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CO_2-DISSOLVED: a Novel Concept Coupling Geological Storage of Dissolved CO_2 and Geothermal Heat Recovery – Part 2: Assessment of the Potential Industrial Applicability in France, Germany, and the U.S.A.

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Abstract

The CO_2-DISSOLVED project aims at assessing the technical-economic feasibility of coupling dissolved CO_2 storage in a saline aquifer and geothermal heat recovery. It targets specifically low-medium tonnage CO_2 emitters (ca. 10-150 kt/yr) because the amount of dissolved CO_2 that can be injected into a geothermal saline aquifer is physically limited by the solubility of CO_2 in brine. This work makes an inventory of the potential candidates to the CO_2-DISSOLVED concept in France, Germany, and the U.S.A. The results evidenced that relatively large geothermal areas match the presence of many industrial sources emitting low rates of CO_2, allowing us to conclude on the potential applicability of the concept in these three countries.

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Keywords: CO_2-DISSOLVED project; carbon capture and storage (CCS) technology; geothermal heat recovery; small to medium CO_2 emitters; France; Germany; United States.

1. Introduction

This study was conducted in the framework of the CO_2-DISSOLVED project [1] funded by the ANR (French National Research Agency). This project proposes to assess the feasibility of a novel CO_2 injection strategy in deep

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saline aquifers, combining injection of dissolved CO_2 (instead of supercritical CO_2) and recovery of the geothermal heat from extracted brine. This approach relies on the geothermal doublet technology (commonly used since the early 70s in the Paris Basin, France), where the warm water is extracted at the production well and re-injected as cooled water, after heat extraction, in the same aquifer via a second well (injection well). Moreover, unlike the standard CO_2 storage approach (injecting supercritical CO_2) which focuses on very large CO_2 emitters (ca. > 1 Mt/yr), the CO_2-DISSOLVED concept opens new potential opportunities for local storage solutions dedicated to small emitters (ca. 10-150 kt/yr) such as food, paper or glass industry, building materials makers, etc. This novel concept is thus complementary to the standard approach. It targets specifically low-tonnage emitters because the amount of CO_2 that can be injected in the geothermal aquifer via a single doublet is physically limited by the solubility of CO_2 in brine. Moreover, it is intended to be a local solution to minimize the costs related to CO_2 transport, provided that the local underground geology is favorable for heat extraction and CO_2 storage. Regarding the heat recovered, it could benefit directly to the emitting industrial plant for its own heating and/or process needs and possibly for heating other buildings close to the storage facilities.

The objective of the work presented here was to make inventories of the potential candidates for the application of the CO_2-DISSOLVED concept in France, in Germany, and in the U.S.A. It mainly consisted in identifying and prioritizing the industrial emitters that could potentially benefit from the application of the proposed CO_2 storage strategy in these three countries, i.e. determining regions where geothermal resources match the presence of industrial plants emitting small rates of CO_2. At this stage of the project, the economic aspects were not accounted for. Further investigations of these aspects will be performed for two test-cases selected from favorable sites identified in France and Germany, respectively.

2. Potential in France

2.1. French CO_2 emitters

Since 2003, industrial companies have to declare their CO_2 emissions to the French government each year if they exceeded 10 kt/yr (for details, see the decree of December 26th, 2012, obtainable on www.declarationpollution.ecologie.gouv.fr). These data are compiled in the French Pollutant Release Register (iREP) and they are available for download at www.irep.ecologie.gouv.fr. The data presented in this paper are those collected by the government for the year 2011.

On average 1,100 facilities declare their CO_2 emissions to the French administrations each year since 2003. These facilities are present throughout the French territory, but the largest ones are concentrated in a few departments, often around the estuaries of the largest French rivers (Fig. 1). Their CO_2 emissions are on average around 160 Mt/yr since 2003 (Table 1). Power plants (Energy sector) are the main source of CO_2. They are responsible for 20.4% of the total CO_2 emissions, which represents about 30 million tons of CO_2 emitted per year. Other large sources of CO_2 in France are the metal industry (including steel industry) and the mineral industry accounting for 17.2 and 14.1% of the total CO_2 emissions, respectively (i.e. 25.5 and 20.9 Mt of CO_2/yr, blue bars in Fig. 2).

Small to medium industrial CO_2 emitters (ca. 10 to 150 kt/yr) are more numerous than large ones (ca.>150 kt/yr) in France. They account for 83% of all the French CO_2 emitters in 2011 (i.e. 881 facilities, Fig. 3a). They are present in most of the French departments, and particularly in the North of France (e.g. Ile-de-France, Nord-Pas-de-Calais and Upper Normandy, red dots in Fig. 1). They have emitted about 33.5 million tons of CO_2 in 2011 (Fig. 3b), which represents 22.6% of the total CO_2 emissions. Waste and waste water management are the main sources of CO_2 in this category of emitters with 7.26 million tons emitted in 2011 (4.9% of the total French CO_2 emissions, green bars in Fig. 2).

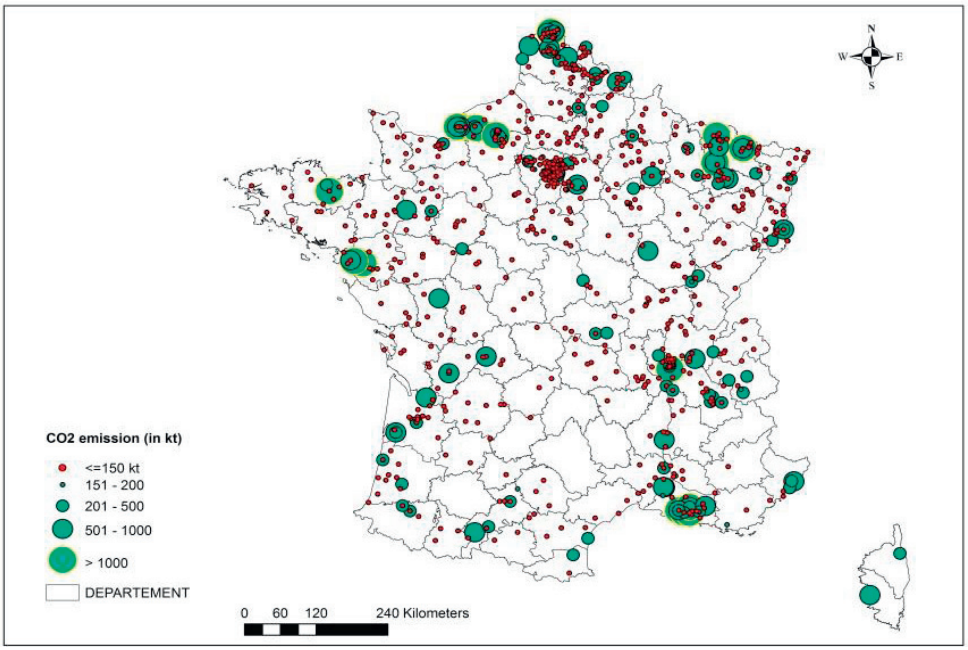

Fig. 1. Location of the French CO_2 emitters and associated quantities (source: iREP). The reported emissions refer to the year 2011 (assumed to be representative of the period 2003-2011).

Table 1. CO_2 emissions declared to the French administration since 2003. The year 2010 is not presented and commented because figures are erroneous (source: iREP).

	2003	2004	2005	2006	2007	2008	2009	2011	2003-2011
Number of reporting facilities	860	1,210	1,197	1,197	1,163	1,099	1,081	1,060	**~1,100**
Annual CO_2 emissions (in Mt)	131.0	202.9	170.9	168.5	166.7	157.3	159.4	148.3	**~160**

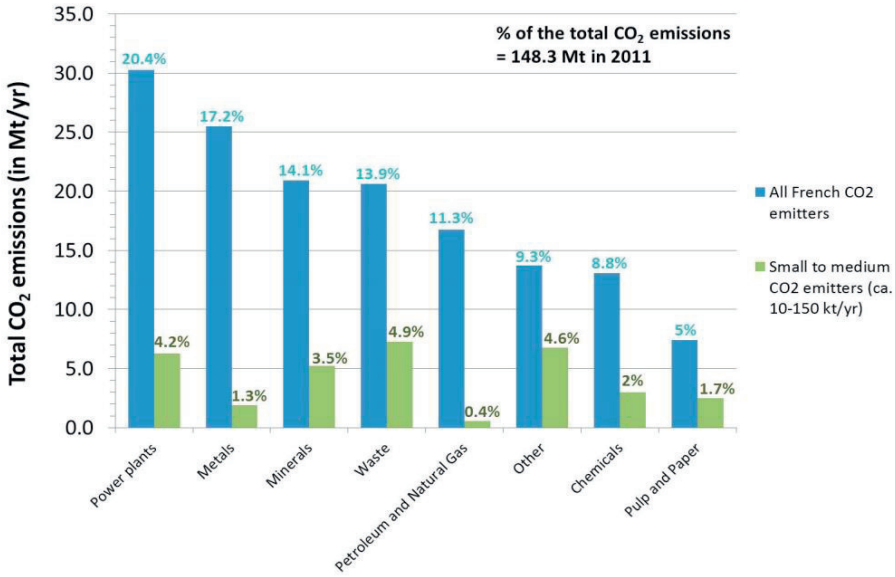

Fig. 2. Total CO_2 emissions (in Mt) in France reported by sector for the year 2011 (source: iREP).

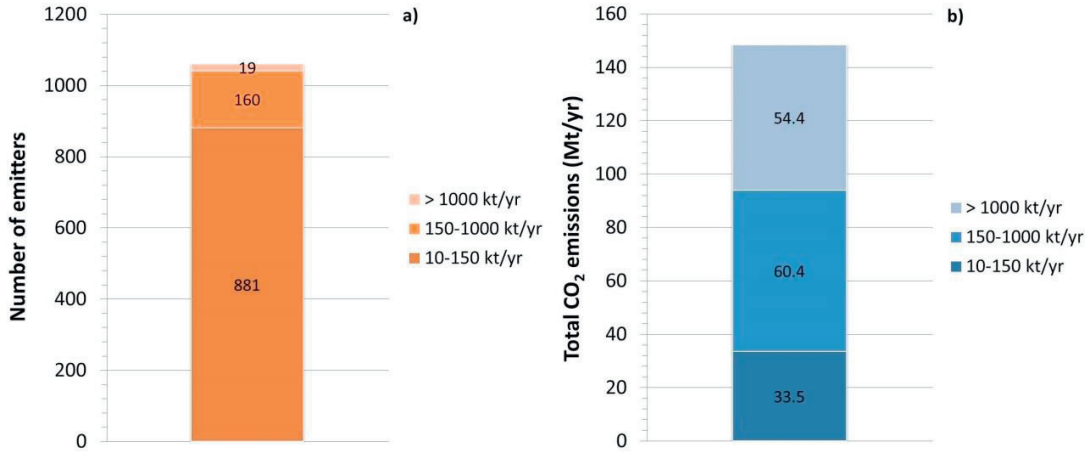

Fig. 3. Importance of small to medium CO_2 emitters (ca. 10-150 kt/yr) in France: comparison with large emitters. a) Number of CO_2 sources in each category of emitters; b) Total amount of CO_2 emitted annually per category of emitters (source: iREP). The reported data refer to the year 2011.

2.2. French geothermal resources

France has several low-temperature (<90°C) to high-temperature (>150°C) geothermal resources [2] located at different depths, geographical locations and geological settings (Fig. 4).

Low-temperature resources (< 90°C) are located in aquifers contained in the major sedimentary basins, i.e. the Paris Basin, the Aquitaine Basin, the Upper Rhine Graben, the Limagne and Bresse regions, the Rhone corridor and the Mediterranean region but also in faulted or folded regions (Fig. 4). Currently, these low-energy resources are mainly exploited in the two major existing basins in France: the Paris and the Aquitaine ones, because the other basins cited previously present geological structures that are more complex and so that their geothermal fields are more localized. In fact, since 1970s, the Paris Basin is the most developed low-enthalpy field in Western Europe with 40 geothermal plants in operation. 90% of these plants exploit the carbonate Dogger aquifer (1,500 to 2,000 m deep and 57 to 85 °C warm) for district heating. Thus, the Dogger aquifer is the most exploited layer in France for geothermal use up to now. This fact is due to its location (below the urbanized Paris area) and the corresponding high demand of energy.

Moderate-temperature resources (90 to 150°C) are in course of evaluation. A recent study, performed by BRGM and co-financed by ADEME, named CLASTIQ (CLAyed sandSTone In Question) explored new or poorly characterized deep siliciclastic geothermal reservoirs. The results of the CLASTIQ study show that these reservoirs are located in the major sedimentary basin, i.e. the Paris Basin, and in graben systems, i.e. the Rhine Graben (Alsace), the Limagne Graben and the Bresse Basin, and produced fluids around 80°C and 150°C. For details on these specific geothermal reservoirs, the reader may refer to [2,3,4].

High-temperature resources (>150°C) are located in the Overseas Departments (the volcanic islands of the Antilles - Guadeloupe and Martinique – and of the Indian Ocean - Reunion) and in the crystalline basement where water is injected into the fractures of an Enhanced Geothermal System (EGS) and the heated fluid is produced again (e.g. Soultz-sous-Forêt scientific pilot plant). These resources are not considered in this CCS project, mainly because of their low native permeability.

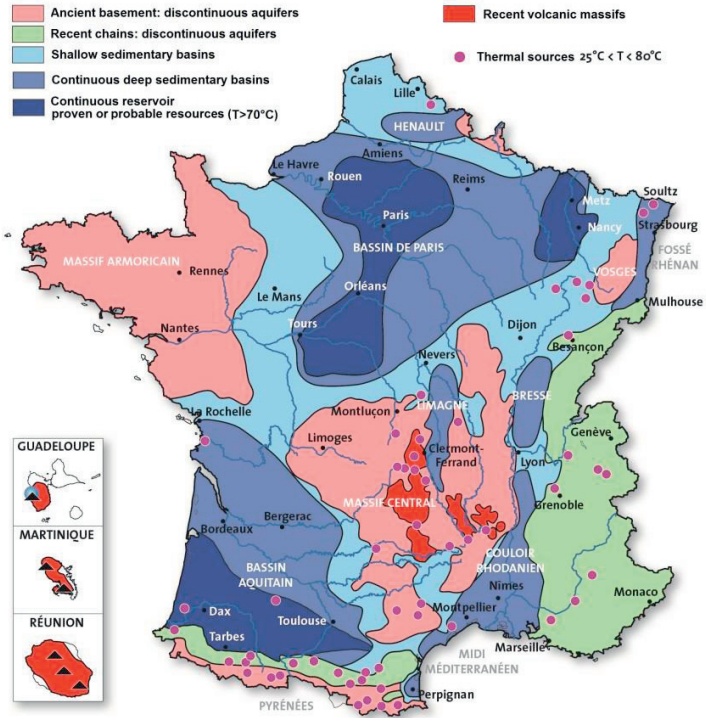

Fig. 4. Geological environments in France (modified from Jaudin et al. [2]).

2.3. Potential areas of application for the CO_2-DISSOLVED concept

In order to select emitters compatible with the requirements of the CO_2-DISSOLVED project, areas need to be defined at locations where CO_2 storage can be coupled with geothermal energy use. Therefore, the potential areas for geothermal energy use (§2.2) and the location of small to medium emitters (§2.1) were combined (intersected). For the potential areas of geothermal energy use, only the continuous hydrothermal areas were considered, because the other areas, composed of crystalline rocks, volcanic rocks, and tight and highly folded/faulted sediments, have too limited geothermal resources and/or low native permeability.

Consequently, the areas where the geothermal resources could potentially match the heat needs of a CO_2 emitting industry are composed by all the major sedimentary basins, i.e. the Paris Basin, the Aquitaine Basin, the Upper Rhine Graben, the Limagne and Bresse regions, and the Rhone corridor, where the geothermal fluids can reach locally 150°C (blue and dark blue areas in Fig. 4 and Fig. 5). Then, 653 small to medium French emitters can be considered as potentially compatible with the CO_2-DISSOLVED concept (Fig. 5). These 653 CO_2 sources have emitted a total amount of 25.1 million tons of CO_2 in 2011 (16.9% of the total French CO_2 emissions).

Most of these potential compatible sites (55%, i.e. 358 facilities) are located in the two major sedimentary basins in France: the Paris Basin and the Aquitaine Basin (13.1 Mt of CO_2 emitted in 2011). The Paris Basin appears to be the most promising area for a future application of the CO_2-DISSOLVED concept, as it comprises 287 of these 653 emitters (Fig. 5) which were responsible for a total emission of 10.8 million tons of CO_2 in 2011 (i.e. 43% of the total CO_2 released by the 653 compatible emitters [25.1 Mt]). In comparison, only 71 of these 653 compatible emitters are located in the Aquitaine Basin; they represent 9.2% of the CO_2 emitted (2.3 Mt in 2011). As a preliminary result, it is then suggested to further focus on the Paris Basin area for the selection of an application test site in France.

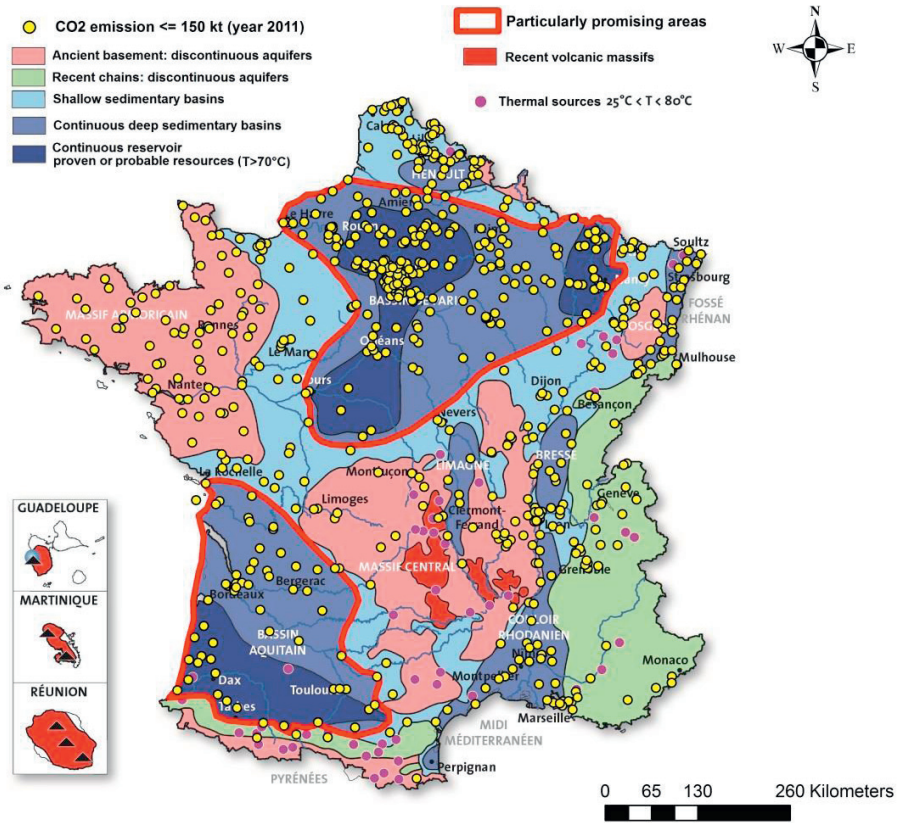

Fig. 5. Small to medium CO_2 emitters (ca. 10-150 kt/yr) *vs*. geothermal resources (modified from Jaudin et al. [2]).

3. Potential in Germany

3.1. German CO_2 emitters

Information and data about German CO_2 emissions are reported by the Federal Environment Agency (UBA) and the German Emissions Trading Authority (DEHSt). General information about the annual atmospheric emissions since 1990 is provided in national trend tables, which are publically available by the UBA. The total annual atmospheric CO_2 emissions in Germany have decreased from about 1000 Mt in 1990 to ca. 800 Mt in 2011 [5]. Thereof, the energy industries accounted for ca. 44% of the emissions, followed by the transport sector with 19%.

Furthermore, DEHSt provides specific data about stationary energy- and industrial installations, which are subject to emissions trading in Germany. The database on stationary emitters used for this project refers to data from the year 2012 [6]. It lists 1732 facilities and contains specific information like name of facility, operator, annual CO_2 emission, annual allocation of CO_2 certificates and process type. A majority of 1158 emitters are from the energy sector. In total, the 1732 listed CO_2 sources emitted 453.9 Mt of CO_2 in 2012. The locations of these emitters are depicted in Fig. 6.

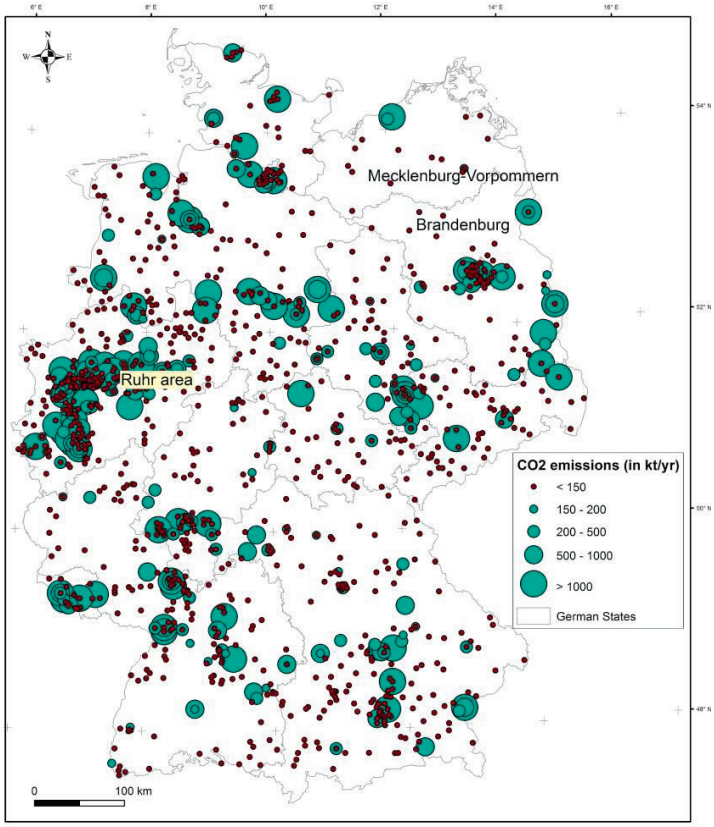

Fig. 6. Classified emissions of CO_2 sources in Germany in the year 2012 (source: DEHSt [6]).

The DEHSt database contains 800 small to medium emitters with annual CO_2 emissions of 10-150 kt. They are responsible for 7.1% of the total CO_2 emissions of the 1732 stationary emitters, which represents about 32.4 Mt of CO_2 emitted in 2012. Though small to medium emitters are located in all states, they cluster in industrial areas (Fig. 6). Especially, in the Ruhr area a high density of emitters is evident. On the other hand, few emitters are located in the Northeast of Germany (Mecklenburg-Vorpommern and the North of Brandenburg).

A comparison of the total CO_2 emissions reported by sectors for all emitters and for small to medium emitters is provided in Fig. 7. It is evident, that combustion plants are responsible for the bulk of CO_2 emissions. The relative importance of small to medium emitters in comparison to large emitters is illustrated in Fig. 8 (a, b). Even so much higher in number, they represent only a small amount of CO_2 emissions in comparison with large emitters.

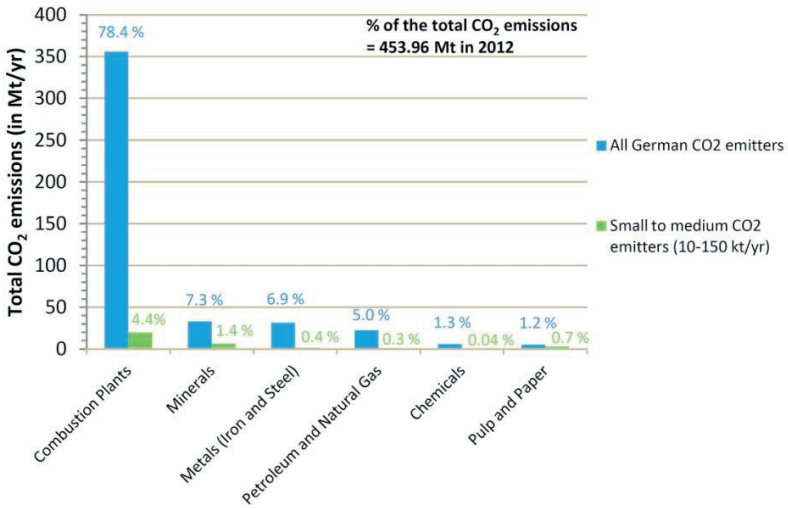

Fig. 7. Total CO_2 emissions of stationary emitters in Germany reported by sector for the year 2012 (source: DEHSt [6])

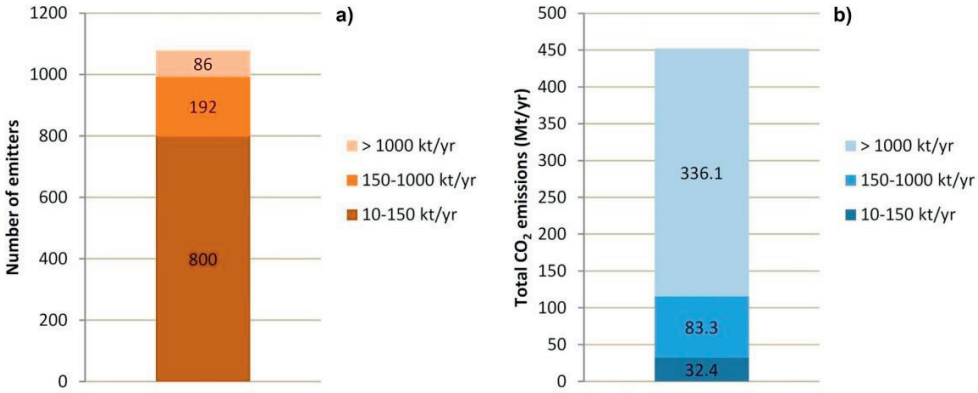

Fig. 8. Importance of small to medium CO_2 emitters (10-150 kt/yr) in Germany: Comparison with large emitters. a) Number of CO_2 emitters for different categories of emission quantity; b) Total amount of CO_2 emitted annually per category of emission quantity (source: DEHSt [6]). The reported data refer to the year 2012.

3.2. Potential areas for geothermal energy use and geological CO_2 storage in Germany

General information about geothermal resources in Germany is provided by the digital geothermal information system 'GeotIS' [7]. Based on 'GeotIS' data, potential areas for geothermal energy use in Germany have been mapped within the framework of the project "Geothermie-Atlas" [8]. The mapping of potential areas was based on the criteria lithology, thickness, and temperature and included various geological horizons in sedimentary basins of Germany. Potential maps have been produced according to the different types of geothermal energy resources and prospectivity: 'proven hydrothermal potential', 'assumed hydrothermal potential' and 'petrothermal potential'.

Areas of proven hydrothermal potential comprise aquifers from Lower Permian (Rotliegend) to Tertiary age, whereas areas of assumed hydrothermal potential are restricted to Rotliegend sediments. The areas of petrothermal

potential comprise crystalline rocks, volcanites and tight sediments. The bulk of proven and assumed hydrothermal potential is located in the North German Basin, in the South German Molasse Basin and in the Upper Rhine Graben (Fig. 9).

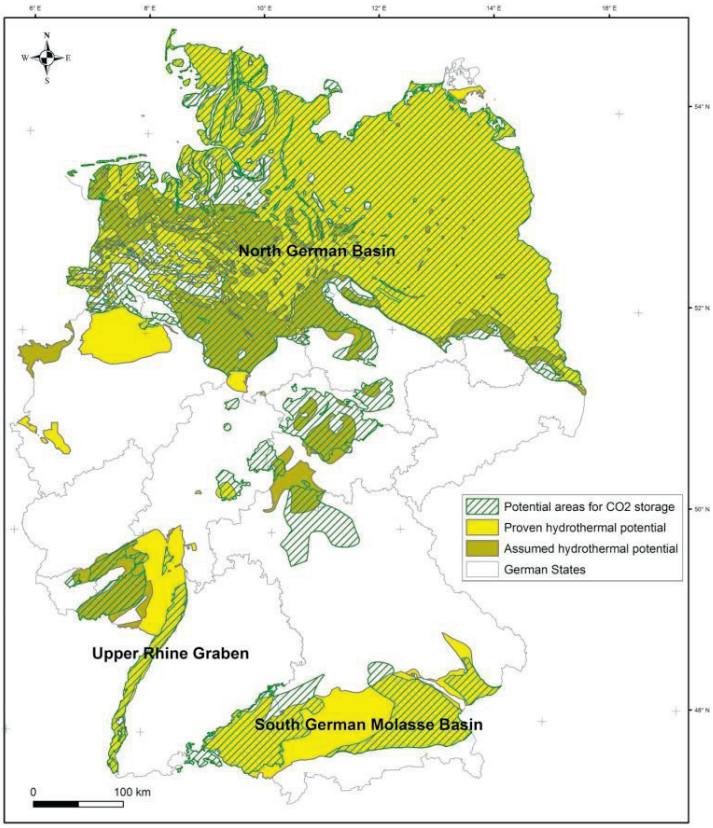

Fig. 9. Potential areas for hydrothermal energy use and geological CO_2 storage in Germany (after Schulz et al. [8])

The distribution and properties of potential reservoir and barrier rock units suitable for CO_2 storage have been obtained from the "Storage Catalogue of Germany" [9]. The maps in this catalogue depicting areas of the rock units 'identified for further investigation' are based on the criteria depth and net thickness (> 800 m depth of the top of the reservoir rock unit and > 20 m net reservoir rock thickness).

The reservoir- and barrier rock units had to be grouped into stratigraphically defined reservoir-seal-pairs. The areas of a prospective reservoir rock unit which intersect with the areas of the associated prospective barrier rock unit delineate the extent of a potentially suitable reservoir-seal-pair ('reservoir-barrier rock unit'). The here presented potential areas for CO_2 storage represent a compilation of all areas of the potentially suitable reservoir-seal-pairs (Fig. 9). Locally, up to four of these pairs can be stacked within the sedimentary succession of the North German Basin.

Most of the CO_2 storage potential in Germany is expected in the North German Basin, which contains reservoir-seal-pairs from Permian to Cretaceous age. The volumetric CO_2 storage capacity of Germany has been estimated to be about 20 ± 8 Gt. About 90% of this capacity results from the North German Basin [10]. Taking into account the need for suitable storage structures and further geotechnical requirements, the technical storage capacity is expected to be less though [11]. The storage potential in the central parts of Germany is provided by units of Permian age and in the South German Molasse Basin and in the Upper Rhine Graben by units of Mesozoic to Tertiary age.

3.3. Potential areas of application for the CO_2-DISSOLVED concept

In order to select CO_2 emitters that fulfill the requirements of this project, areas had to be outlined, where geothermal energy use can be coupled with geological CO_2 storage. To achieve this, the potential areas for geothermal energy use and the potential areas for CO_2 storage were intersected. The resulting area is depicted in Fig. 10 (green area).

For the potential areas of geothermal energy use, only the hydrothermal potential areas (proven and assumed) were considered. 242 small to medium emitters are located in potential areas both for hydrothermal energy use and CO_2 storage in Germany (Fig. 10). In total, these 242 CO_2 sources emitted 9.98 Mt of CO_2 in 2012.

It is evident from Fig. 10, that the most potential candidates for the CO_2-DISSOLVED concept are situated in the potential area of the North German Basin. In detail, 190 emitters are situated there, representing mostly combustion plants (129 emitters), followed by emitters of the minerals sector (31), petroleum and natural gas (11), metals (9), pulp and paper (9) and chemicals (1). In total, these 190 CO_2 sources emitted 7.95 Mt of CO_2 in 2012. Further potential candidates are mainly situated in the South of Germany (Upper Rhine Graben and South German Molasse Basin).

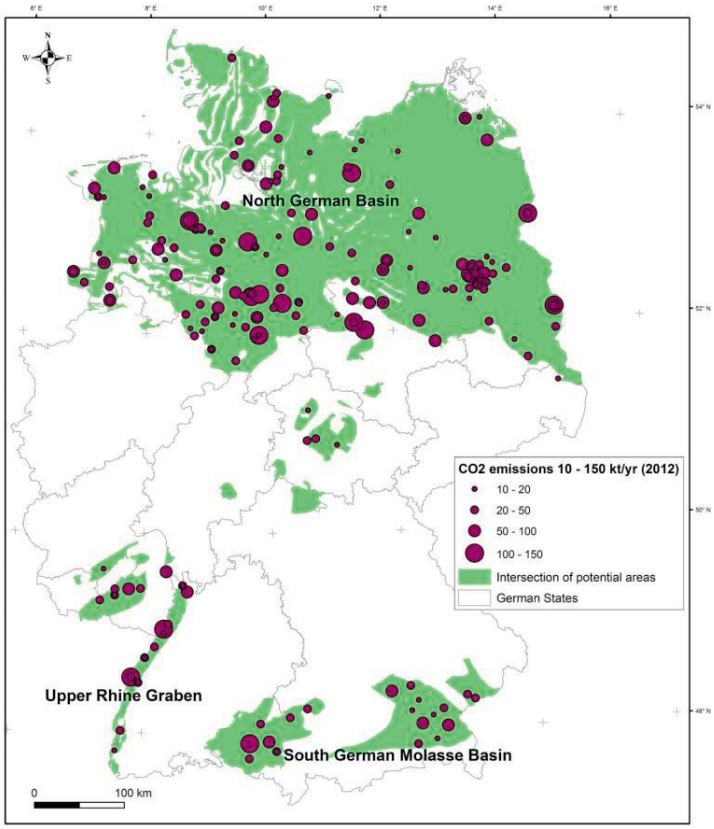

Fig. 10 Small to medium CO_2 emitters in Germany that are located in potential areas both for hydrothermal energy use and geological CO_2 storage.

4. Potential in the U.S.A.

4.1. The U.S. CO_2 emitters

The United States Environmental Protection Agency (EPA) is responsible for characterizing greenhouse gas emissions using two complementary programs designed to help the public and policymakers understand both the sources and the magnitude of these emissions:

- The Inventory of U.S. Greenhouse Gas Emissions and Sinks. It is a document prepared annually by the EPA, for over 20 years, that estimates the total greenhouse gas emissions across all sectors of the economy using national level-data;

- The Greenhouse Gas Reporting Program (GHGRP). It is a relatively new program that collects detailed data from the largest greenhouse gas emitting facilities in the U.S. Facilities that emit 25,000 metric tons of CO_2 "equivalent" (CO_2e) or more per year are requested to submit annual reports to the EPA via the electronic greenhouse gas reporting tool (e-GGRT). The collection of data began in 2010 for most emission sources. For the reporting year 2011, approximately 8,000 facilities reported 3.3 billion tons carbon dioxide equivalent (CO2e) of direct emissions which account for 85-90% of the total U.S. GHG emissions. Since January 2012, these data are available to the public through an interactive data publication tool called Facility Level Information on Greenhouse gases Tool (FLIGHT). This tool allows users to review information quickly and easily by filtering GHG data in a variety of ways including by facility, industry, location or gas. In addition to FLIGHT, data are available for download.

The data presented in this paper are those collected by the GHGRP during the year 2011. About 6,600 facilities emit CO_2 in the U.S. Most of them are located in the eastern part of the U.S. (81% of the US emitters are located from the east coast to Texas), and also in California and Colorado (Fig. 11). 3,024 million tons of CO_2 were emitted in 2011 in the U.S (more than 20 times the French emissions, cf. §2.1). As in France, the power plants are the main sources of CO_2 in the U.S. They are responsible for 73.1% of these total emissions (i.e. 2,209 Mt) whereas petroleum and natural gas systems (production/storage and refineries, excluding power plants) contribute only for 10.5% of these emissions (316 Mt, blue bars in Fig. 12).

Small to medium industrial emitters (ca. 25-150 kt) represent 70% of all the total U.S. emitters in 2011 (i.e. 4,645 facilities, Fig. 13a). These emitters are present throughout the U.S., but, notably in Texas, in California, and in the eastern part of the U.S., (Fig. 14). Their emissions only account for 6.64% of the total CO_2 emitted in the U.S. (i.e. 200.6 Mt, Fig. 13b). Petroleum and natural gas systems are the main sources of CO_2 in this category of industrial emitters (small to medium) with 69.7 million tons of CO_2 emitted in 2011 (that is only 2.3% of the total U.S. emissions, green bars in Fig. 12).

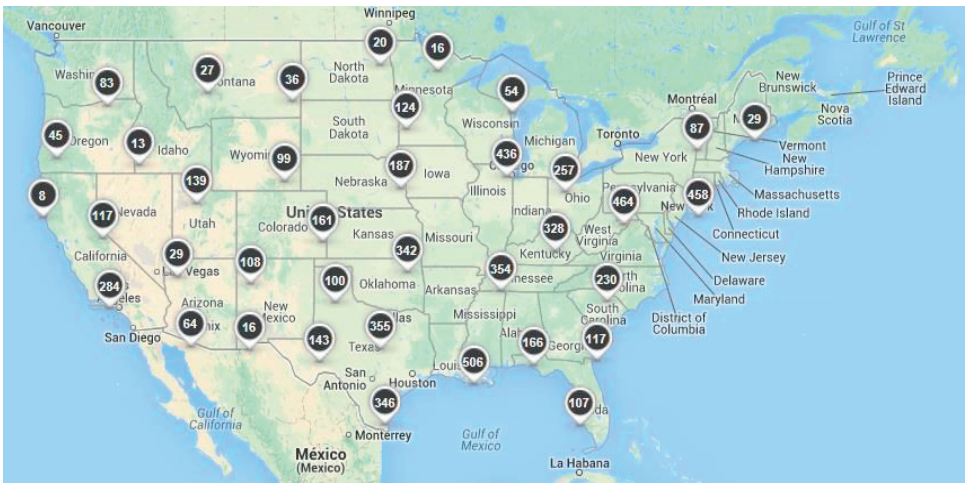

Fig. 11. Total number of CO_2 emitters (CO_2 emissions > 25 kt/yr) in various regions of the contiguous states of the U.S. (source: FLIGHT).

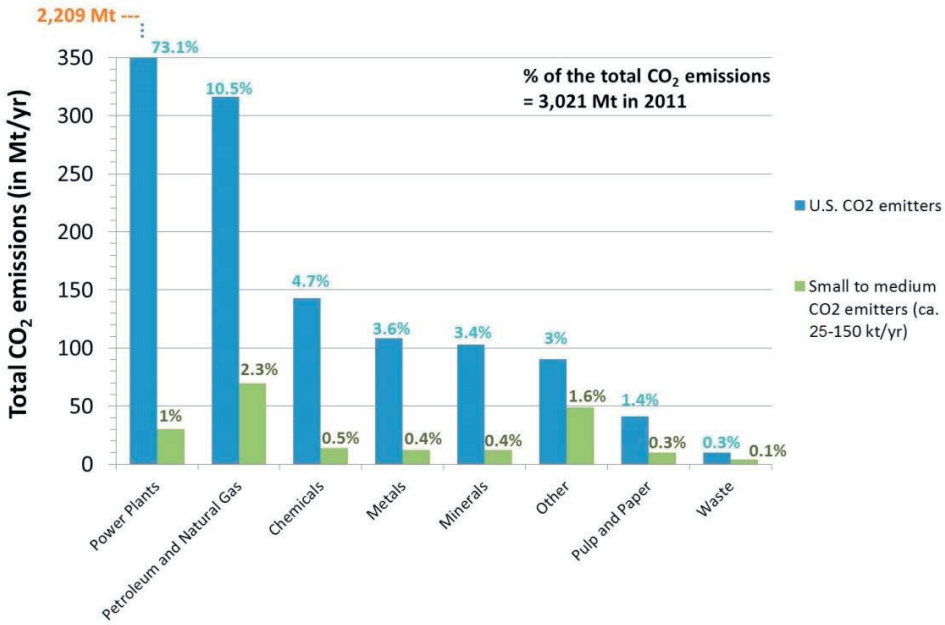

Fig. 12. Total CO_2 emissions (in Mt) in the U.S. reported by sector for the year 2011 (source: FLIGHT). The total CO_2 emissions of the U.S. power plants are figured in orange (2,209 Mt/yr).

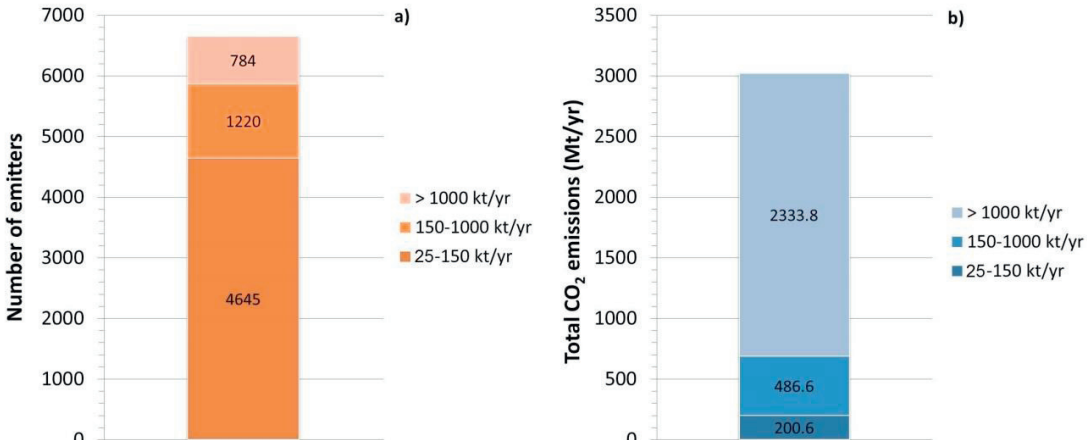

Fig. 13. Importance of small to medium CO_2 emitters (ca. 25-150 kt/yr) in the U.S.: comparison with large emitters. a) Number of CO_2 sources in each category of emitters; b) Total amount of CO_2 emitted annually per category of emitters (source: FLIGHT). The reported data refer to the year 2011.

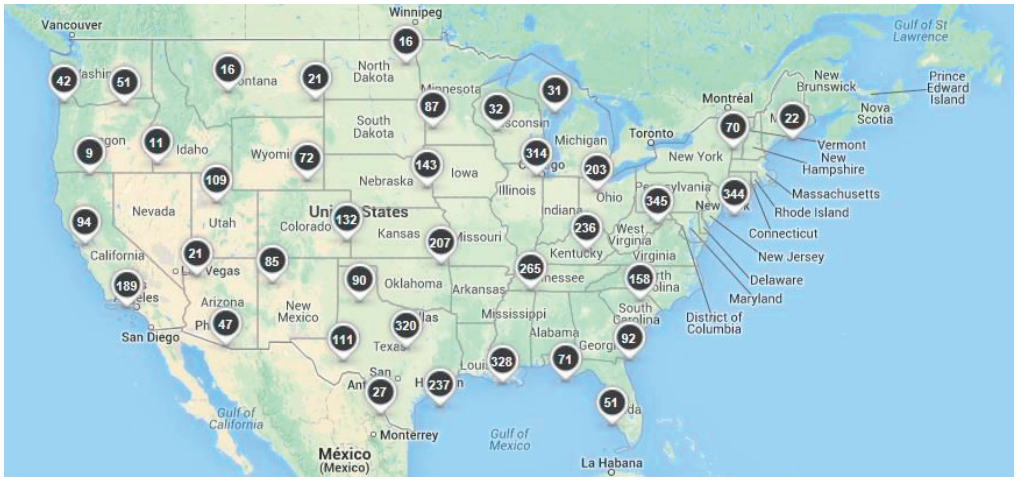

Fig. 14. Total number of small to medium CO_2 emitters in various regions of the contiguous states of the U.S. (ca. 25-150 kt/yr) (source: FLIGHT).

4.2. U.S. geothermal resources

The United States have low to high-temperature geothermal resources [12,13]. These resources are mainly located in the western part of the U.S., including North and South Dakota, Nebraska, Kansas, Texas, Alaska and Hawaii (Fig. 15 to Fig. 17). Some of these resources are already exploited for district heating and other applications (Fig. 15 and Fig. 16). However, moderate and high-temperature geothermal systems are only present in 13 states of the West: Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming (Fig. 15 to Fig. 17).

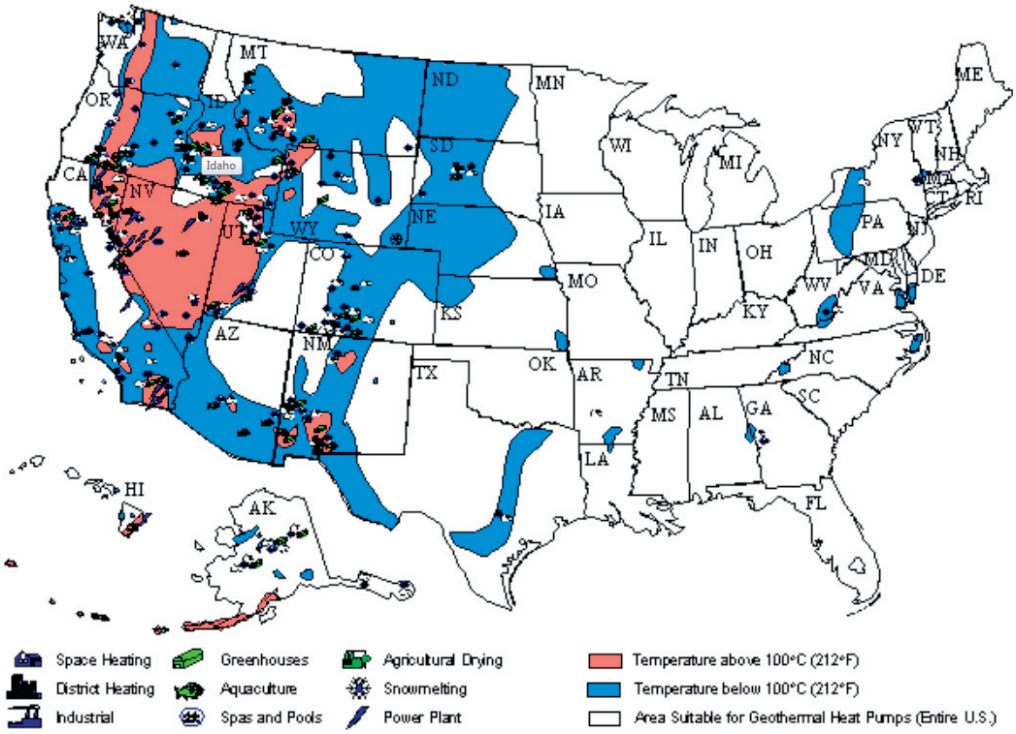

Fig. 15. U.S. geothermal projects and resources areas (source: Geo-Heat Center's website http.//geoheat.oit.edu/index.htm).

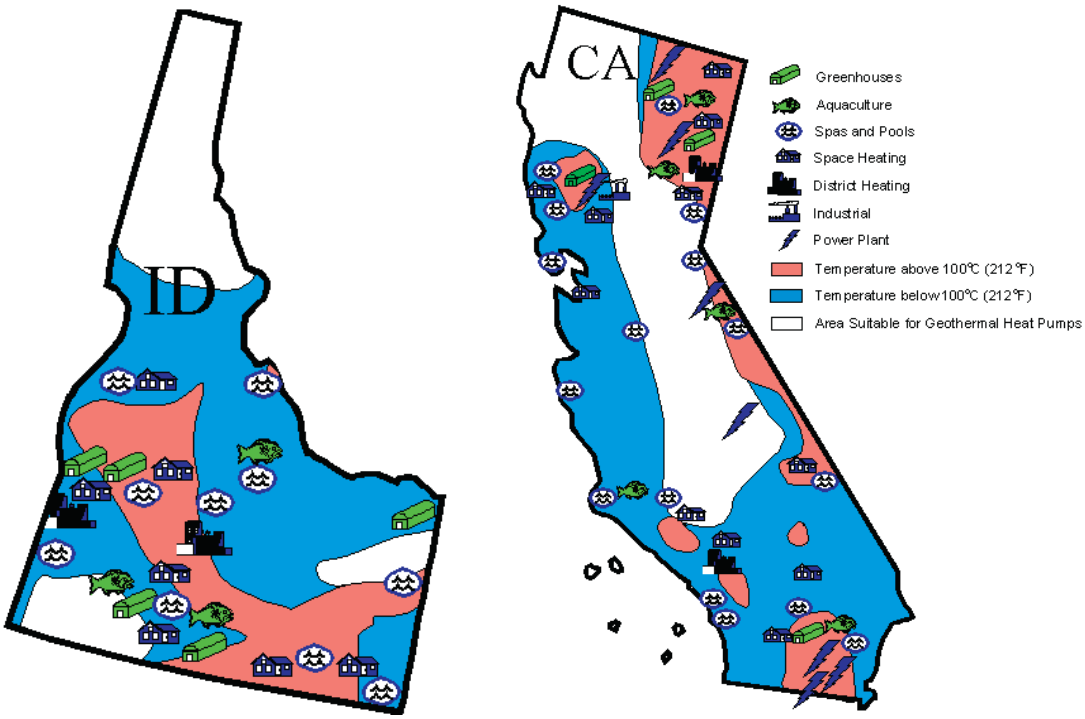

Fig. 16. U.S. geothermal projects and resource areas: focus on the states of California (right hand) and Idaho (left hand) (source: Geo-Heat Center's website http.//geoheat.oit.edu/index.htm).

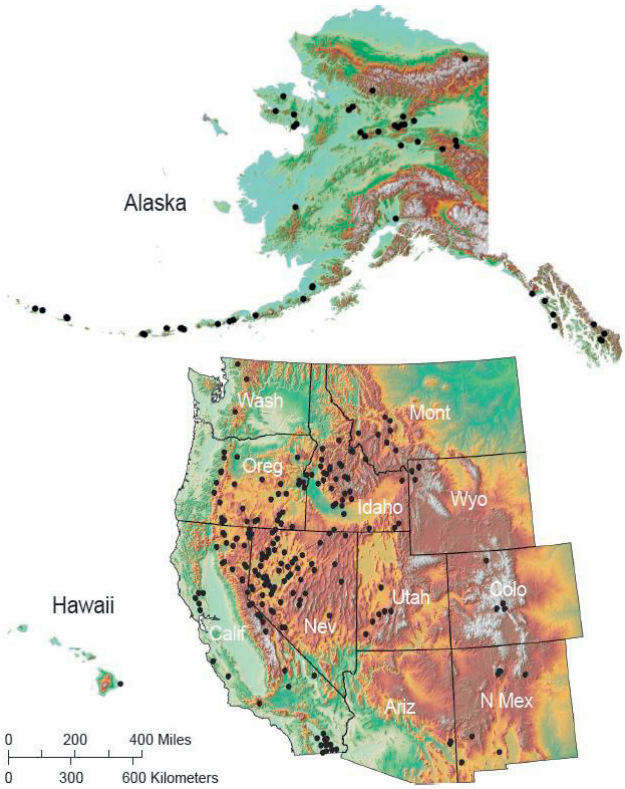

Fig. 17. Map showing the location of identified moderate-temperature and high-temperature geothermal systems in the United States. Each system is represented by a black dot [13].

4.3. Potential areas of application for the CO_2-DISSOLVED concept

The eastern part of the U.S. is almost devoid of geothermal resources (§4.2). Indeed, only a few states such as New York, Pennsylvania and West Virginia have low-temperature geothermal systems. Thus, the potential areas where the CO_2 storage could be coupled with geothermal activity are mostly concentrated in the western U.S., including Alaska and Hawaii.

5. Discussion and conclusion

This assessment of the potential industrial applicability is based on national databases regarding stationary industrial CO_2 emission sources in France, Germany and the USA. The used databases for the three countries do not have similar contents. For example, the attribution of the listed emitters in regard of the industrial type is different. In France and in the USA, power plants are considered as a single category, whereas in the German database the category ‘combustion plants’ includes power plants and waste incinerating plants, without any further differentiation. This has to be considered, when comparing the total CO_2 emissions reported by sector. Furthermore, the U.S. database only lists emitters with annual CO_2 emissions of at least 25 kt, while the French and German Data bases include minimum emission rates of 10 kt per year. Beyond the differences however, all three databases enable

identifying and prioritizing industrial emitters at a national scale accounting for the requirements of the CO_2-DISSOLVED concept.

In the three countries, there are numerous small to medium emitters listed in the databases. They represent 83, 70, and 46% of all the total CO_2 emitters in France, the USA, and Germany, respectively. However, it has to be noticed that France and Germany have quite similar numbers of small and medium CO_2 sources (881 and 800, respectively). Unsurprisingly, in the U.S., the number of this category of emitters is much higher (4,645). Moreover, the total CO_2 annually released by these low emitters is also almost the same in France and Germany (33.5 and 32.4 Mt, respectively) while it is five times higher in the U.S. (200.6 Mt). But, one has to remember that the USA is one of the largest countries by total area and population (9.62 million km² and around 318 million people). The population of the USA is thus twice as large as those of France and Germany combined.

The small to medium emitters are quite evenly distributed in Germany and France, although a higher density of low emitters is locally evident in both of these countries (e.g. in the Ruhr German area and in the Ile-de-France French department). On the contrary, in the USA, these low emitters are clearly more present in Texas, California and in the eastern part of the country (88% of the low US emitters).

In Germany combustion plants are responsible for the bulk of CO_2 emission of small to medium emitters (about 20 Mt/yr, around 62% of the total CO_2 released by these emitters). In France the 'waste' and the 'power plants' sectors are also the main sources of CO_2 (13.5 Mt in 2011, about 40.3% of the total CO_2 emitted by the small to medium French industrial emitters). Furthermore, these sectors annually emit an amount of CO_2 quite similar to the German 'combustion plants' category. In contrast, in the USA, emitters from the 'petroleum and natural gas' sector are the most important type of small to medium CO_2 sources with 69.7 Mt emitted in 2011, which is not at all the case in France and Germany (where only 0.56 and 1.36 Mt, respectively, are emitted annually by this category of emitters).

Comparing the locations of small to medium emitters with areas of geothermal resources, it can be concluded that in all three countries there are relatively large areas matching the presence of many potential candidates for the CO_2-DISSOLVED concept. In France and Germany the concept could be applied to all major sedimentary basins and in particular to the Paris Basin and the North German Basin. In the USA the most favorable areas are situated in the western part of the country (the bulk of geothermal resources is situated there) and therefore leaving out a majority of the small to medium emitters in the USA, which are more present in the eastern of the country than in the western states.

In all three countries there is no specific information publicly available about the compositions of the emitted smokes of the stationary CO_2 emitters. However, the relevant issue of smoke composition will be addressed later in the project for two selected test-cases in France and Germany.

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