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A systematic study of harnessing low-temperature geothermal energy from oil and gas reservoirs

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ABSTRACT

Mature hydrocarbon fields co-produce significant volumes of water. As the produced water increases over the life of the field, the project's operating costs increase (due to greater water management expenditure), while the oil revenues decrease. Typically, these waste streams of water have temperatures of 65–150 °C. The combination of moderate temperatures and large water volumes may be suitable for electricity generation and/or district heating. Being able to capture the geothermal energy from existing hydrocarbon fields could extend their lifespan by delaying their economic cut-off point.

In this paper, mature oil and gas reservoirs worldwide are critically reviewed, where waste heat recovery has already been tested, or its potential identified. A roadmap of screening criteria based on geological, reservoir, production and economic parameters is then proposed, to assess how, where and when low-temperature waste heat recovery is feasible. The roadmap is tested against the Villafortuna–Trecate oil field in Italy, where the aquifer not only provides pressure support to the reservoir, but also represents a natural, in-situ hydrothermal resource. The results suggest that a single-well could recover approximately 25 GWh of electric power over a 10-year period, with an installed capacity of 500 kW.

1. Introduction

The rapid economic growth worldwide creates a strong market demand for energy, which leads to an increased use of conventional fossil fuels and hence an adverse impact on the environment. On the other hand, the more environmentally friendly renewable energy resources still have a long way to go before they can replace fossil fuels. This transition can be facilitated by hybrid projects combining different types of energy sources. Harnessing the geothermal potential of the water co-produced in hydrocarbon developments is an example of hybridization.

Since the 20th century, electrical power has been generated from high-temperature geothermal fluids such as steam (e.g. the Geyers in USA) or a mixture of steam and water (e.g. the Krafla in Iceland). These geothermal resources are typically mined with dry steam power plants or single/double flash power plants [1]. As the more favorable geothermal resources have been already discovered and given the natural predominance of low-to medium-temperature resources, the latter have become the focus of the geothermal sector. Thanks to modern technologies, converting low-temperature heat to electric power has become possible [2], particularly via binary power plants [3]. These use working fluids with liquid-vapor phase change in the secondary loop to allow the system to run more effectively at temperatures below the boiling point of water. Considering that many oil and gas wells around the world produce fluids at temperatures between 65 and 150 °C, there is scope for applying binary power plant technology in hydrocarbon developments. Here, the reservoir, the wells and the production system are already in place, which means that significant capital expenditure has already been invested for the hydrocarbon development and does not need to be made again for the geothermal add-on. It should be noted that some authors [4–6] classify the extraction of geothermal energy from oil and gas reservoirs under the category of engineered geothermal systems (EGS).

Primarily, in hydrocarbon reservoirs, low-temperature geothermal energy could be recovered from:

1) The naturally co-produced water from hydrocarbon reservoirs

In oil and gas fields, the water co-produced with the

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hydrocarbons must be separated and disposed of in respect of the environment, considering that it may contain salt or heavy metals. Depending on location (onshore or offshore) and field development scheme, the treated water may be re-injected underground or discharged overboard, for example. Water treatment and disposal carry significant costs to the operators. In the petroleum industry, several oil and gas wells have achieved or are about to reach their economic. In the Texas Gulf Coast alone, thousands of wells have already been abandoned [7]. Normally, when a hydrocarbon well is abandoned, public authorities formulate enforceable regulations for environmental protection and public safety in the areas nearby, which is an addition charges for the operators. Generating green electrical power from the co-produced water can offset fuel costs and reduce operational expenditure, delaying decommissioning liabilities and increasing ultimate oil recovery.

2) Water re-circulation through previously steam-flooded heavy oil reservoirs

Limpasurat et al. [21] discussed the opportunity to harness geothermal energy from heavy oil fields that have undergone steam-flooding and so accumulated substantial heat from steam injection. Once the steam-flooding process reaches economic cut-off, due to high water cut and/or high steam-to-oil ratio, the reservoir would be abandoned, leaving behind stored energy in the form of heat. From this point, the reservoir could be regarded as an artificial geothermal system, and its intrinsic heat recovered by water circulation. Preliminary investigations showed that it could be possible to advantageously extend the life of heavy oil fields by means of a heat-recovery phase after the oil-recovery phase.

2. Overview of low-temperature geothermal energy recovery from oil and gas fields worldwide

Even though the concept of extracting heat from hydrocarbon production is relatively novel, a few field pilots and preliminary studies have been successfully carried out in recent years. In the following section, six case studies worldwide are critically reviewed to assess the feasibilities of harnessing heat from mature hydrocarbon fields.

2.1. Mature fields with implemented heat extraction projects

Geothermal power units have already been installed at the Naval Petroleum Reserve (USA) and Huabei (China) oil fields.

2.1.1. Naval Petroleum Reserve NO.3 (NPR-3), Wyoming, USA

Naval Petroleum Reserve NO.3 (NPR-3), which was operated by the U.S. Department of Energy (DOE), is located at Teapot Dome field in the north of Casper. Its commercial production started in the early 1920s, after which it was shut-in for a relatively long time. In 1976, NPR-3 was fully developed at a field level. Its average reservoir temperature is around 110 °C, with a geothermal gradient of 2.5 °C/100 m. The oil production creates large volume of co-produced hot water with temperatures of 80–90 °C from more than 700 active wells. The site has a steady and abundant water supply from the Big Horn Range which is located in the northwest of the field, with a 2438 m hydraulic head above the field's surface [8].

Because of increasing operational costs and declining oil production, DOE decided to employ NPR-3 as a demonstration site for low-temperature geothermal energy recovery in 2007. In August 2008, a 250 kW Organic Rankine Cycle (ORC) power plant was installed to utilize the low-enthalpy energy from hot co-produced water in the field. In order to accommodate the new geothermal component, some field infrastructure was upgraded, including insulation of surface pipes to minimise heat losses and additional water storage tanks [9]. Until the beginning of 2011, the ORC unit outputted more than 1900 MWh of power [10]. This was the first use of co-produced hot water in an operating oil field to generate electricity. In 2013, DOE recommended to US Congress that NPR-3 should be sold to the private sector, to be continuously used as a productive oil field. In 2015, the DOE finalized the sale of the Teapot Dome oilfield to a private company [11]. The historical milestones of NPR-3 are summarized in Table 1.

Table 1
Historical milestones of NPR-3.

Years	Milestones
1920	Production started
1976	Fully developed at field level
2000	Oil production declined
2007	Employed as a demonstration site for geothermal energy extraction
2008	250 kW ORC power plant installed
2011	Cumulative electrical output of over 1900 MWh
2014	Sold to a private company

2.1.2. Huabei oil field, Hebei, China

The Huabei oil field, which is operated by China National Petroleum Corporation (CNPC), is located in the Hebei province of northern China. It is a typical buried hill oil field with a nose-shaped peak surface. In 1970s, the field made a great contribution to the development of the Chinese petroleum industry. For around 15 years, it occupied the third place in the country for hydrocarbon production. In June 1978, the LB reservoir, which is located to the east of the Huabei field, was put on production, mainly by natural depletion. Only four month later, water injection was initiated to increase the efficiency of oil recovery. There are 27 existing wells in place and only 6 of them are production wells. After more than 30 years of water flooding, the total flow rate has declined from the original 700 m^3/day to about 150 m^3/day. The current reservoir temperature is about 120 °C, with a geothermal gradient of 3.5 °C/100 m [12]. As a result of very high water cut (>97%) and consequent declining hydrocarbon production, its development is almost completed [13]. In 2007, CNPC conducted a pilot test to harness geothermal energy from the LB reservoir [14].

In early April 2011, a 400 kW binary power generator was installed, representing the first heat-electricity unit to use low-enthalpy energy from co-produced fluids in a hydrocarbon field in China. At surface, the temperature of the geofluids is around 110 °C. The total flow rate is approximately 2880 m^3/d, from 8 active wells. Until the end of 2011, the effective operation time was 2880 h and cumulative electricity generation was around 31×10^4 kWh [12]. A summary of the historical milestones of the LB reservoir of the Huabei oilfield is shown in Table 2.

2.1.3. Additional projects

In addition to the above two cases, the DOE recently announced that geothermal power was successfully generated from petroleum

Table 2
Historical milestones of the LB reservoir of Huabei oilfield.

Years	State points
1975	Discovered
1976	Production started
1986	Oil production declined
2007	Employed as a pilot site for geothermal energy extraction
Early April 2011	400 kW binary power plant installed
End of 2011	Cumulative electrical output of over 310 MWh