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Low-carbon lithium extraction makes deep geothermal plants cost-competitive in future energy systems

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ABSTRACT

Lithium is a critical material for the energy transition, but conventional procurement methods have significant environmental impacts. In this study, we utilize regional energy system optimizations to investigate the techno-economic potential of the low-carbon alternative of direct lithium extraction in deep geothermal plants. We show that geothermal plants will become cost-competitive in conjunction with lithium extraction, even under unfavorable conditions and partially displace photovoltaics, wind power, and storage from future renewable energy systems. Our analysis indicates that the deployment of 33 deep geothermal plants in municipalities in the Upper Rhine Graben area in Germany could provide enough lithium to produce about 1.2 million electric vehicle battery packs per year, equivalent to 70% of today's annual electric vehicle registrations in the European Union. As this number represents only a small fraction of the techno-economic potential in Germany, this lithium extraction process could offer significant environmental benefits. High potential for mass application also exists in other countries, such as the United States, United Kingdom, France, and Italy, highlighting the importance of further research and development of this technology.

1. Introduction

Lithium is crucial for the transition to greenhouse gas neutral energy systems. In 2019, over 60% of lithium produced was utilized for the manufacturing of lithium-ion batteries, the compact and high-density energy storage devices for low-carbon-emission electric vehicles and secondary storage media for renewable energy sources like solar and wind [1,2]. In 2 °C compatible scenarios, today's global lithium demand would be expected to grow by another 500% by 2050 [3].

However, established lithium extraction procedures like hardrock mining are highly carbon-intensive and contribute to air and water pollution, require large amounts of water and land, and are associated with human rights violations and poor worker protection [4]. With roughly 90% of lithium extraction taking place in Australia, Chile and China, and almost 100% of its processing occurring in China, Chile and Argentina, most other countries in the world are completely dependent on lithium imports [5]. Increased production and diversification of lithium supply are needed to meet anticipated demand and improve mineral security, whereas sustainable extraction methods are required to reduce carbon intensity and environmental impacts [6,7].

One promising sustainable extraction option that involves reduced water and land footprints is hybrid geothermal plants, which combine deep geothermal power and heat production with low-carbon direct lithium extraction (DLE) [8]. Currently, pilot projects utilizing this technology are being developed in the Upper Rhine Graben (URG) in France [9] and Germany [10], Cornwall in the United Kingdom [8], and the Salton Sea in California, United States [11]. From an economic perspective, deep geothermal energy is not yet viable in low- to intermediate-enthalpy regions such as Germany [12,13] and thus not competitive with other renewable energy sources. In contrast to low-cost photovoltaics [14] and wind energy [15,16], future cost reductions are expected to be fairly low [17]. In view of the wide range of possible applications and rising lithium prices [5,18,19], dispatchable deep geothermal systems could yet play a major role in future energy systems. To assess this requires integrated energy system analysis that involves geothermal plants together with DLE.

Previous studies on lithium extraction from geothermal brines have focused on technical and economic potential, especially for the Salton Sea Known Geothermal Resource Area (KGRA) [20–22], supply chain impacts of increased lithium supply [23], geochemical characteristics of geothermal brines in Germany (Molasse Basin [24], Upper Rhine Graben [25,26] and North German Basin [27–29]), and environmental impacts of lithium extraction [30,31].

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Only a few studies have incorporated deep geothermal systems into techno-economic analyses of decentralized energy systems. For example, the studies by Marty et al. [32], Weinand et al. [33] and Molar-Cruz et al. [34] focus on the utilization of deep geothermal heat in district heating networks. While Marty et al. [32] and Weinand et al. [33] optimize the heat supply by a geothermal plant for single commercial consumers or communities, Molar-Cruz et al. [34] optimize large-scale district heating networks with several plants and consumers for a federal state (Bavaria, Germany). Østergaard et al. [35] and Østergaard and Lund [36] also consider only heat supply from geothermal plants, but in the context of holistic energy system simulations for the Danish municipalities of Aalborg and Frederikshavn, respectively. Further studies go beyond the sole heat consideration and include the simultaneous supply of electricity and heat in municipalities by deep geothermal sources. Weinand et al. show in energy system optimizations that simultaneous electricity and heat supply by deep geothermal energy can only be worthwhile in certain regions in Germany with favorable hydrothermal conditions [17] or if the municipalities are off-grid [12,37], i.e. do not have electricity and gas grid connections. Kleinebrahm et al. [38] also show in an energy system optimization for the German city of Karlsruhe with good hydrothermal conditions (130–160 °C) that the use of deep geothermal plants can reduce energy system costs. In addition, Moret et al. [39] demonstrate in an energy system optimization of the city of Lausanne, Switzerland, that in particular the combination of deep geothermal energy with biomass plants can be beneficial by using excess geothermal heat to increase the efficiency of biomass conversion processes. Furthermore, energy system optimization studies with deep geothermal as an option also exist for much larger regions than the municipalities considered in the articles above, for example, for Dutch regions in Sahoo et al. [40]. However, in addition to the often simplistic representation of the plants, none of the holistic energy system optimization studies to date have considered the option of direct lithium extraction in geothermal plants.

Therefore, this article is the first to examine the techno-economic implications of installing and operating deep geothermal systems with lithium extraction in decentralized energy systems. Thereby, we address the following research questions:

- Under what conditions are deep geothermal plants for providing electricity and heat cost-competitive with other renewable energy sources in future regional energy systems?
- How will the economics of the plants in these energy systems change if lithium is additionally extracted and sold, and which technologies will then be primarily displaced from the energy systems?
- How much low-carbon lithium could be extracted with large-scale deployment of many geothermal plants?

To answer these questions, we focus on the Upper Rhine Graben in Germany, whose brine lithium deposits are comparable to currently exploited evaporative brine and hard rock mining lithium operations [26,41]. An integrated energy system model, based on the open-source framework ETHOS.FINE [42], is extended to include hybrid geothermal plants (Section 2) and applied to optimize greenhouse gas-neutral energy systems of municipalities located in the Upper Rhine Graben in Germany for the year 2045 from a macroeconomic perspective (Section 3). Thus, based on expert evaluations of the key parameters of lithium extraction plants and through distinctive sensitivity analyses, we show the conditions under which deep geothermal energy with DLE will become an indispensable component of future energy systems. In Section 4, we discuss our findings in the context of the global energy transformation and derive conclusions.

2. Methods

In the methodology section, we first describe the energy system optimization framework used, on which the regional model for individual municipalities is based (Section 2.1). Subsequently, we address the key equations used to represent the geothermal plant (Section 2.2), as well as how hydrothermal temperatures and drilling are incorporated in the model (Section 2.3). Most of the techno-economic equations for heat and power supply as well as capital and operating costs of the geothermal plant are based on Weinand et al. [12] and Schlagermann [43]. Therefore, in the following we only show the most important equations or what was modeled differently than in Weinand et al. [12]. The implementation of the DLE plant is shown in Section 2.4 along with key cost assumptions.

2.1. Energy system optimization model

This study utilizes a municipal energy system optimization model, which is based on the open-source *Framework for Integrated Energy System Assessment* (ETHOS.FINE) Python package [42]. The model provides a framework for modeling, optimizing, and assessing regional energy systems using high-resolution generation and consumption data. The objective of the model is the minimization of total annual costs (TAC) for supplying all demand sectors of greenhouse gas-neutral municipal energy systems in 2045 while considering technical and environmental constraints. This means that we compare future energy systems based locally on 100% renewables and imports, i.e. supplied by intermittent renewable generation plus storage, base load technologies such as biomass or deep geothermal, and/or imports. Since only one year is optimized due to computational constraints [44,45] (as we optimize over 330 energy systems here), the pathways of the energy system transformations over several years are not considered in this study. The total annual system costs (TAC) are composed of the total annual costs of all built renewable power generation technologies (TAC_p), conversion technologies (TAC_c), and storage technologies (TAC_{st}), as well as sources/sinks (TAC_s), and are determined using each technology's per unit capital costs (CAPEX), annuity factor (AF), number of built installations (N), as well as operation and maintenance costs (OMF) as a fraction of the total capital cost (see Eqs. (1) and (2)).

$$TAC = \sum_{p\in P} TAC_p + \sum_{c\in C} TAC_c + \sum_{st\in ST} TAC_{st} + \sum_{s\in S} TAC_s \quad (1)$$

$$TAC_i = CAPEX_i \cdot N_i \cdot \left(AF_i + OMF_i\right) \qquad \forall i = p, c, st, s \quad (2)$$

The total costs of components may be negative, as revenues from sources/sinks are included in the operational costs (e.g., through electricity or lithium carbonate sales). Sources and sinks are components for which no conversion is considered in the optimization. For example, wind turbines and photovoltaic systems are considered as sources with generation time series, i.e. no conversion of wind energy or radiation is accounted for. Sinks are, for example, household energy demands that are not broken down further by conversion units (e.g., by special appliances). On the other hand, biomass CHP plants, for example, are defined as conversions, since the purchase of biomass is included as a cost in the optimization model. The optimization is performed from the perspective of a central planner with perfect foresight. Although the model can also be used for analyses at the NUTS-3 administrative level or higher, those presented in this work take place at the municipal level. The application of a hierarchical clustering approach with the *Time Series Aggregation Module* (TSAM) [46] with 60 periods and 16 segments enables the analysis of a high number of energy systems at an hourly resolution (8760 h) without significant accuracy losses (mean deviation in optimized total annual costs: 0.3%).

The optimization model includes onshore wind, rooftop photovoltaics (PV), open-field photovoltaics (OFPV), biomass, biogas, waste, and storage, and is extended by deep geothermal plants and the commodities of lithium and lithium carbonate (Li_2CO_3) (see Fig. 1). Regional potentials for rooftop and open-field PV, as well as wind, are determined using the *Tool for Regional Renewable Potentials* (TREP) [47]. Storage options include centrally and decentrally placed batteries, pit

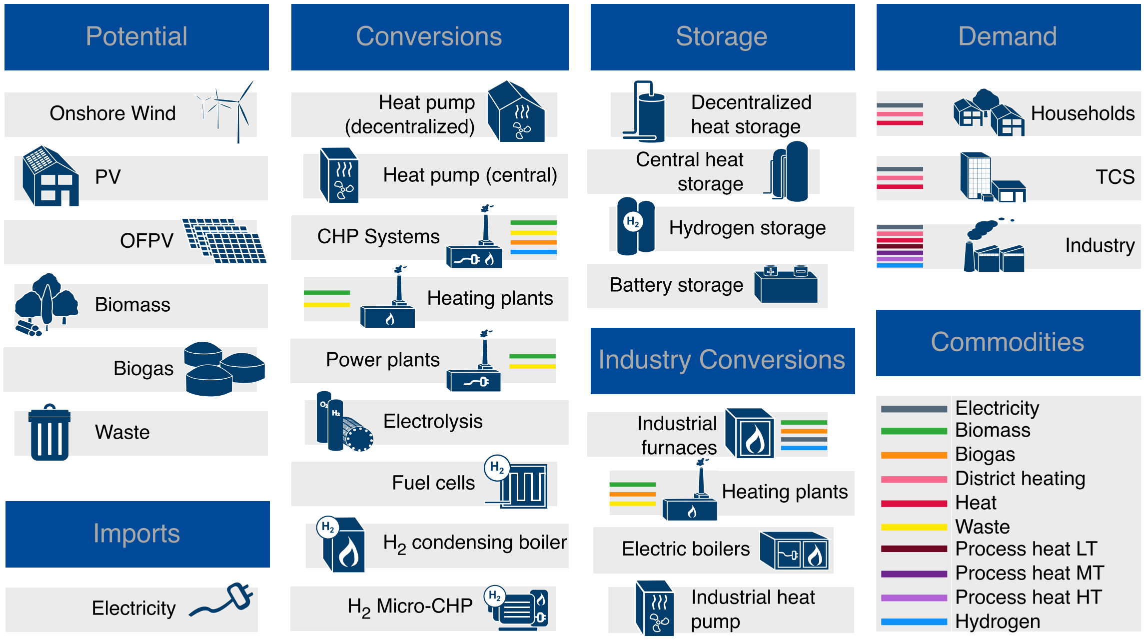

Fig. 1. Components of the energy system optimization model, including renewable potentials, imports, conversion, and storage technologies, as well as demand sectors. Commodities that are in demand or supplied are indicated with different colors, and only if the technology involves more than one.

storages as central heat storages, decentrally placed tanks for heat storage, and high-pressure tanks for storing hydrogen. Energy demand sinks are households, the trade commerce and service sector (TCS), and industry, as well as their respective commodities. Industrial energy demand consists of the demand for electricity, heat, and process heat. Process heat is implemented in three different forms: low-temperature for up to 100 °C, medium-temperature for between 100 and 500 °C, and high-temperature for processes above 500 °C. For the regional demand time series, top-down demand data for each sector [48,49] is regionalized based on employment, population, and CO_2 emissions data [50]. The parameterization of the specific energy requirements of the transport sector is based on a longitudinal model which performs driving cycle simulations [51]. Data for the residential sector are based on a bottom-up model that creates a spatially distributed set of typical residential buildings from census data via an aggregation algorithm [52].

2.2. Deep geothermal plant model

A geothermal plant utilizes thermal energy in deep hydrothermal aquifers to produce heat and/or electricity (see Fig. 2). The power generation P_{el} of the Organic Rankine Cycle plant and the heat generation $\dot{Q}_{th}$ of the district heating plant per time step t are determined as follows [12]:

$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot \left(T_{PW}(t) - T_{ORC}(t)\right) \cdot \eta_{el} = P_{el}(t) \qquad \forall t \tag{3}$$

$$\dot{V}_B \cdot \rho_w \cdot c_{p,w} \cdot \left(T_{ORC}(t) - T_{DHP}(t)\right) \cdot \eta_{th} = \dot{Q}_{th}(t) \qquad \forall t \tag{4}$$

where $\dot{V}_B$ is the volumetric flow rate of the geothermal brine in l/s, ρ_w the mean density of the geothermal water in kg/l, $c_{p,w}$ the mean heat capacity of the geothermal water in kJ/(kg·K), and T_{PW}, T_{ORC}, and T_{DHP} the temperatures in the production well and after heat transfer to the Organic Rankine Cycle or the district heating network, respectively. As the flowrate $\dot{V}_B$ can vary greatly depending on local geological conditions, the mean flow rate of 75 l/s for existing deep geothermal systems in Germany is utilized in this model unless stated otherwise (see scenarios). A mean heat density ρ_w of 0.95 kg/l and mean heat capacity $c_{p,w}$ of 4.31 kJ/(kg·K) are assumed [12]. The minimum injection temperature is 50 °C, which directly affects the temperature after heat transfer to the district heating network T_{DHP}. The optimization model can choose to build a district heating plant and/or Organic Rankine Cycle plant and decides how to allocate the heat source between the two if both are built. The efficiency of the ORC plant η_{el} is assumed to be 10%, with 65% assumed for the efficiency η_{th} of the district heating plant [12].

2.3. Hydrothermal temperatures and drilling

Drilling costs account for the majority of geothermal plant investment costs, with a share of up to 70% [12]. As these cost functions are non-linear (see Eq. (5) [12]) the optimization model must select one drilling depth from amongst a set of up to 400 discrete options in steps of 10 m from 1000 m, and up to 5000 m. The lower limit of 1000 m is used, as lithium reserves are only present at greater depths. It is assumed that economies of scale apply to these drilling costs, with the cost of the second well being 90% those of the first. The drilling costs are calculated using the drilling depth z_D in meters, as well as the distance between the production well and injection well d_D in meters, for which we assume $d_D = 1500$ m [12]:

$$C_D = 610,000€ + 1.015 \cdot 1.198e^{0.00047894} \cdot \sqrt{z_D^2 + d_D^2} \cdot 10^6€ \tag{5}$$

The selected drilling depths then dictate the maximum achievable hydrothermal temperature in the optimization, the theoretical maxima of which can be found for German municipalities [13] up to a depth of 5000 m in Fig. 3. The assumed mean temperature gradients for the major geothermal basins, the Molasse Basin, the North German Basin, and Upper Rhine Graben, are 32 °C/km, 35 °C/km, and 43 °C/km, respectively. Locally, however, the temperature gradient for the Upper Rhine Graben may be much higher [56], particularly at depths of up to 3 km, with average values of up to 110 °C/km. Therefore, for the Upper Rhine Graben the assumed average temperature gradient has been divided into three sections with 47 °C/km until a depth of 1900 m, 41 °C/km between 1900 m and 3250 m, and 33 °C/km from 3250 m and above. Compared to real values of four existing plants in the Upper Rhine Graben, this linearization leads to an average deviation of 3.5% in the drilling depth to reach a certain hydrothermal temperature [12].

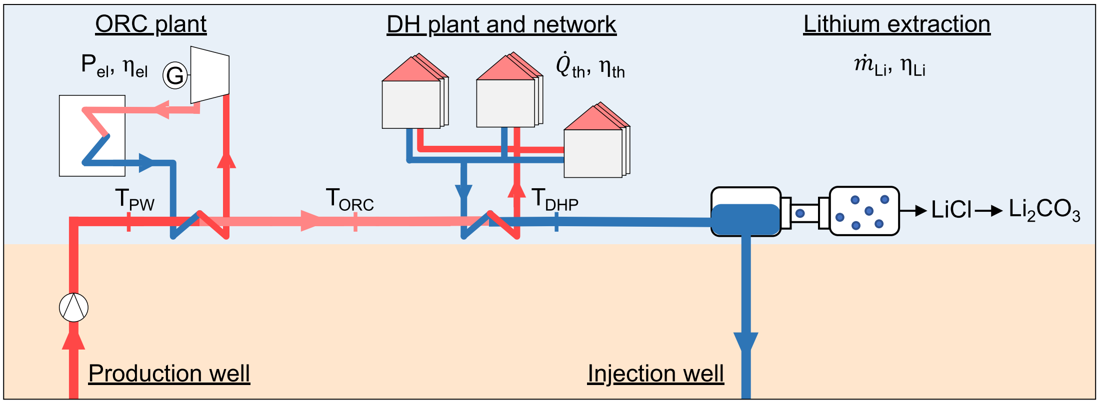

Fig. 2. Schematic representation of the Organic Rankine Cycle (ORC) and district heating (DH) plant and network, as well as lithium extraction considered in this study. Geothermal brine is pumped up by the production well pump and fed to a heat exchanger, where it heats a working fluid in the ORC plant, which in turn drives an electric generator, producing electricity. The brine then goes through another heat exchanger at the district heating plant, which supplies heat to the district heating network. The cooled brine can then be transported to the lithium extraction plant and brought in contact with a lithium-selective adsorbent that binds with the lithium ions. The lithium is then separated from the adsorbent and can be upgraded to lithium carbonate, after which the cooled lithium-depleted brine is returned underground via the injection well.

2.4. Direct lithium extraction

After the heat exchange with the Organic Rankine Cycle and district heating network, the cooled brine is transported to the lithium extraction plant and brought in contact with a lithium-selective adsorbent that binds with the lithium ions [57]. The lithium is then separated from the adsorbent and upgraded to lithium carbonate, and the cooled lithium-depleted brine is returned underground via the injection well Fig. 2). In the optimizations, a mean lithium concentration of 175 mg/l is assumed based on measured data for the Upper Rhine Graben (Fig. 3). The quantity of lithium extracted from lithium-bearing geothermal brines is determined using Eq. (6):

$$\dot{V}_B \cdot C_{Li} \cdot \eta_{Li} = \dot{m}_{Li} \tag{6}$$

where $\dot{V}_B$ is the brine flow rate measured in l/s, C_{Li} the concentration of lithium in the brine measured in mg/l, η_{Li} the extraction efficiency, with the final product being elemental lithium $\dot{m}_{Li}$ measured in mg/s. After the extraction, the lithium is processed with a conversion factor of 5.324 [20] into lithium carbonate, which is a largely traded raw material to produce, e.g., lithium-ion batteries [6]. In the optimization model, we used binary variables to ensure that the direct lithium extraction plant can only be built if a geothermal plant is installed.

Economic and technical data on lithium extraction from geothermal brines is scarce and therefore subject to major uncertainties. Whilst we were able to find literature values for all needed parameters, we assessed the impact of each of these in extensive sensitivity analyses (see Section 3.3). Furthermore, we assume fixed contract prices for the lithium carbonate market prices of between 8500 €/t and 25,500 €/t. The average annual lithium carbonate price for fixed contracts has more than doubled since 2020, reaching 17,000 €/t in 2021 [5]. Typically, such fixed contracts for lithium carbonate last three to five years [4]. More recently, spot prices have shown even greater volatility, rising from roughly 5500 €/t in September 2020 to over 76,000 €/t in September of 2022 [5]. However, spot prices are typically higher than contract prices, and studies anticipate that in the long-term, the market price will be significantly lower than the current spot market price [58,59]. Lithium carbonate market volatility has been observed in the past, with fixed contract prices increasing from 2015 to 2018 and then decreasing sharply until 2020. The 2015 and present spikes in pricing can be attributed to “unexpected and explosive EV market growth” [59], while the latter is also attributable to the COVID-19 pandemic. Future market prices will largely be determined by available reserves, as well as the growth of electric vehicle sales. In the long-term, lithium carbonate pricing could decrease to as low as 10,000 €/t [59].

3. Results

In this section, we first describe our case studies and scenarios in Section 3.1. Then, we show results of energy system optimizations for the municipality of Bruchsal in four scenarios in Section 3.2 and in sensitivity analyses of the most important parameters of the geothermal and DLE systems in Section 3.3. Finally, we examine the optimal energy systems of all municipalities with hydrothermal potential in the Upper Rhine Graben in Section 3.4.

3.1. Case studies and scenarios

A total of 330 municipalities in the Upper Rhine Graben in Germany have achievable hydrothermal temperatures of 60 °C or more (see Fig. 3). We investigate the optimal energy systems of these municipalities with and without the DLE option in the Mean URG scenario (see Table 1 and Section 3.4). The municipalities have about 4.5 million inhabitants, the mean population density is 400 inhabitants/km^2 and the total demand for electricity and heat is about 51 TWh$_{el}$ and 48 TWh$_{th}$, respectively (see Fig. 4). The three most populous cities in the Upper Rhine Graben are Karlsruhe (about 312,000 inhabitants and 1800 inhabitants/km^2), Mannheim (310,000 inhabitants and 2140 inhabitants/km^2), and Freiburg (230,000 inhabitants and 1510 inhabitants/km^2).

One of the 330 municipalities in the URG, Bruchsal (see Fig. 4), is examined in more detail in this article. The Bruchsal geothermal well in the Upper Rhine Graben is currently being investigated in pilot projects to identify qualified lithium-selective adsorbents [61], determine reservoir sustainability, assess environmental impacts, and evaluate whether lithium extraction from geothermal brines can be economically competitive with lithium sourced from South America and Australia using conventional methods. Bruchsal has a favorable lithium content (159 mg/l), temperature gradient (on average 43 °C/km), and reservoir temperature (131 °C) for such a project [26,53] and is therefore investigated here as a first case study in four scenarios (Table 1, Section 3.2) and various sensitivity analyses (Section 3.3). With a population of about 44,800 inhabitants and a municipality area of 93 km^2, the population density of Bruchsal is roughly 480 inhabitants/km^2 [60]. The maximum renewable potentials for the municipality include 75 MW$_{el}$ of onshore wind, 31 MW$_{el}$ of open-field PV, and 290 MW$_{el}$ of rooftop PV [47]. In addi-

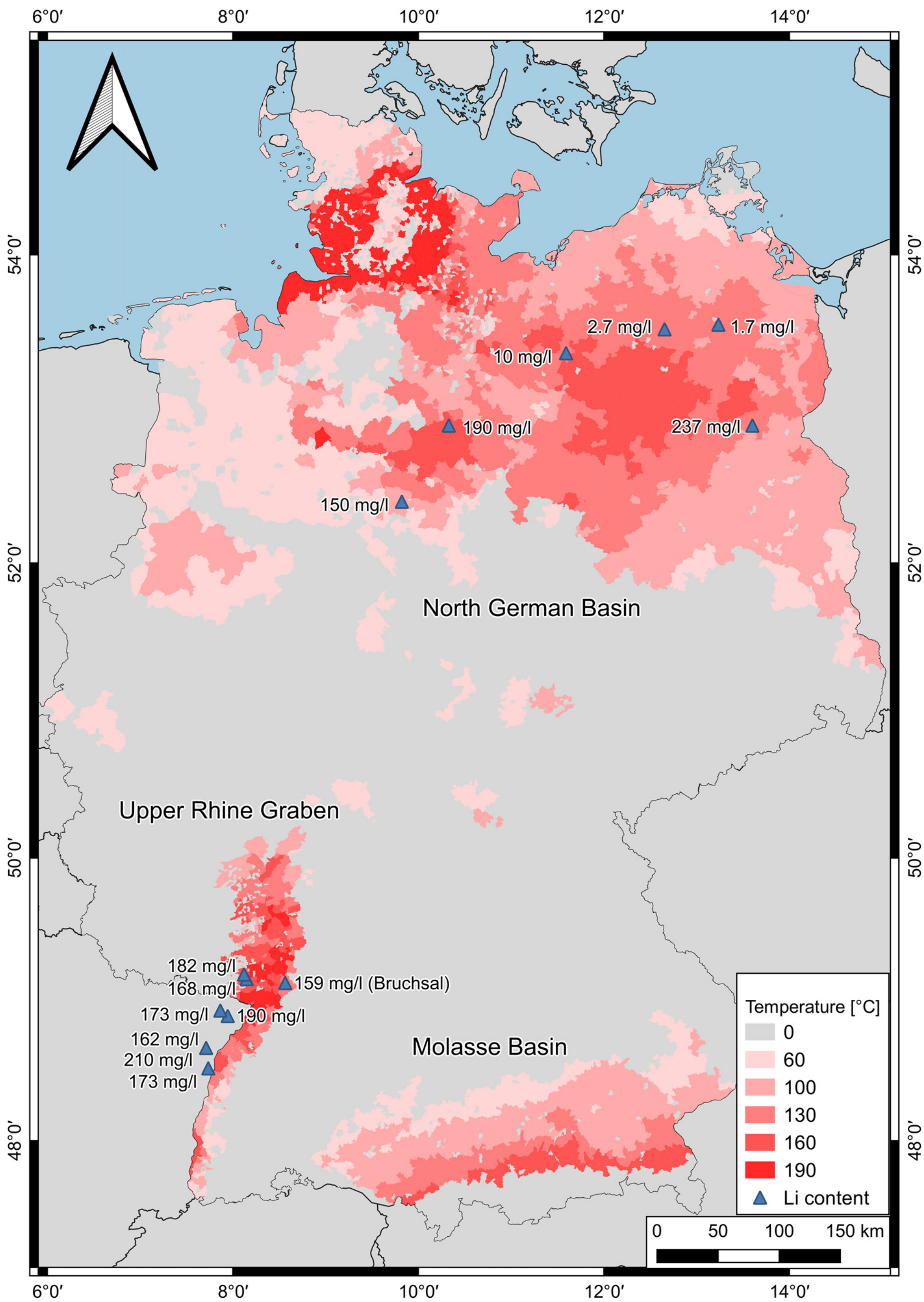

Fig. 3. Achievable hydrothermal temperatures in Germany at a depth of up to 5000 m [53] and measured lithium contents [25,28,29,54,55].

Table 1
Energy system optimization scenarios considered in this article. The baseline scenario contains proven existing values of the Bruchsal location, as well as the mean or most probable values for the direct lithium extraction (DLE) plant based on literature and expert opinions. Worst and best case scenarios include the worst or best values from the literature or existing plants, respectively. The optimistic scenario represents a state that might be reached and applies mean values between the baseline and best case scenarios. The mean URG scenario is applied to the energy system optimizations of all municipalities of the Upper Rhine Graben in Section 3.4 and represents the mean values of all existing plants in the region for flow rate and lithium concentration. The other DLE values are taken from the baseline scenario, which represent the most probable values based on literature and expert opinions. Since the data on the maximum achievable temperatures are available for each municipality, the used temperature is specific to each of these and ranges from 60 to 190 °C in this scenario.

Parameter	Worst case scenario	Baseline scenario	Optimistic scenario	Best case scenario	Mean URG scenario
Flow rate (l/s) [63]	24	24	82	140	75
Maximum wellhead temperature (°C) [63]	65	131	176	220	60–190
Lithium concentration (mg/l) [25,26,28,54,55,64]	86	159	198	237	175
DLE CAPEX (M€) [65]	31.2	20.8	15.8	10.9	20.8
DLE OPEX (€/t) [20]	8000	4000	3000	2000	4000
DLE efficiency (-) [66]	50%	70%	80%	90%	70%
Li carbonate market price (€/t) [5]	8500	17,000	21,250	25,500	17,000

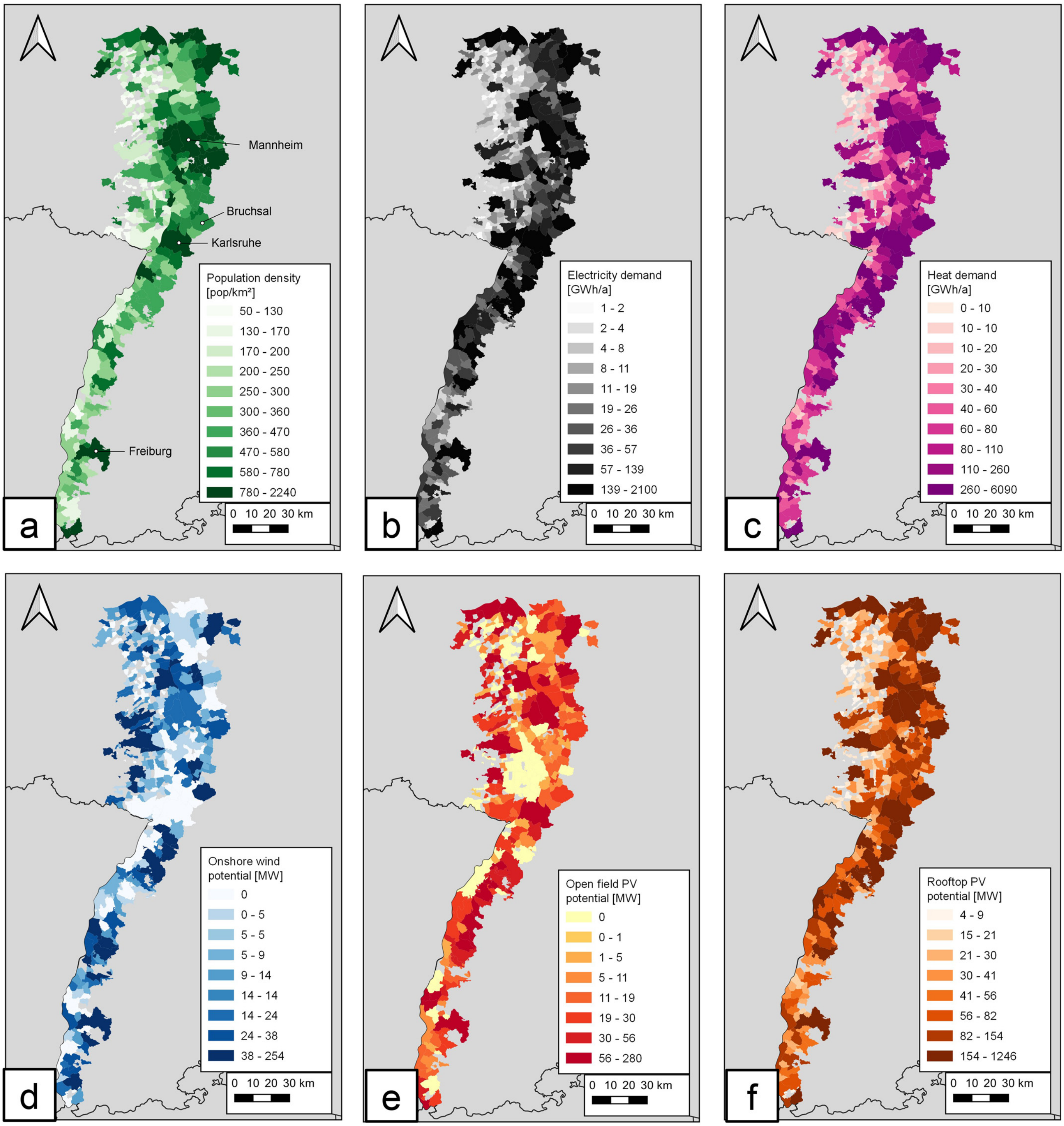

Fig. 4. Overview of a few key characteristics of the 330 investigated municipalities in the Upper Rhine Graben with hydrothermal potential. The maps show the population density (a), electricity demand (b), heat demand (c), onshore wind potential (d), open field PV potential (e) and rooftop PV potential (f) in the municipalities. The population density corresponds to official statistical data [60], the energy demands were regionalized [50] using official statistical data, and the renewable potentials were determined on a site-specific basis using the TREP tool [47]. Except for the population density, there is only low spatial autocorrelation between the municipalities (a: Moran index of 0.405, z-score of 13.393, and p-value of 0.000; b: Moran index of 0.021, z-score of 4.881, and p-value of 0.000; c: Moran index of 0.106, z-score of 4.059, and p-value of 0.000; d: Moran index of 0.074, z-score of 2.616, and p-value of 0.009; e: Moran index of 0.103, z-score of 3.523, and p-value of 0.000; f: Moran index of 0.105, z-score of 3.710, and p-value of 0.000).

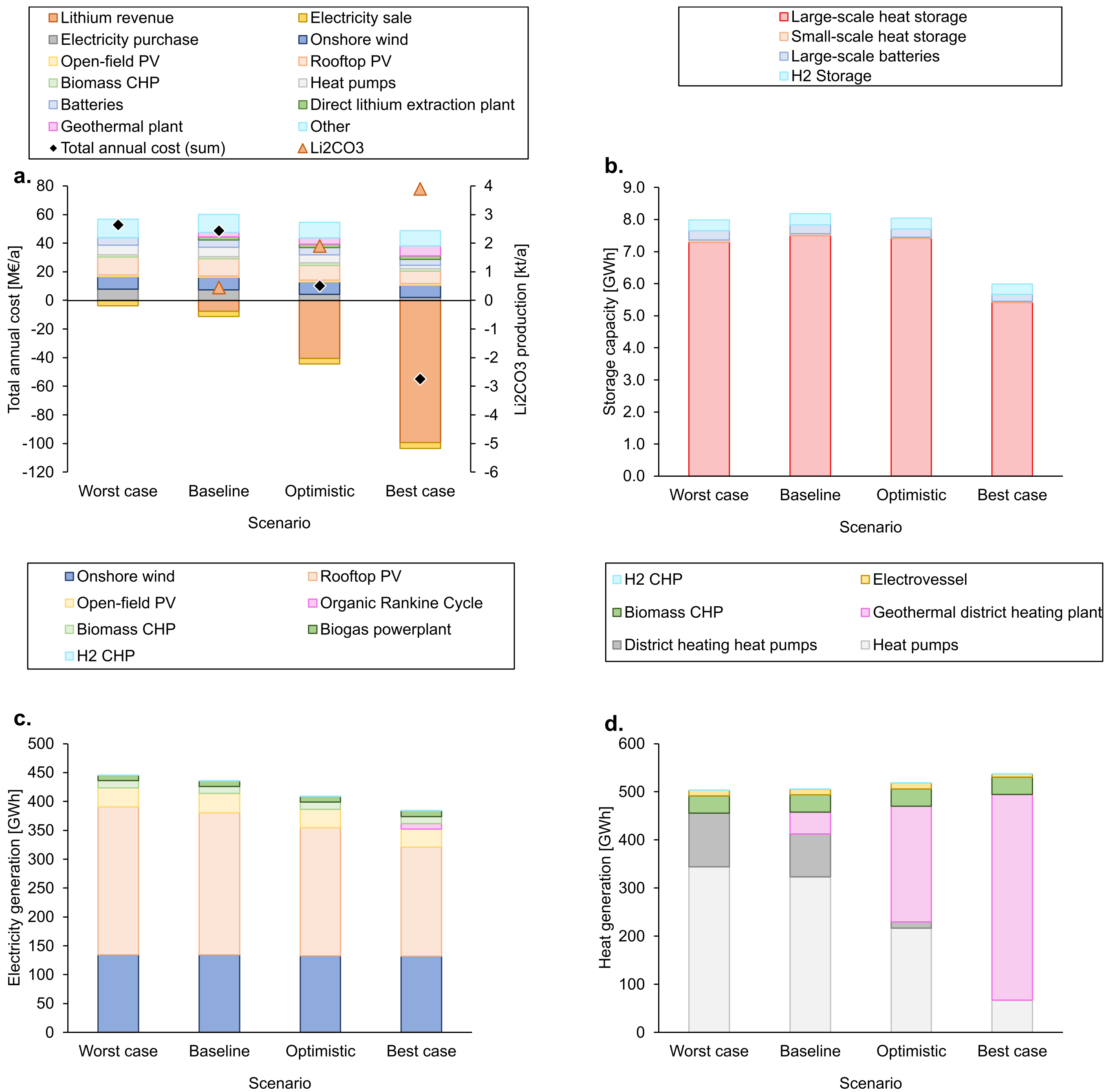

Fig. 5. Optimized energy system by 2045 in the worst case, baseline, optimistic, and best case scenarios for the municipality of Bruchsal. The different panels show the total annual cost (a), storage capacities (b), electricity generation (c), and heat generation (d) for the cost-optimal energy systems in the different scenarios.

tion to these potentials, Bruchsal has an already installed capacity of 1.22 MW_{el} for open-field PV and 24 MW_{el} for rooftop PV, which were included in this study as existing capacity. Currently, renewables account for 9% of local electricity supply and 4% of heat supply, while the majority of energy supply is based on natural gas and oil. The total electricity demand of the municipality is approximately 235 GWh_{el} and the total heating demand is roughly 465 GWh_{th}. Residential heating demand comprises roughly 45% of the total heat demand, while industry electricity demand makes up the largest portion of the total electricity demand at about 31%. Our model-based demand data is not far from available real values: while electricity demand values are not available, the heat consumption of Bruchsal is given in the Bruchsal Energy Guide [62] as 480 GWh_{th} (+3% above our model result) and the share of the residential sector is 51%.

3.2. Direct lithium extraction benefits deep geothermal plants

Deep geothermal plants for power and heat generation alone are only cost-competitive under very favorable conditions and thus are not installed in optimal energy systems due to the low achievable flow rate in Bruchsal. This finding is in line with previous analyses using different energy system optimization models [12,17,38]. If no geothermal plant is built, most of the electricity or heat will be provided by onshore wind, rooftop and open field PV, or heat pumps, respectively; see the worst case scenario in Fig. 5, which results in the same energy system as the baseline scenario without DLE.

However, depending on the geological characteristics of the geothermal source, the option of lithium extraction and sale makes deep geothermal plants cost-competitive (see the baseline, optimistic, and best case scenarios in Fig. 5). Although the deployment of geothermal plants increases the annual costs for the energy supply technologies, this is offset by the revenues from lithium carbonate sales in quantities of 450–3900 tons, even leading to negative annual costs of -54 M€ in the best case scenario. Depending on the flow rate, wellhead temperature, and lithium concentration and extraction efficiencies, the geothermal plant displaces 6–29% of rooftop photovoltaics, 3–15% of electricity storage, 1–5% hydrogen storage and up to 27% of heat storage. The district heating plant is favored over the Organic Rankine Cycle, leading to the latter only being built in the best case scenario, assuming excellent hydrothermal resources. Due to the base load capacity of the geothermal plant and the large district heating displacing 7–75% of the heat pumps, overall power generation and the need for heat and electricity storage decreases.

The developed model of the geothermal plant reflects the reality fairly well. If the real temperature of the existing Bruchsal plant (123 °C) is fixed in the baseline scenario, similar values are chosen by the model with a 2470 m drilling depth compared to a 2542 m one in reality (-3%), as well as 4.66 MW_{th} district heating plant capacity compared to 5.7 MW_{th} (-18%) (real values can be found in Ref. [12]). In this assessment, it is important to keep in mind that average parameters were assumed to ensure the applicability of the developed model for every municipality in Germany, e.g., for temperature gradients and efficiencies, etc. However, the most uncertain aspect of a geothermal project, the drilling costs, cannot be estimated very accurately using our model. Here, the model results of 11.4 M€ are 41% higher than the real costs of 8.1 M€ (real values can be found in Ref. [12]). For the costs, a safe conservative estimate had to be made in our model, as geothermal projects can become more expensive than initially estimated due to unexpected costs arising. This means that the valuation of geothermal plants in this study could be slightly underestimated for specific regions.

3.3. Cost-competitiveness even under pessimistic conditions

So far, the focus has been on the characteristics of the existing plant in Bruchsal. As this site has the lowest flow rate of all existing plants in Germany and thus tends to underestimate the potential of deep geothermal energy in the baseline or worst case scenarios, we now consider the mean values of geothermal plants in the Upper Rhine Graben for several sensitivity analyses of the Bruchsal energy system (wellhead temperature of 115 °C; for the other parameters, see the mean URG scenario in Table 1). Unlike the worst case scenario, in which the combination of unfavorable parameter values resulted in no geothermal system being installed despite the DLE possibility, in the sensitivity analyses we change only one parameter at a time to understand the individual effects on energy system design and costs.

Geothermal plants with lithium extraction remain competitive in energy systems if only individual parameter values are varied and otherwise average values assumed. As geothermal energy and lithium procurement are directly correlated with the flow rate, changes in this assumption significantly impact the results (Fig. 6). The mean flow rate of geothermal plants in Germany of 75 l/s differs greatly depending upon local geological conditions. In Germany, brine flow rates range from 24 l/s at the Bruchsal geothermal plant to up to 150 l/s in the Molasse Basin [12]. Increasing flow rates is achievable through additional drilling as the operator of DLE pilot plants Vulcan Energy Resources Ltd. intends to achieve flow rates of 100–120 l/s in the Upper Rhine Graben [65]. However, as indicated by the results of the sensitivity analysis, even at greatly reduced flow rates, combined geothermal–lithium plants are still beneficial in a cost-optimized energy system.

Another significant assumption is the utilization of the mean lithium concentration in geothermal brines measured by previous studies, given the lack of publicly available data. However, this neglects the fact that measured lithium contents in geothermal brines vary greatly by location. This may have an especially high impact on the results for the North German Basin, as the lithium deposits in that area are highly concentrated and the measured contents range from 0 to 237 mg/l [28] which is another reason why we chose the Upper Rhine Graben for our investigation. Furthermore, although experts assume lithium concentrations of 0 mg/l in the Molasse Basin, further research may also reveal lithium deposits there. Different technologies based on precipitation, adsorption, solvent extraction and membranes could potentially be used to increase the concentration in the future [67] but were not considered in this study.

When conducting this study, many questions also arose surrounding the economics of DLE, its efficiency, and the market price of lithium carbonate. The extraction efficiency rates in the literature vary from 50 to 90% [10,65] and have a significant impact on total system costs (Fig. 6). The same applies to the market price of lithium carbonate, which has increased substantially in recent months. The U.S. Geological Survey estimates an average annual lithium carbonate price of 17,000 €/t for fixed contracts in 2021, which is more than double the same value in 2020 [5]. However, the spot market price for September 2022 was up to roughly 76,000 €/t and is forecast to increase [68].

Sustainable low-carbon lithium may also command a premium price compared to lithium from conventional extraction due to growing demand for low-carbon products. This demand is present in the automotive sector, with a push for electric vehicle manufacturers to decarbonize supply chains, including Volkswagen and Toyota, which have set the lofty goal of eliminating carbon emissions from their value chains [69]. The commercial interest in low-carbon lithium has already been proven in the form of offtake agreements for geothermal lithium signed by Renault, Volkswagen, Umicore, LG Energy Solutions, and Stellantis [70]. As the lithium market price has a significant impact on overall costs, such premium pricing could further improve the economics of energy systems, including combined geothermal–lithium plants.

The operating expenses (OPEX) and capital expenses (CAPEX) of DLE plants have a negligible effect on the energy system design and costs. The operating expenses identified during the literature review vary from just under 2000 €/t, per Vulcan Energy [65], to roughly 4000 €/t, as reported by the US Department of Energy [20], to up to roughly 8000 €/t per a discussion with experts. CAPEX are also quite uncertain: although we utilized a value of 20,800 M€, the actual CAPEX value for such a project could significantly differ.

3.4. Large-scale impacts of geothermal plants with lithium extraction

In contrast to the previous sensitivity analyses, we now optimize the energy systems of all 330 municipalities of the Upper Rhine Graben in the Mean URG scenario. This scenario utilizes the actual maximum wellhead temperature specific to each municipality, rather than being fixed at 115 °C. Even without the option of building a DLE plant, deep geothermal systems were developed in 152 of 330 municipalities (46%). These municipalities have medium- to high-enthalpy resources with a hydrothermal temperature range of 130–190 °C and an average temperature of 131 °C. This result is in line with the findings of previous studies [12,17] and demonstrates that for sites with very suitable conditions, deep geothermal plants are cost-competitive with conventional energy sources. All 152 municipalities installed district heating systems, whereas Organic Rankine Cycle plants were built in 113 of 330 municipalities (34%).

With the option of building a lithium extraction plant and the added revenue from the sale of lithium carbonate, deep geothermal plants are cost-competitive in all 330 municipalities. On average, the total annual costs are reduced by 22.4 M€/a or 1000% for a municipality in the URG, illustrating the added benefit of combined geothermal-lithium plants (see Fig. 7, "> 100%" cost decrease means that municipalities make profit). Especially in smaller communities, the profit from the lithium sales obviously has a particularly strong effect. Key electricity generation technologies of the 330 municipalities include rooftop and open field photovoltaics (with average capacities per municipality of roughly 67 MW and 23 MW for each type, respectively) and onshore wind tur-

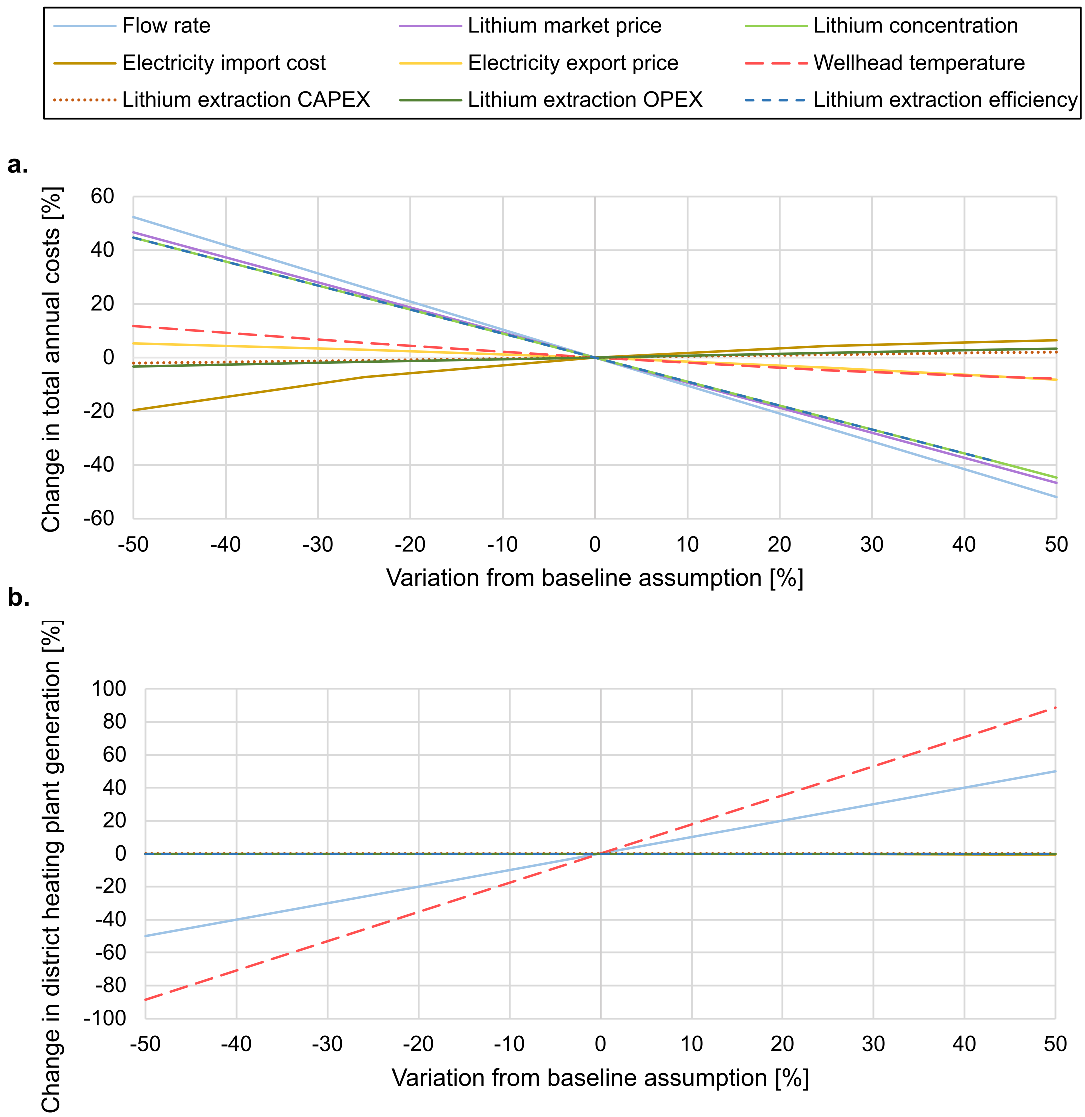

Fig. 6. Impacts of parameter variations on the design of the optimal energy system in Bruchsal. Panel (a) shows the effect of the sensitivity analyses on the total annual costs and panel (b) on the district heating plant generation. As the Organic Rankine Cycle was not installed in these analyses, its generation is not shown in the figure. The largest impact on costs comes from parameters that directly influence lithium carbonate production and sales, such as the flow rate, as well as the lithium extraction efficiency, market price, or concentration. The impact of the flow rate is the largest, as it also directly affects the maximum achievable district heating plant capacity and generation. Apart from the flow rate and wellhead temperature, the other analyzed parameters have no significant influence on the district heating plant design.

bines (average capacity: 11 MW), and to a lesser extent deep geothermal Organic Rankine Cycle plants (average capacity: 0.9 MW), whereas heat is primarily supplied by heat pumps and deep geothermal district heating plants.

The development of Organic Rankine Cycle plants is associated with municipalities that have low or no onshore wind and PV potential and high achievable hydrothermal temperatures, whereas district heating plants are more favorable in larger and more densely populated municipalities like Karlsruhe, Heidelberg or Mannheim. Compared to the optimal systems in the scenario without DLE, deep geothermal systems primarily displace rooftop PV capacity (average of 2.0 MW or -24% of original capacity), followed by open-field PV (1.9 MW or -14%) and onshore wind (1.2 MW or -29%), whereas district heating plants primarily displace heat pumps (2.1 MW or -64%). The tendency to displace more photovoltaics, even though the cost of electricity generation is lower, can be explained by the higher system integration costs compared to wind power [71]. As there is more base-load energy provision and less intermittent renewable generation, the required capacities for batteries (average of -3.0 MWh or -30% of original capacity), large-scale (-103.5 MWh or -28%) and small-scale (-0.3 MWh or -11%) heat storage as well as hydrogen storage (-3.6 MWh or -18%) also decrease.

If every municipality in the URG were to install a hybrid geothermal plant with lithium extraction, around 510 kt of lithium carbonate could be produced, which lies well within the range of current estimates. With a typical electric vehicle lithium-ion battery pack (NMC523 type) containing *ca.* 8 kg of lithium [72] enough to manufacture over 11.9 million battery packs annually, greatly exceeding the 1.7 million new electric vehicle registrations recorded in 2021 for the entirety of the European Union [73]. However, given the significant barriers to future development of hybrid deep geothermal projects including exploratory risks, financial uncertainty, and public opposition (see discussion in Section 4), it is unlikely that 100% of the municipalities would be developed with combined geothermal–lithium plants. Nevertheless, if only 10% of the municipalities in the URG were to deploy such a plant,

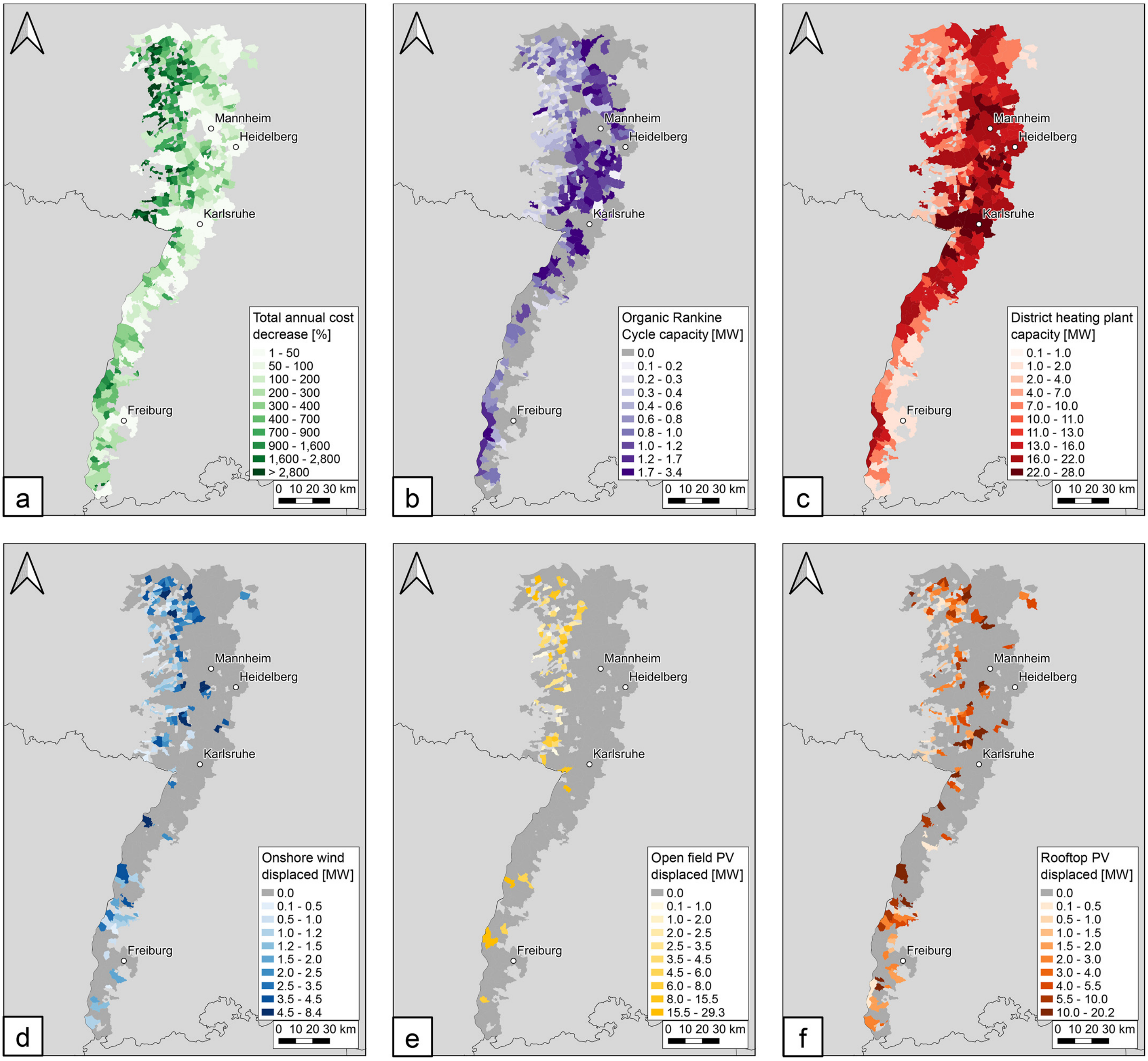

Fig. 7. Cost-optimal energy systems of 330 municipalities in the Upper Rhine Graben with the option of direct lithium extraction compared to energy systems without this option. The figure panels show how the total annual cost (a), capacities of Organic Rankine Cycle (b), district heating plant (c), onshore wind turbines (d), open field (e), and rooftop (f) photovoltaics are affected if the option to install direct lithium extraction is given compared to optimal energy systems without this option.

this could yield substantial benefits (see Fig. 8). Assuming deployment would occur where geothermal potential is highest, total annual costs per municipality could be significantly reduced, with an average decrease of about 190%, whereas the total capacities of DHP and ORC plants would be about 655 MW_{th} and 75 MW_{el}, respectively. More than 50 kt/a of lithium carbonate could be produced in these municipalities – enough to manufacture about 1.2 million electric vehicle battery packs annually.

4. Discussion

Research on the extraction of lithium from geothermal brines dates to the early 1980s, while DLE technology has been in use for over 20 years at Livent Corporation's mine in Argentina [74]. Although the technology has been proven technically feasible with salar brines, uncertainties exist as to its application with geothermal brines, and its commercial efficacy remains to be proven. While presenting enormous potential, it is important to acknowledge that there has been a recent surge of hype with regard to geothermal lithium extraction that may exaggerate this potential [23]. One such example is that of Vulcan Energy's Zero Carbon Lithium project in the Upper Rhine Graben, which anticipates operating expenses roughly half those for geothermal–lithium operations in the Salton Sea area, despite having a significantly lower flow rate and lithium concentration [20,65]. Additional concerns regarding the sustainability of such lithium extraction are not without merit, as the geological source and refresh rate of these lithium deposits are not fully understood. Furthermore, social opposition, induced seismicity risks, and financial uncertainty could present major barriers

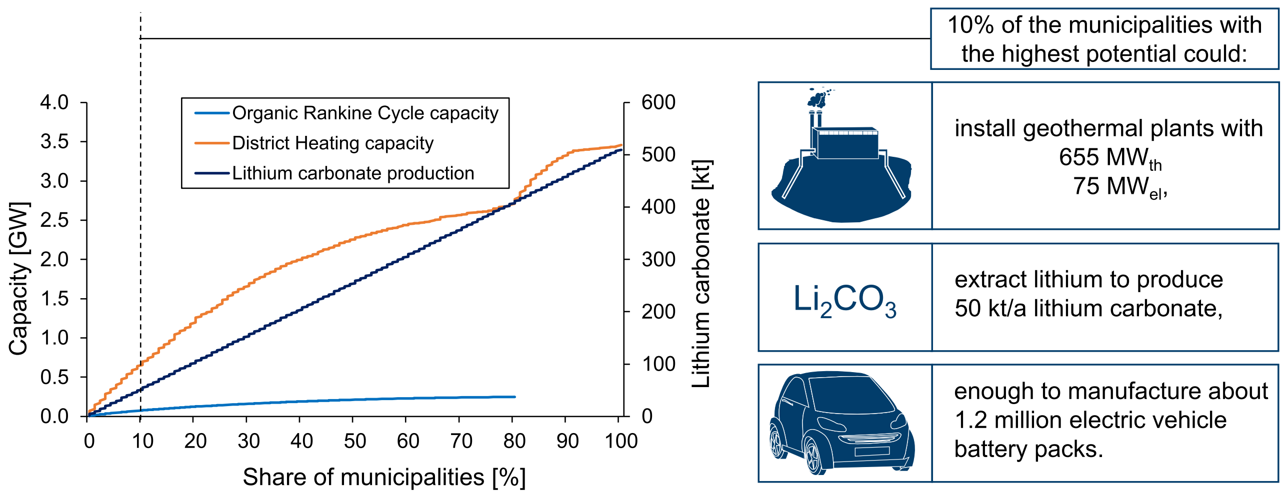

Fig. 8. Optimized capacities of Organic Rankine Cycles and district heating plants, as well as lithium carbonate production over the share of municipalities in the Upper Rhine Graben, whereas the share of 100% corresponds to 330. The municipalities are ordered by maximum achievable wellhead temperature (i.e., highest potential), as well as Organic Rankine Cycle capacity. The latter leads to the leap in the curve of district heating plant capacity, as no Organic Rankine Cycle plants are installed in the remaining municipalities.

to future development, which should be further investigated in future studies.

The geological source and refresh rate of lithium deposits are not yet fully understood; however, these factors may significantly impact results [26]. Geothermal brines are rich in minerals such as magnesium, potassium, and sodium and possess significant quantities of total dissolved solids, which may cause scaling in the geothermal plant, leading to the degradation of plant components and an increase in costs arising from maintenance and cleaning [22,75]. It is unknown how the addition of a lithium extraction facility would impact scaling and corrosion. In addition, the capital-intensive drilling phase is associated with considerable risk, which we accounted for in the model with conservative assumptions regarding the exploration costs. Subsurface geothermal resources are often not fully understood, and drilling may be unsuccessful in locating a hydrothermal resource with favorable characteristics for geothermal exploitation. Germany in general is considered a high-cost country for geothermal development, with drilling costs exceeding those in the U.S., for example. The risk of unsuccessful drilling can create significant financial losses and delays [76].

Furthermore, literature on deep geothermal energy, including the present article, focuses primarily on technical barriers to its use [77]. However, social acceptance is critical for the further deployment of geothermal plants. A seismic event attributed to a geothermal plant in Basel, Switzerland in 2006, with a magnitude reaching 3.4 on the Richter scale, marked a turning point in public perception of geothermal energy use in Germany and led to the emergence of a strong anti-geothermal protest movement [78]. Since then, incidents of subsidence and injection-induced seismicity with magnitudes of up to 2.6 in some German towns have solidified concerns about geothermal energy use [78,79]. The importance of social acceptance is illustrated in the example of the now-abandoned Brühl geothermal site in the Upper Rhine Graben, where construction of the planned geothermal plant was halted due a lack of public acceptance, despite drilling success and the achievement of high flow rates [80]. In addition to strategies for improving social acceptance, including preventing and minimizing undesirable effects, compensating local communities when damages occur, creating benefits for the latter, and enhancing community engagement [81], combined lithium extraction may also have a positive impact as “green lithium” and has received significant positive media coverage recently, and provides an attractive talking point for geothermal plant operators to present to the public. Furthermore, other renewables such as onshore wind face strong opposition too [82,83] and would partially be replaced by deep geothermal plants as shown in our study, which in turn could promote the acceptance of deep geothermal.

If combined geothermal–lithium technology is not commercially-successful due to one of the above-mentioned reasons, the demand and environmental impacts of lithium procurement will potentially further increase. With current lithium supply insufficient to meet the anticipated 60-fold increase in lithium needed by 2050 to fulfill European Union demand, dependence on lithium imports from countries such as China, Australia, and Chile will likely increase, which could in turn impact the security of energy supply and transition to carbon-neutral energy systems. In addition, environmental and climate impacts associated with conventional lithium extraction will likely increase and lithium markets may become increasingly volatile due to highly concentrated supply [3]. If lithium market prices will also continue to rise, this could lead to new lithium resources being developed, especially carbon-intensive hard-rock deposits in Australia with a carbon footprint of about 15.8 kg $CO_{2,eq}$ per kg lithium carbonate equivalent [84]. This can be compared with estimated carbon footprints of 0.3 kg $CO_{2,eq}$ for brine deposits in South America [85]. Further research found that brine extraction has a carbon footprint of 3.2 kg $CO_{2,eq}$ and it is predicted that this will increase to 3.3 kg $CO_{2,eq}$ in 2100 [86]. The impacts are exacerbated by lithium having a low estimated end-of-life recycling rate [6]. Assuming a carbon abatement potential of 15.8 kg $CO_{2,eq}$ when compared with conventional hard-rock procurement methods, the implementation of approximately 30 such geothermal-lithium plants in the Upper Rhine Graben could lead to an abatement of 800 kt $CO_{2,eq}$ annually. Assuming a lifetime of 30 years for the geothermal plants, this would reduce CO_2 emissions by a total of 24 Mt $CO_{2,eq}$. Therefore, combined geothermal–lithium projects could decarbonize the lithium supply chain, reduce supply risks [87] and could have a net negative carbon impact if the offsets of the generated power/heat are sold to the grid and displace coal-fired generation. At this point, it should be noted that recycling of critical metals from lithium-ion batteries [88] or reusing retired batteries [89,90] was not considered in our study, however, high future end-of-life recycling rates could have significant impacts on the abatement potential. Moreover, the use of different storage types such as vanadium redox flow batteries [91] or compressed air storage [92] as well as storage capacity reduction through innovative mechanisms such as tracking of renewable energy generation [93] or smart battery management [94,95] could reduce the need for lithium in future energy systems.

Given the numerous ongoing pilot projects demonstrating the potential of DLE from geothermal brines and the rapid advancement of the technology in recent years, the assumption of commercial success may be strengthened. With a total technical potential in Germany of 4155 TWh_{el}/a, deep geothermal energy could play a key role in the achievement of climate goals [96]. These geothermal plants could reduce CO_2 emissions from the energy sector and provide a much needed baseload supply of renewable heat and electricity not affected by weather and with a low land-use intensity [96]. The baseload heating is highly relevant in light of the energy crisis and desire to phase out imports of Russian natural gas [97]. Lithium extraction in combination with geothermal energy use could also increase and diversify lithium supply, reduce the environmental and climate impacts of lithium extraction, and aid in the energy transition by promoting the development of low-carbon technologies such as electric vehicle batteries and lithium-ion batteries for grid scale energy storage. Hybrid geothermal plants could also provide significant economic benefit in the form of stable jobs and a new domestic lithium industry in Germany, which possesses abundant lithium resources in the Upper Rhine Graben [5,26].

5. Conclusion

In conclusion, this study highlights the potential of utilizing deep geothermal plants for direct lithium extraction as a low-carbon alternative to conventional procurement methods that have significant environmental impacts. Our optimizations of 330 greenhouse gas neutral regions in 2045 show that geothermal plants with lithium extraction will become cost-competitive even under unfavorable conditions. The base-load capable plants will partially displace rooftop (-24% of capacity on average compared to optimal energy systems without geothermal plants) and open-field (-14%) photovoltaics, onshore wind power (-29%), heat pumps (-64%) as well as batteries (-30%), heat storage (-28%) and hydrogen storage (-18%) from future renewable energy systems. The results suggest that if all municipalities in the Upper Rhine Graben area in Germany constructed deep geothermal plants, they could provide enough lithium to produce about 11.9 million electric vehicle battery packs per year, greatly exceeding the current annual electric vehicle registrations in the European Union. Even with the installation of deep geothermal plants in only 10% of the municipalities, approximately 800 kt of $CO_{2,eq}$ could be avoided annually compared to conventional hard rock lithium procurement methods. This lithium potential is not limited to Germany alone: significant lithium geothermal brine deposits have also been identified in the U.S., France, the U.K., and Italy suggesting that the utilization of combined geothermal-lithium plants in future transformation strategies is essential.

Data and code availability

The ETHOS.FINE framework used is publicly available on GitHub (https://github.com/FZJ-IEK3-VSA/FINE). The TSAM tool for Pareto-optimal time series aggregation can also be found on GitHub (https://github.com/FZJ-IEK3-VSA/tsam). The potentials for renewable energies used in the optimizations are deposited on Zenodo (https://zenodo.org/record/6414018#.Y4m6bHbMI2w). The dataset for achievable hydrothermal temperatures in German municipalities is published together with a data article in the journal Scientific Data (https://www.nature.com/articles/s41597-019-0233-0).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jann Michael Weinand: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ganga Vandenberg:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Stanley Risch:** Methodology, Software, Writing – review & editing. **Johannes Behrens:** Methodology, Writing – review & editing. **Noah Pflugradt:** Writing – review & editing. **Jochen Linßen:** Writing – review & editing. **Detlef Stolten:** Funding acquisition, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

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