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Repurposing Hydrocarbon Wells in a Circular Economy Perspective: the Integration of Geothermal Energy in Biogas Plants

Claudio Alimonti[1]* and Davide Scrocca[2]
Sapienza University of Rome, DICMA[1]*, Consiglio Nazionale delle Ricerche - IGAG[2]
claudio.alimonti@uniroma1.it (*)

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ABSTRACT

A hydrocarbon-producing well is permanently closed once its production is no longer economically viable. Therefore, before making this irreversible decision and costly decision, it is advisable to evaluate all possible alternatives for repurposing existing wells, such as their reuse for geothermal applications. A geothermal assessment for oil and gas fields in Italy identified 42 fields at depths between 2000 and 3000 m. Temperatures associated with these oil and gas wells are often low to medium, approximately 50-80 °C. Therefore, temperatures in this range can contribute to the energy supply of plants that require thermal energy from a circular economy perspective. The biogas plants convert materials previously regarded as waste into a renewable energy source, nutrient-rich organic fertiliser and novel materials. They require heat to keep the reactor at a constant temperature and to heat the incoming biomass. The wells in the Irminio fields (Sicily, Italy) were chosen for a case study. The current business involves oil production and the use of coproduced gas in a cogeneration plant. This solution was adopted to integrate a cogenerator into the production process to make the most of the plants' tail gas. This case study evaluated the use of the organic fraction produced in the municipalities of the province of Ragusa (RG). The proposed scheme has general applicability in all possible existing wells.

1 INTRODUCTION

The EU's ambitious decarbonisation goals and the need for energy security require transitioning from fossil fuel-based systems. In this context, the accelerated phase-out of hydrocarbon production, as implied by the decarbonisation strategy to control climate change, results in many additional hydrocarbon well abandonments and decommissioning. According to 2018 estimates, the well decommissioning and restoration costs for the global oil and gas industry totaled 11.7 billion USD. Between 2019 and 2021, approximately 32-36 billion USD was spent worldwide (Khalidov *et al.*, 2021). Plugging and reclaiming abandoned onshore hydrocarbon wells can cost hundreds of thousands of dollars, although costs vary widely based on location, age and other technical factors. However, if an abandoned well is plugged, it is closed permanently (Vrålstad et al., 2019). Therefore, before taking this irreversible decision involving high costs, it is advisable to evaluate all possible solutions for alternative uses of existing hydrocarbon wells, such as Natural Gas storage projects, CO2 capture and sequestration projects, and geothermal applications.

Several studies have explored the repurposing of oil and gas (O&G) infrastructure for geothermal energy production, focusing on both methodological approaches and technical challenges associated with this endeavour. Between 2018 and 2024, Santos et al. (2022) reviewed closed-loop and open-loop system conversions, identifying five main challenges: well selection, data access, infrastructure, integrity, and regulations. Davoodi et al. (2024) emphasised technical and environmental aspects, especially heat recovery and wellbore integrity. Jello & Baser (2023) examined abandoned wells, associated risks, and pilot studies for repurposing. K. Wang et al. (2018) detailed oilfield geothermal resources and suggested interdisciplinary innovations. Case studies from the U.S. and China are provided by Sanyal & Butler (2010), S. Wang et al. (2016), McKenna J. et al. (2005), Bennett et al. (2011), and Nordquist J. & Johnson L. (2012), while European perspectives were offered by Barbacki (2000), Alimonti & Gnoni (2015), Maurel et al. (2020), Watson et al. (2020), and Alimonti et al. (2021).

Moreover, the economics of a geothermal project are generally less profitable than those of an O&G one. Thus, reducing investment costs is fundamental to achieve a bankable project. Depending on depth and location, drilling a new well may cost several million Euros. When comparing those costs and the investment in the plant, it becomes clear that the opportunity to reuse the wells gives them a new lease on life. The repurposing of oil

wells increases the economic viability of the geothermal project, reducing investment costs by up to 50% (Chmielowska et al., 2020; Alimonti et al., 2023). These results confirm the benefits of producing renewable energy using the hydrocarbon industrial infrastructure and highlight the benefits for surrounding populations.

These findings also demonstrate that applying circular economy principles to O&G wells is feasible and appropriate. In contrast to the linear economy model ("make, use, dispose"), the circular economy aims to extend the lifespan of resources, recover materials at the end of their life, and minimise raw material consumption and emissions (Velenturf & Purnell, 2021). In the oil and gas (O&G) sector, circular economy principles are applied through two key stages of the technical cycle: reuse and refurbishment (Figure 1). Reuse preserves the product's original form and function, as in gas storage applications, where depleted wells continue to serve hydrocarbon production with no alteration in completion. When gas storage is no longer viable due to increased water production, co-production of heat and power using produced fluids or tail gas in a combined heat and power (CHP) system becomes an effective solution. Refurbishment, the next step in the cycle, restores and enhances the asset by replacing components and shifting the well's purpose from hydrocarbon production to heat production. Rather than decommissioning, the site is converted into a geothermal facility. This process requires evaluating key parameters, including subsurface temperature and energy conversion technologies. Most O&G wells produce fluids at low to medium temperatures (50–80 °C). While these fluids are typically unsuitable for power generation, they can be efficiently exploited for thermal energy uses—e.g., district heating and industrial processes—thereby contributing to supporting the circular economy transition in the energy sector.

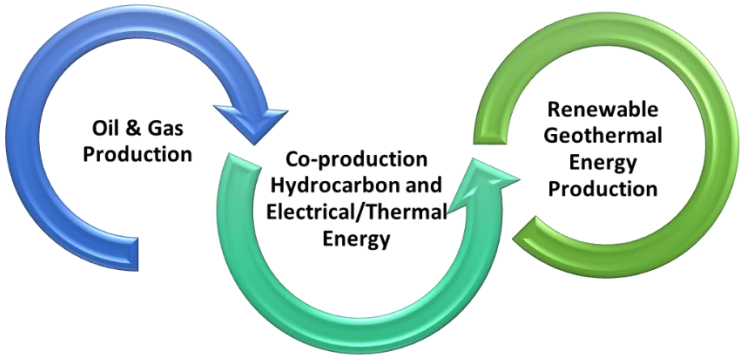


Figure 1 - Circular economy perspective of hydrocarbon wells

This paper aims to discuss how an existing hydrocarbon plant can be integrated into a circular economy asset to produce biogas. It examines the emerging problem of the continuously increasing production of municipal solid waste (MSW) in cities and explores alternative solutions and disposal methods. The proposed solution aims to combine an anaerobic digester (AD) plant with the heat produced by the existing wells to produce biogas. The plant will be realised in the same area as the oil centre. Biogas is one of the most economically viable and environmentally friendly renewable energy resources (Deublein & Steinhauser, 2009). The most promising organic matter is food waste, which has high biomethane production potential. Before use, biogas should be upgraded to biomethane as a fuel (Mirmohamadsadeghi et al., 2019). Food waste is the main component of municipal solid waste (MSW), accounting for 20–54% of it (Yasin et al., 2013). Moreover, the AD of food waste has a lower environmental impact than other processes, such as incineration and landfilling (Aghbashlo *et al.*, 2019).

The validity of this approach has been tested in the Irminio hydrocarbon field, located in Sicily (Southern Italy), where current activities involve producing oil and utilising the coproduced tail gas in a cogeneration plant (reuse stage). It is demonstrated that the energy required for AD systems, which involve heating incoming biomass and maintaining the reactor at a constant temperature, can be economically obtained through the hot fluid produced from the wells. It also discusses how the proposed sustainable strategy, which leverages widespread medium-enthalpy geothermal resources, can significantly contribute to increased biomethane production.

2 MATERIALS AND METHODS

The Irminio oil field has been selected as our case study. This field is in Southeastern Sicily, near the Irminio River, between the Municipalities of Ragusa and Scicli. The geological and geothermal characteristics of the area are briefly discussed in the following paragraph.

2.1 Geological Setting and Geothermal Assessment of the Hyblean Plateau

The Irminio oil field lies in the Hyblaean domain of southeastern Sicily (Figure 2), also known as the Ragusa Basin, forming the foreland of the Sicilian thrust belt (e.g., Scrocca et al., 2003; Catalano et al., 2013; Barreca et al., 2016). This passive-margin domain developed from the Late Palaeozoic to Triassic, with Meso-Cenozoic carbonate successions of basinal-pelagic and shallow-water facies (e.g., Patacca et al., 1979; Carbone et al., 1987; Lentini et al., 1991). Together with the adjacent offshore, it hosts a proven Upper Triassic–Lower Jurassic petroleum system (e.g., Frixa et al., 2000; Granath & Casero, 2004; Bertello et al., 2010), generally yielding low-API° oils, except for the Irminio light-oil field, discovered in 1982 at ~2,500 m depth.

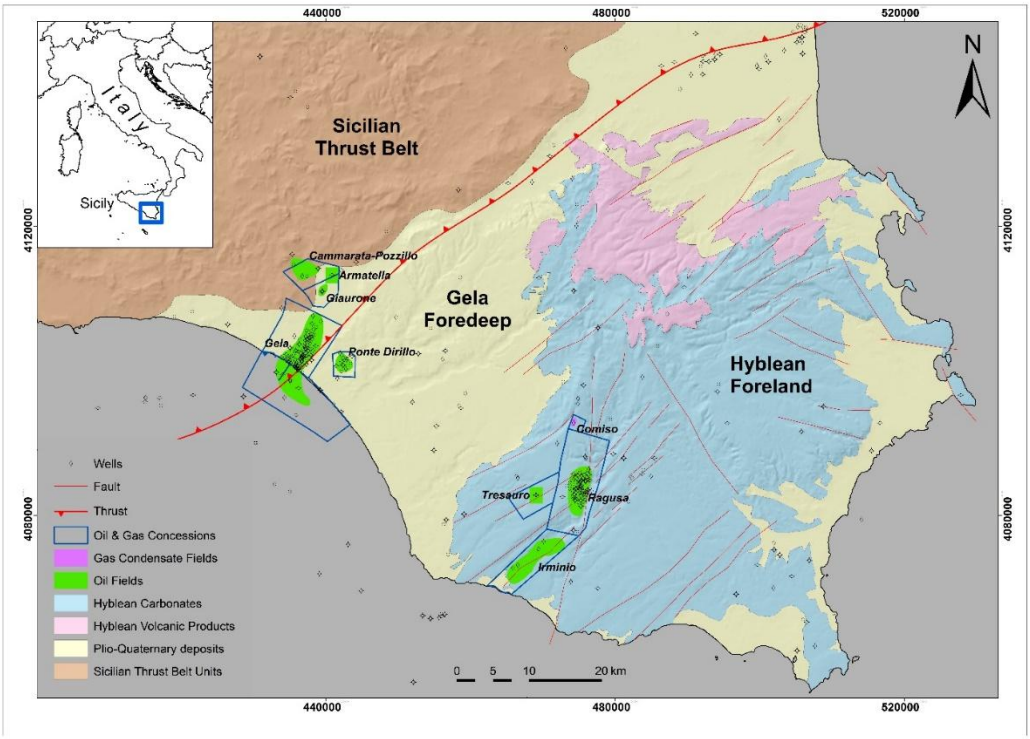


Figure 2 – Geological setting of Southeastern Sicily (after Alimonti & Scrocca, 2025**). Hydrocarbon fields (modified after** IHS Energy Group (2002)**), wells and licenses** (UNMIG, 2025a) **are also shown.**

In wells drilled in the Irminio oil field (Irminio, 2020), the pressure gradient remains normal up to approximately 1150 m (bottom of the Hybla Formation). From this depth, a gradual and continuous increase in the gradient is observed up to a depth of approximately 1,650 m, from approximately 1.1 kg/cm^2 to 1.2 kg/cm^2. At this depth, following an abrupt the gradient continues to increase steadily, reaching approximately 2,100 m at about 1.4 kg/cm^2. It then gradually decreases, returning to values around 1.03 kg/cm^2 at approximately 2,400 m in the reservoir rocks made up by Rhaetian microbial mounds developed in the Mila Member of the Noto Fm (Frixa et al., 2000;Irminio, 2020;Frixa et al., 2013, and Longaretti & Rocchi, 1990).

The poor poroperm properties of the Irminio reservoir are improved by hydrothermal dolomitisation close to the existing faults (Frixa *et al.*, 2013). Based on the analysis of bottom cores, porosity averages 3% and reaches a maximum of 8%, while permeability averages 4 mDarcy and reaches a maximum of 1 Darcy (in vuggy and fractured samples).

According to the published compilation of geothermal data (e.g., Cataldi et al., 1995;Della Vedova et al., 2001), in the Irminio field area, heat flow values are in the 70-90 mW/m^2 range while expected temperatures at a depth of 2,000 m below sea level are in the 70-80°C range. However, according to the available well data, the temperature at reservoir depth in the Irminio field is slightly higher than 100°C (Irminio, 2020). Figure 3 shows the map of oil wells locations used in the temperature gradient analysis following the approach reported by Trumpy and Manzella (2017).

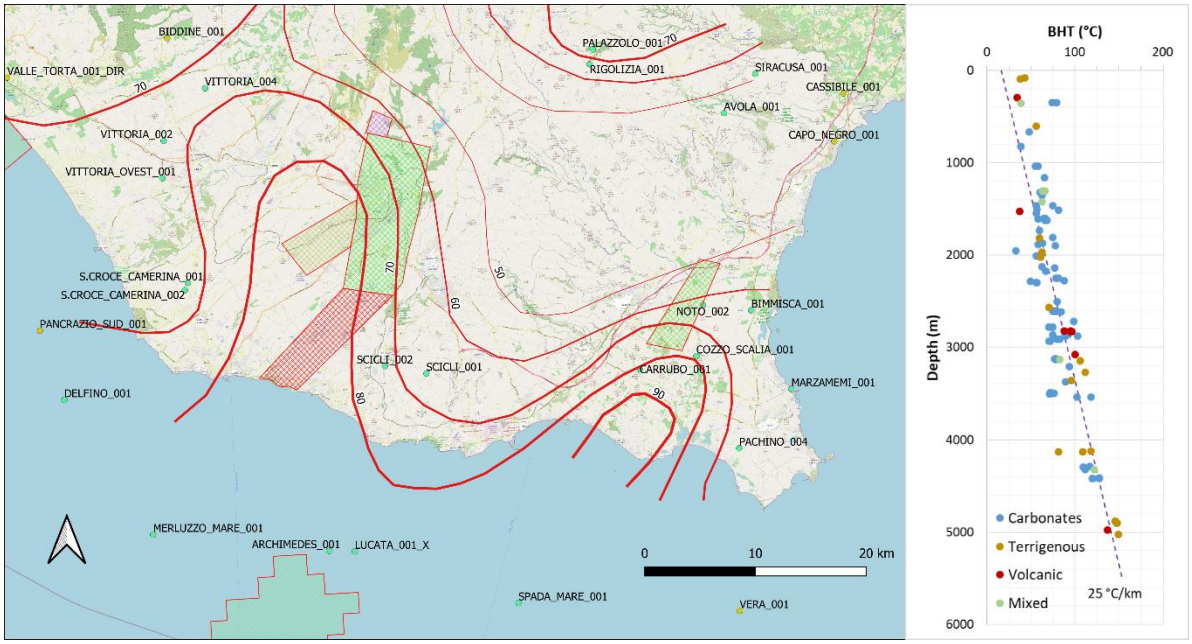


Figure 3 - Bottom hole temperatures from hydrocarbon wells. Left: Map reporting the location of hydrocarbon wells (ViDEPI Project, 2023) **used in temperature gradient analysis and the temperature at -2000 msl** (UNMIG, 2025b)**. Right: The corrected data are reported as the whole data set, distinguishing the formation where the measurement takes place**

Analysing available temperature measurements in the Hyblean plateau enhances knowledge of its geothermal potential. The temperature data comes from petroleum exploration and onshore/offshore production activities. The analysis of the corrected bottomhole temperatures highlights the characteristics of geothermal behaviour. The complete database presents a geothermal gradient with an average of 25 °C/km (Figure 3). The geothermal gradient is lower in the carbonates, around 10 °C/km, indicating active fluid circulation that homogenises the temperatures. This result allows us to consider the presence of a low-temperature geothermal system (<100°C), suitable for direct use. The existence of the oil field reduces exploration risk, and the productive wells guarantee the potential production of hot water with temperatures between 70°C and 90°C.

2.2 Irminio field

In the Irminio field, there are four wells and an oil centre, where oil, separated from natural gas and water, is stored before marketing. Two wells are productive, and the other two are non-productive.

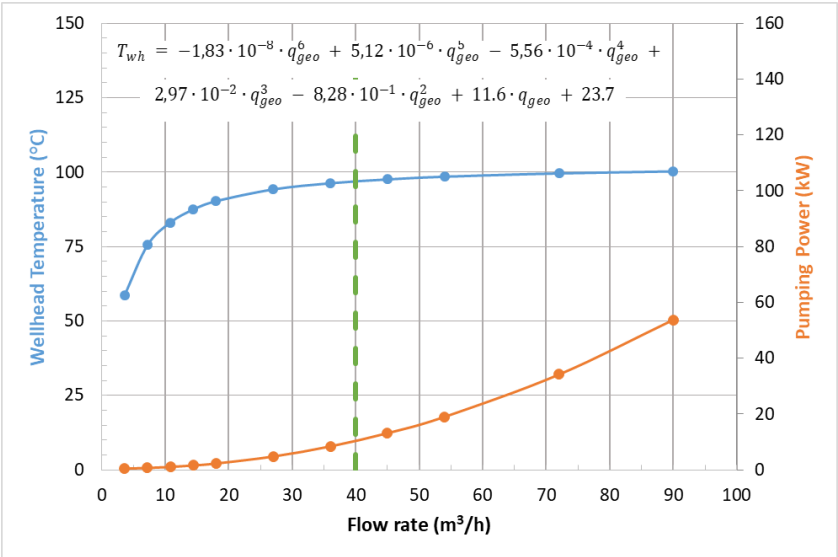


Figure 4 – Well production curve. In blue is the wellhead temperature and in orange there is the required pumping power vs. the flow rate, both obtained from flow simulation model.

The oil centre and wells area has about 18,000 m^2. Pumping produces oil, allowing a maximum flow rate of 5.1 m^3/h with a wellhead temperature of about 40 °C. To utilise the produced natural gas instead of injecting it into the reservoir, the oil company installed a CHP plant in the oil centre with a thermal power of 990 kW and an electrical production of 981 kW. Moreover, the natural gas produced cannot cover the entire supply of the CHP plant. Therefore, it works at 36% of its capacity with an electrical power of 353 kW and a thermal power of 356 kW. A part of the electricity generated by the CHP plant is used to power up production pumps and other field services.

Numerical simulation of the well flow provides wellhead pressure and temperature as functions of the flow rate. This flow model was developed and calibrated using well data. The simulation results are shown in Figure 4. From the calculations, a correlation between wellhead temperature and flow rate was developed. Increasing the flow rate can result in higher temperatures than those encountered during hydrocarbon production. However, this also increases the required pumping power.

2.3 Ragusa Province Municipality Solid Waste Evaluation

To determine the appropriate size for the anaerobic digestion (AD) plant, data on sorted waste collection in Sicily, specifically for municipal solid waste (MSW) in the province of Ragusa (ISPRA, 2022;ISPRA, 2023), were utilised. Over the past five years, recycling efficiency has improved significantly, resulting in a substantial increase in sorted waste, from 15% in 2016 to 66% in 2021. During this period, the organic fraction of municipal solid waste (OFMSW) also grew, reaching 32% of the total MSW in 2021. These trends indicate an increased collection of sorted waste and a greater availability of organic material to feed the digester.

While Sicily has 25 waste composting plants, only one is in the province of Ragusa (Legambiente Sicilia, 2019), with a treatment capacity of 16,800 tons of OFMSW per year. Given the 2021 OFMSW production of 43,000 tons and anticipating a 20% increase in the coming years, a proposed plant size of 35,000 tons per year would ensure the long-term closure of the waste cycle within the province. This plant would bring the total treatment capacity in Ragusa to 51,800 tons per year, comfortably exceeding the internal OFMSW production.

The characterisation of the OFMSW in the Ragusa province is not available, and the required data for plant sizing are taken from the literature, assuming the best operational conditions (Cecchi et al., 2005). The OFMSW obtained from the waste sorting collection is characterised by a percentage of total solids (TS) of 20% and a percentage of total volatile solids (TVS) of 85% (Cecchi et al., 2005; Castellani et al., 2023; Campuzano & González-Martínez, 2016). The density and specific heat of the OFMSW are assumed to be 750 kg/m^3 and 2.72 kJ/kg K, respectively.

3 RESULTS

The conversion of hydrocarbon wells for geothermal energy production to fuel a biogas plant was developed in two phases. The first phase aims to achieve the primary objective of generating enough biogas to fully power the existing cogeneration plant. The electrical capacity of 981 kW requires a gas supply of 239 Nm3/h with a LCV of 10 kWh/Nm3. The second phase will bring the plant to process up to 35,000 tons per year, and the excess biogas produced will be converted into biomethane to fuel the fleet of garbage trucks.

The AD plant is sized according to the model presented in Alimonti & Scrocca (2025). The process type selected is mesophilic, based on its greater efficiency. Based on the idea of utilising the area currently occupied by the oil centre and well platforms, the optimal configuration should ensure not only greater production efficiency but also a smaller footprint.

The plant configuration considered consists of two bioreactors. The first, with a diameter of 17.5 m, produces 238 Nm^3/h of biogas, which is sent directly to the CHP plant. The second bioreactor, with a diameter of 23.9 m, produces 358 Nm^3/h of biogas, which is then purified into biomethane and fed to the organic waste collection fleet. A substantial volume of water is recovered by filtering and drying the digestate. The volume of digestate is about 208 tonnes per day and it is used to produce fertiliser after aerobic treatment and drying.

The regulation of the heat supply to the plant is controlled by adjusting the flow rate extracted from the well. Having fixed a constant injection temperature of 50 °C, the flow rate is calculated. Figure 5 reports the trend of the monthly mean temperature and the temperature of the produced fluid from the well.

Figure 6 shows the plant scheme proposed. It considers two digesters, one used to supply the CHP unit and the second to provide the garbage truck fleet after biogas upgrading to biomethane. The heat produced by the CHP unit is used in the conversion process of the digestate into fertiliser.

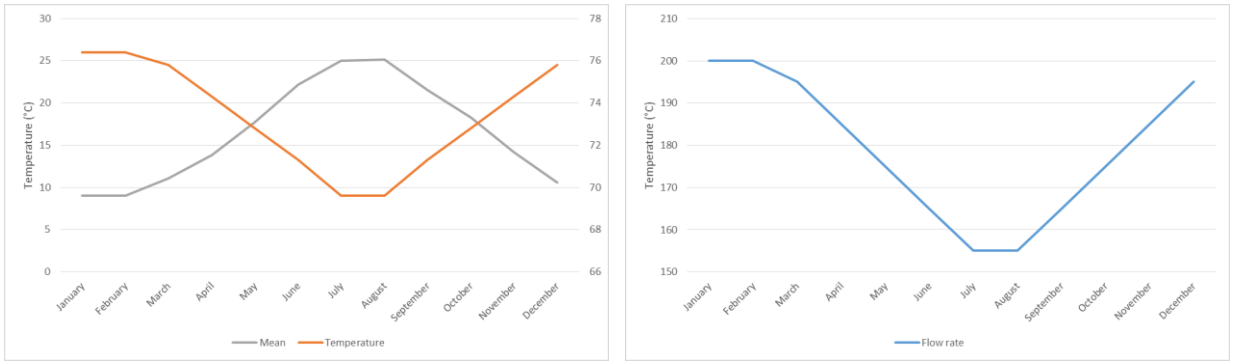


Figure 5 – Left: Average monthly air temperatures and the temperature of the produced fluid from the well. Right: Flow rate obtained from regulation, maintaining an injection temperature of 50 °C

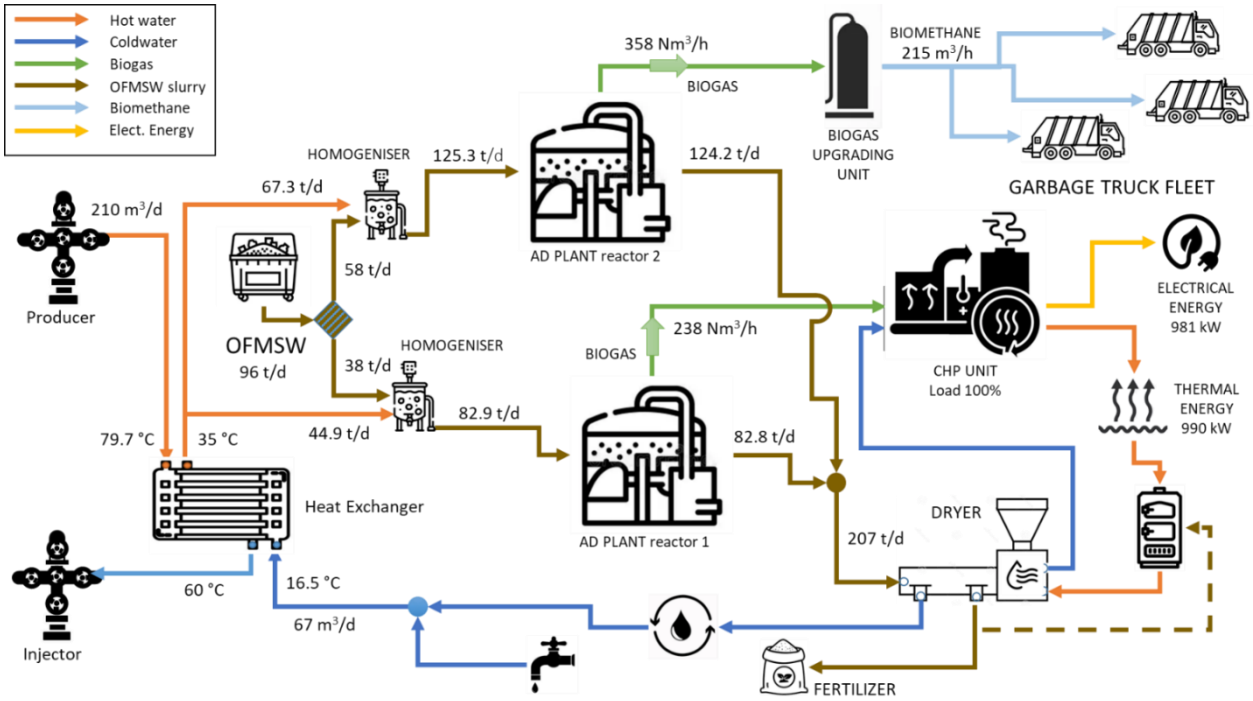


Figure 6 – The dual-plant system operating in parallel, where the first stage fuels a CHP system, and the second stage provides power for a fleet of garbage trucks. The flow rates and temperature refer to the mean yearly temperature (after Alimonti & Scrocca, 2025).

A simplified representation of the footprint of the plant is reported in Figure 7. The treatment plants are located in the most remote area after the wells. Near the access to the area, there is the storage building for OFMSW, and further, there is the digestate deposit.

4 DISCUSSION AND CONCLUSIONS

The geothermal conversion of existing oil and gas infrastructure exemplifies a significant application of the circular economy approach, which adheres to the fundamental principles of reuse, recycling, and refurbishment. Although biogas was used to power the cogeneration unit and truck fleet in the Irminio case study, it is worth noting that, in line with the circular economy approach, using heat harvested from an existing medium-low temperature hydrocarbon field in an anaerobic digestion plant to produce biogas has general value.

The RepowerEU plan has set the target of producing 35 billion m^3 of biomethane by 2030. Sustainable biomethane production should be waste-based, avoiding the use of food and raw materials that would lead to land use change issues. Furthermore, by 2024, Member States will be required to separately collect organic waste, which can be valorised in anaerobic digesters. Consequently, in this scenario, it is relevant to evaluate how low and medium temperature geothermal resources, available in hydrocarbon deposits and easily accessible through existing or potentially productive wells, can contribute to increasing Italian biomethane production.

Our results indicate the feasibility of building two reactors that are fed by 35,000 tons of organic waste per year and are capable of producing 596 cubic meters of biogas per hour. The plant's footprint remains within the existing oilfield site, where the cogeneration unit and wells are located. Geothermal reuse of existing hydrocarbon wells will provide 1.7 GWh/year of heat for biomass feeding and digester operations, avoiding 312 tons of CO_2 emissions per year.



Figure 7 - Plant areal distribution. In the picture, the wellhead, CHP areas, and the safety flare are highlighted. 1 Storage building OFMSW; 2 Preparation tank; 3 Anaerobic Digestor step 1; 4 Anaerobic Digestor step 2; 5,6 Biogas Storage tank; 7 Aerobic storage of digestate.

Using the results obtained from the Irminio case study, the heat required to produce one cubic meter of biomethane in the mesophilic process is 0.56 kWh/m^3. According to the RepowerEU plan, Italy is required to produce 6 billion cubic meters of biomethane per year. Therefore, the heat required by anaerobic digestion plants is 3.36 TWh/year. Assuming a flow rate of 5 l/s through the production pipe of a conventional well and a temperature difference of 20 °C across the heat exchanger, the heat exploitation is approximately 10,000 kWh/day per well.

In Italy, 42 hydrocarbon fields with temperatures above 60-70 °C have already been identified (Alimonti *et al.*, 2021), and there are 846 productive and potentially productive wells available on the Italian territory. Limiting this preliminary approach to the productive wells, which number around 340, the exploited heat is approximately 1.25 TWh/year, allowing it to cover 1/3 of the thermal energy required by the planned AD plants. In conclusion, despite some limitations in the model assumptions and some approximations in the data reported above, the amount of biomethane producible with the proposed approach would be in the range of 3-6 billion m3/year, considering only the productive well or the potentially productive ones. Finally, our case study highlights the significant value of producing CO_2-neutral biogas using the heat recovered from an existing hydrocarbon field with medium-low temperatures.

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