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Camille Maurel, Virginie Hamm, Frederik Bugarel and Charles Maragna

BRGM, 3 av. Claude-Guillemin - BP 36009, 45060 Orléans Cedex 2 – France

c.maurel@brgm.fr

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ABSTRACT

The repurposing of oil and gas wells for geothermal energy production and resource assessment can provide sustainable solutions to meet the objectives of renewable energy balance targeted within 2030 by the French Parliament in the "energy transition law for a green growth" promulgated in August 2015. Approximately 12 500 wells have been drilled in France since the 19th century for hydrocarbon reservoir exploration and exploitation. Most of them are closed and abandoned or nearing the end of production due to the planned end of exploitation of hydrocarbons in France by 2040. Several sustainable cases of conversion for geothermal energy production have been reported in France and abroad, demonstrating the possibility of using former wells for heat extraction from aquifers or coaxial heat exchangers. This paper presents an overview of the wells drilled in France and the methodology proposed to identify and rank them according to the *a priori* feasibility of open and closed loop conversion. To this purpose, wells data, geological and hydrothermal information acquired by the BRGM (geometry and dynamic aquifer properties from models) and land occupation have been cross-referenced. The quantitative overview should be followed by a detailed analysis of selected wells to assess their conversion potential for geothermal energy production (possible use at surface, well drilling and abandonment reports, hydrodynamic properties of the reservoir, technology to be implemented, etc.).

1. INTRODUCTION

More than 12 500 wells have been drilled in France for hydrocarbon reservoir exploration and exploitation according to a recent overview of Lahaie and Bouffier (2017). The majority are located in the Paris basin, the Aquitaine basin, the South-Est sedimentary basin (Languedoc-Roussillon and Provence area) and Rhine rift (Figure 1).

Under certain conditions (e.g. accessibility, state of the well, depth, etc.), these boreholes could be reused for low or high enthalpy geothermal energy recovery and heat extraction. The inventory of potential conversion operations presented here concerns all existing wells on national territory, regardless of their status. The law n°2017-1839 of December 31, 2017 sets an end to the exploration and exploitation of hydrocarbons in 2040. It also introduces an obligation for hydrocarbon concession holders to assess the potential to convert wells to other uses, five years before the concession expiration date: geothermal, water supply, waste storage, etc.

Several successful cases of conversion have been identified in France (6) and abroad from the early 1970s in the present study. In addition to the potential savings in drilling and decommissioning costs, new projects could also increase the share of renewable energy production and promote geothermal energy sources.

This study was funded by the French *Agence de l'environnement et de la maîtrise de l'énergie* (ADEME, Agency for environment and energy management) and the BRGM. Its aim is to propose an overview of well conversion cases in France and abroad and identify the potential of well conversion for heat extraction from aquifers (open-loop system) or using coaxial heat exchangers (closed-loop systems) among the hydrocarbon exploration and exploitation existing wells in France. The open-loop conversion potential assessment of existing wells is based on a qualitative analysis and cross-referencing of well data, geological and hydrogeological data and land occupation. Data analysis for closed-loop repurposing has been performed for coaxial heat exchanger, by estimating the annual energy extractable based on numerical and semi analytical modelling and sensitivity analysis. The study also investigates operational risks associated to geothermal energy recovery from existing wells.

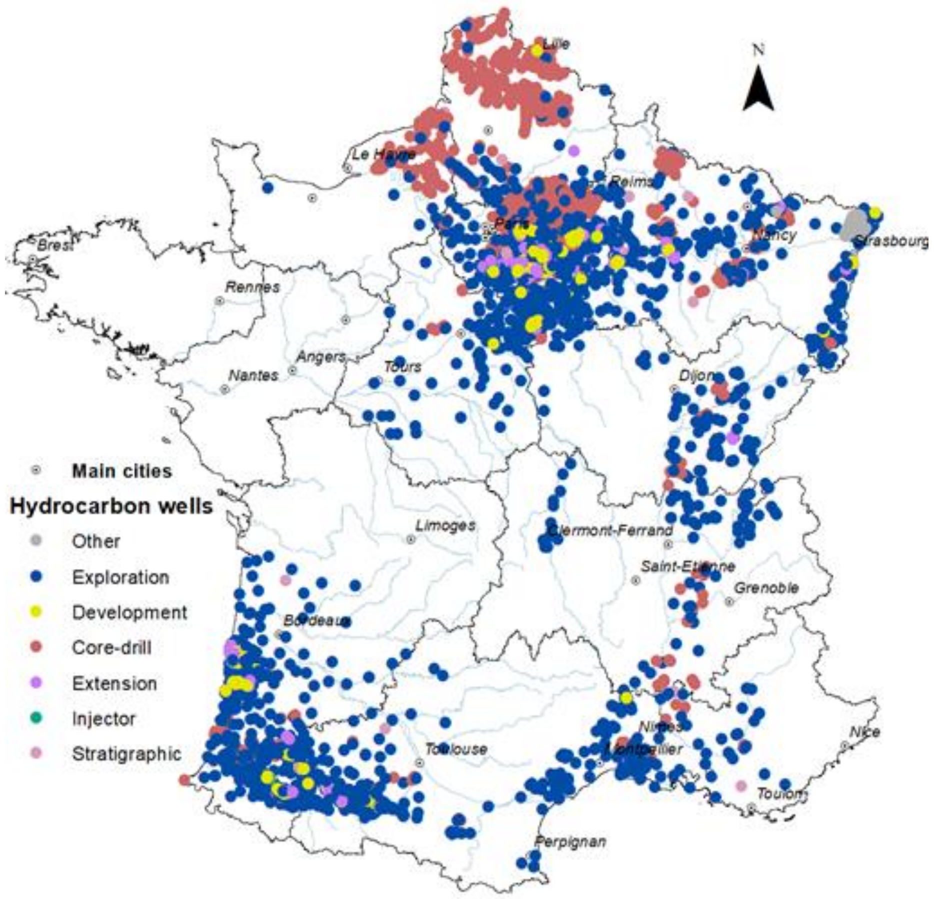

Figure 1. Location of hydrocarbon exploration and exploitation wells in France based on the inventory carried out by Lahaie and Bouffier (2017)

2. TECHNICAL SOLUTIONS FOR WELL CONVERSION AND ASSOCIATED RISKS

2.1 Techniques used to produce the resource from converted wells

Geothermal resources can be produced from converted oil and gas exploration or exploitation wells using open-loop or closed-loop systems.

2.1.1 Open-loop systems: doublet or single well

The open-loop systems produce water from deep aquifers at sufficiently high temperature to extract heat or produce electricity. When the water is extracted with a producer well and reinjected in the aquifer through a second well, the system is called a doublet. It ensures water resource sustainability, avoids depletion of the aquifer and environmental impacts with surface discharge. For instance, the geothermal operations aiming at the Dogger limestone reservoir of the Paris basin have been following this principle since the 1970s. Different well configurations can be implemented: vertical, deviated or sub-horizontal.

In single well operations, water is not reinjected in the aquifer. It is the case of around twenty operations in France, mostly located in the Aquitaine basin, where the water quality allows a direct discharge at surface and eventual reused for fish farming, aqua-ludic activities and thermal use. French legislation regulates such practice and, with some exceptions, based on water quality and environmental considerations, the reinjection in the same horizon for new geothermal operations is mandatory (article 47-III of the order from October 14, 2016 related to mining exploration and exploitation drilling).

2.1.2 Closed-loop systems: deep borehole heat exchanger

The most common heat exchanger encountered in well conversion for geothermal heat recovery is the deep borehole coaxial heat exchanger Kohl, Salton, and Rybach (2000); Schneider, Strothöffer, and Broßmann (1996). This technology is commonly used for very low enthalpy geothermal energy recovery using heat pumps.

The coaxial probe or exchanger (Figure 2) consists of a thermally insulated tube lowered and centered in a borehole where a secondary heat transfer fluid, generally glycol water, flows. During its descent into the outer annulus of the tube the fluid is heated due to the temperature gradient between the wellbore wall and the surrounding rock, an infinite radial heat source Macenić and Kurevija (2017). It then rises from the bottom of the wellbore to the surface through the inner annulus.

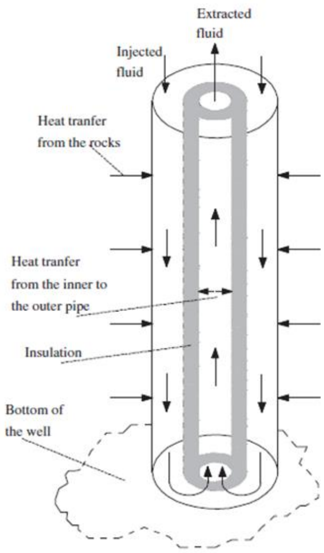

Figure 2: Deep borehole coaxial heat exchanger Bu, Ma, and Li (2012)

2.2 Risks associated with oil and gas well conversion

In term of risk assessment, it is important to distinguish between environmental risks, inherent to geothermal operations and in fact all extractive industries, and operational risks related to drilling operations.

Gombert, Lahaie, and Cherkaoui (2018) provide an overview of the environmental risks and impacts related to geothermal resource exploitation based on feedbacks and incidents. Drilling and well testing operations are the most sensitive phases. The following risks have been identified:

- fluid, solid or gas effusion to the surface (e.g. H_2S, CH_4, CO_2, geothermal water);
- aquifer pollution either caused by hydraulic communication between aquifers or leakage due to flaws in cement and tubing, corrosion or bacterial activity;
- induced seismicity and ground elevation caused by modification of natural geo-mechanical constraints;
- ground elevation or lowering caused by dissolution or swelling of shallow formations.

Unlike environmental risks, which are impacting ecosystems and population centres, operational risks may have financial impact for well operators. Four major operational risk factors have been identified when repurposing a well for geothermal energy recovery mostly in an open-loop system.

First, hydrocarbon wells design may prove inappropriate for geothermal use leading to potential technical difficulties during work-over and cost overrun. In geothermal wells, for instance, the fluids flows directly in the casing, without production line, to favor the exploitation rate and avoid head losses. Consequently, article 47-III of the decree from October 14, 2016 related to mining exploration and exploitation drilling, states that casings in geothermal wells should be cemented to their full height. This is not necessarily the case of all existing hydrocarbon wells which are generally equipped with a production line meant to transport fluids from the reservoir to the surface while protecting steel casing from scaling and corrosion phenomena.. The resumption of casing cementation could be sensitive and expensive with no guarantee of outcome.

The integrity of cement and casing of the well, sealing the borehole from surrounding formations and aquifers, and aging assessment of the wellbore are key information to define the conversion work program and ensure exploitation durability. For wells currently in exploitation, the integrity of the wellbore is considered to be known from the operator. The operational risks and cost uncertainty related to conversion are then limited. For abandoned wells (i.e. permanently closed with cement plugs), the integrity may have been evaluated during decommissioning, but becomes uncertain with time. Consequently, a comprehensive diagnosis is required when considering conversion, using available drilling or decommitment reports, wellbore logging devices after reentry. Such operations, like all work-over operations, can be expensive, depending on the equipment used or the investigated depth and may present technical risks (e.g. lost or caught tools, damage on casing). Vernoux and Manceau (2017) studied well reentry through cement plug for several cases in France and proposed a methodology for analyzing the quality of plugs during reopening drilling operations. Overall, this operational risk is, *a priori,* more important for abandoned wells compared to those currently in exploitation.

All extractive industries may suffer from geological hazard, the fact that the geological body under study may have been mischaracterized. For geothermal operation, the main uncertainties are the maximal flow rates, related to reservoir properties and inner well diameter, the temperature of the fluid and the heat capacity of the formations. To this end, operators of the French geothermal industry contribute to a state-managed guarantee fund to cover these geological and geothermal resource hazards for new drilling projects during drilling phase ("short-term guarantee") and during exploitation ("long-term guarantee"). For example, the short-term guarantee can cover up to 90% of drilling costs in operations targeting the Dogger aquifer in the Paris Basin. In order to cover this operational risk, it would be beneficial to extend these guarantees to the repurposing of hydrocarbon well for geothermal energy recovery.

Article 17-2 of the decree from October 14, 2016, requires reinjection of fluids in the same geological horizon when producing geothermal energy through open loop. The ability of a given formation to sustain water inflow is measured by the injectivity index. However, while the productivity index is of great interest to oil and gas industry, a high injectivity index is not necessarily required, and reinjection may not be technically or economically feasible for converted operations. Granted the necessary legal exception, surface reuse of geothermal water may be considered.

3. INVENTORY OF CONVERTED WELLS IN FRANCE AND ABROAD

The inventory of deep hydrocarbon well conversion cases for geothermal energy production was carried out in France and at international level.

3.1 In France

Six cases have been identified in France, among which, five are still operational in 2019. The cases are detailed in Table 1. All wells have been converted for direct heat use with a single well producing from the aquifer. After extraction of heat, water is discharged at surface in accordance to environmental and water laws in application or used for fish farming and thermal baths (e.g. Pézenas and Saint-Paul-lès-Dax).

Table 1: Summary of hydrocarbon well converted for geothermal use in France

Location	*Site name*	*Geological basin*	*Drilling date*	*Conversion date*	*Status*	*Water T (°C)*	*Flow rate (m3/h)*	*Initial depth (m)*	*Depth after conversion (m)*	*Usage*	*Targeted aquifer*	*Technicology used*
Montpensier	Aigueperse	Limagnes	-	-	In operation	43	60	-	-	Greenhouse	Basement	-
Merkwiller	Hélions 1	Rhine graben	1910	1925	Shut down (1974)	65	12	1157	1157	District heating	Muschelkalk limestone (Triassic)	Single well
Argelouse	Sore 1A	Aquitaine basin	1954	1964	In operation	48	8	3632	1646	Fish farming	Dolomite and limestone (Upper Jurassic)	Single well, reentry in plugged well
Pézenas	Pézenas	South-Est basin	1949	1970	In operation	37,4	68	735	735	Fish farming & pool	Limestone and dolomite (Middle Jurassic)	Single well, discharge water used for fish pond
Saint-Paul-lès-Dax	Sébastopol 1 bis	Aquitaine basin	1954	1975	In operation	46	130	2155	865	Thermal baths	Limestone (Late Paleocene - Upper	Single well
Le Teich	Mios Le Teich	Aquitaine basin	1964	1983	In operation	74	120	3758	2491	Fish farming	Dolomite and sandstone (Upper Jurassic)	Single well, reentry in plugged well

The operations of Argelouse and Le Teich consist in reentry in closed and plugged hydrocarbon exploration and exploitation wells. Conversion works have thus consisted in drilling through cemented plug placed inside the wellbore, cleaning of the well, casing perforation and eventually well stimulation to launch production. The well Hélions 1 in Merkwiller (Alsace) was shut down to make way for new production wells, Hélions 2 in 1974 and Hélions 3 in 1993, in order to produce at higher flow rates. After finding traces of hydrocarbons from neighboring oil field (Pechelbronn), a prefectural decree declared the produced waters polluted and unfit for thermal use and human consumption.

Water produced from oil fields can also be used for heat production when temperature at the outlet of fluid and gas separators is sufficient. The coproduction of heat and petroleum is often used in the United-States and several cases have been identified in France: Le-Test-de-Buch (Gironde), Itteville (Essonne) and Parentis-en-Born (Landes). In the French coproduction sites, water is produced between 64°C and 70°C for district heating (Itteville and Le-Teste-de-Buch) and greenhouse heating (Parentis-en-Born).

3.2 Abroad

An inventory of hydrocarbon well conversions abroad has been conducted as part of the project PréGo, funded by the "*Agence Nationale de la recherche"* (ANR, National Agency for Research) by Lafortune (2015). Deep drilling conversions for geothermal energy recovery have been identified in Poland Sapińska-Śliwa and Kotyza (2000), Switzerland Kohl et al. (2000) and Germany Schneider et al. (1996) using deep borehole heat exchangers (DBHE) with coaxial probes as presented in Table 2. The maximum depth reached by the DBHE is up to 2786 meters in Poland.

Several cases of active exploitation hydrocarbon wells use for heat recovery have been identified in the United-States. In Pleasant Bayou Campbell and Hattar (1990), an hybrid power plant produced 1MW of electricity using gas and binary cycle turbines powered by hot water from hydrocarbon reservoirs fluid production.

Table 2: International well conversion cases for geothermal energy recovery and cogenerations

Country	*Geothermal well location and name*	*Initial use, before conversion*	*Total well depth (m)*	*Technology used after conversion of the well*
Switzerland	Weissbad (Appenzell) & Weggis (Lucerne)	Water supply	2302 m in Weissbad & 1213 m in Weggis	Deep coaxial borehole heat exchanger
Germany	Prenzlau	Geothermal direct use	2786	Deep coaxial borehole heat exchanger
Poland	Jachowka 2K	Oil well	2040	Deep coaxial borehole heat exchanger
United-States	Pleasant Bayou	Oil well	-	Cogeneration using binary cycle turbine

3.3 Study and research on hydrocarbon well repurposing

Many countries are conducting research or working on hydrocarbon well conversion projects for the production of electricity and geothermal heat. The research studies are essentially based on closed-loop borehole conversion using deep coaxial heat exchangers (e.g. Bu et al. (2012); Davis and Michaelides (2009). Cheng, Li, Nian, and Xie (2014) studied the influence of different parameters (e.g. fluid composition, depth, insulation, injection pressure, etc.) on simulations. The results of their study highlighted the influence of insulation thickness between internal and external tube of the coaxial exchanger on temperature at the outlet of the probe. Noorollahi, Pourarshad, Jalilinasrabady, and Yousefi (2015) studied the modelling of coaxial borehole heat exchanger over two wells of 4 423 m depth and fluid temperatures of around 160°C and estimated the maximal energy retrieved by the system to 364 kW. Ghoreishi-Madiseh, Hassani, and Al-Khawaja (2012) proposed a study on heat extraction using single U-tube heat exchanger and simulation of heat extraction over 700 meter deep wells. After 10 years of production, the model predicted an energy recovery of 20 kW. Simulation of heat extraction using double-U-probes have been studied for instance by Al-Khoury and Bonnier (2006).

Feasibility studies of hydrocarbon well conversion have been conducted in several country including Hungary Toth, Szucs, Pap, Nyikos, and Fenerty (2018), Pakistan Farah (2017), Poland Barbacki (2000), the United-States Caulk and Tomac (2017) or New Zealand Reyes (2007) considering closed or open-loop systems. Overall, a great interest seems to be present among the oil companies and industrials, as for the potential of reconversion of the drillings. For example, in Canada, and specifically in the Alberta region, *Precision Drilling* company and the Devon mayor have begun discussions for geothermal energy recover, based on old petroleum exploitation wells in the area Richter (2017).

3.4 Overall recommendation for hydrocarbon well repurposing for geothermal energy recovery

In general, conversion of wells for geothermal energy recovery, in open-loop or closed-loop, requires prerogatives before engaging in development operations such as:

- having access to the well at surface and the ability to positioned materials and engines to reenter the well and perform work-overs;
- sufficient knowledge of the well, drilling work, work-over history or decommissioning using relevant documentation;
- suitable well design (cementation along the wellbore, inner diameter) and well integrity (of the cementation, tubing or casing) and its identification using logging tools;
- sufficient aquifer or formation temperature;
- sufficient production and injection capacity of the reservoir which are dependent on hydrogeological and geological parameters in case of open-loop system (e.g. transmissivity, thickness, lithology, hydraulic connection between the well and surrounding aquifer, depth of the reservoir, lithology) and on technical characteristics of the structure and geology for closed-loop systems (e.g. internal diameter, available vertical depth, heat capacity of formations, local gradient);
- ability to reinject produced water in another existing well or a new well, distant from the producer to reduce cold water breakthrough;
- knowledge of fluid composition to identify the possible reuse of produced water if injection capacity are limited;
- sufficient demand of end users (e.g. district heating, greenhouse or fish farming).

4. DATA ANALYSIS AND METHODOLOGY TO ASSESS CONVERSION POTENTIAL

4.1 First selection of wells with conversion potential in France

Lahaie and Bouffier (2017) classified listed 12 500 deep wells according to their nature (oil and gas exploration or production well, geothermal, storage), location, status, age, depth, internal structure and available documentation associated to each wells. Out of the 12 500 deep boreholes, only a fraction display a potential for conversion to geothermal energy recovery in open and closed-loop system:

- only **hydrocarbon exploration and exploitation operations located onshore** are studied;
- only wells **drilled after 1970** are considered, to avoid the impact of aging, corrosion and potential sealing issues of cement and tubing;
- only wells **deeper than 200 meters** are considered, to produce enough heat from aquifers or closed-loop systems;
- only wells with **at least one associated document** are considered (e.g. drilling report, geological cross section, log data) to assess well integrity or condition of decommissioning;
- **core drilling wells are removed** from the selection due to their limited depth and diameters;
- wells from the Pechelbronn oilfield (Alsace) are not considered.

After this selection process only 2 014 wells remain. Location of those wells and their characteristics are detailed in Figure 3 and Table 3.

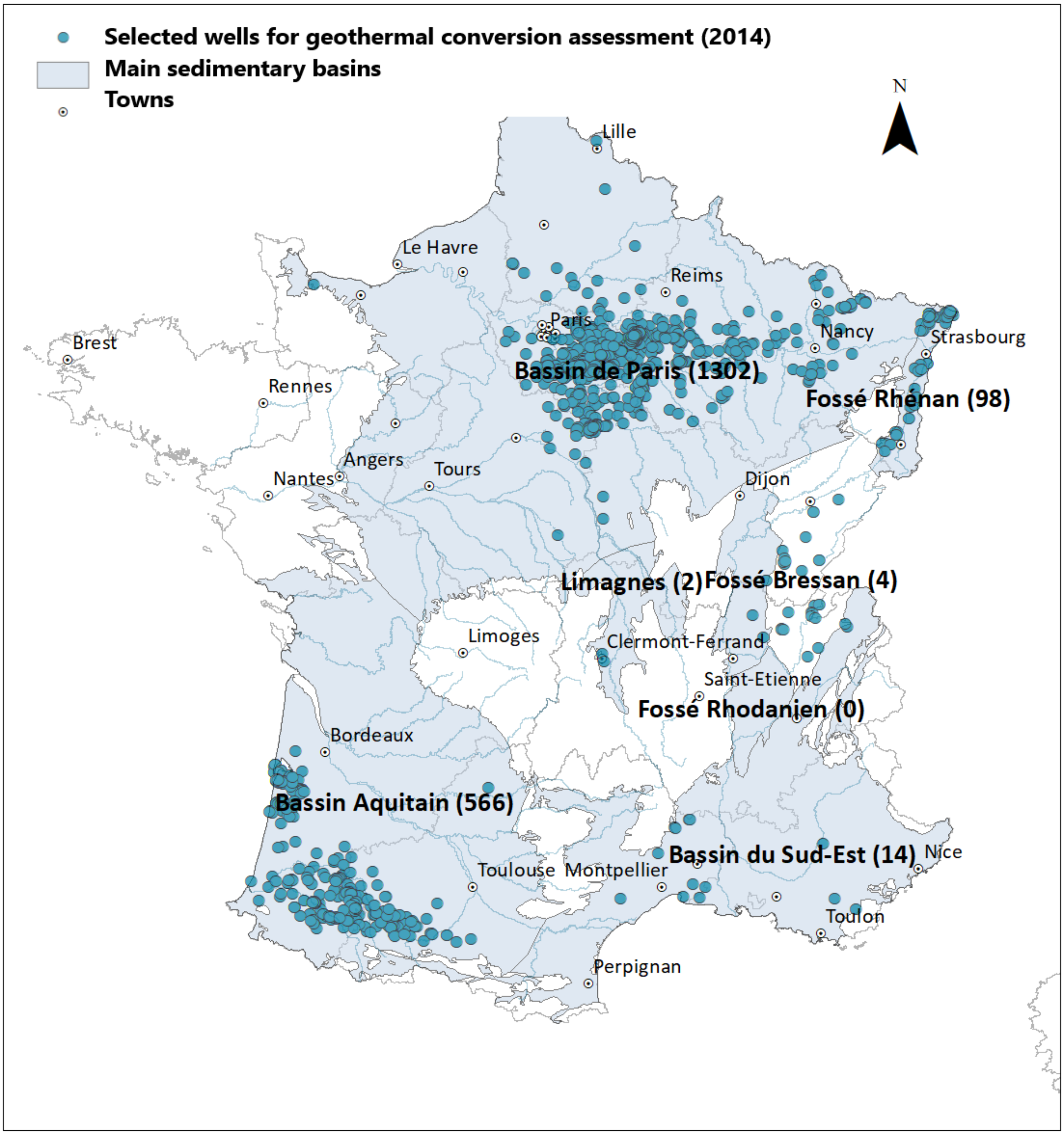

Figure 3: Location of 2 014 selected wells for geothermal conversion potential assessment

Table 3: Depth of wells considered for conversion at the national level and for the three main French sedimentary basins

	Paris basin	*Aquitaine basin*	*Rhine rift*	*National level*
Number of wells after first selection	**1303**	**566**	**98**	**2014**
Wells total depth				
200 to 1000 m	213	1	13	232
1000 to 2000 m	395	34	15	449
2000 to 3000 m	616	190	6	813
more than 3000 m	28	224	0	255

About 60% of the wells were drilled between the 1980s and 1990s, at the time of increase in petroleum activity globally, and only 13% of 2 014 were drilled in the last 20 years. 55% of the wells selected are vertical and only 3% are horizontal or sub-horizontal. For deviated wells, the angle and azimuth are not documented in the compiled database. The last use (e.g. oil or gas producer, auxiliary, injector) and status (e.g. open, definitively closed, in observation) of the well is provided for 1 980 wells out of the 2 014 selected.

4.2 Geological and hydrogeological data

Wells data are supplemented with:

- models of geothermal potential: temperature maps (Figure 4), geological and hydrogeological maps and models of aquifer formations in the main French sedimentary basins (see Table 4);
- geographical extent and characteristics of hydrogeological units from the national BD LISA database Seguin, Mardhel, Schomburgk, and Allier (2013);
- well logs from the LOGISO database, harmonized and validated by the BRGM, providing detailed of geological passes, formation name and lithology. Geological and hydrogeological models are based, in part, on these logs;
- land occupation from the European database Corine Land Cover 2012 managed by the European Environmental Agency (EEA).

Table 4: Aggregated geological and hydrogeological data per basin

Sedimentary basin	*Geological or hydrogeological formation modelled*		*Available data*	*Source of information*
National level	Iso depth (1000 m, 2000 m, 3000 m and 4000 m)		Temperature	Bonté et al. (2010), Bonté (2014)
Paris basin	Lower Cretaceous	Albien-Neocomien	Temperature, top and base formation depth, thickness, hydraulic transmissivity	Caritg et al. (2014)
	Upper Jurassic	Lusitanien		Seguin et al. (2015)
	Middle Jurassic	Dogger		Hamm et al. (2017)
	Lower Jurassic	Lias		
	Upper and Lower Triassic	Rhetien, Keuper - Chaunoy and Buntsandstein - Donnemarie	Isophypse maps and isotherms	Caritg et al. (2018), Bouchot et al. (2012), Housse et Maget (1976)
	Basement			
Aquitain basin	Paleogene			Saltel et al. (2016)
	Upper Cretaceous			
	Lower Cretaceous	Lias	Isophypse or hysobath maps and isotherms	
	Upper and Lower Jurassic	Rhetien		Caritg et al. (2018), Housse et Maget (1977)
	Upper Triassic			
	Basement			
South East basin	Upper and Lower Jurassic			
	Upper and Middle Triassic	Muschelkalk and Buntsandstein	Isophypse or hysobath maps and isotherms	Caritg et al. (2018), Debrand-Passard et al. (1984)
	Basement			
Rhone rift	Upper, Middle Jurassic			
	Lower Jurassic	Domerien, Carixien, Sinemurien, Hettagien	Isophypse or hysobath maps and isotherms	Caritg et al. (2018), Couëffé et Tourlière (2008)
	Middle and Lower Triassic	Muschelkalk and Buntsandstein		
	Basement			
Rhine rift	Upper Jurassic			
	Middle and Lower Triassic	Muschelkalk and Buntsandstein	Isophypse or hysobath maps and isotherms	Caritg et al. (2018) and Capar et al. (2015), GeORG study (2013), Bouchot et la. (2012)
	Basement			
Limagnes	Eocene		Isophypse maps and isotherms	Caritg et al. (2018), Genter et al. (2004), Calcagno et al. (2014)
	Basement			

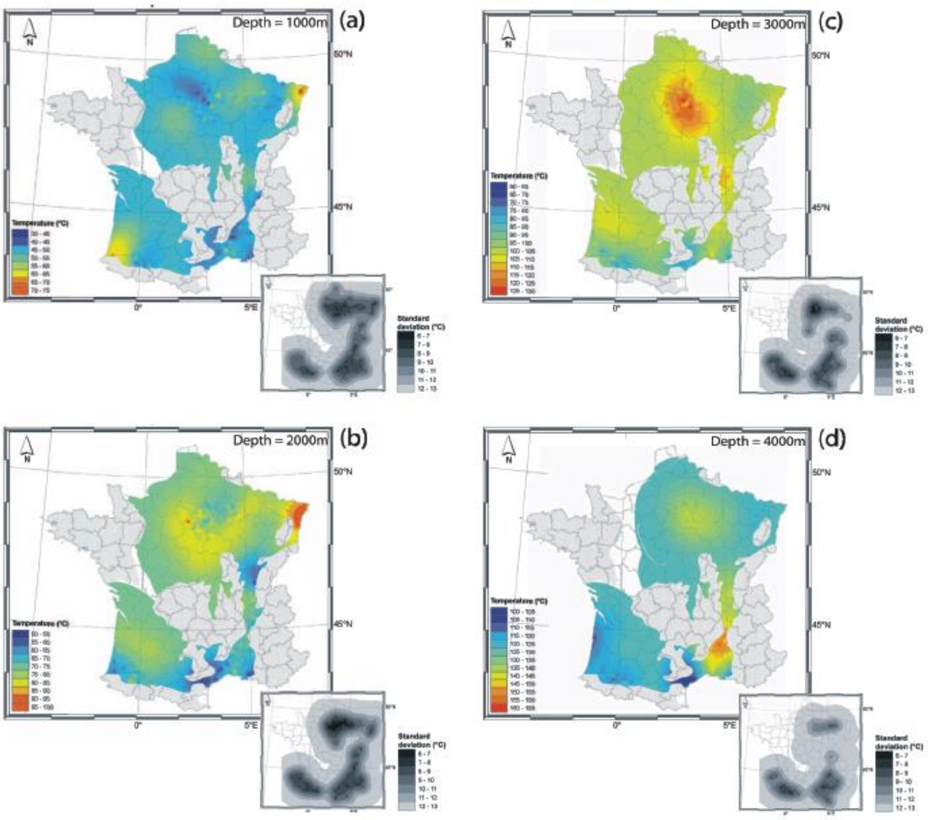

Figure 4: Temperature estimation of the medium from 1000 m to 4000 m depth Bonté et al. (2010)

4.3 Open-loop conversion cases

4.3.1 Methodology

The objective is to assess whether a given well intercepts one or several aquifers with geothermal potential. Therefore, wells data were crossed-referenced with the geological and hydrogeological models and maps from Table 4 or with validated logs from the LOGISO database and geographical extent of hydrogeological units from the BD LISA database.

Wells are also tagged according to the Corine Land Cover database depending on whether the borehole is located in a rural or urban area, which would condition its use in case of conversion. Fish farming and greenhouse heating are favored with the former and district heating with the latter. The distance from nearest neighbor is also estimated to identify suitable wells for geothermal fluid reinjection using a doublet.

4.3.2 Results

The synthesis of wells presenting potential for conversion and recovery of geothermal energy recovery in open-loop system is provided in Table 5 and in the map in Figure 5. Only 2% (47 wells) of the selected wells could not be covered by available geological or hydrogeological data and 10% of the selected wells are crossing none of the geothermal resource identified over the sedimentary basins.

Table 5: Potential for open-loop conversion of wells at the national level and for the three main French sedimentary basins

	Paris basin	*Aquitaine basin*	*Rhine rift*	*National level*
Number of wells after first selection	**1303**	**566**	**98**	**2014**
Number of aquifers of interest intersected				
Unknown	28	2	1	47
0	23	115	63	218
between 1 and 3	556	365	27	953
above 3	696	84	7	796
Number of wells crossing more than 1 aquifer	**1252**	**449**	**34**	**1749**
Number of wells crossing at least 1 aquifer located in a rural areas	**675**	**294**	**8**	**984**
Number of wells crossing at least 1 aquifer located in an urban areas	**577**	**155**	**26**	**765**

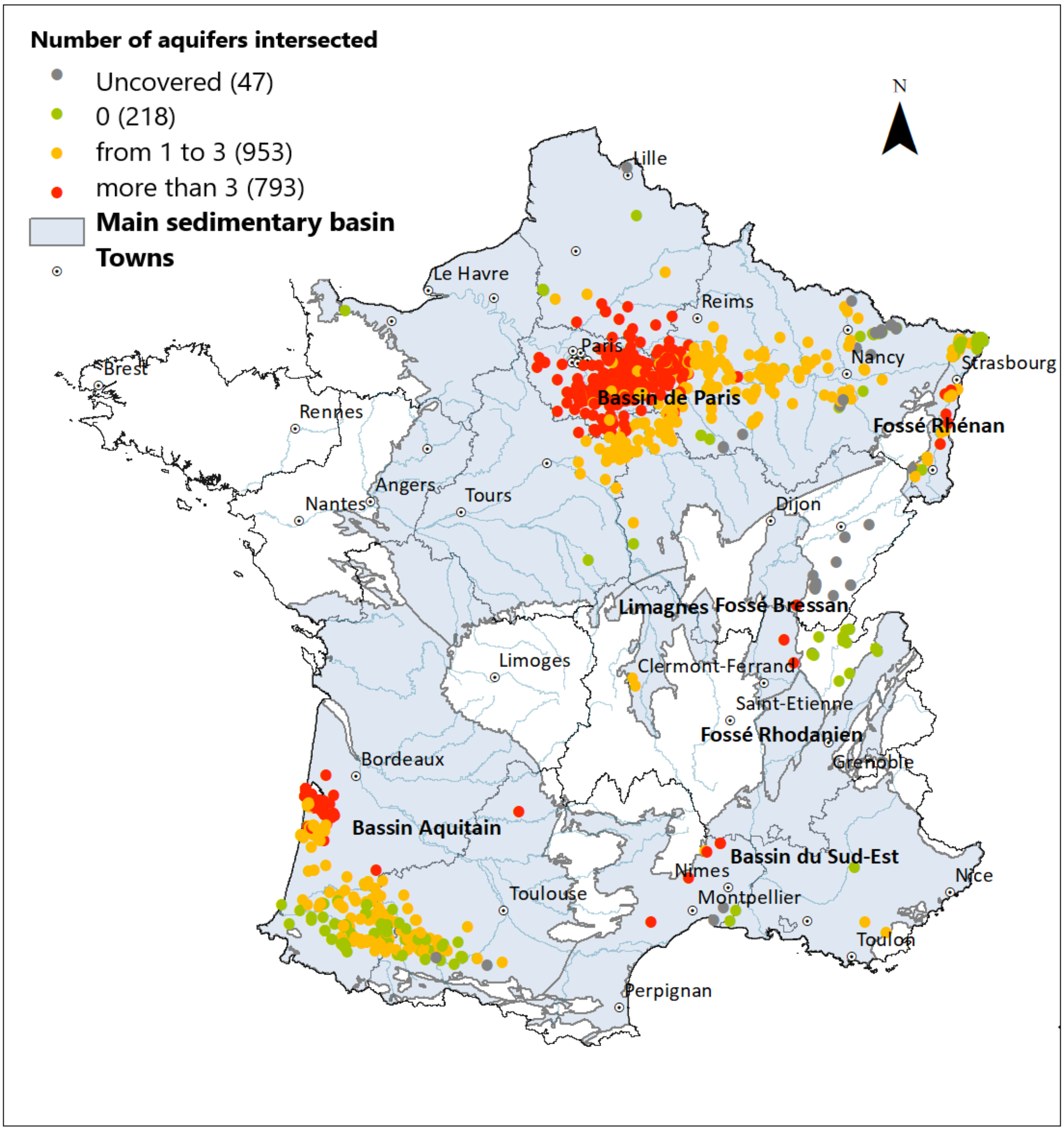

Figure 5: Location of the 2 014 wells selected for conversion assessment using open-loop systems

4.4 Closed-loop conversion cases

4.4.1 Methodology

The potential for closed-loop reconversion was estimated by assuming that the borehole is equipped with a coaxial heat exchangers, which is the technology most often observed during hydrocarbon well conversion abroad (Kohl et al. (2000); Sapińska-Śliwa and Kotyza (2000); Schneider et al. (1996)). The subsequent Borehole Heat Exchanger (BHE) is the "cold sink" of a Heat Pump (HP). The cold fluid leaving the HP evaporator is injected between the annular and the casing, and goes upwards through the inner pipe (Figure 2).

A thermal dynamic model was developed to assess the evolution of BHE fluid temperature and HP performance given the time-varying required thermal power for heating and domestic hot water (DHW). This model, initiated in the framework of the ANR Prégo project, solves the vertical profiles on downward and upward fluid temperature with a one-dimensional finite difference scheme, while the heat exchange with the surrounding rock is modeled with semi-analytical methods. After a primary sensitivity analysis, a set of significant parameters with related ranges was identified (cf. Table 6). The following hypothesis and fixed values were considered: production temperature for heating is 35°C and 50°C for hot water production, casing conductivity is fixed at 40 W.K- 1.m-1 , surface ground temperature is defined at 12°C, rock heat capacity is fixed at 2.2 MJ.K-1.kg-1 and its conductivity at 2.5 W.K-1.m-1, ratio of diameter versus thickness of central tube (SDR) is 11. The model was run for many configurations (more than 200) on 10 years of operation so that to build polynomial regressions on the "seasonal performance factor" (SPF) of the heat pump, i.e. the ratio between the energy delivered by the HP to the electrical consumption (HP and BHE circulation pump), and the minimum HP outlet fluid temperature (lowest temperature of the geothermal loop) Tmin (see Figure 6). Note that in the dynamic simulation the flow-rate is optimized at every time-step so that to find the best trade-off between HP electrical consumption and pump efficiency.

Table 6: Parameters used to run the model of HP-BHE systems

Parameter	Minimum value	Maximum value
Heat delivered by the heat pump per length of BHE *e* [kWh/an/ml]	100	2000
Share of domestic hot water (DHW) in the demand *β* [-]	0	1
BHE depth equipped the borehole *H* [m]	500	4000
Casing external radius $r_{e,f}$ [cm]	5.67	10.16
Inner pipe thermal conductivity λ_c [W.K^{-1}.m^{-1}]	3.10^{-3}	0.3
Geothermal gradient *α* [K/km]	20	60

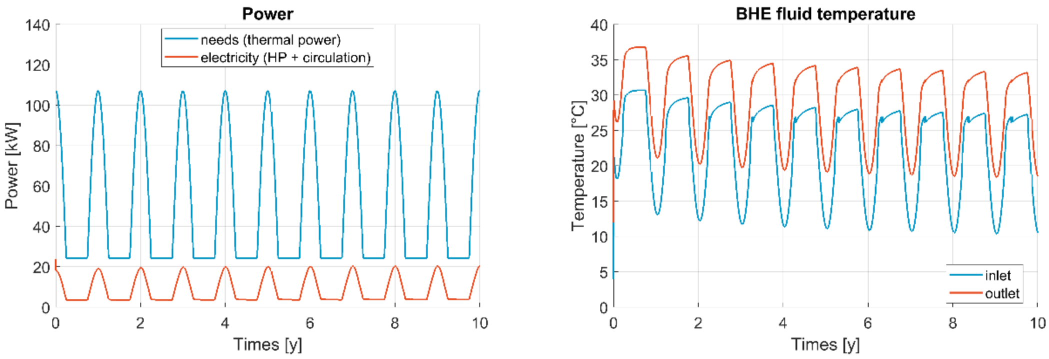

Figure 6: Dynamic simulation over 10 years: power balance (left) and temperature evolution (right). Set of parameters: e = 439.3 kWh/an/ml, β = 0.479, H = 1000 m, $r_{e,f}$ = 8.27 mm, λ_c = 0.1055 W.K^{-1}.m^{-1}, α = 56.1 K/km. Results: *SPF* = 5.81, T_{min} = 10.38 °C.

The **depth distribution** is represented in Figure 7, left. The **geothermal gradient** over the French territory is estimated based on temperature maps produced by Bonté et al. (2010). 5 boreholes were excluded from the analysis since there were outside these temperature maps. The **casing inner radius** is not known on a systematic basis, though it will have a tremendous effect on the pressure drop, the circulation pump consumption, and therefore the energy potential. However, a sample of 129 wells shows that 4 casings are predominant (4"1/2, 6", 7", 8"1/2) (Figure 7, right), so for every borehole the energy potential is estimated for each of these values. Further, the potential is estimated for 3 values of **central pipe thermal conductivity**: 0.3 W.K^{-1}.m^{-1} (inner pipe made of polyethylene without enhanced insulation), 0.03 W.K^{-1}.m^{-1} and 3.10^{-3} W.K^{-1}.m^{-1}, so that to test the interest of using more efficient and expensive inner pipes.

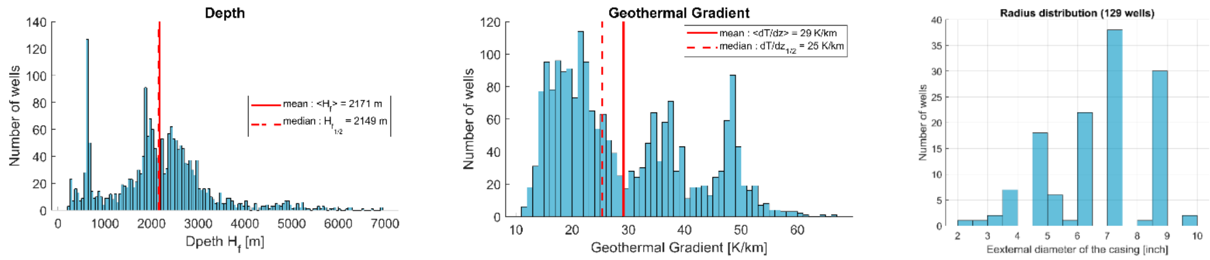

Figure 7: Depth distribution (left). Geothermal gradient distribution (middle). Distribution of the casing external radius for 129 wells (right).

Once a "surrogate model" (polynomial regression) of *SPF* and T_{min} is built, the potential of the 2009 boreholes is estimated. For every borehole, the objective is to maximize the amount of **heat delivered by the heat pump *e* × *H***, by optimizing three variables: the **BHE length equipped the borehole *H***, the **quantity of heat delivered per length of BHE *e***, and the **DHW share in the demand *β*** under the following constraints: the system **SPF must be greater than or equal to 4** (typical value of geothermal heat pumps), and **T_{min} is greater than +3 °C**. The whole process (model development, sampling, optimization) was carried out in Matlab®.

4.4.2 Results

The parameters that have a significant influence on the energy provided by the heat pump are mainly the drilling diameter, the central tube insulation, the equipped depth and the geothermal gradient. The larger the diameter, the more geothermal energy can be extracted. However, it can be noted that beyond a certain length equipped, one reaches a limit in the extractable energy due to the pressure losses, which increase with depth.

Thus, for a diameter of 4"1/2, the optimum depth of the coaxial heat exchanger varies between 1 500 and 1 800 m; for an 8"1/2 diameter, the optimum varies between 3 000 and 3 500 m. The energy supplied by the heat pumps, cumulated on all the boreholes, is between 1 800 GWh/year for a diameter 4"1/2, and 4 500-4 900 GWh/year for a diameter 8"1/2. Given the distribution of well radius shown above, we can estimate the supply potential at national level and using heat pumps to be 3 800 GWh/year. Considering a housing equivalent that consumes a total of 10 MWh/year of heat and hot water, the energy conversion potential from deep drilling into deep borehole heat exchangers is of the order of 380 000 housing equivalents.

CONCLUSIONS

This paper presents a first inventory of hydrocarbon exploration and exploitation wells with conversion potential for geothermal energy recovery in France. To assess the feasibility of open-loop well conversion, the deep wells inventory by Lahaie and Bouffier (2017) was crossed-referenced with supplementary geological and hydrogeological information provided by several BRGM databases and models. At the national level, 1 749 wells show potential of reuse. For closed-loop conversion, the well inventory was complemented by a semi-analytical model of deep borehole heat exchanger.

Obviously, if conversion is seriously considered, the present study does not obviate the need to perform a detailed, well-by-well feasibility study, including an assessment of operational risks and costs.

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