

Harnessing Geothermal Energy from Mature Onshore Oil Fields- The Wytch Farm Case Study

Harkaran Singh¹, Gioia Falcone², Alexandre Volle³ and Laurent Guillon⁴

¹ Imperial College London, South Kensington Campus, London SW7 2AZ, UK

harkaran.singh@hotmail.com

² Cranfield University, College Rd, Cranfield MK43 0AL, UK

g.falcone@cranfield.ac.uk

³ Perenco Holdings, 15-19 Britten Street, SW3 3TY, London, UK

avolle@uk.perenco.com

⁴ Perenco Holdings, 15-19 Britten Street, SW3 3TY, London, UK

lguillon@uk.perenco.com

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ABSTRACT

All mature oil fields co-produce significant volumes of water with oil, which is a consequence of waterflooding and/or aquifer influx. Water cut increases with the life of the field, sometimes reaching as high as 99 %, leading to a decrease in oil revenues. Such volumes of co-produced water require costly treatment to remove the oil before it can be safely disposed of or re-injected back into the reservoir. Typically, these waste streams of water have temperatures in the range of 65 to 150 °C (149 to 302 °F). This combination of moderate temperatures and large volumes is favourable for generating electricity or for use in district heating. Being able to harness geothermal energy from existing oil and gas fields could extend their lifespan by delaying their economic cut-off point. This would be achieved by generating new revenue streams, using in-field generated power to offset fuel costs and reduce operational expenditure, delaying decommissioning liabilities, and increasing ultimate oil recovery. The emissions of greenhouse gases could also be reduced by providing renewable, low carbon energy.

The objective of this study is to assess the potential for geothermal exploitation of the co-produced water from mature onshore hydrocarbon fields in the UK. The Wytch Farm oil field, located in Dorset, Southern England (**Figure 1**), was chosen as the case study, with the necessary data provided by the field's operator. The available geothermal energy could be harnessed in the form of electricity, via an Organic Rankine Cycle (ORC) power plant, or as thermal energy for direct use, via heat exchangers. An analytical model is developed to compute the power generated from co-produced water by ORC technology over a range of operating conditions and with different working fluids. Flexibility is built into the model to account for time-variant properties, such as increasing water cut and decreasing reservoir temperature over the life of the field.

At 65°C (149 °F), the co-produced water at Wytch Farm represents a low- to moderate-temperature geothermal resource, with associated low cycle thermal efficiencies. However, in comparison with gas turbines or diesel engines, the ORC's thermal efficiency is not critical in power generation, as the fuel source is essentially free and abundant.

The results of this study indicate that, for the power generation option, a maximum of 1.4 MW of electricity could be produced at site M at the Wytch Farm oil field, and 850 kW at site F. With the combined heat and power (CHP) scenario, a total of 2600 households could be served with district heating from site M, with a total thermal energy of 37 GWh delivered annually. However, these results must be interpreted vis-à-vis overall economics and users' availability.

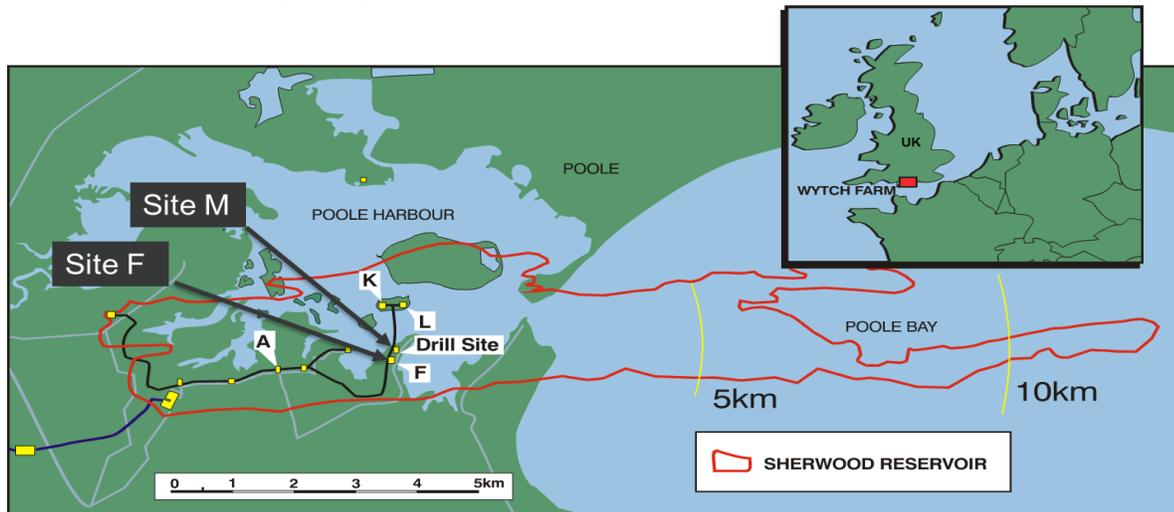


Figure 1: Map of Wytch Farm oil field

1. INTRODUCTION

Many ageing oil and gas fields have very high water cut, sometimes as high as 95% and above, and are on the verge of being watered out as water production keeps increasing over time. Towards the end of their life, oil fields are associated with high operational expenditure (OPEX), due to the technical and economic challenges of separating, treating and disposing of co-produced water, against the marginal sales figures. The cost of produced water management eventually renders the oil field uneconomic and, in some cases, forces the operator to abandon the field before all the potentially recoverable hydrocarbons are extracted. At this stage, the only way to extend the life of an oil and gas field is by reducing the OPEX or generating additional revenue; otherwise, decommissioning costs will be incurred.

One way of extending the life of an oil field is to harness geothermal energy from the waste stream of co-produced water. Even though the geofluid is a low enthalpy energy source, the significant volumes produced can make the concept viable. The thermal energy recovered can be used to generate electricity with an ORC or binary power plant and for direct heating of local communities, depending on users' availability.

ORC is the most common technology used to extract energy from moderate-temperature geothermal resources, and ORC plants are operational in many parts of the world. In 2006, two ORC power plants, fuelled by 74 °C (165 °F) of geothermal resource, were installed at the Chena Hot Springs Resort, Alaska, and provided a power generating capacity of 400 kW, which represented the lowest temperature at which geothermal energy had been converted into electrical power (Holdmann, 2007).

Several studies and pilot projects have been conducted to assess the technical and economic feasibility of harnessing the geothermal energy of co-produced water in mature hydrocarbon developments. Riney (1991) was the first to report the geothermal potential of Pleasant Bayou field in Texas, USA (Riney, 1991). Barbacki (2000) estimated that 2 MW of heat energy could be extracted from a doublet well configuration in the Grobla field in Poland (Barbacki, 2000). Milliken (2007) reported that the gross power potential of the Naval Petroleum Reserves-3 well (NPR-3) in Wyoming, USA, from a rate of 130 MBWPD at 104 °C (220 °F) would be 76 MW (Milliken, 2007). The first ORC (250 kW capacity) installed at NPR-3, in August 2008, produced a net power of 132 kW from 40 MBWPD at 77 °C (170 °F). Upgrades to this unit and installation of an insulated storage tank to avoid heat loss from the geofluid, boosted the net power to almost maximum at 225 kW (Johnson and Walker, 2010).

Studies have identified significant geothermal resources in several oil and gas fields. Erdlac Jr et al. (2007) reported that Texas has thousands of wells drilled to sufficient depths to reach temperatures of over 121 to 204 °C (250 to 400 °F). In the five large areas defined in the Texas deep sedimentary basins, there exists the possibility to generate 47 to 75 billion MWh of electricity equivalent to 29-46 billion barrels of oil (Erdlac Jr et al., 2007). Liu et al. (2013) reports that a single well in the Villafortuna-Trecate oil field in Italy—a high-pressure high-temperature oil field with strong aquifer support can potentially generate in excess of 25 GWh of electricity over a period of 10 years with a 500 kW capacity of ORC power plant (Liu et al., 2014). Xin et al. (2012) reported the successful installation and operation of a 400 kW ORC power plant in Huabei oilfield, China. The geofluid flowing at 18 MBWPD (2880 m³/d) at 110 °C (230 °F) produced 31*10⁴ kWh of electricity in nine months (Xin et al., 2012).

The objective of this study is to assess the technical and economic feasibility of harnessing geothermal energy from a mature onshore oil field in the UK. The data for this case study were provided by the operator of the Wytch Farm oil field. The harnessed geothermal energy can be utilised to generate electricity via an ORC power plant, for direct heating of district community, or CHP generation option.

2. DATA GATHERING ¹

The Wytch Farm oil field is located in Dorset, Southern England. The produced fluids from wells are corrosive (120,000 ppm of chlorides), oil loaded, gas loaded, and the pressure in the line varies from 15 to 50 bars (218 to 725 psi) during operation. Downstream of the wells is a separator, which separates the oil, gas and ‘dirty’ water. The outlet water is still corrosive, but its oil content is reduced to 100 to 1000 ppm of oil, and the pressure is relatively stable at 12 to 16 bars (174 to 232 psi).

Site M at the Wytch Farm oil field’s process facilities treats 160,000 bwpd (~290 kg/s), which can be increased to 180,000 bwpd if required. The temperature of the geofluid at the outlet of the separator is in the range of 65 to 67 °C (149 to 152.6 °F) (**Figure 2** shows 75 °C (167 °F) which is incorrect and explained later). Site F at the Wytch Farm oil field treats 90,000 bwpd (~170 kg/s), which can be increased to 130,000 bwpd. Water outlet temperature, post separation, is around 66 °C (151 °F) (**Figure 2**)¹.

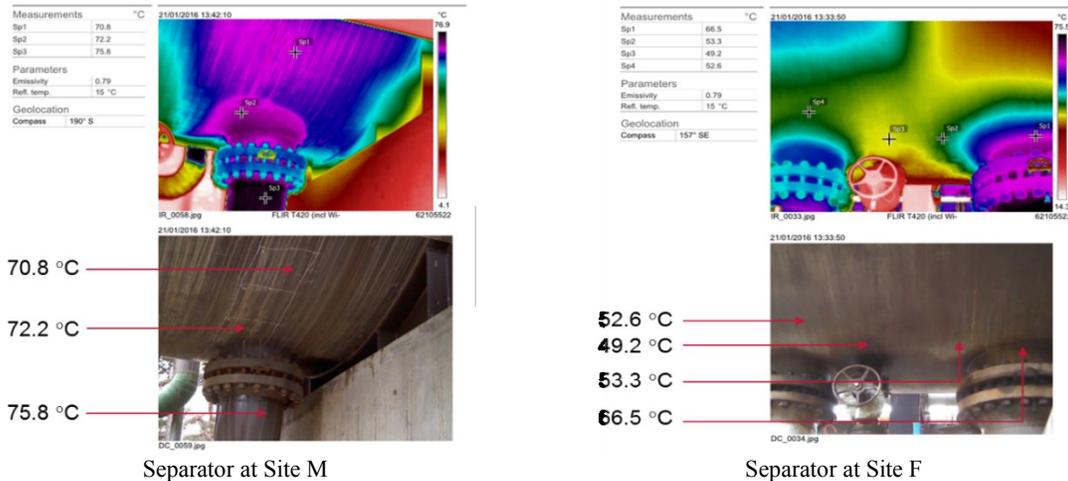


Figure 2: Thermal images of separators¹

3. ORGANIC RANKINE CYCLE: DESCRIPTION

The ORC relies on the same principle as the water-steam Rankine cycles, but instead of water-steam, the ORC system utilises an organic, high molecular mass fluid with a liquid-vapour phase change, or boiling point, occurring at a lower temperature than the water-steam phase. (Auld et al., 2013; DiPippo, 2012).

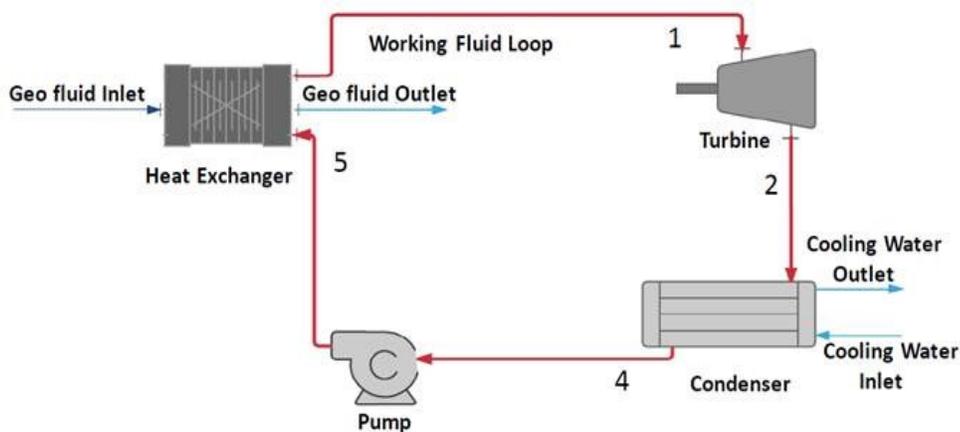


Figure 3: Schematic diagram of an Organic Rankine Cycle (ORC)

¹ Data provided by the Operator, 2016.

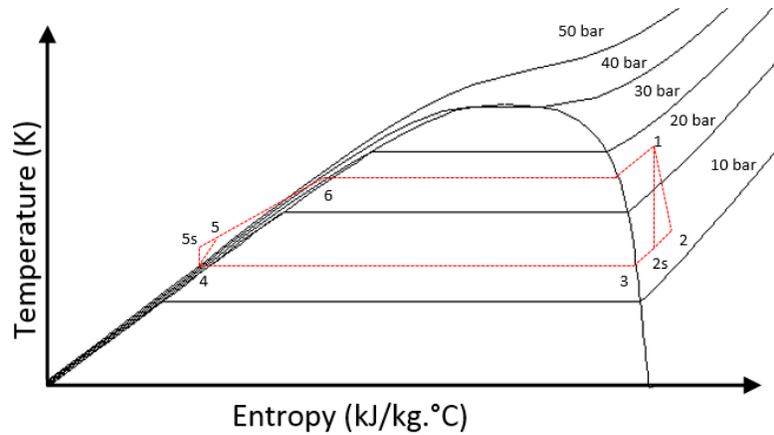


Figure 4: Temperature-Entropy diagram for ORC- Red dotted line represents the Rankine cycle thermodynamic process

A schematic of the ORC is shown in **Figure 3**. It has four main components: turbine, heat exchanger (evaporator), condenser, and feed pump. The thermodynamic cycle of the working fluid in the ORC is illustrated in the Temperature- Entropy (T-s) diagram (**Figure 4**). The dome encompasses the two-phase region of the fluid on the T-s diagram and the lines cutting across the dome represents the constant pressure contours. The red dotted line is the Rankine cycle thermodynamic process.

For this study, it is assumed that, after being separated from the produced oil and gas, the co-produced water passes through the evaporator of the ORC, where it transfers its heat to the working fluid of the ORC power plant (point 5-1 in **Figure 3** and point 5-6-1 **Figure 4**). The heated working fluid, as saturated or superheated vapour, expands through the prime-mover (point 1-2), where the mechanical work generated is converted into electricity via an alternator. Working fluid at the outlet of the turbine is then condensed (point 2-4) and re-pressurised by the feed pump (point 4-5) so that the Rankine cycle starts again.

4. INITIAL ASSESSMENT

To assess the heat exchange performance of the ORC power plant, the cycle thermal efficiency of the power plant is analysed. The method proposed by the Massachusetts Institute of Technology is to find a correlation between the geofluid inlet temperature and the cycle thermal efficiency derived from the ORC power plant (Tester et al., 2006). The data list shown in **Table 1** was established from the information from fourteen ORC power plants in six countries and ORC power plants manufactured by Turboden (Liu et al., 2014). All the data in **Table 1** are plotted in **Figure 5**.

Table 1: Thermal efficiencies of ORC power plants

Plant Name	Location	Inlet Temp (°C)	Efficiency (%)
Chena Hot Spring	USA (Alaska)	73	8.2
Neustadt - Glewe	Germany	98	6.6
Amedee	USA (California)	103	5.8
Wabaska	USA (Nevada)	105	8.0
Brady	USA (Nevada)	109	7.0
Húsavík	Iceland	122	10.6
Unterhaching	Germany	124	12.0
Otake	Japan	130	12.9
Nigorikawa	Japan	140	9.8
Steamboat SB - 2	USA (Nevada)	152	8.2
Ormesa II	USA (California)	157	13.5
Soultz	France	158	13.9
Heber SIGC	USA (California)	165	13.2
Miravalles Unit 5	Costa Rica	166	13.8
Turboden ²	n/a	75	5.8
		68	5.0

² Personal communication with Rocco Altieri. 2016. Electronic mail: Turboden

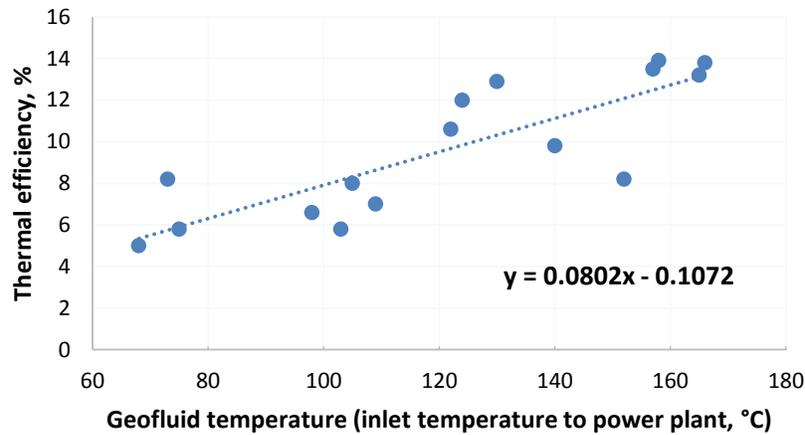


Figure 5: Correlation of cycle thermal efficiency and the inlet geofluid temperature of the ORC power plants

The efficiency correlation in **Figure 5** shows the dependence of the thermal efficiency on the temperature of the geofluid available. The thermal efficiency of the ORC can be estimated by the inlet geofluid temperature using the obtained linear regression equation:

$$\eta = 0.0802T_{in} - 0.1072 \quad (1)$$

Electric power output of the ORC power plant can be computed using:

$$Q = c_p m (T_{in} - T_{out}) \eta \quad (2)$$

Where, c_p is the weighted average specific heat capacity of oil and water

m is the total mass flow rate.

Using **Equations 1 and 2** and the data provided by the Operator, initial estimates of the potential of power production are evaluated. **Table 2** contains the relevant inputs and the results.

Table 2: Range of relevant parameters used to estimate the potential power production in the Wytch Farm oil field

Site M		Site F	
Inlet temperature, °C	67	Inlet temperature, °C	66
Thermal efficiency, %	5.2	Thermal efficiency, %	5.2
Mass flow rate, kg/s	290 to 330	Mass flow rate, kg/s	170 to 220
Outlet temperature range, °C	50 to 55	Outlet temperature range, °C	41 to 46
Output power, kW	1100 to 1450	Output power, kW	700 to 1120

5. ORC MODEL

An analytical model of the ORC is developed, based on Auld *et al.* (2013) and DiPippo (2012), to evaluate the performance of the ORC power plant for any geofluid and cooling medium conditions. The model is designed for maximum flexibility. It can evaluate any heat source and heat sink conditions, model the cycle with any organic fluid, and optimise the power output based on the input conditions. The model uses standard thermodynamic heat-balance relations to calculate the state of fluids at each point in the system. RefProp (version 9.1) software is used to calculate the thermodynamic properties of the working fluid used in the cycle.

The heat source in the model is defined based on the properties of the geofluid, namely the oil API gravity, the specific heat capacity of both the oil and the co-produced water, the amount of oil remaining in the separated water and the mass flow rate of the oil-water mixture. The heat sink is assumed to be a pure stream of water. In reality, this stream will be salty brine, but the thermodynamic properties are very similar, which allows one to make this assumption. Pinch point analysis is used to model the heat exchange process. A pinch point is a place in the heat exchanger where the temperature difference between the geofluid and the working fluid is the least. The value of the temperature difference at this location is called the pinch point temperature difference (ΔT_{PP}). As per Auld *et al.* (2014), a pinch point relates to the physical constraints in designing the heat exchanger and a value of 5 °C is assumed to be realistic. The true feasibility of an ORC system is determined by the difference between the heat source and the heat sink conditions, not the absolute temperature of the heat source (Auld *et al.*, 2014). The ORC modelling strategy is shown in **Figure 6**.

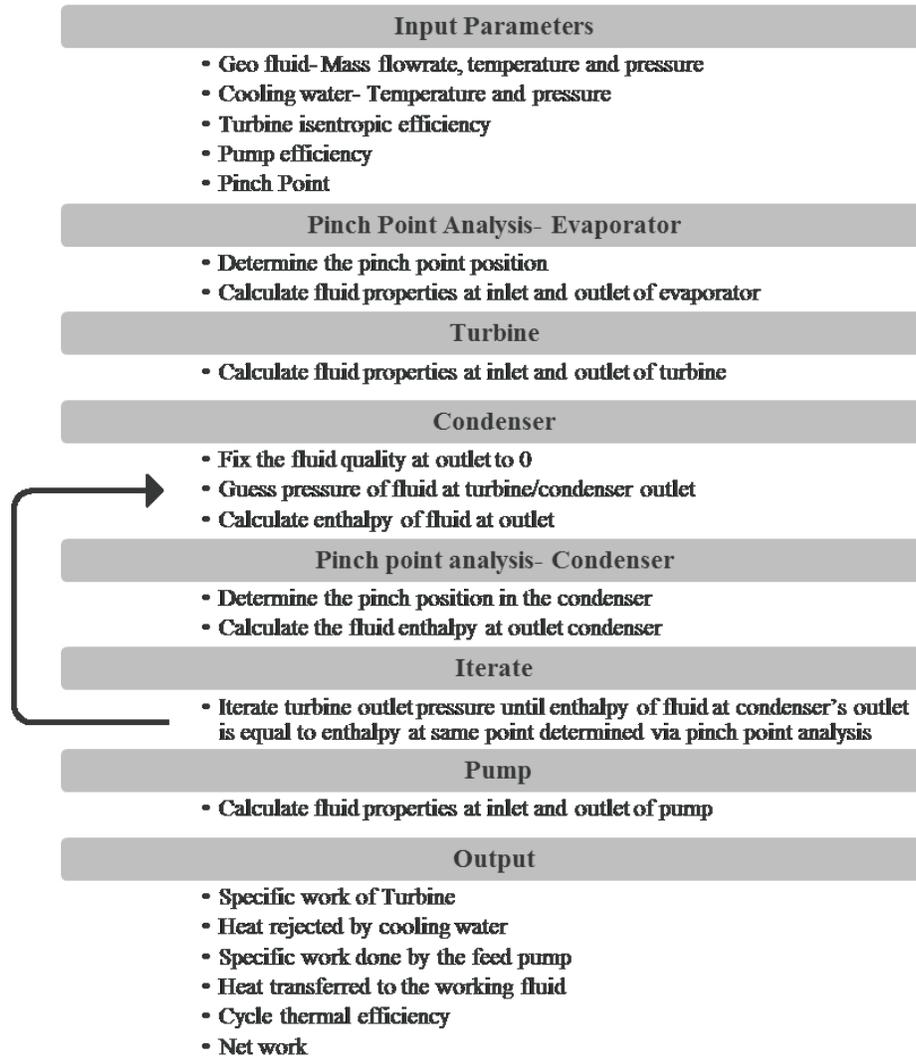


Figure 6: Flow diagram of the ORC model implemented

5.1 Results of the base model

Inputs are based on the data from Wytch Farm site M. The cooling water input data are discussed in the condenser section.

Table 3: Input parameters and the results of the ORC base model

Input Parameters			Results		
m_G	Geofluid mass flow rate (kg/s)	290	W_T	Specific work of the turbine (kJ/kg)	23.92
T_G	Geofluid temperature (°C)	65	Q_c	Heat rejected in the condenser (kJ/kg)	347.37
P_G	Geofluid pressure (MPa)	1.2	W_p	Specific work done by the pump (kJ/kg)	0.73
m_{CW}	Cooling water mass flow rate (kg/s)	1000	Q_{fi}	Heat transferred to the working fluid (kJ/kg)	370.55
T_{CW}	Cooling water source temperature (°C)	9	η_{th}	Cycle thermal efficiency (%)	6.26
	Working fluid	Isobutane	W_{net}	Net work (kW)	1391
η_T	Turbine isentropic efficiency (%)	85		Geofluid outlet temperature (°C)	47.0
η_P	Pump isentropic efficiency (%)	75	m_{wf}	Working fluid mass flow rate (kg/s)	60
ΔT_{PP}	Pinch point temperature difference (K)	5	TIP	Turbine inlet pressure (MPa)	0.6

5.2 Optimising net power of base model

The configuration of the ORC model is characterised by the mass flow rate of the working fluid (m_{WF}) and turbine inlet pressure (TIP) (Auld *et al.*, 2014). **Figure 7** shows the power generated by the geofluid for different configurations of the ORC system. The working fluid simulated is Isobutane (R600a), and the corresponding input parameters and results are shown in **Table 3**. The ‘oval’ that can be seen in the centre of **Figure 7** represents the maximum power generated from the input conditions of the model and the arrows point to the configuration at maximum power.

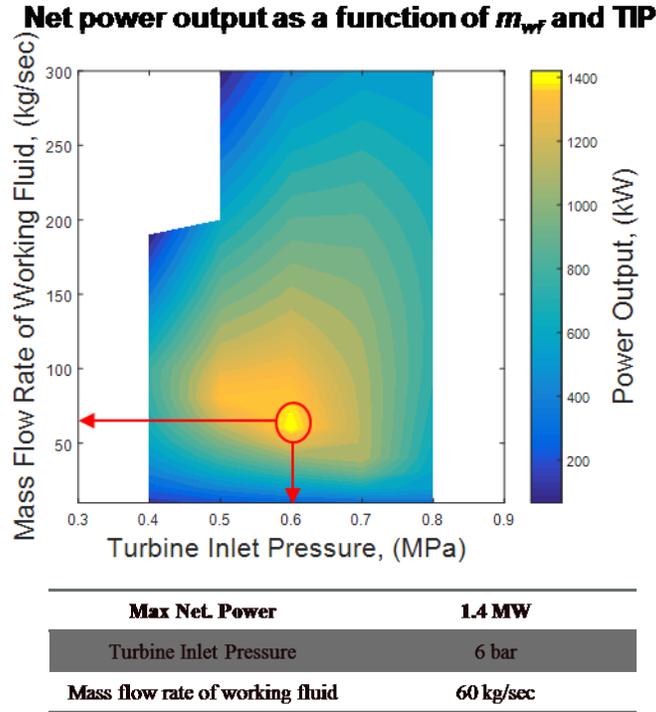


Figure 7: Net power output as a function of mass flow rate of the working fluid and turbine inlet pressure

Figure 7 shows that, for a given set of field input data (Wytych farm Site M, in this case), the maximum power is not generated at the maximum turbine inlet pressure (TIP) and the maximum mass flow rate of the working fluid (m_{WF}), but at an optimised value. This is because a balance between the TIP and m_{WF} has to be achieved, which is determined by the heat source, to generate maximum power. For a fixed mass flow rate of working fluid, the TIP is determined by the temperature and mass flow rate of the heat source. The higher the energy flux of the heat source, the higher the TIP that can be adjusted to optimise the cycle, ensuring the working fluid at the turbine inlet is saturated or superheated vapour. However, turbine outlet pressure (TOP) is determined by the cooling medium. To optimise the cycle, the TOP must be as low as possible, while ensuring that the quality of the working fluid at the outlet of the condenser is zero i.e. saturated liquid conditions for the working fluid. For given heat source and heat sink conditions, the maximum difference between TIP and TOP results in maximum power output from the cycle.

5.3 Geofluid temperature sensitivity

According to the Wytych farm operator, the thermal image of site M separator in **Figure 2** was inaccurate (too high) due to the partial errors of the imaging equipment resulting from hot weather during the day. The thermal signature of the separator outlet was re-examined at night time, using the same equipment, and it showed a temperature of 65 °C. For this study, power output is evaluated for geofluid temperatures from 65 °C to 75 °C. **Figure 8** shows the net power output for a range of geofluid temperature (keeping the rest of the parameters as per **Table 3**).

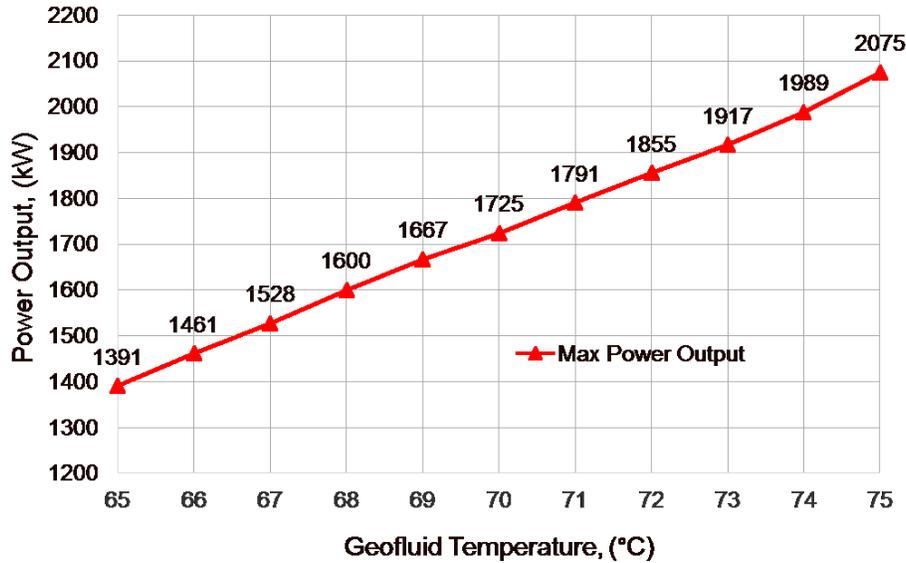


Figure 8: Net power output with geofluid inlet temperature from 65-75°C

5.4 Fluids selection

The performance of the ORC is directly linked to the thermodynamic properties of the working fluid. There are several possible working fluids that can be used, but there are many constraints impacting on the selection process, mainly related to the temperature, composition and pressure of the geofluid, as well as health, safety and environmental considerations.

Desirable properties of fluids suitable for ORC applications include low specific volumes, high efficiency, moderate pressures in heat exchangers, low cost and low environmental impact (Tchanche *et al.*, 2009).

The first criterion for the selection of working fluid is that its critical temperature should be higher than that of the geofluid (65 °C at Wytch farm site M) to ensure subcritical cycle operation. Based on this, **Table 4** lists possible fluids for this study, with corresponding physical and environmental data.

The second selection criterion is that the working fluid should be maintained at moderate pressure within the ORC, to limit the size of plant components, thus reducing the plant's capital expenditure (CAPEX). Operating limits are defined based on the heat source and sink conditions for Wytch Farm, which are 10 °C (average sea water temperature) to 75 °C (maximum geofluid temperature), and the saturation pressures at these temperature limits are evaluated (**Table 4**). An organic fluid with moderate pressures and operating range at these conditions is a good option for ORC application.

An important feature for a possible candidate organic fluid is to exhibit retrograde behaviour (DiPippo, 2012). This ensures that, after expanding through the turbine, the fluid remains in superheated condition, which is required to avoid moisture at the turbine exit. Organic fluids which have a positive slope for a portion of their vapour saturation line are known as dry fluids. Fluids with a straight vapour saturation curve are known as isentropic fluids. Dry fluids require zero degree of superheat, and isentropic fluids require a small degree of superheat to achieve this as compared to fluids like water, which require a considerable degree of superheat to avoid dropping into the wet zone during the expansion through the turbine. The fluids shortlisted for ORC simulations are R134a, R152a, Isobutane, Butane, Propane, and Ammonia. **Figure 9** compares the saturation curves of all shortlisted fluids with water.

Table 4: Physical and environmental data of organic fluids

Refrigerant	Physical data				Environmental data		
	Boiling point at atmospheric pressure (°C)	T _{crit} (°C)	P _s at 10 °C (bar)	P _s at 75°C (bar)	Atmospheric life time (yr.)	Ozone Depletion Potential	Global Warming Potential (100 yr.)
RC318	-6	115.2	1.88	12.00	3200	0	10,250
R600a (Isobutane)*	-11.7	135	2.21	12.11	0.019	0	~20
R114	3.6	145.7	1.29	8.31	300	1	10,040
R600 (n-Butane)*	-0.5	152	1.48	9.06	0.018	0	~20
R113	47.6	214.1	0.24	2.32	85	1	6130
Cyclohexane	80.7	280.5	0.06	0.85	n.a.	n.a.	n.a.
R290 (Propane)*	-42.1	96.68	6.37	28.49	0.041	0	~20
R407C	-43.6	86.79	6.45	35.60	n.a.	0	1800
R32	-51.7	78.11	11.07	54.17	4.9	0	675
R500	-33.6	105.5	4.99	24.68	n.a.	0.738	8100
R152a*	-24	113.3	3.73	21.05	1.4	0	124
R717 (Ammonia)*	-33.3	132.3	6.15	37.10	0.01	0	<1
Ethanol	78.4	240.8	0.03	0.88	n.a.	n.a.	n.a.
Methanol	64.4	240.2	0.07	1.51	n.a.	n.a.	n.a.
R718 (water)	100	374	0.01	0.39	n.a.	0	<1
R134a*	-26.1	101	4.15	23.64	14	0	1430
R12	-29.8	112	4.23	20.81	100	1	10,890
R123	27.8	183.7	0.51	4.30	1.3	0.02	77
R141b	32	204.2	0.43	3.71	9.3	0.12	725

* Organic fluids shortlisted based on the criteria mentioned above.

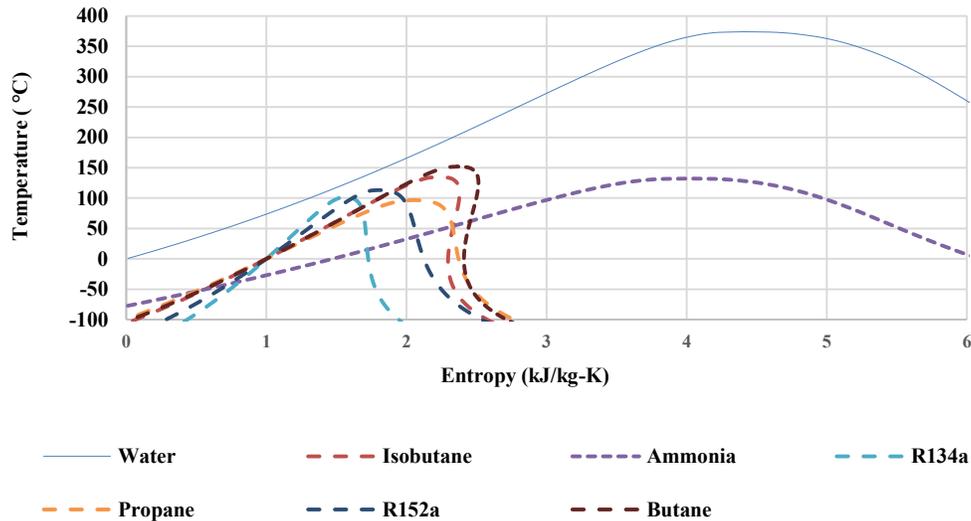


Figure 9: T-s plots for water and selected organic fluids (properties obtained from RefProp software)

Using the first and second laws of thermodynamics, the performance of the ORC model, under Wythc farm operating conditions, is evaluated. Net power output for the shortlisted organic fluids is computed and optimised (with geofluid at 65°C) using the ORC model. Comparison of the results in **Table 5** shows that R134a is generating the maximum net power, but it requires a very high mass flow rate of the working fluid, which would increase the size and cost of the plant, and therefore make it unfeasible. Ammonia requires the smallest mass flow rate to achieve a power output of over 1.4 MW, but the high TIP required would increase the cost of the turbine. The most economical fluids are Isobutane and Butane. These produce a net power of over 1.4 MW, with moderate mass flow rate and TIP, and have relatively high cycle thermal efficiency.

Table 5: Comparison of the performances of different working fluids

Refrigerant	Mass flow rate (kg/s)	Turbine inlet pressure (bar)	Turbine outlet pressure (bar)	Net power (kW)	Cycle efficiency (%)
R600a (Isobutane)	60	6	2.9	1423	6.3
R600 (n-Butane)	60	4	2.0	1453	5.6
R290 (Propane)	60	15	8.2	1452	6.0
R152a	80	10	5.1	1414	5.9
R717 (Ammonia)	20	16	8.5	1411	5.6
R134a	120	11	5.6	1468	5.8

5.5 Evaporator and Condenser

The heat exchange processes of the ORC system are tabulated in **Table 6**.

Table 6: Comparison of heat transfers within the ORC model as a function of geofluid inlet temperature and mass flow rate of the working fluid (Isobutane)

Temperature of geofluid (°C)	Mass flow rate of working fluid (kg/s)	Power generated (MW)	Heat extracted from geofluid (MW)	Heat dumped into the condenser (MW)	Evaporator In/Out (Geo Fluid) (°C)	Condenser In/Out (Working Fluid) (°C)
75	80	2.1	29.9	27.8	75 / 52	28 / 21
	30	1.2	12.4	11.2	75 / 65	36 / 17
	18	0.5	7.7	7.5	75 / 69	48 / 16
65	60	1.4	22.8	21.4	65 / 47	31 / 19
	18	0.5	7.3	6.8	65 / 59	38 / 16

5.5.1 Evaporator

It is crucial to know the heat exchange process in the evaporator to compute the area required for heat transfer. The area can be estimated by the global UA value derived from the equation, $Q_H = U * A_H * LMTD$, where Q_H is the heat extracted from the geofluid. The estimated area required to generate the maximum power of 1.4 MW is between 1200 to 6000 m². The large uncertainty in area is due to the uncertain overall heat transfer coefficient, U , which varies with different types and arrangements of the heat exchangers.

The Wytch Farm oil field operator considers the modification of oil collector pipelines for the sole purpose of installing the ORC system as risky. The geofluid produced at Wytch Farm is highly corrosive (S.G of 1.14, due to high salt content). Installing the evaporator heat exchanger within the collector pipe, prior to the separator, would require expensive metals and design of the evaporator to withstand its effect. It will also lead to a pressure drop in the pipeline, which would have to be compensated by increasing the capacity of the reinjection pumps, as the geofluid (after separation) is injected back into the reservoir. Installing the equipment downstream of the separator is less efficient, as the geofluid has already suffered heat loss, and the pressure drop in ORC has to be compensated with higher reinjection pump capacity.

A possible solution is the double pipe heat exchanger, which is cheap for both design and maintenance. The advantage of this type of heat exchanger in Wytch Farm is that there is no requirement to modify the current layout of pipelines as it can be clamped onto the existing pipeline. It also prevents heat loss to the atmosphere from the pipelines, does not cause any pressure drop in the geofluid line, and can be extended to the hottest point in the system. The drawbacks are that the heat exchange surface area is limited by the length of the pipe from the well head to the separator, and the efficiency of these heat exchangers is lower than the shell and tube or plate type heat exchangers. An innovative design of the fluid flow through the clamp-on double pipe heat exchanger could solve this problem.

A simple double pipe heat exchanger is designed to estimate the length of the geofluid pipe required to achieve the heat duty. **Figure 10** shows a simple schematic of double pipe heat exchanger. Site M has a principal rack pipeline of 12 inch OD. For design purposes, a 16 inch OD pipe is clamped onto the principal rack. Using the input mass flow rate as 305 kg/s (oil+water flow rate before the separator), the length of the geofluid pipe required to achieve the duty is evaluated (**Table 7**).

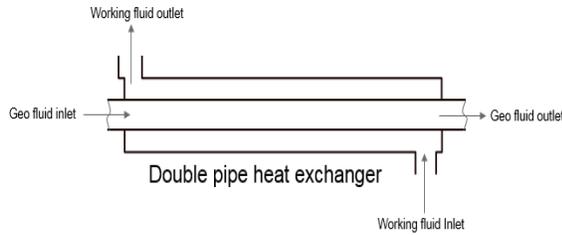


Figure 10: Schematic of double pipe heat exchanger

Table 7: Length of double pipe heat exchanger for different configurations of ORC

T_G (°C)	m_{wf} (kg/s)	W_{net} (MW)	Q_H (MW)	Length of the pipe required (m)	ΔT (°C)	η (%)
75	80	2.1	29.9	1,820	23.5	7.1
	30	1.2	12.4	575	9.7	9.8
65	60	1.4	22.8	1,365	17.9	6.3

5.5.2 Other Possible Evaporator Designs

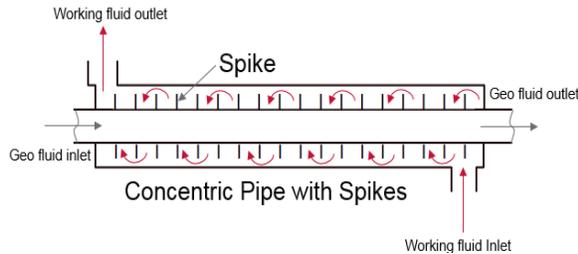


Figure 11: Concentric pipe heat exchanger with spikes

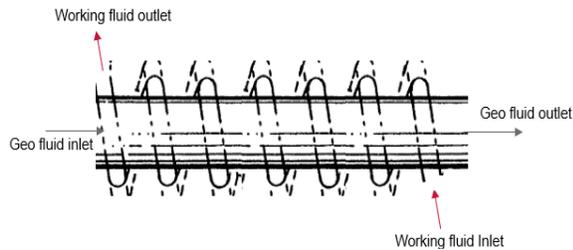


Figure 12: Helical coil heat exchanger

A concentric pipe heat exchanger with spikes is similar in design to double pipe heat exchanger, with the exception that it has more surface area available for exchanging heat (Figure 11). Assuming spikes of 1.5 inches in height on the circumference of the pipe are placed at 2 inches apart, the length of the pipe required is tabulated in Table 8. Similarly, a helical coil of 4 inch OD wrapped around the geofluid line (Figure 12) can achieve the heat duty for length of the geofluid line as tabulated in Table 8. Velocity in all these scenarios is well below the erosional velocity of the double pipe heat exchangers.

Table 8: Length of the pipe required for various designs of heat exchangers

T_G (°C)	W_{net} (MW)	Q_H (MW)	Area required to achieve duty (m ²)	Concentric pipe with spikes	Helical coil heat exchanger
				Length of the pipe required (m)	Length of the pipe required (m)
75	2.1	29.9	1300-6500	320-1600	800-4000
	1.2	12.4	770-3800	190-940	470-2350
65	1.4	22.8	1200-6000	296-1480	740-3700

5.5.3 Condenser

Basic thermodynamic considerations result in a significant amount of waste heat in ORC systems. The cycle thermal efficiency of ORC power plants is inherently low (5 to 9 %) due to the low enthalpy fuel source, which results in large amount of waste energy that must be rejected from the cycle, some 9 to 15 times the useful power delivered by the plant (Table 6). To optimise the cycle, heat rejection method must be efficient and economic.

Sea Water Cooling

To maximise the system performance and to utilise the cold sea water resources available locally, the ORC model was initially designed to be water-cooled. The sea water temperature in Poole Harbour is assumed to be 9 °C. The parasitic load of auxiliary sea water pump is evaluated and the mass flow rate of cooling medium optimised to maximise the net power generated by the ORC plant.

The mass flow rate of the sea water has a major influence on the efficiency of the ORC power plant. Increasing the quantity of the cooling medium increases the overall cycle efficiency of the plant, but it also increases the parasitic loads on the system. By balancing these two quantities, maximum net power is achieved. The sea water mass flow rate is optimised at 1000 kg/s. Such large volume of sea water is beyond environmental recommendations for the ‘Natura 2000’ protected area and therefore, other condenser options are discussed in the next section.

5.5.4 Other Condenser Options

Alternative options that can reject large amounts of heat as required by the plant are adiabatic coolers, evaporative towers, air coolers and air condensers.

Evaporative towers have a smaller footprint than air condensers and are more efficient in hot dry climate, whereas the air condensers are efficient in cold climates. The water consumption is high in evaporative cooling, which also requires chemical water treatment, which has an adverse impact on the environment. Air condensers require no water consumption and have no virtual impact on the environment. Input power is higher in evaporative towers as compared to the air condensers.

Adiabatic coolers are the modern alternative to air cooling towers. These coolers are a hybrid of air coolers and evaporative towers. Much smaller in size, these coolers have reduced maintenance costs, capital costs, water consumption and are less harmful to the environment.

6. COMBINED HEAT AND POWER SCENARIO

Combined heat and power (CHP) application is an extension of electric power generation via the ORC plant. Geofluid temperature at the outlet of the evaporator is in the range of 47 to 52 °C (depending on the geofluid inlet temperature and specifications of ORC). The heat energy from this outlet stream can be utilised for direct heating. Since the geofluid contains dissolved gases and has high corrosion and scaling potential, it is not advisable to circulate it in the pipelines for direct heating, but instead, transfer the heat into a secondary loop of fresh water via a heat exchanger (**Figure 13**).

Downstream of the separator at site M, the geofluid, at 65 °C and 290 kg/s of mass flow rate, enters the ORC power plant. The geofluid exits the ORC at 47 °C (generating 1.4 MW of electrical power) and flows into the second heat exchanger to transfer its residual heat to the direct heating plant. Assuming a pinch point of 5 °C in the heat exchanger, the direct heating loop achieves a temperature of 42 °C.

At 42 °C, the system can be classified as ultra-low temperature district heating. Supply temperatures required for under floor heating is in the range of 35 to 40 °C, but a minimum of 50 °C is required for preparing domestic hot water (Gudmundsson *et al.*, 2014). To solve the issue of low supply temperatures, heat pumps could be used at the user end to boost the temperature to 55 °C to reach a target of 50 °C for domestic hot water application.

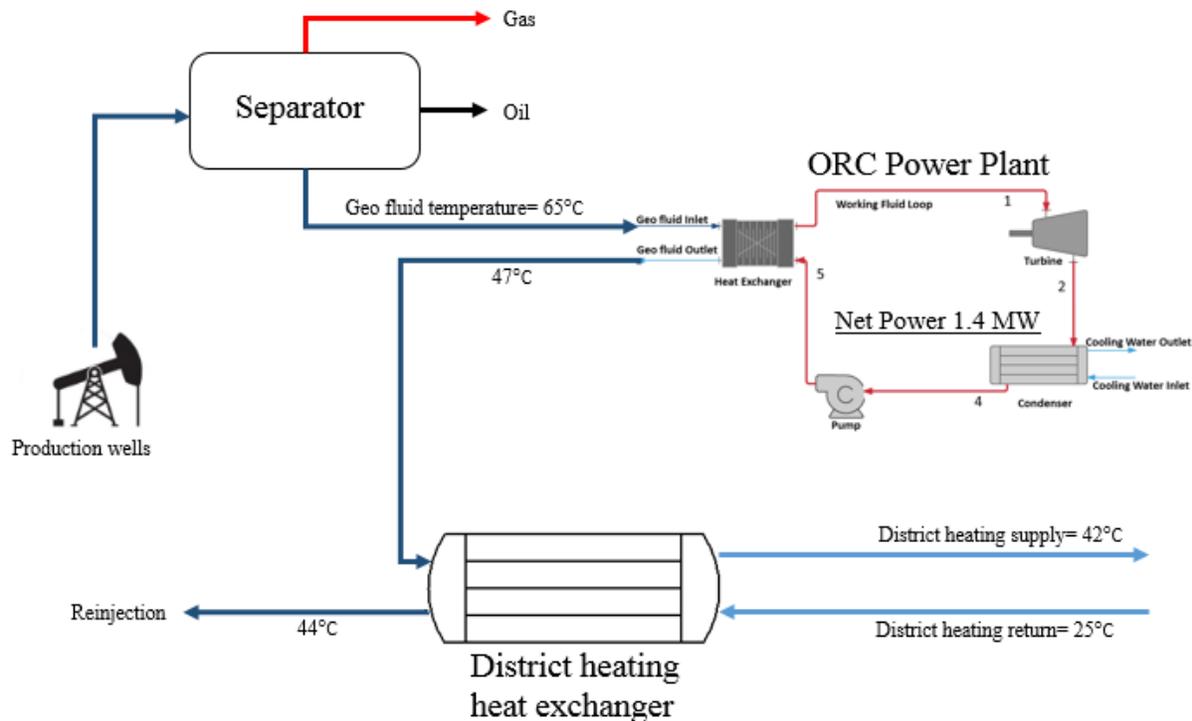


Figure 13: Schematic layout of the Combined Heat and Power (CHP) plant

As the closest local community is 4 km from Wytch Farm site M, temperature drop in the transmission pipe is a concern. By insulating the supply and return pipes, these losses can be minimised. The supply temperature of direct heating is 42 °C, flowing at a rate of 50 kg/s and at a velocity of 1.8 m/s (well below the erosional velocity). Assuming it is flowing through a main pipe of DN 200 mm (219.1 mm OD) with an insulating coating of 25.4 mm (1 inch) in thickness and thermal conductivity of 0.027 W/mK, the maximum temperature drop computed over a length of 5 km of pipeline is under 0.5 °C for the supply line, and 0.3 °C in the return line, with a maximum pressure drop of 4.06 bar.

If the return line temperature is set to 25 °C, as per the ultra-low temperature district heating configuration (Gudmundsson *et al.*, 2014), the energy delivered to the end users is 4.24 MW or 37 GWh annually. According to the report, “Energy Consumption in the UK” by Department of Energy & Climate Change (DECC, 2016), the average gas consumption for heating per household is 14,263 kWh in 2014, which suggests the direct heating option of the CHP scenario can serve up to 2600 households per year.

7. DIRECT HEATING FOR DISTRICT

The scenario to use the moderate temperature of geofluid for application in direct heating is considered. This heat could be used by the local community within a 5 km radius of Wytch Farm site M. The direct heating option may also qualify for external investment via DECC’s Heat Networks Investment Project (HNIP). This government initiative aims to provide £320 million of capital support to increase the volume of heat networks being built, deliver carbon savings, and help create the conditions necessary for a self-sustaining heat network market to develop.

The following hypothesis has been assumed: the pinch point analysis determines the efficiency of the heat exchanger and the pinch point temperature difference is set at 5 °C. The flow rate of the geofluid is 290 kg/s at 65 °C and flow rate of the water in the direct heating loop is 50 kg/s at a maximum temperature of 60 °C. Since the entire flow rate of geofluid is not required for this application, it can be split into two streams, one to fuel the direct heating plant, while the other stream bypasses the plant. The geofluid is likely to suffer a pressure loss in the heat exchanger, which must be compensated by increasing the capacity of re-injection pumps. A pressure drop of 1 bar across the evaporator requires 80 kW of additional power supply to the re-injection pump to maintain a re-injection pressure of 90 bars³.

The return temperature is set to 25 °C. The power consumed by the circulating pump, only in the primary distribution network of pipes, is evaluated to be 19.6 kW. The maximum length of the main distribution pipe is 5 km, based on the consumers located in the proximity of Wytch Farm. Flowing through a main pipe of DN 200 mm (219.1 mm OD) with an insulating coating of 25.4 mm (1 inch) in thickness and thermal conductivity of 0.027 W/mK, the maximum temperature drop computed over a length of 5 km of pipeline is under 0.7°C for the supply line, and 0.3°C in the return line, with a maximum pressure drop of 4.06 bar from direct heating plant to the consumers. Using 14,263 kWh as the average heating requirement per household per annum (Energy Consumption in the UK, 2014), a total of 62 GWh per year of energy can be supplied, which can serve over 4350 households.

8. TIME-VARIANT PROPERTIES

Forecasting the performance of the reservoir is critical for evaluating the potential of harnessing the geothermal energy from the co-produced water. The water production data and the decline in the reservoir temperature have the biggest impact on harvesting thermal energy and without this data, the feasibility study will be uncertain. As per the operator of the field, the temperature decline of the reservoir is negligible with time and can be assumed constant. **Figure 14** shows the oil and water production from May 1991 to August 2041. Production data of Wytch Farm before December 2015 are available in the public domain. Data from January 2016 onwards is obtained from the operator’s numerical simulator model’s forecast and the operator’s “do-nothing” production strategy for the next 25 years, which implies no new wells will be drilled to boost production. The drop in the water production at the beginning of the year 2028 is part of the production strategy to shut off wells that have marginal oil production. A scenario could be considered where the wells are kept active, despite producing a limited amount of oil, if the power production project creates more revenue than the field’s OPEX. However, as the OPEX of the Wytch Farm oil field is considered to be confidential data by the operator, this scenario is not included in the study.

³ Personal communication with Rocco Altieri. 2016, Turboden and the Operator. 2016

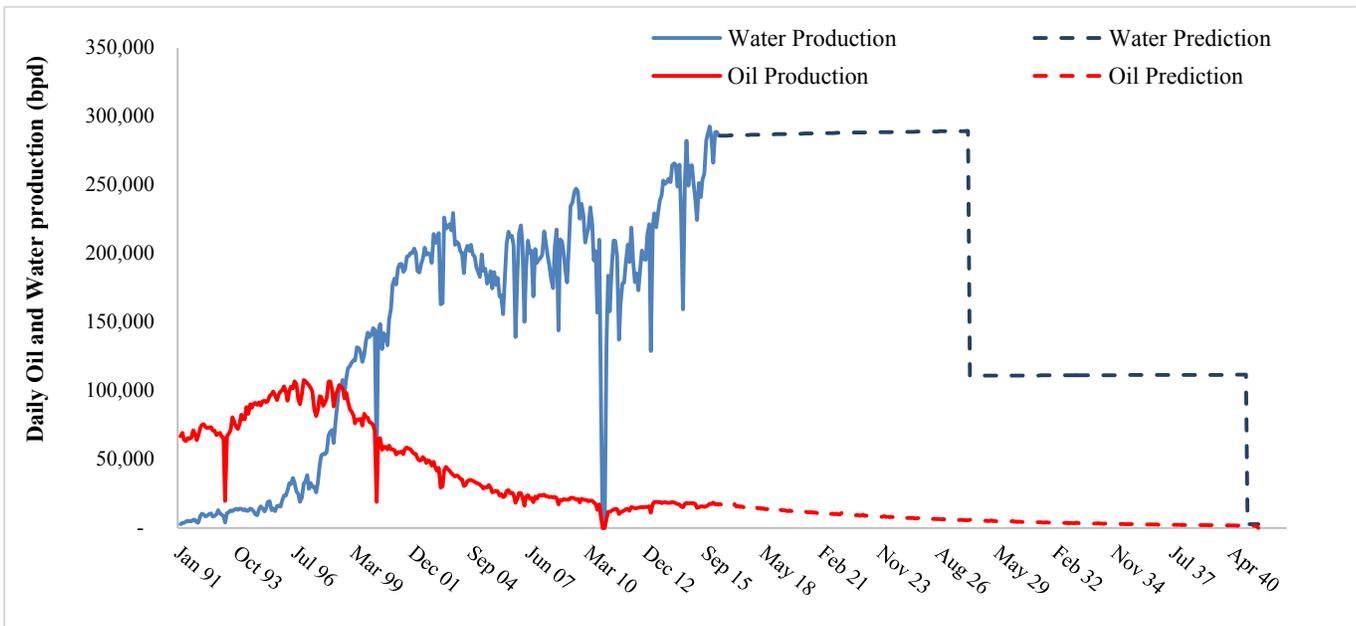


Figure 14: Oil and Water production over time for Wytch Farm Oil Field

9. ECONOMIC EVALUATION

A cost-benefit analysis is performed to assess the feasibility of power generation in Wytch Farm oil field. The generated electricity could be used to power the field production equipment and offset the need to purchase electricity from the local grid, thus reducing OPEX and pollution. Another profitable option could be to sell the generated electricity back to the local grid at a higher price. This is made possible by the UK government's Feed-In Tariff scheme (FiT), which is based on the electricity generated by renewable resources that can be used for internal consumption or sold back to the grid at a premium. There also exists the Renewable Obligation scheme (RO), which encourages electricity suppliers to supply power generated from renewable sources for a higher price (OFGEM, 2016). Unfortunately, as the business model of harnessing geothermal energy from a hydrocarbon development does not exist in the UK, it does not feature in any of the renewable schemes mentioned, but it is hoped that it will be considered for future renewable schemes by the UK government.

Compared to the conventional geothermal projects, the current infrastructure in the oil field has already removed the need for much of the front end investment required for an expensive drilling and fluids gathering systems. Consequently, only the fixed or capital cost of installing the ORC power plant and the cost of operating and maintaining (O&M) it are considered in the cash flow.

According to a report from the Geothermal Energy Association (2005), the average capital cost of a binary power plant is \$2360 /kWh (£1595 /kW in 2016 with 2 % inflation). The operation and maintenance cost of binary plants depend on the properties of the geofluid and the relevant legal regulations. A World Bank Group report (2006) studied O&M cost of 200 kW and 20 MW binary power plants. As the installed electric power of the ORC power plant will be between 1 and 2.3 MW, the O&M cost should be in the range of \$0.017 to 0.03 /kWh. Given that the smaller size of the plant has relatively higher O&M costs than larger size plants, the O&M costs of the ORC power plant in this study are assumed to be \$0.024 /kWh (\$0.03 /kWh or £0.16 /kWh in 2016 with 2 % inflation) (Liu *et al.*, 2014).

At present, the operator is purchasing electricity from the grid at £60 /MWh in 2016. The DECC survey of energy suppliers (2016) reports the price of purchasing electricity for large size consumers to be £91.5 /MWh. According to SKM (2011), having a FiT and RO Certificate will allow the supplier to sell electricity to the grid at £130 /MWh (£143.5 /MWh in 2016 with 2% inflation).

All the prices mentioned are increased annually at an inflation rate of 2%. The pre-tax, pre-interest discounted cash flow is calculated: discount rates of 8 %, 10 % and 12 % are considered for saving calculation.

The forecast of cumulative power generated on sites M and F of Wytch Farm are tabulated in **Table 9**, assuming downtime of the ORC power plant to be 10 % and the condenser consumes 25 kW of power. For economic evaluation, the construction and installation of the project is carried out in 2017, and the ORC is brought into operation in January 2018. As the water production declines at the beginning of 2028, economic evaluation is carried out for two different time periods; one till the end of 2027, and the other till the end of 2040 (the end of the production license of the Wytch Farm oil field).

Table 9: Cumulative power generated at sites M and F

From Jan 2018- Dec 2040			From Jan 2018- Dec 2027		
Location	Geofluid Temperature (°C)	Cumulative Power Generated (GWh)	Location	Geofluid Temperature (°C)	Cumulative Power Generated (GWh)
Site M	75	288.87	Site M	75	181.23
	65	185.22		65	115.50
Site F	75	180.03	Site F	75	111.12
	65	116.27		65	73.16

Table 10: Economic evaluation- Site M

Parameters	Value			Parameters	Value		
Geofluid Temperature, °C	75			Geofluid Temperature, °C	65		
Installed Power, MW	2.4			Installed Power, MW	1.6		
CAPEX, million £	3.90			CAPEX, million £	2.55		
O&M, million £	4.78			O&M, million £	3.00		
Lifetime, years	23			Lifetime, years	23		
Electricity Price (2016), pence/kWh	6	9.15	14.35	Electricity Price, pence/kWh	6	9.15	14.35
NPV 8%, million £	3.21	7.96	15.80	NPV 8%, million £	2.04	5.08	10.10
NPV 10%, million £	2.29	6.29	12.89	NPV 10%, million £	1.44	4.00	8.22
NPV 12%, million £	1.59	5.00	10.63	NPV 12%, million £	0.99	3.17	6.77
End operations in Dec 2027				End operations in Dec 2027			
NPV 10%, million £	1.17	4.36	9.63	NPV 10%, million £	0.72	2.75	6.10

Table 11: Economic evaluation- Site F

Parameters	Value			Parameters	Value		
Geofluid Temperature, °C	75			Geofluid Temperature, °C	65		
Installed Power, MW	1.5			Installed Power, MW	1.0		
CAPEX, million £	2.40			CAPEX, million £	1.59		
O&M, million £	2.92			O&M, million £	1.89		
Lifetime, years	23			Lifetime, years	23		
Electricity Price, pence/kWh	6	9.15	14.35	Electricity Price, pence/kWh	6	9.15	14.35
NPV 8%, million £	2.04	4.98	9.84	NPV 8%, million £	1.29	3.21	6.37
NPV 10%, million £	1.46	3.93	8.02	NPV 10%, million £	0.92	2.53	5.19
NPV 12%, million £	1.02	3.12	6.60	NPV 12%, million £	0.64	2.01	4.28
End operations in Dec 2027				End operations in Dec 2027			
NPV 10%, million £	0.74	2.69	5.92	NPV 10%, million £	0.47	1.76	3.88

The results in **Table 10** and **Table 11** show that production of electricity from low-temperature geothermal resources using ORC system is economically feasible at both sites at the Wytch Farm oil field.

A pressure drop of 2 bars is expected across the evaporator, which must be compensated by supplying 160 kW of additional power to the re-injection pumps to maintain re-injection pressure of geofluid at 90 bars. Economic evaluation with this additional parasitic load on the ORC is given in **Table 12**.

Table 12: Economic evaluation with increased parasitic load

Site M		Site F	
Parameters	Value	Parameters	Value
Geofluid Temperature, °C	65	Geofluid Temperature, °C	65
Lifetime, years	23	Lifetime, years	23
Cumulative Power Generated, GWh	156.18	Cumulative Power Generated, GWh	87.23
Electricity Price, pence/kWh	14.35	Electricity Price, pence/kWh	14.35
NPV 10%, million £	6.83	NPV 10%, million £	3.80

10. CONCLUSIONS

This study was aimed at demonstrating the potential of UK's mature hydrocarbon fields to provide geothermal energy from co-produced water. ORC systems have been modelled with the heat supplied from co-produced water from wells in the Wytch Farm oil field. Simulations show that even with low-temperature brines this project can be technically feasible. Site M has a potential of generating power of over 1.4 MW, and site F up to 850 kW, without interfering with the oil production processes.

It has been shown that the optimal cycle configuration is strongly dependent on the heat source as well as the heat sink. Thermodynamic characteristics and performances of different organic fluids were analysed for the given input conditions of Wytch Farm, and Isobutane was found to be most suitable. The optimised arrangement and design of the evaporator and condenser are discussed to reduce project's CAPEX, reduce the footprint of the ORC plant and to avoid modification of the current piping layout. The CHP and direct heating for district scenarios are also potentially viable options to utilise the thermal energy extracted from the geofluid.

The economic study of harnessing geothermal energy is independent of the oil production process. The net present value (NPV) created could compensate for the substantial expenses for purchasing electricity for the production facility. The possibility of generating additional revenue and extending the life of the field by utilising waste heat of the co-produced water should be an attractive proposal for all oil and gas operators.

Waste heat recovery from ageing onshore oil fields can be technologically and economically feasible. This study reports, with geofluid temperature of 65 °C, 10 % discount rate and the renewable scheme provided by the UK government, a maximum cumulative power of 185 GWh in 23 years can generate an NPV of £8.22 million at site M; whereas 116 GWh in 23 years at site F can generate £5.19 million.

11. RECOMMENDATIONS FOR FUTURE WORK

- For the practical application of this project, a detailed study on designing and sizing the evaporator and condenser needs to be carried out. For the evaporator, the arrangement of the clamp-on heat exchanger should be dismantlable to allow for the inspection of pipelines. Selection of materials and the appropriate design needs to be investigated to evaluate the maximum heat transfer area and maximum efficiency of the heat exchanger. The condenser's footprint and the power rating should be optimised for maximum output and lower CAPEX and OPEX.
- The pressure and temperature drop across the heat exchanger should be modelled dynamically, taking into consideration the fluid flow regimes (laminar or turbulent), as this will have a prominent effect on the heat transfer and the pressure loss. The temperature loss will negatively impact the oil separation process and the loss of pressure would have to be compensated for re-injecting it back into the reservoir.
- Clarity on the incentives provided by the government is required to accurately understand the value of the project and create a business model to attract oil and gas operators.
- Detailed CAPEX and OPEX values of the more technologically advanced ORC power plants of today would improve the cost-benefit analysis.

NOMENCLATURE

Roman

W	Work done (kW or MW)
Q	Heat transferred (MW)
C_p	Specific heat capacity ($\text{kJ kg}^{-1}\text{K}^{-1}$)
m	Mass flow rate (kg s^{-1})
T	Temperature ($^{\circ}\text{C}$ or K)
h	Enthalpy (kJ kg^{-1})
s	Entropy ($\text{kJ kg}^{-1}\text{ }^{\circ}\text{C}^{-1}$)
TIP	Turbine inlet pressure (MPa)
TOP	Turbine outlet pressure (MPa)
U	Overall heat transfer coefficient ($\text{W m}^{-2}\text{ K}^{-1}$)
A	Heat transfer area (m^2)

Greek

η	Efficiency
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Subscript

G	Geofluid
cw	Cooling water
wf	Working fluid
T	Turbine
P	Feed pump
pp	Pinch point
C	Condenser
H	Evaporator
th	thermal
crit	Critical point
s	Saturation point

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