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DGE-ROLLOUT

Socio-economic potential mapping for Deep Geothermal Energy in the Upper Rhine Graben

Deliverable T1.2.3

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Disclaimer

The purpose of the following report is to give a short overview of the aspect that has been defined as a milestone in the socio/economic mapping potential inside the DGE Roll-out project in Germany. It should provide general information to local, regional, and national public authorities, project developers, politicians and enterprises with heat demand. However, this report does not replace the own independent research on this topic. Appropriate legal advice should be obtained in actual situations.

The recommendations given herein are the authors' subjective opinions based on the research which has been done for this report. It does not rely on experience during drilling or seismic exploration in the field. It mainly sums up the opinion of experienced project partners and actual goals in contributing as much as possible to stop climate change.

We cannot guarantee the accuracy, reliability, correctness or completeness of the information and materials given in this report and accept no legal responsibility. For further reading, please refer to the literature mentioned herein about the socio-economics aspect above mentioned.

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1 Introduction

For several decades, the Upper Rhine Graben (URG) has been one of the main targets of deep geothermal exploration and utilization in Central Europe due to its comparatively high temperature gradient, which locally exceeds 10 K/100 m. Several geological units were identified as potential geothermal reservoirs based on their favorable thermal and hydrogeological properties. These mainly include the crystalline basement, sandstones and volcanics of the Permo-Carboniferous, sandstones and conglomerates of the Triassic and Tertiary, and Mesozoic carbonate formations. Since the late 1970s, about one and a half dozen deep geothermal projects have been completed in the region, with seven of them currently in operation. However, the total installed thermal and electrical capacity of 50 MW_{th} and 10 MW_{el} is well below the technical potential, thus significant growth is still to be expected in this sector in the coming years.

In addition to the geological framework, surface conditions play an equally important role for the site selection of geothermal wells. Therefore, this report summarizes relevant data on the social, economic and environmental situation in the URG. Based on this, a socio-economic potential map for geothermal projects was calculated, which represents an important decision-making basis for stakeholders. Note that in particular the aspects of the legal and financial framework for deep geothermal utilization have already been intensively discussed in previous reports of the DGE-ROLLOUT project and are therefore not further elaborated here:

- "WP T1 - 3.1 Legal Framework" (Van Malderen 2020)
- "WP T1 - 3.2 Financial Risk Management" (Taşdemir and Arndt 2020)
- "WP T1 - 3.3 Examination of the German regulatory framework and financial risk management of DGE, A recommendation approach" (Taşdemir and Dombrowski 2021)

2 Geographic Overview

The URG is an approximately 300 km long and 30-40 km wide NNE/SSW striking passive rift system that extends roughly from the Jura Mountains in the south to the Rhenish Massif in the north (Fig. 1). Laterally, the basin is bounded by the Palatinate, the Odenwald, the Vosges and the Black Forest. Most of the URG is part of Germany and France, while the southern end also extends into northern Switzerland. In Germany, the region is divided among the 3 states of Baden-Württemberg, Hesse and Rhineland-Palatinate. The French URG belongs mainly to the region Grand Est (European Collectivity of Alsace) and to a smaller extent to the region Bourgogne-Franche-Compté (Départements Doubs and Territoire de Belfort).

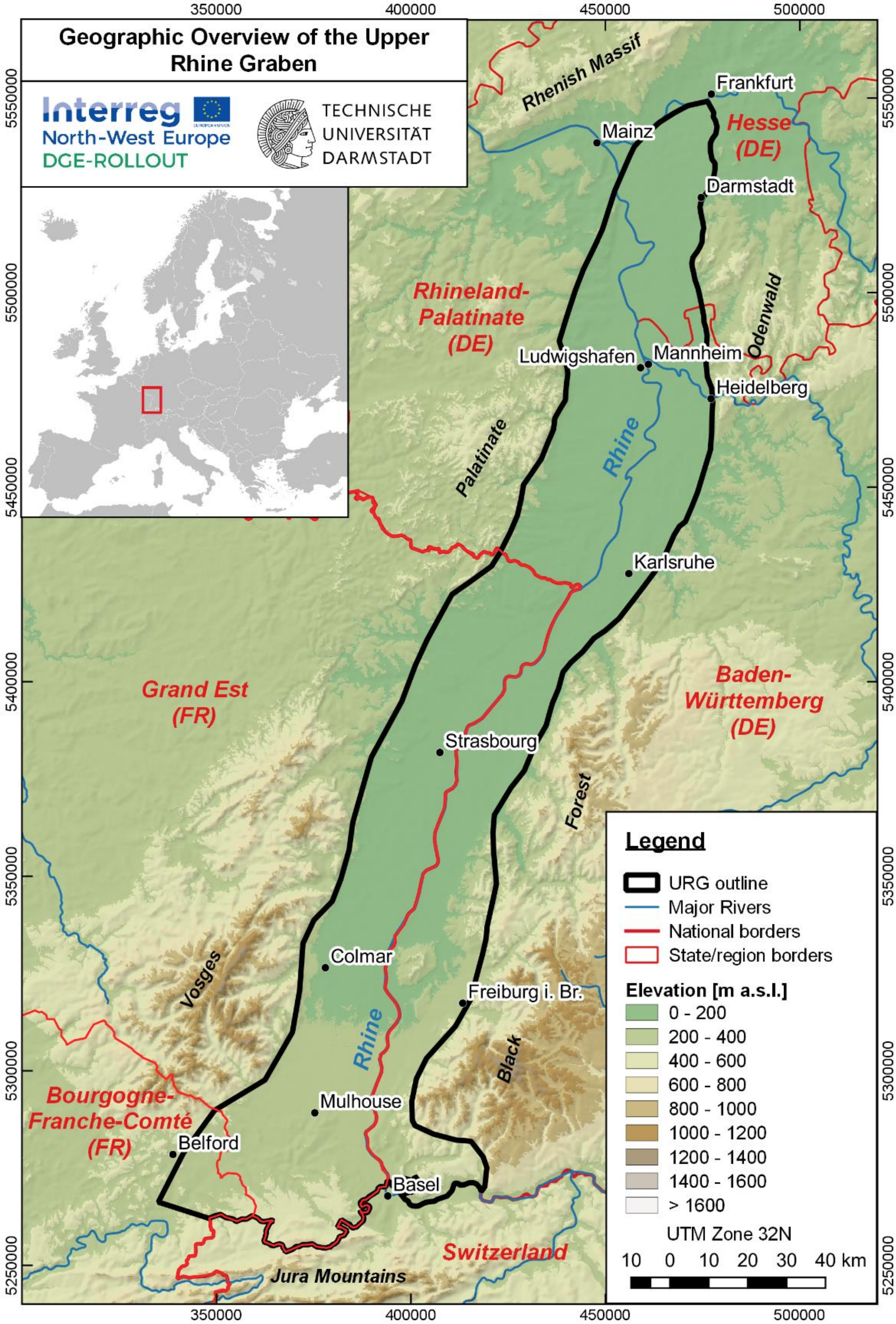

Figure 1: Geographic overview of the URG.

3 Methods

For this report, the exploration and decision workflow of Moeck (2014) is adapted and extended (Fig. 2). Therein, the surfaces and subsurface parameters are summarized in groups and integrated to evaluate a geothermal project. Here, the focus is on the societal-technical pyramid; subsurface conditions are addressed separately in, for example, WP T1 - 1.3 and WP T2 - 4.1.

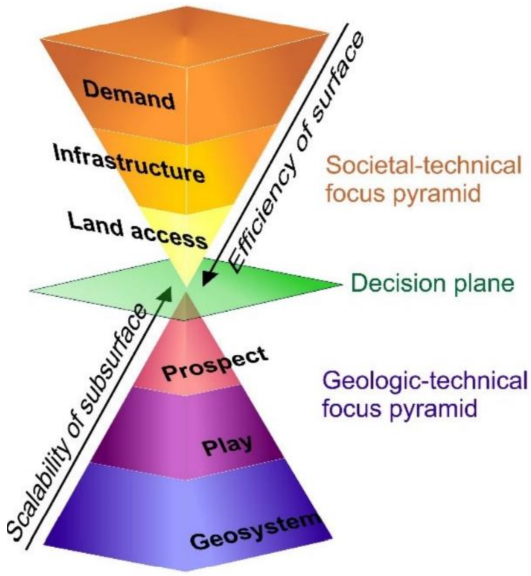

Figure 2: Decision-making factors to start a geothermal project (Moeck et al. 2020).

Table 1 Categories and factors defined for the socio-economic analysis of geothermal projects.

Social	*Country information*	Population distribution
		Heat demand
		Impact of Geothermal Projects
		Social level map
	Acceptance	Political parties map / Election maps
Economic	*Infrastructure*	District heating
	Economic performance	Gross domestic product
	Investment	Level of debt of municipalities
		Private Investments
Environmental	*Land access*	Environmentally sensitive areas
	Greenhouse gas emissions	

The investigated components of the socio-economic potential are summarized in Table 1. Three main dimensions are considered: social, economic and environmental. These consist in total of 11 individual indicators. The social dimension includes aspects related to population, including population density, heat demand, income, and social level. Other factors are the acceptance and the impact of geothermal projects. The economic dimension includes the existing district heating network infrastructure, potential investments in geothermal energy and regulations that have to be considered during the project realization. Finally, the environmental dimension examines the aspects of land access and greenhouse gas emissions.

3.1 Collecting Data

The information is mainly available in two formats: tables in text format and shapefiles. Note that the information differs in date or spatial resolution due to the diversity of topics. Most sources are either in German or French, except for international sources like the websites of the EU Statistical Commission or the DGE-Rollout project.

The German URG comprises three states subdivided into four governmental districts ("Regierungsbezirke"), 32 districts ("Landkreise" and "kreisfreie Städte") and ca. 390 municipalities. The French URG consists of with two regions divided into four departments, 14 arrondissements and ca. 650 municipalities. Data are generally available at one of these spatial resolution levels, with the exception of electoral maps, as the geometry of electoral districts may differ from the general administrative division in both countries. Since the Swiss URG represents only a very small portion of the total region, no additional data were collected for this part.

Shapefiles of administrative levels, election districts and NUTS regions in Germany and France can be found at the following sources:

- BKG Germany | geometry administrative levels
- Bundeswahlleiter Germany | geometry electoral districts
- DIVA | geometry administrative levels France
- data.gouv France | geometry election districts
- Eurostat | geometry of NUTS regions

Detailed information on the sources of the investigated socio-economic parameters are given in the respective chapters.

3.2 Socio-Economic Index

The different quantifiable components of the socio-economic potential for deep geothermal energy were combined into a joint index. The parameters population density, social progress index, acceptance of renewable energies, availability of district heating networks, gross domestic product, public debt, environmentally sensitive areas and greenhouse gas emissions were considered. For the other components, a harmonized and spatially resolved data set is not available, which is why they are not included in the calculation of the index.

Detailed discussions of aggregation of various indicators is given e.g. in Lustig (2011), Decancq and Lugo (2013) and Annoni and Bolsi (2020). Following this, a simplistic approach is adopted in this report, where the composite index I is calculated via an unweighted generalized mean:

$$I = \left(\frac{1}{n}\sum_{i=1}^{n} x_i^{\beta}\right)^{\frac{1}{\beta}}$$

Where n is the total number of components, xi is the i-th component of the socioeconomic potential, and the constant β describes the compensability between the individual components. A β of 1 corresponds to the arithmetic mean. In accordance with Annoni and Bolsi (2020), a β of 0.5 was used, being between the arithmetic and geometric means.

Before the components can be combined, a normalization is necessary to scale the parameters between 0 and 100 (for some parameters, like the social progress indices or the acceptance, this is already the case). For this purpose, a min-max transformation was performed:

$$x_{norm} = \frac{100 * (x - x_{min})}{(x_{max} - x_{min})}$$

Respectively for the parameter public debt (high debt corresponds to low potential):

$$x_{norm} = 100 - \frac{100 * (x - x_{min})}{(x_{max} - x_{min})}$$

The minimum and maximum values are either based on the database or were defined individually. They are summarized in Table 2.

Table 2: Min/max values of some components for the normalization.

Component	Unit	Minimum	Maximum
Population density	Ppl/km²	0	4892
Total heat demand of municipality	MWh/ha/yr	0	248
Gross domestic product	€/cap/yr	0	96593
Public debt per capita	€/cap	0	7143
Household carbon footprint	t(CO_2e)/cap	0	14000

4 Results

In this chapter, the selected factors to determine the socio-economic potential for deep geothermal energy projects are extensively described for the URG. The quantified and spatially resolved parameters are presented in the form of maps. Some data are available from various sources at different administrative levels. Preference was given to EU sources if applicable, as these datasets are generally harmonized and allow a better comparison between German and French areas. However, data from sources at country or state/region/department level generally have a higher resolution. The last available version of the datasets was used.

4.1 Social Components

4.1.1 Population Distribution

Fig. 3 shows the population density in the URG separated for each municipality. This parameter gives a good indication of where the demand for heat and electricity is high, which can be considered as a high potential for geothermal projects. At the same time, high population density poses a problem for reservoir development, as the impact of potential induced seismicity is significantly increased.

The URG is one of the most densely populated regions in Europe with a total of about 6 million inhabitants, whereby the population is heterogeneously distributed. In the northern part, there are the two metropolitan regions, Rhine-Main and Rhine-Neckar, each consisting of several cities with more than 100,000 inhabitants (e.g. Frankfurt, Darmstadt, Ludwigshafen, Mannheim, Heidelberg) as well as numerous medium-sized settlements. Here, the population density is generally above 500 ppl/km² on the countryside and well above 1000 ppl/km² in the cities. Towards the south and especially in the French URG, population density decreases significantly and averages about 100 to 200 ppl/km² on the countryside. However, also the central and southern parts of the region comprise major cities, for example Karlsruhe, Strasbourg, Freiburg im Breisgau, Mulhouse and Basel, where the population density exceeds 1000 ppl/km².

Source: Data on the population of each municipality in Germany is available on the website of Federal Agency for Cartography and Geodesy (BKG Germany | Population of Municipalities). For France, data is provided by National Institute of Statistics and Economic Studies INSEE (INSEE France | Population of Municipalities).

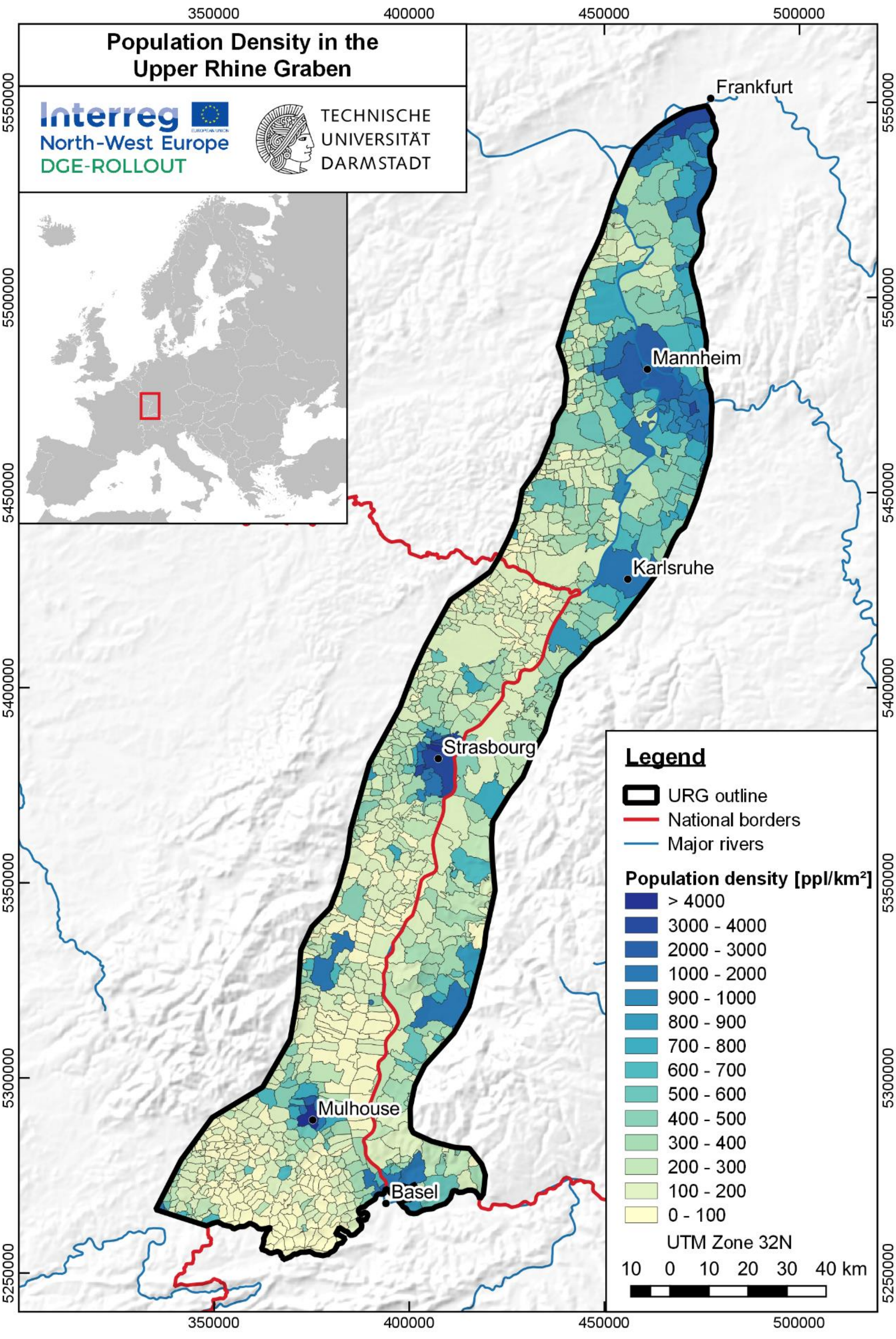

Figure 3: Population density in the URG.

4.1.2 Heat Demand

Space heating for residential and commercial buildings accounts for about one third of the total final energy consumption in the European Union. About 75% of the primary energy used for heating is covered by fossil fuels. To reduce the resulting greenhouse gas emissions, a significant expansion of renewable energies and especially geothermal energy is required. The heat demand in Northwest Europe was described and analyzed in the DGE-ROLLOUT report "WP T1 - 2.1 Map of the spatial distribution of the heat demand at the surface" (Strozyk et al. 2021). The map was generated from heat demand (HD) data measured or calculated by each project region in North-West Europe and has a spatial resolution of 100 x 100 m^2.

Fig. 4 shows the total HD, which amounts to 62.9 TWh per year in the URG. The residential sector accounts for 51.4% and the commercial sector for 48.6%. The HD generally follows the population distribution. The highest demand is found in the Rhine-Main and Rhine-Neckar metropolitan areas. However, the remaining major cities in the URG are also characterized by increased HD. The lowest HD is found in the rural areas in the southern URG.

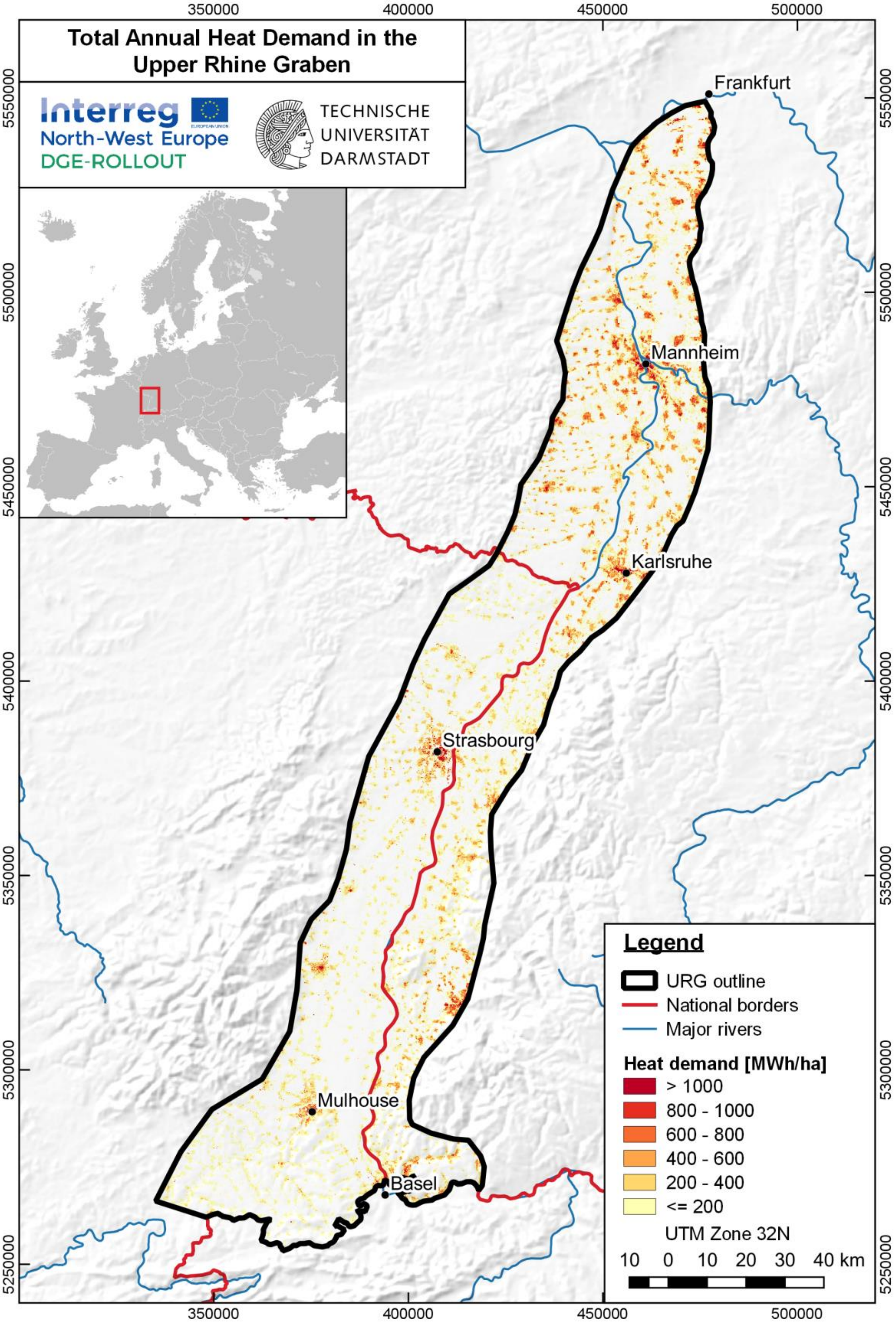

Figure 4: Combined residential and commercial heat demand in the URG in MWh/ha per year.

4.1.3 Impact of Geothermal Projects

Geothermal exploitation has a long tradition in the URG, as deep thermal groundwaters have been used for balneological purposes in the region for centuries. Beginning in the early 20th century, this application was further expanded by drilling several shallow and medium-deep boreholes (Fig. 5). The utilization of deep geothermal resources for heat and power generation began in the late 1970s and early 1980s with projects in Bühl, Cronenburg, and Bruchsal. This was followed by the extensive European EGS (Enhanced Geothermal Systems) project at Soultz-sous-Forêts. Other successful projects were realized in Riehen, Landau, Weinheim, Insheim and Rittershoffen. Two other projects near Strasbourg, Vendenheim and Illkirch, were recently discontinued due to large induced seismicity. By 2020, geothermal power plants with a total capacity of about 50 MWth and 10 MWel have been installed in the URG. Several deep geothermal projects were stopped because of induced seismicity, unsuccessful drilling or other reasons.

The acceptance of realized geothermal projects varies strongly among the population. The main reason for the low acceptance is the potentially perceptible induced seismicity, as for example in Basel (ML = 3.4), Landau (ML = 2.7), Insheim (ML = 2.4), Soultz-sous-Forêts (ML = 2.9) and Vendenheim (ML = 4.0). Locally, citizens' initiatives have been formed to prevent further expansion of geothermal energy. Elsewhere, public support is considerably better (e.g. in Trebur), which can be attributed to extensive public relations work.

Apart from this, the geothermal industry in the URG provides a considerable number of jobs, however, they are not quantified at the moment. Companies working in the development of geothermal projects in the region include Deutsche ErdWärme, Eavor, GeoThermal Engineering, and Vulcan Energie Ressourcen. Recently, especially the aspect of lithium extraction has led to significant growth. Additional jobs in the field exist at universities (e.g. in Darmstadt, Freiburg im Breisgau, Heidelberg, Karlsruhe, Strasbourg) and the various geological services.

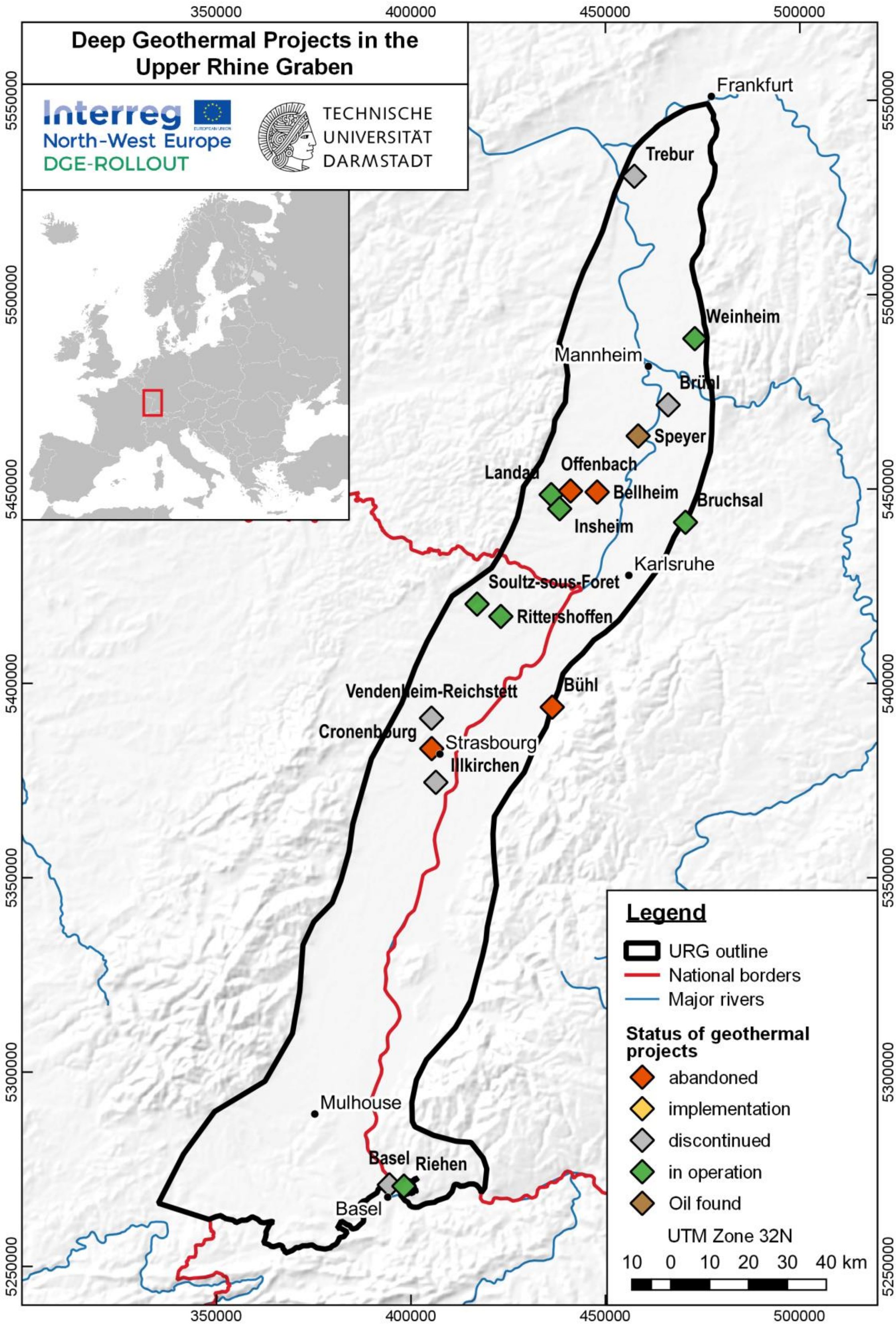

Figure 5: Overview of deep geothermal projects including their current status in the URG.

4.1.4 Social Progress Index

There are various indices that measure the social level of a region in addition to economic indicators such as the GDP, with the Human Development Index (HDI) being the most widely used. The HDI considers mainly simple indicators such as health, education and income, while neglecting other key factors that have gained importance in recent years. The European Social Progress Index (EU-SPI), first published in 2016, develops this simple approach further (Annoni and Bolsi 2020). EU-SPI describes the "capacity of a society to meet the basic human needs of its citizens, establish the building blocks that allow peoples and communities to enhance and sustain the quality of their lives, and create the conditions for all individuals to reach their full potential". The following three dimensions of social progress are quantified: basic human needs, the foundations of well-being, and opportunity, each consisting of four components (1. nutrition and basic medical care, 2. water and sanitation, 3. shelter, and 4. personal security, in the basic human needs dimension; 5. access to basic knowledge, 6. access to information and communication technologies (ICT), 7. health and wellness, and 8. environmental quality, included in the foundations of wellbeing dimension; 9. personal rights, 10. personal freedom and choice, 11. tolerance and inclusion, and 12. access to advanced education). This allows a more differentiated presentation of social progress.

Fig. 6 shows the EU-SPI in 2020 for the six NUTS 2 regions in the URG. In all regions, the index is above the EU average of 67. The lateral variability of the EU-SPI is extremely low, with the lowest value of 71.03 found for the administrative district of Darmstadt and the highest value of 72.68 found for the Alsace. For some of the subcategories, however, especially access to advanced education, personal freedom and choice, environmental quality, and personal security, significant differences of partially more than 10 points can be observed, but these differences largely balance each other out.

Source: EU-SPI is provided by the European Commission for the regions of the EU, at the NUTS 2 level (European Commission | Social Progress Index).

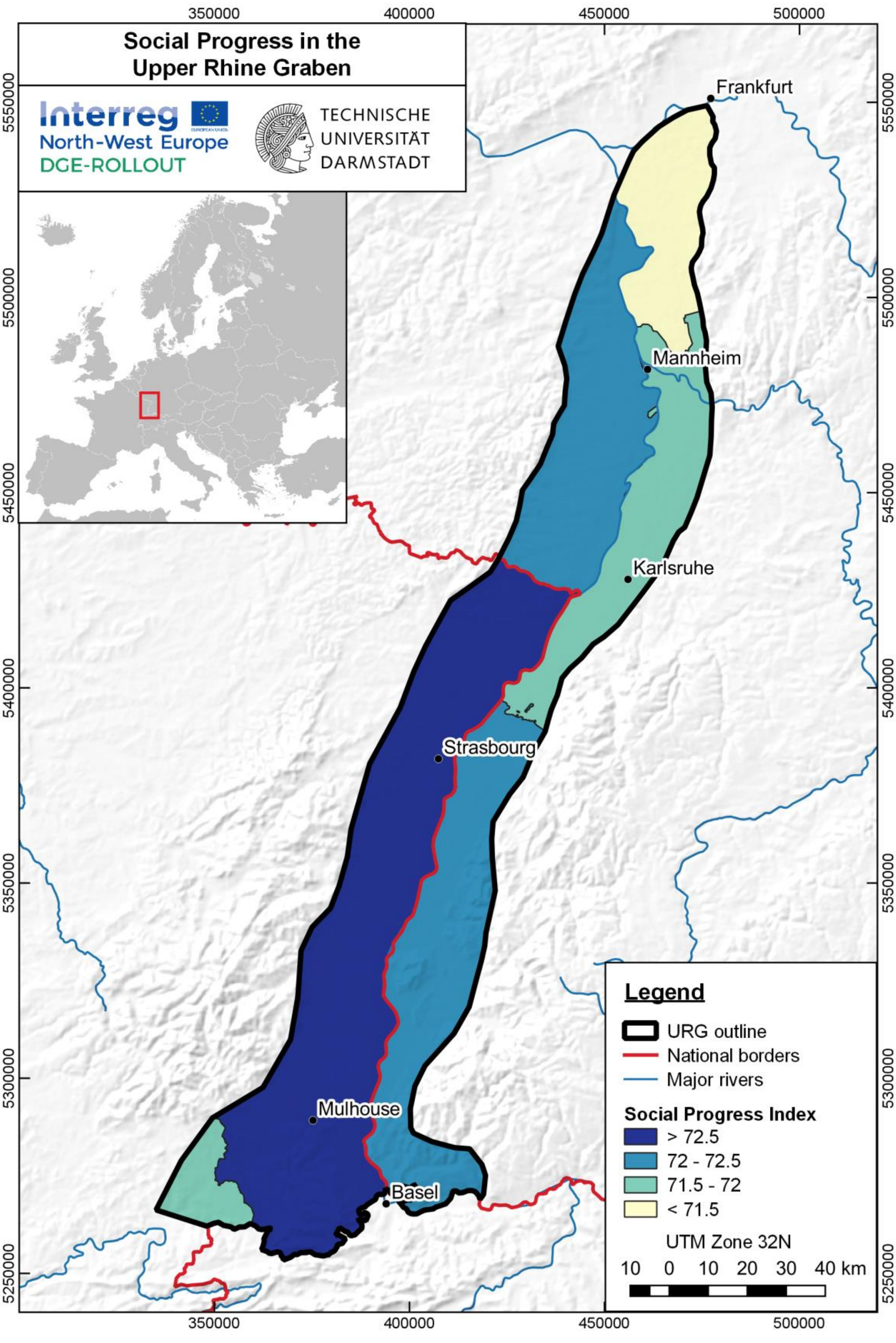

Figure 6: European Social Index (EU-SPI) for the NUTS 2 regions in the URG.

4.1.5 Political Orientation/Acceptance of Renewables

The results of the most recent parliamentary elections in Germany and France are valuable indicators of the political mindset of the population, from which the acceptance for renewable energy and in particular geothermal heat and power can be inferred. It should be noted, however, that elections always represent snapshots that are sensitive to the current situation and to individual political personalities. Election results can therefore vary greatly within one legislative period. Furthermore, Germany and France are characterized by widely differing party and electoral systems (proportional vs. majority voting), limiting the data comparability.

Fig. 7 summarizes the results of the 2017 French legislative election and the 2021 German federal election. The pie charts show the proportion of votes cast by each party (Germany: second vote; France: first round). The color on the background indicates which party won the electoral district (Germany: first vote; France: second round). In the rural areas of the URG, conservative parties usually dominate (CDU in Germany; LR/UDI/DVD in France). In contrast, urban electoral districts are mainly won by social democratic, liberal and green parties. The acceptance of renewable forms of energy is thus presumably highest here.

The German Renewable Energy Agency commissioned a survey to investigate how important the expansion of renewable energies is considered to be by the population in 2021. 83 % of the 1051 respondents consider it important or very important. Accordingly, renewable energies are included in the election programs of most parties. The Bundesverband Erneuerbare Energie e.V. (BEE) conducted a survey on energy policies among the parties represented in the federal parliament, with one of the questions directly referring to the expansion of renewable heat through geothermal sources. The parties CDU/CSU, BÜNDNIS 90/DIE GRÜNEN, SPD, FDP, DIE LINKE each stated that they intend to continue promotion and funding programs. The AfD party, on the other hand, focuses on coal and nuclear power in its energy concept. Based on this statement, a correlation of votes for the AfD with the acceptance of renewable energies is proposed. Further smaller parties are not considered.

No specific statements on geothermal energy could be found for the French parties. Therefore, the general energy policy goals were extracted from the respective election programs. The parties REM/MoDem, FI, PS/DVG/PRG and EELV aim at expanding renewable energy forms, but to different extents. The LR/UDI/DVD and FN parties oppose this and focus on nuclear energy supply.

Fig. 8 illustrates the public acceptance of renewable energy forms in the URG based on the election results. In the German part, acceptance is consistently high, with the highest value reached in Frankfurt at around 95 %. In France, acceptance is generally lower and shows strong spatial heterogeneity. The values range from around 30% in the southern Bas-Rhin to around 79% in Strasbourg.

Source: The results of the 2017 legislative elections in France are provided by the French government (data.gouv.fr | 2017 Legislative Election Results). The results of the 2021 federal election in Germany are provided by the Federal Election Commissioner (Bundeswahlleiter | 2021 Fedel Election Results).

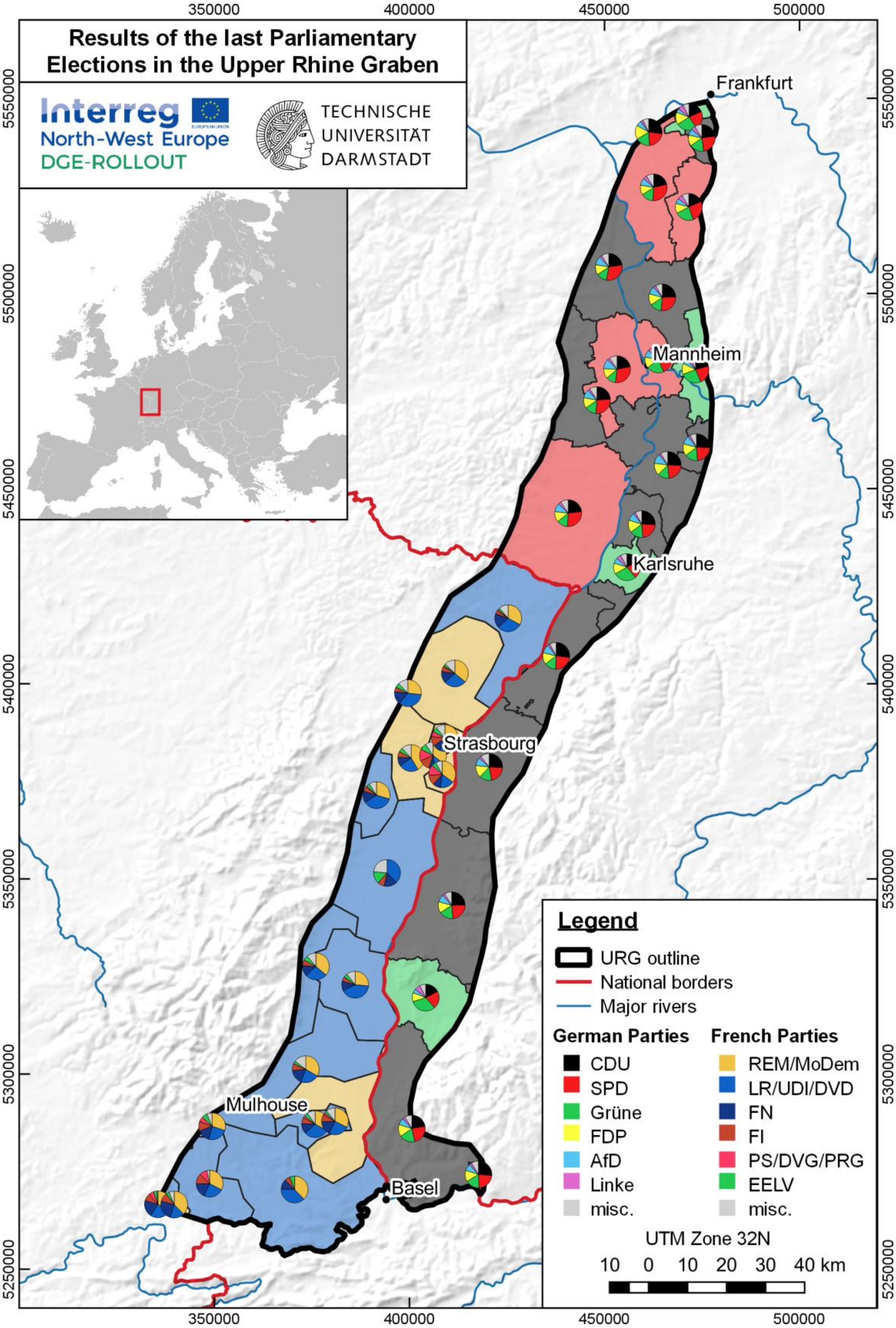

Figure 7: Results of the 2017 French legislative election and the 2021 German federal election for the URG. The pie charts show the ratio of votes for the parties in each electoral district. The background color indicates the winning party.

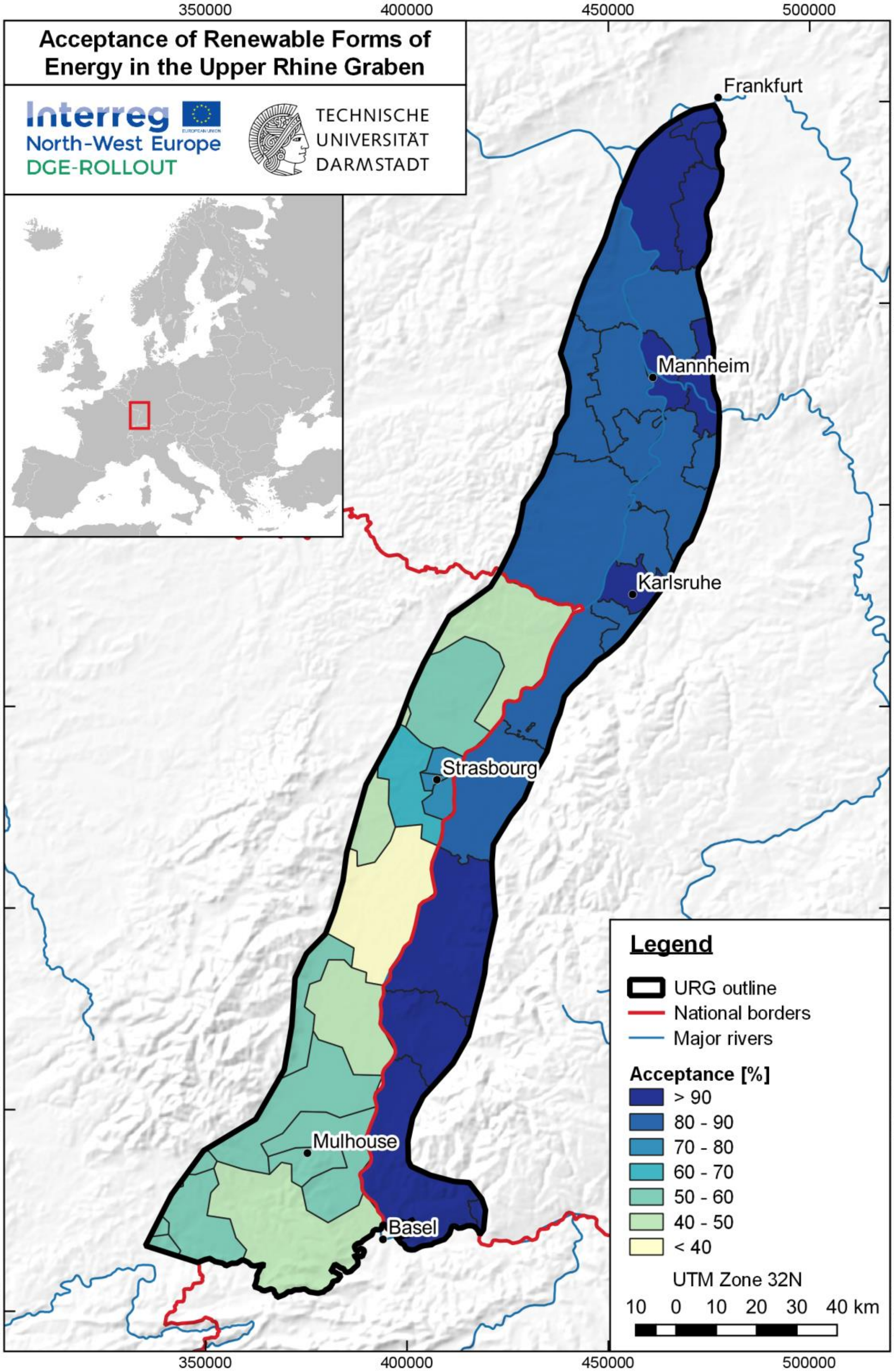

Figure 8: Acceptance of geothermal energy based on the election results shown in Map 5.

4.2 Economic Components

The URG is an economically thriving region in Europe. A large number of major companies are based here or have production facilities, including BASF, Deutsche Bahn, EnBW, HeidelbergCement, Merck, Opel, SAP and Stellantis. In addition, several important trans-European rail and road routes traverse the URG. In the following, the economic aspects directly relevant for deep geothermal projects will be described in more detail.

4.2.1 District Heating

Because the URG comprises exclusively low-enthalpy reservoirs, pure electricity production by geothermal plants is often not economically viable. Instead, the focus is on direct heat utilization or combined heat and power production. In this context, an existing district heating network (DHN) is an important prerequisite for the realization of geothermal projects, since a new construction of a DHNs is hardly financially feasible. Therefore, locations are targeted that result in the relatively small connection fees. A major advantage of DHNs is furthermore the adaptability compared to other energy supply infrastructures, which enables a gradual replacement of fossil fuels with renewable heat sources.

Fig. 9 shows the municipalities in the URG with existing DHNs, compiled from the German District Heating Atlas and the Pan-European Thermal Atlas. It should be noted that the data basis includes only the medium and large networks. Accordingly, there are additional small DHNs in the region that may supply heat to only a few hundred units, but they are not considered further. In the URG, less than 10% of municipalities are connected to a major DHN, including all of the larger cities in the region. DHNs are particularly well developed in the Rhine-Main and Rhine-Neckar metropolitan regions in the northern URG. The network in Mannheim and Ludwigshafen has the largest capacity, with around 7040 GWh of distributed heat per year.

Source: Data on existing district heating networks are compiled for Germany in the District Heating Atlas of the Hildesheim/Holzminden/Göttingen University of Applied Sciences and Arts (HAWK | Fernwärmeatlas) and for all of Europe in the Pan-European Thermal Atlas (EU | Pan-Euopean Thermal Atlas).

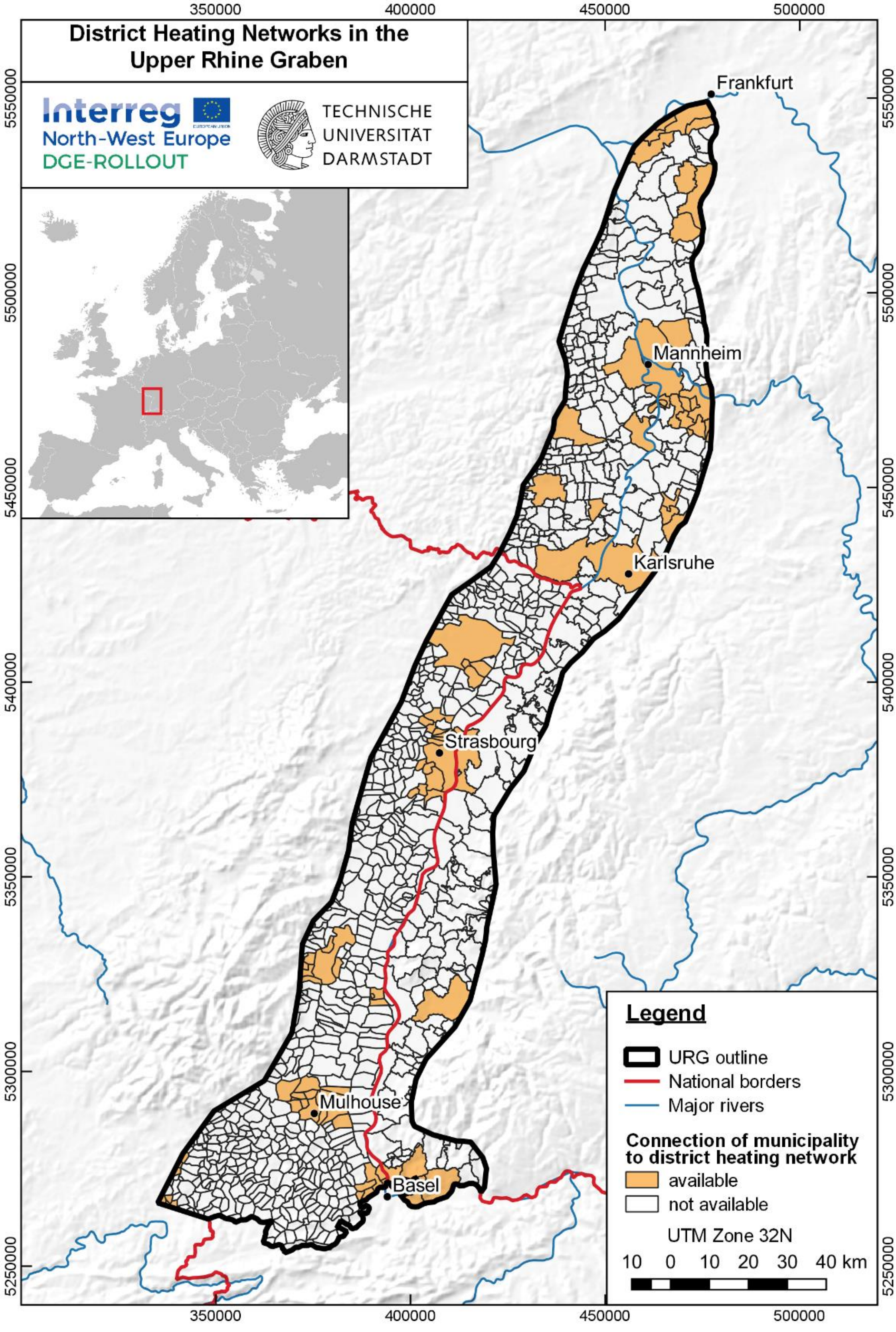

Figure 9: Total votes for the established parties with energy policy in agreement

4.2.2 Gross Domestic Product

The gross domestic product (GDP) is a measure of the economic performance of a country or region in a given period. It summarizes the total value of domestically produced goods and services after deducting the inputs consumed in their production. GDP per capita allows a comparison of economic entities of varying size with each other and thus to quantify the material wealth of a region. In general, GDP is expressed in purchasing power standards (PPS) to avoid distortions due to different price levels in individual countries.

Fig. 10 shows the GDP per capita of the NUTS 3 level regions in the URG for the year 2019. Values range from about 20,300 € in the Rhein-Pfalz-Kreis to 96,600 € in Frankfurt am Main, therefore exhibit strong lateral heterogeneity. For reference, the mean GDP per capita of the entire EU is about €31,000. A clear urban-rural trend can be observed especially in the northern URG, reflecting a concentration of industry in large cities such as Darmstadt, Mannheim, Ludwigshafen and Karlsruhe. In addition, there is a disparity between north and south. While the GDP per capita is below the EU average in almost all regions in the French URG, except Bas-Rhin, significantly higher values are measured in the northern URG.

Source: The results of the 2017 legislative elections in France are provided by the French government (data.gouv.fr | 2017 Legislative Election Results). The results of the 2021 federal election in Germany are provided by the Federal Election Commissioner (Bundeswahlleiter | 2021 Fedel Election Results).

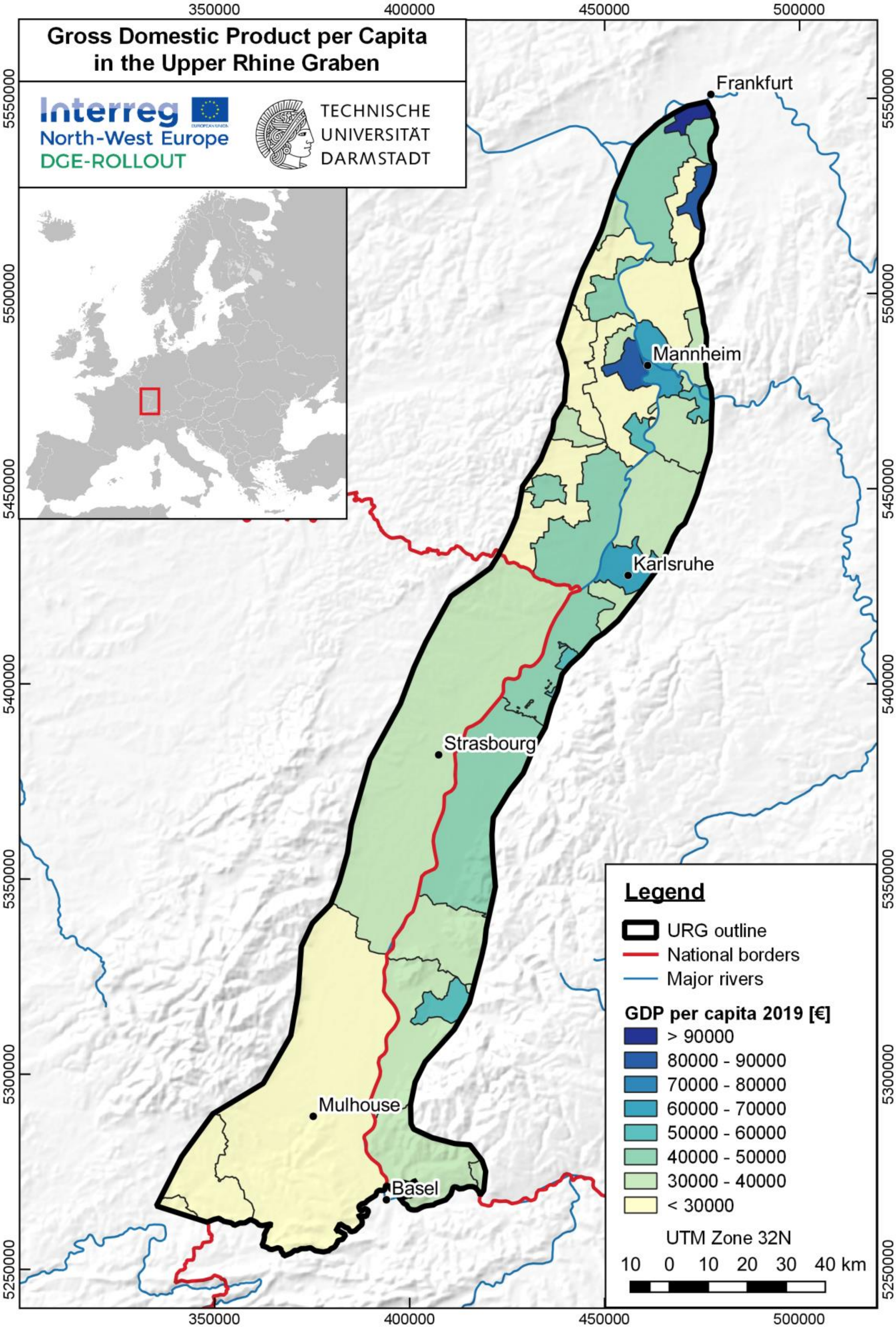

Figure 10: Gross domestic product per capita for NUTS 3 level regions in the URG.

4.2.3 Level of Public Debt

In many cases, investments by the public sector play a key role in the development of deep geothermal energy. In this context, possible funding at the municipal level is highly dependent on public debt.

Fig. 11 shows the public debt per capita of the municipalities in the URG in order to compare regions of different population sizes. The debt is very heterogeneously distributed and a clear urban-rural trend can be observed. The highest public debt per capita is achieved in medium-sized and large cities in the German URG. The highest value of around 7,140 €/cap was determined for Ludwigshafen. On the French side, the public debt is significantly lower in most municipalities and especially in the cities.

Source: Data on public debt of municipalities in 2021 are provided by the statistical offices of each state in Germany (Baden-Württemberg: Statistics BW | Debt of Municipalities, Hesse: Statistics Hessen | Debt of Municipalities, Rhineland-Palatinate: Statistics RLP | Debt of Municipalities). Data on public debt in France in 2018 can be found at France | Debt of Municipalities.

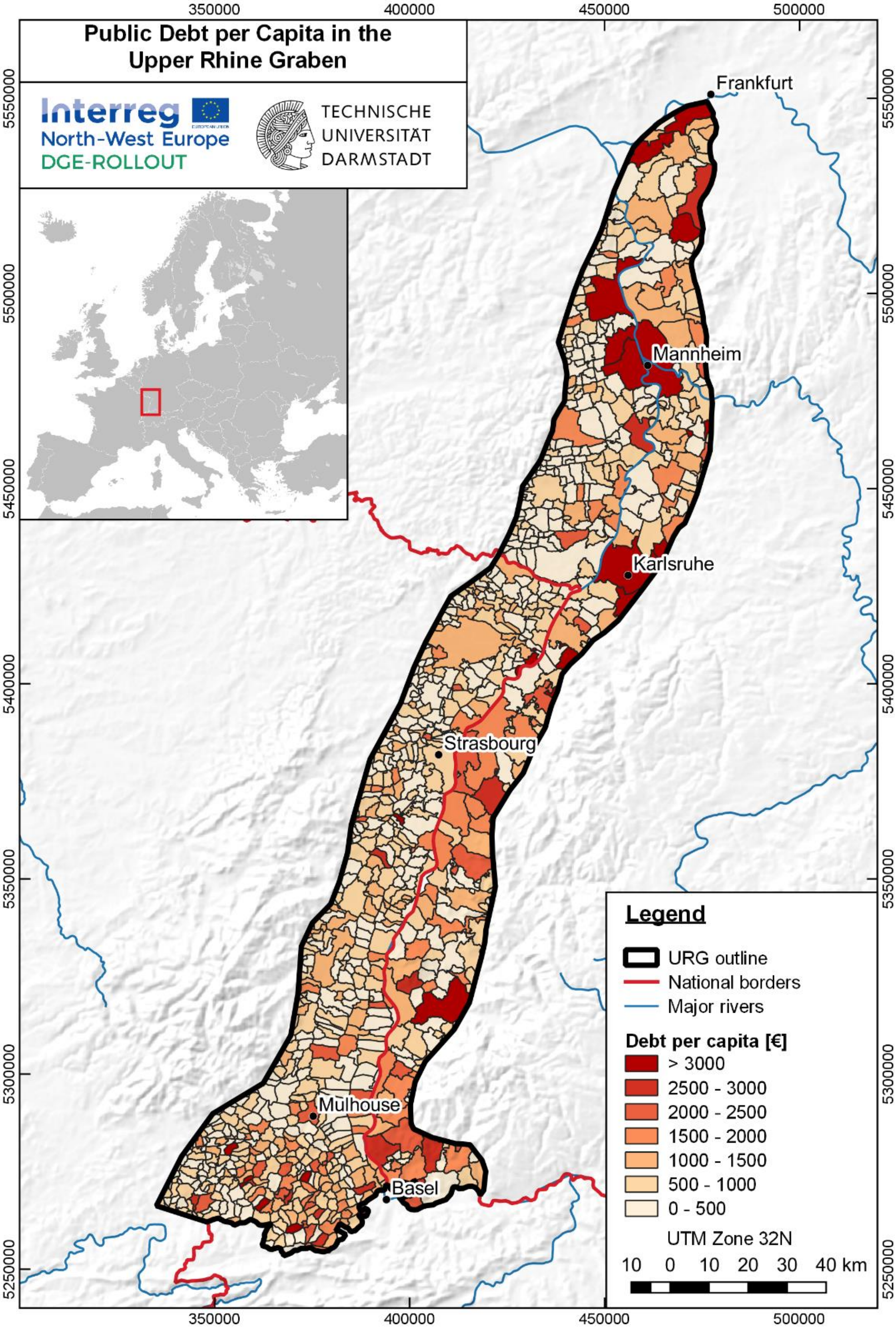

Figure 11: Public debt per capita in the municipalities of the URG.

4.2.4 Private Investment

In addition to public funds, investments by private companies in environmental protection play an important role. A distinction can be made between investments in waste management, wastewater management, water protection, noise and vibration protection, air pollution control, species and landscape protection, soil, groundwater and surface water protection and remediation, soil remediation and climate protection. Air pollution control and climate protection are directly related to the expansion of geothermal energy. In Hesse, for example, 373 M€ were invested in environmental protection in 2016 , while in Baden-Württemberg the figure was as high as 974 M€ in 2017 (Statistical Office BW 2019). However, a harmonized and spatially resolved analysis of such investments is not yet available for the URG.

4.3 Environmental Components

4.3.1 Land Access

When planning geothermal projects, it is important to consider that access to resources may be limited by surface conditions. Reasons for this include e.g. the presence of military areas and, most importantly, designated ecologically sensitive areas. Therefore, all nature and landscape conservation areas in the URG are shown in Fig. 12. Nature reserves account for about 7% and landscape reserves for about 19% of the total area of the URG. Larger contiguous protected areas are located mainly in the central and northern parts of the region. In the vicinity of these areas, a detailed environmental impact assessment is required prior to the implementation of geothermal projects.

Source: Shapefiles of the protected areas can be downloaded at European Environmental Agency | Protected Areas for whole Europe. Detailed information are furthermore provided for France at Geoportal France | Protected Areas and for Germany at Geoservices BfN Germany | Protected Areas.

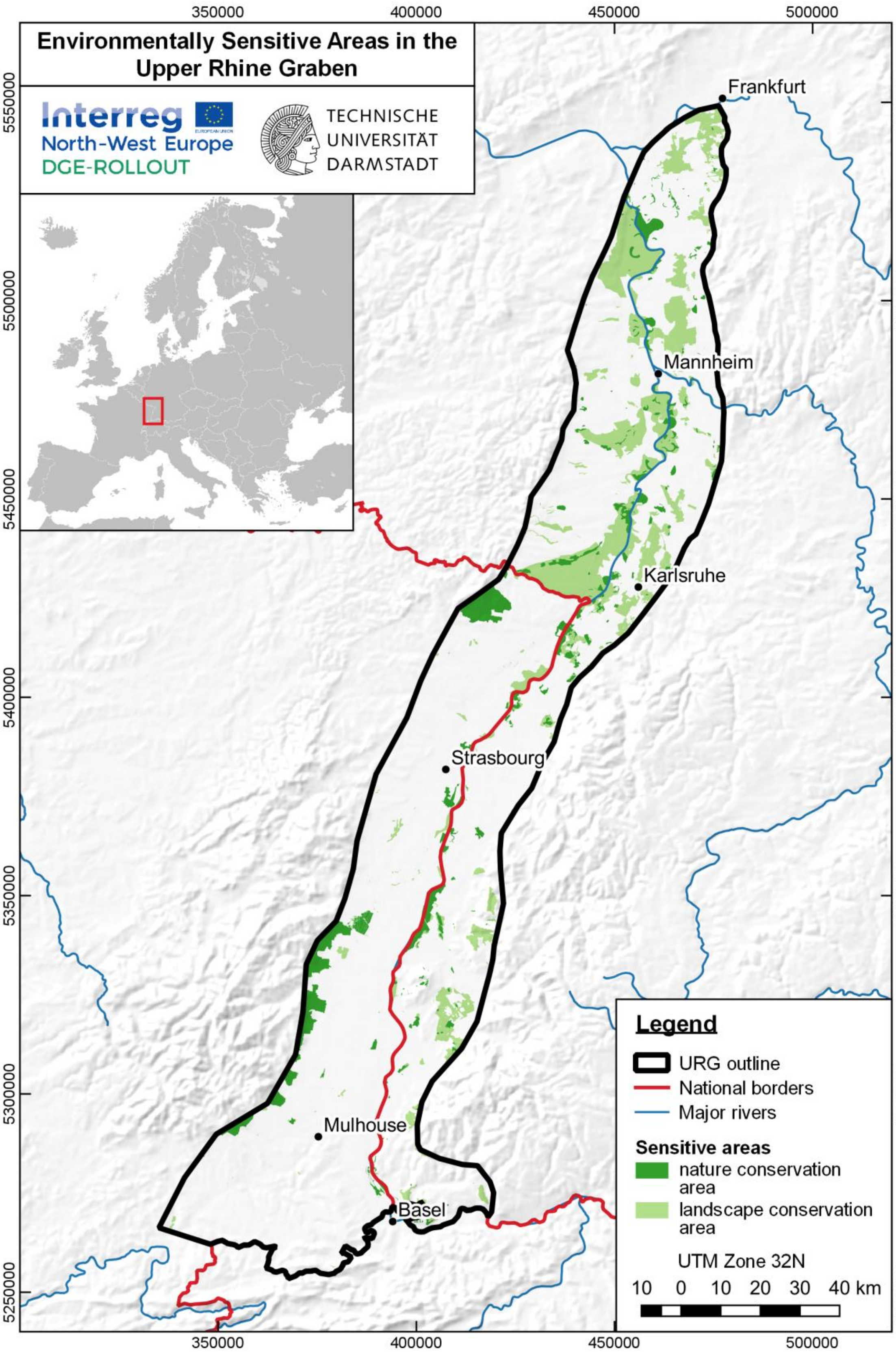

Figure 12: Nature and Landscape conservation areas in the URG.

4.3.2 Greenhouse Gas Emissions

A rapid reduction of greenhouse gas (GHG) emissions is essential to meet the binding climate protection goals, defined for example in the Paris Agreement. This will be achieved primarily through the extensive replacement of fossil fuels with renewable energies. Since wind, solar, and hydropower have limitations both in terms of expansion capacities and temporal availability, geothermal energy can significantly contribute to closing this gap.

A harmonized dataset of GHG emissions for all EU regions was compiled by Ivanova et al. (2017). The calculations are based on consumer expenditure surveys and data from the EXIOBASE 2.3 multiregional input-output database. In the URG, average household carbon footprint exhibits significant spatial heterogeneity (Fig. 13). In the French part, the average emissions are the lowest with 10.5 tCO_2e/cap. In Germany, emissions are generally higher, with the highest value of about 14 tCO_2e/cap in Hesse. The main reason for the variation is the differences in the electricity mix. While nuclear power is dominant in France, a large part of the electricity supply in Germany is secured by fossil fuels. In addition, the GDP also has a significant influence on the carbon footprint, which is on average higher in the German URG than in the French URG, especially in the north. Other aspects of influence that are not further quantified are household size, urban-rural typology, level of education, expenditure patterns, temperature, resource availability and carbon intensity of the electricity mix.

Source: Data on the average household carbon footprint for the NUTS 2 regions can be obtained at Environmental Research | Carbon Footprint EU.

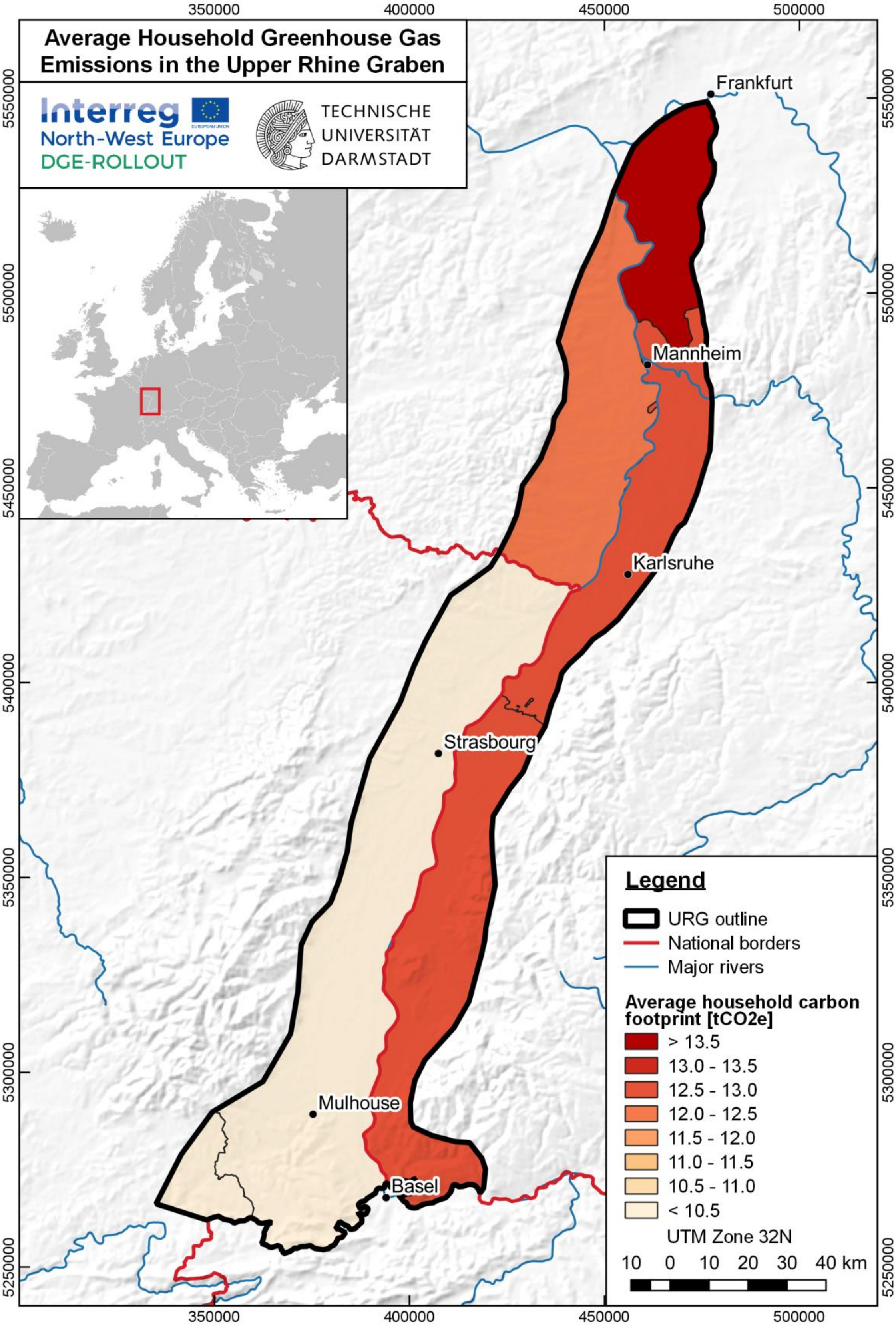

Figure 13: Average household carbon footprint in the NUTS

4.4 Socio-Economic Potential

Based on the data described above, a composite index for the socio-economic potential for deep geothermal energy in the URG was calculated (Fig. 14). The values range from 0 in the nature reserves to about 75 in Frankfurt, Heidelberg and Strasbourg. It should be noted, however, that the absolute values are strongly dependent on the calculation approach, which is why the map is mainly suitable for a qualitative interpretation of the potential. In general, a clear urban-rural trend is again observed, which is due to the concentration of population and industry in the major cities.

In addition, the potential in the French URG is on average lower than in the German URG, because on the one hand the population density and on the other hand the acceptance for renewable energy forms is lower.

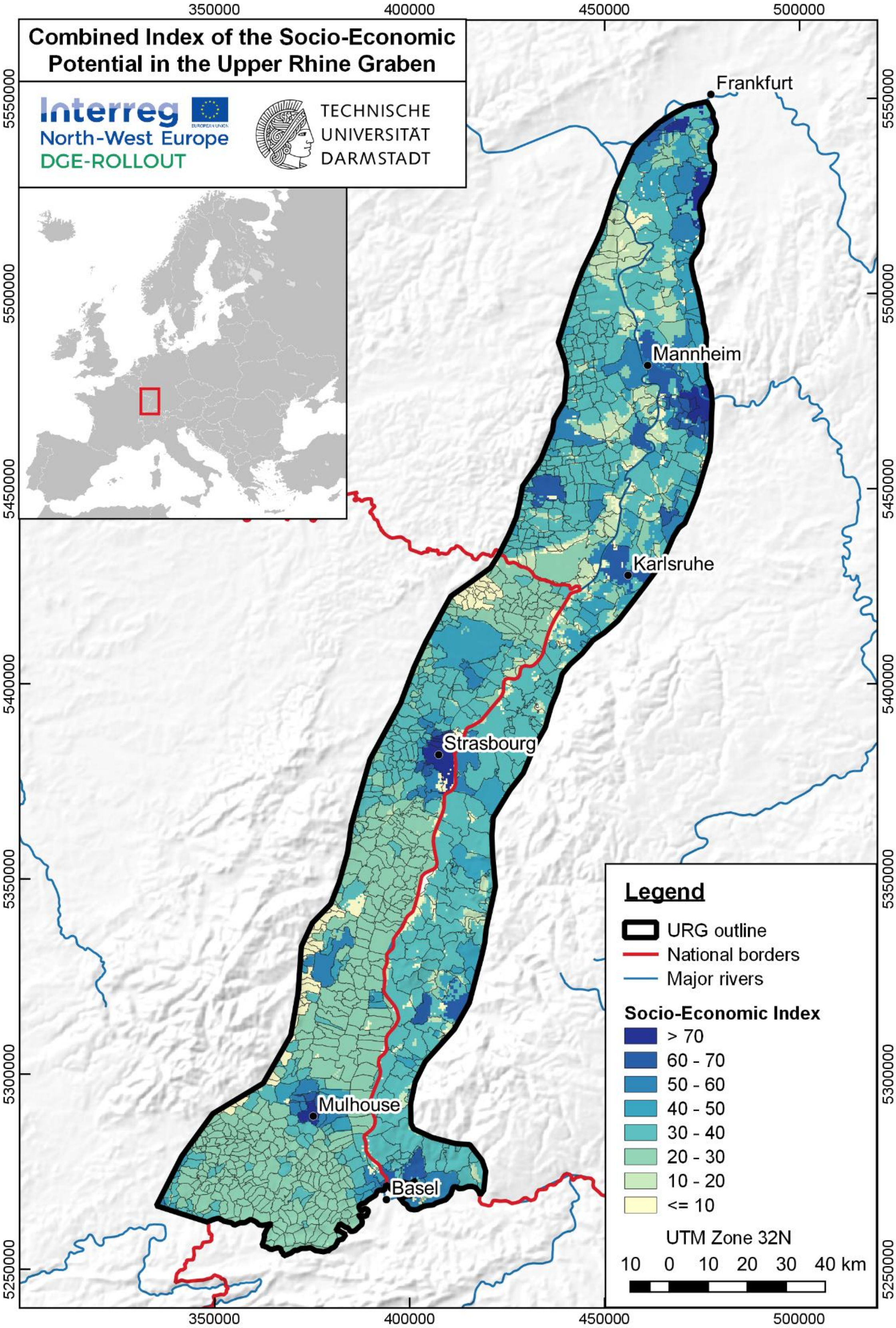

Figure 14: Socio-Economic potential index for the URG.

4.5 Case Studies

In the following, the results of the socio-economic analysis are presented in detail exemplarily for two metropolitan regions in the URG, both characterized by an overall high potential.

Fig. 15 illustrates selected indicators for the Rhine-Neckar region in the central/northern URG, which includes the major cities of Heidelberg, Ludwigshafen and Mannheim as well as several medium-sized municipalities. The population has a generally positive view of renewable forms of energy, which is a basic prerequisite for the development of deep geothermal energy. The generally high population density leads to an increased HD in urban and suburban areas. In this context, the well-developed DHNs allow an area-wide supply with geothermal energy. Furthermore, the region is characterized by a high economic performance and especially in the cities the GDP is significantly above the EU average. The highest GDP is found in Ludwigshafen, which is mainly due to the chemical group BASF. Rather negative is the high public debt rate in the larger municipalities, which can be a barrier to public investment. In addition, there are numerous protected areas, which limit or complicate access to geothermal resources on site.

Fig. 16 shows selected socio-economic indicators for the Strasbourg metropolitan area. The acceptance of renewable energy forms is significantly lower in the French than in the German URG, but the highest acceptance levels of almost 80 % are reached in Strasbourg. However, recent experiences from the geothermal projects in Insheim and Vendenheim, especially the induced seismicity, may have caused resistance in the population. Strasbourg is characterized by an even higher population density and HD than the Rhine-Neckar region. However, the HD is concentrated in the city center, while the HD is comparatively low in the rural areas around Strasbourg. The district heating network, which is comparably as well developed as in the Rhine-Neckar region, is to be evaluated very positively. The economic capacity on the French side is significantly lower than on the German side. This is offset by a lower debt ratio of the municipalities. Nature conservation areas restricting the access to geothermal resources occur mainly along the Rhine river.

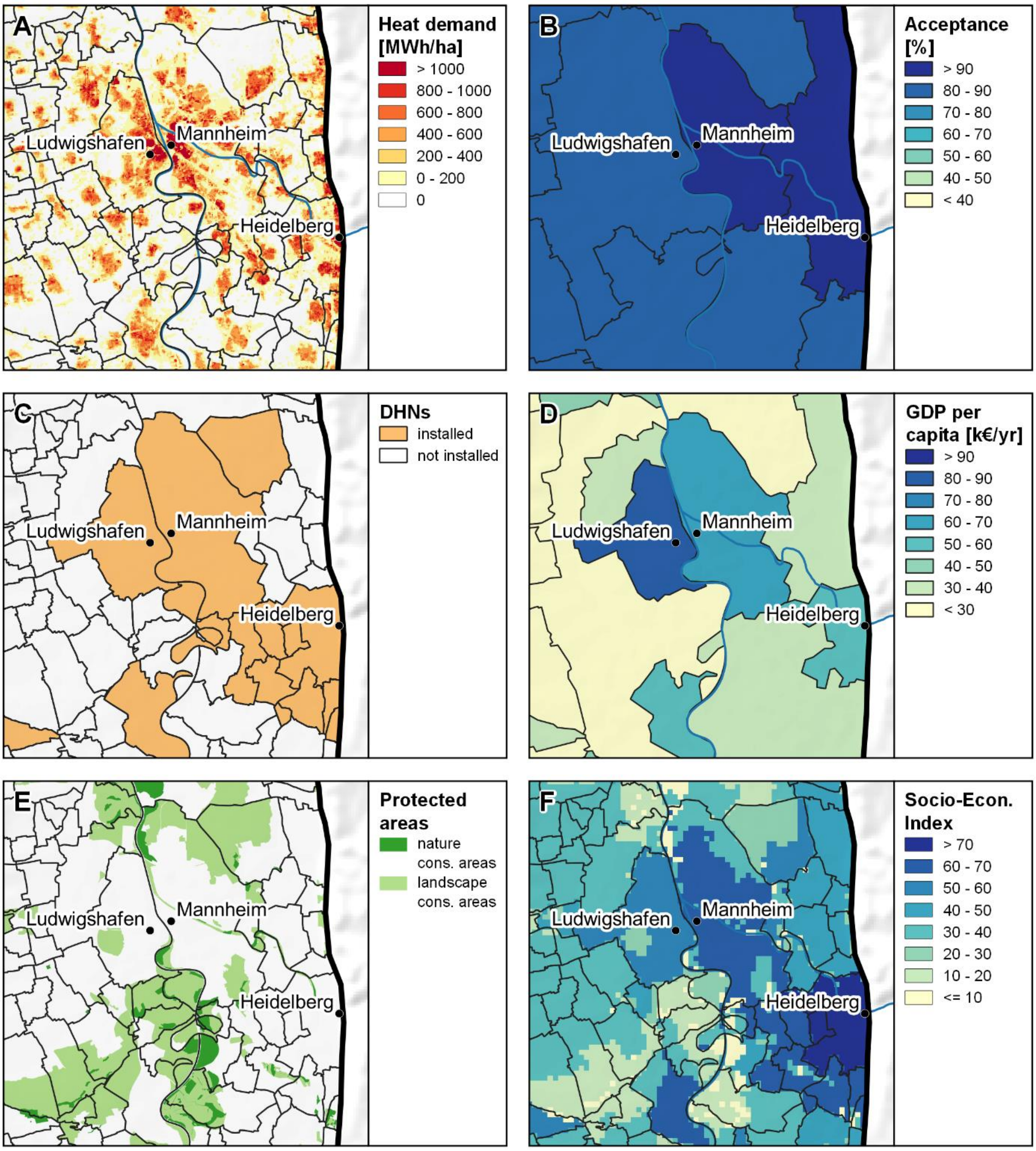

Figure 15: Selected socio-economic potential indicators for the Rhine-Neckar Region: (A) total annual heat demand, (B) political acceptance for renewable energies, (C) municipalities with district heating networks, (D) gross domestic product per capita, (E) nature and landscape conservation areas, and (F) composite socio-economic potential index.

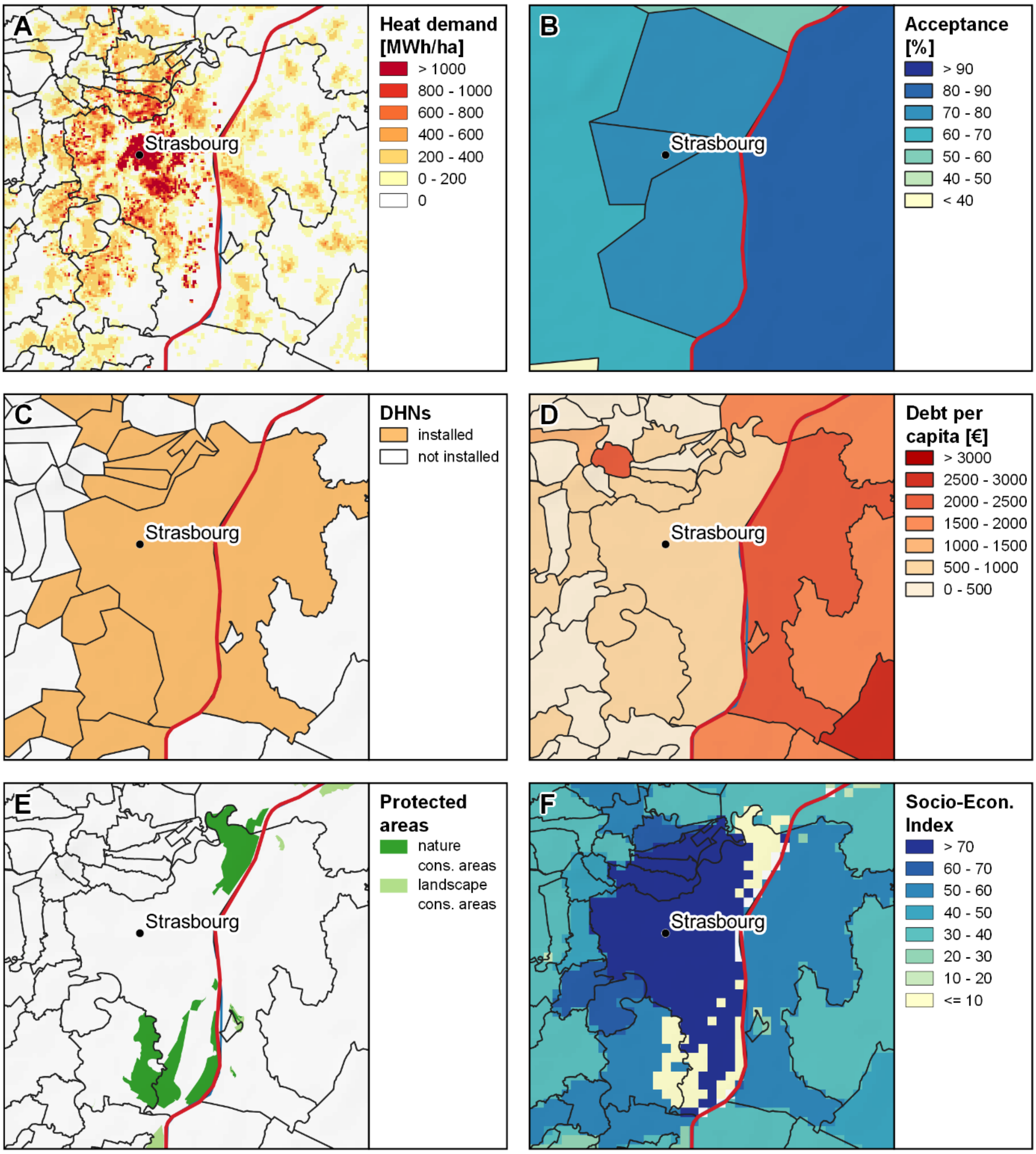

Figure 16: Selected socio-economic potential indicators for the Rhine-Neckar Region: (A) total annual heat demand, (B) political acceptance for renewable energies, (C) municipalities with district heating networks, (D) gross domestic product per capita, (E) nature and landscape conservation areas, and (F) composite socio-economic potential index.

5 Discussion and Conclusions

For the URG, 11 different indicators describing the socio-economic potential of deep geothermal energy were collected and combined into a multidimensional index. There is an increased potential in large parts of the region, which together with the high technical potential offers optimal conditions for the development of future geothermal projects. The socio-economic potential is particularly driven by the high population density and strong economic performance, which are accompanied by high heat demand and a well-developed DHN infrastructure. However, surface conditions are laterally severely variable. The overall best conditions are found in the larger cities throughout the URG and in the suburban municipalities of the northern URG. The rural municipalities of the French URG have the lowest potential. Here, the population density and the resulting heat demand are the smallest. In addition, the acceptance of renewable energies is traditionally lower in France than in Germany due to the traditional dominance of nuclear energy.

No weighting was applied to the individual parameters, as this can be very subjective, which may significantly distort the results. The Socio-Economic Index thus only provides a basis for an initial site selection. At local levels, a hierarchical decision-making process (e.g. Raos et al. 2022) is then required to reconcile subsurface and surface conditions.

Finally, it should also be noted that the URG consists of various regions with different legal and financial frameworks, which can have a significant impact on the planning of geothermal projects. These have been described in detail for example in Van Malderen (2020) and Taşdemir and Arndt (2020).

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Appendix A

Topic	Database
Population distribution	BKG Germany | Population of Municipalities INSEE France | Population of Municipalities
Heat demand	
Income	Eurostat | Gross Domestic Product
Employment / Forecast	Branchen im Fokus - Statistik der Bundesagentur für Arbeit (arbeitsagentur.de)
Social level map	European Commission | Social Progress Index
Political parties map / Election maps	data.gouv.fr | 2022 Legislative Election Results Bundeswahlleiter | 2021 Fedel Election Results
District heating	HAWK | Fernwärmeatlas EU | Pan-Euopean Thermal Atlas
Level of debt of municipalities	Statistics BW | Debt of Municipalities Statistics Hessen | Debt of Municipalities Statistics RLP | Debt of Municipalities France | Debt of Municipalities
Environmentally sensitive areas	European Environmental Agency | Protected Areas
Greenhous gas emissions	Environmental Research | Carbon Footprint EU

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