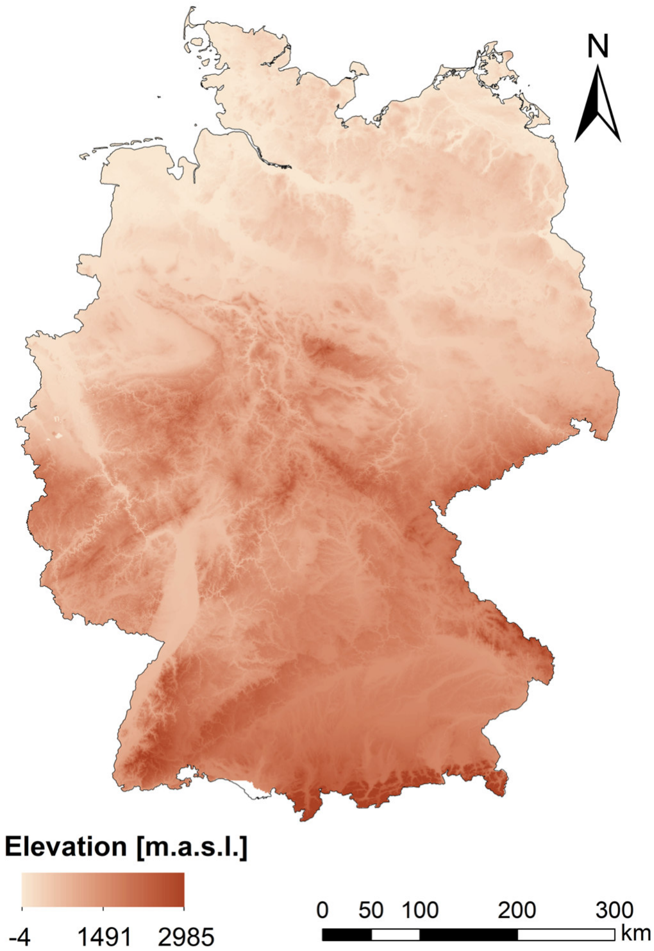


Fig. SD2: Digital terrain model of Germany (DGM1000, modified from BKG (2021)).

## SD3. Consistency check of the pairwise comparison matrix

The consistency check is used to identify possible contradictions in the execution of the pairwise comparisons and is based on calculating the so-called consistency ratio *CR*. The approach described here is based on Bunruamkaew (2012) and Lu et al. (2019).

First, the consistency vector $v$ is calculated from the comparison matrix $A$ of the $n$ criteria and the vector $w$ of the weighting factors as:

$$v = A \cdot w$$

with

$$w = \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix}$$

and has the form

$$v = \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix}$$

The entries $v_i$ of the consistency vector $v$ are divided by the corresponding entries $w_i$ of the weighting vector $w$:

$$c_i = \frac{v_i}{w_i} \qquad \text{with } i = 1,2,\dots,n$$

The so calculated consistency measure $c_i$ can be used to determine an approximate solution of the principle eigenvalue $\lambda_{max}$ of the comparison matrix $A$:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} c_i$$

The consistency of matrix $A$ can be assessed using the consistency index $CI$, which is a measure of deviation from perfect consistency (Drobne and Lisec 2009). It is calculated as:

$$CI = \frac{\lambda_{max} - n}{n-1}$$

The final step of the consistency check consists of calculating the consistency ratio $CR$ which is defined as:

$$CR = \frac{CI}{RI}$$

$RI$ represents a random index, which corresponds to the consistency index of a comparison matrix of randomly generated pairwise comparison of $n$ criteria. The value of $RI$ depends on the criteria number $n$ and can be found in table SD3.1.

Table SD3.1: Values of $RI$ in dependence of $n$ according to Saaty (1980) and Lu et al. (2019).

| ***n*** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ***RI*** | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 |

A widely used threshold value for *CR* is 0.10, which is also adopted in this study. *CR* values below this threshold indicate an acceptable consistency of the pairwise comparison matrix (Lu et al. 2019; Chen et al. 2010). *CR* values greater than 0.10, on the other hand, require the reevaluation of the assigned relative weightings.

Table SD3.2 shows the *CR* values for the reference pairwise comparison matrix (Table 4) that is used to create the ATES potential map of Germany (Fig. 4), as well as the *CR* values of each of the three alternative weighting schemes (Table SD4). All *CR* values are below 0.10 and thus the respective criteria weighting factors are suitable to be used for further steps in the MCDA.

Table SD3.2: Values of *CR* for the reference and alternative pairwise comparison matrices.

| | **Reference** | **Alternative 1** | **Alternative 2** | **Alternative 3** |
|---|---|---|---|---|
| ***CR*** | 0.06 | 0.004 | 0.09 | 0.04 |

## SD4. Alternative weighting schemes

Table SD4: Pairwise comparison matrices and weighting factors representing three alternative perspectives (A1, A2, A3) on the topic of ATES.

| | **Aquifer productivity** | | | **Iron and manganese contents in groundwater** | | | **Groundwater flow velocity** | | | **Ratio CDDs/HDDs** | | | **Weighting factor** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A1** | **A2** | **A3** | **A1** | **A2** | **A3** | **A1** | **A2** | **A3** | **A1** | **A2** | **A3** | **A1** | **A2** | **A3** |
| **Aquifer productivity** | 1 | 1 | 1 | 2 | 7 | 7 | 3 | 3 | 1 | 3 | 1/3 | 3 | 0.45 | 0.31 | 0.39 |
| **Iron and manganese contents in groundwater** | 1/2 | 1/7 | 1/7 | 1 | 1 | 1 | 2 | 1/3 | 1/8 | 2 | 1/5 | 1/7 | 0.26 | 0.06 | 0.04 |
| **Groundwater flow velocity** | 1/3 | 1/3 | 1 | 1/2 | 3 | 8 | 1 | 1 | 1 | 1 | 1/3 | 2 | 0.14 | 0.14 | 0.36 |
| **Ratio CDDs/HDDs** | 1/3 | 3 | 1/3 | 1/2 | 5 | 7 | 1 | 3 | 1/2 | 1 | 1 | 1 | 0.14 | 0.48 | 0.20 |

**SD5. Heating Degree Days for 2021-2050 and corresponding cokriging prediction standard error**

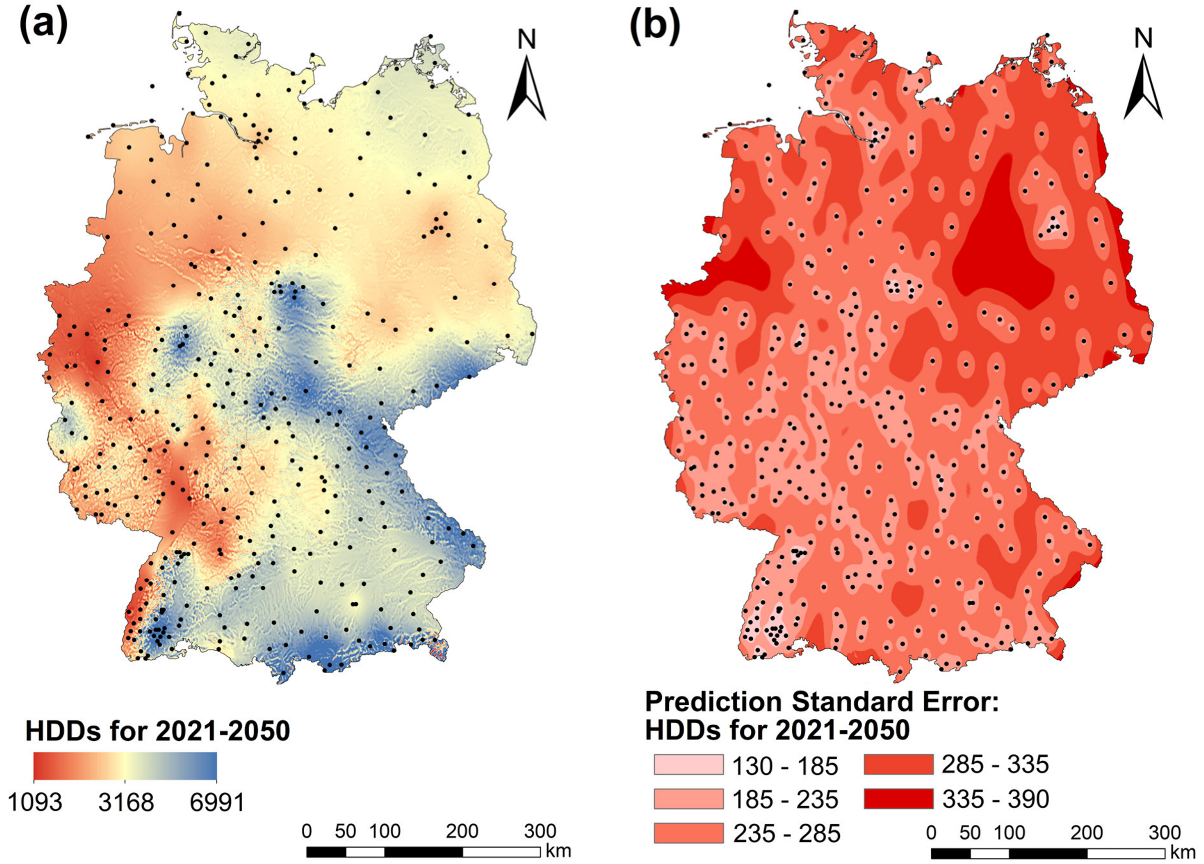


Fig. SD5: HDDs for 2021-2050: (a) Germany-wide HDD values interpolated between 383 weather stations (black marks) via cokriging, (b) Prediction standard error (i.e. standard deviation) of the cokriging interpolation.

## SD6. Change of mean degree days ratio for all time periods

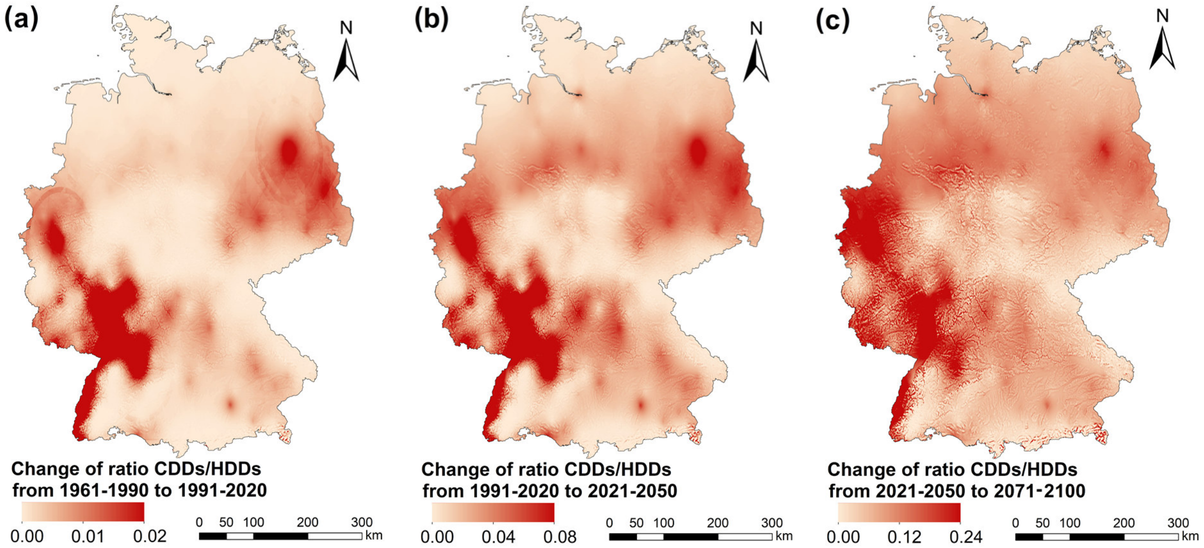


Fig. SD6: Change of mean ratio of CDDs to HDDs: (a) From *far past* (1961-1990) to *near past* (1991-2020), (b) from *near past* to *near future* (2021-2050), (c) from *near future* to *far future* (2071-2100).

## SD7. Alternative ATES suitability potential maps of Germany for 2021-2050

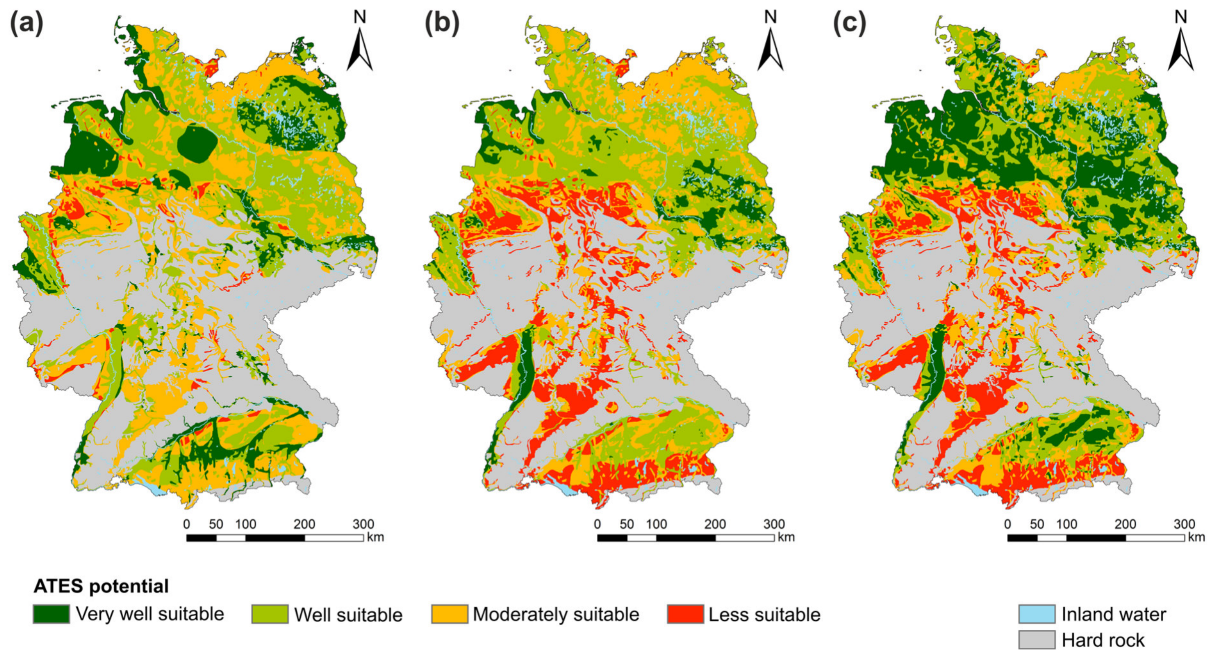


Fig. SD7: ATES suitability potential in Germany for the period *near future* (2021-2050) based on the three alternative weighting schemes: (a) Alternative 1, (b) Alternative 2, (c) Alternative 3.

## References


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