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Geothermal energy: Power plant technology and direct heat applications

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A R T I C L E I N F O

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A B S T R A C T

The transition from current fossil-fuel energy system towards a sustainable one-based requires renewable energy technology. Although geothermal energy presents its own particular challenges in comparison with other renewable energy technologies, geothermal energy has showed significant potential to reduce environmental impact and greenhouse gas emissions from electricity production. Advantages of geothermal energy are not only the generation of electricity in different plant configurations but also the direct application of heat in industry and household uses regardless of meteorological conditions. In this study, a research review is carried out on the aspect of geothermal energy development, assessing power plant technology and direct heat applications. Five power plant configurations are studied: single-flash, double-flash, dry-steam, binary and advanced. The thermodynamic aspects are addressed in order to consider them for future geothermal power plant analysis. Furthermore, the most common direct uses of geothermal heat are discussed. Results illustrate that Binary – Organic Ranking Cycle Power Plants might play a vital role in the exploitation of low temperature geothermal resources. Furthermore, it is identified a need for research in hybrid geothermal-solar-biomass configurations for poly-generation purposes. These configurations increase the energy output, increasing the thermal efficiency and increasing the life of the geothermal reservoir. Similarly, direct applications of geothermal heat present good opportunities for increasing the revenue of a geothermal project. Depending of the geographic zone, cascade configurations contributes to maximise the use of geothermal resources. Future research reviews should consider the financial, economic and policy aspects of geothermal developments along with the geology, geophysics, geochemistry, drilling, reservoir engineering and environmental aspects. The main goal of addressing these topics is to provide the state-of-the-art of geothermal development for developers, policy makers, researchers and communities interested in geothermal energy.

1. Introduction

Worldwide, the transition from current fossil-fuel-dependent energy system towards a sustainable one based primarily on renewable resources requires proofed green-technology evidence-based decision-making [1]. Technology transfer and development of new technologies are vital for sustainable development and climate change mitigation [2]. Geothermal energy has showed significant potential as renewable energy resource because of its low environmental impact, low greenhouse gas emissions and technology feasible [3,4]. Moreover, geothermal resources can be exploited regardless of meteorological conditions [5,6].

Geothermal energy is an indigenous environmentally benign source of renewable heat contained in the Earth's interior [7,8] commonly associated with volcanic and tectonic activity [9]. This heat is primarily stored in hot rocks at high depths from the earth's surface [10,11], and

Abbreviations: FAM, Financial Analysis model; SRAM, Sensitivity and Risk Analysis Models; NPV, Net Present Value; UNFCCC, United Nations Framework Convention on Climate Change; IGA, International Geothermal Association; WB, World Bank; MW, Megawatt; kW, Kilowatt; kWh, Kilowatt-hour; kg/s, Kilogram per second; kg/h, Kilogram per hour; °C, Centigrade degree; %, Percentage; bar, Bar; yr, Year; kPa, Kilopascal; USD, United State Dollars; Mtoe, Millions tons of oil equivalent; GHG, Greenhouse gas emissions; GJ, Gigajoules; tCO2, Tonnes of carbon dioxide; CH4, Methane; N2O, Nitrous oxide; Ctv, Cents of dollar; EGS, Enhanced geothermal systems; T&D, Transmission and distribution

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it is also found in complex structures of hydrothermal reservoirs at high temperatures [12]. Many authors agree that geothermal energy is a renewable energy resource [8,13–17]. However, the speed of exploitation of geothermal reservoirs is usually faster than the replacement of its heat on depending on geologic time scale, geothermal applications and methods of heat reinjection [18].

Overall, brine has been characterised as a heat medium which can be use either for fluid and vapour or steam. Furthermore, scientists in geochemistry and thermo-fluids have classified geothermal fluids in two types: steam (vapour-dominated systems) and mineral-laden hot water also called 'brine' [19]. These fluids transport the geothermal heat stored underground into the surface, for electricity generation and non-electricity (direct uses) purposes, through wells drilled into the localised high-temperature geothermal reservoir [20]. Depending on the features of the reservoir, depths of production wells range from 300 m to more than 3000 m where thermo-fluids are naturally contained in porous hot rock of the hydrothermal and geo-pressured geothermal reservoirs [18].

Then, free flow or pumping, depending on the reservoir characteristics, is applied to extract the hot native fluids (brine). In order to optimally use the valuable heat, different management techniques of geothermal fluids (including surface hot water - brine) uses are needed [9,21,22]. Finally, different configurations of the power conversion system convert the geothermal heat flowinto electricity [7,23–26] or other direct heating purposes [20,26–31]. In this regard, the main focus of this study is to review the power conversion and direct use configurations to harvest energy from geothermal energy resources along with their economics implications.

Currently, the total installed capacity worldwide of geothermal power plants is 12.729 MW and forecasted to be 21.443 MW by 2020. Geothermal power plant is classically defined as binary (14%), back pressure (1%), single flash (41%), double flash (19%), triple flash (2%) and dry steam plant (23%) [32]. Similarly, the global installed thermal capacity is 70.885 MWT distributed in nine direct-use geothermal energy applications [33].

The Geothermal handbook developed by the Energy Sector Management Assistance Program (ESMAP), The World Bank Group (WBG), establishes eight stages of a geothermal development project, Fig. 1 [34]. Particularly, this work explores the up-to-date geothermal power plant technologies and direct heat applications, discussing the need for researching and developing new geothermal configurations. Some of the new configurations discussed are geothermal-other-energy-source hybrid systems and cascade configurations to maximise the use of the geofluid. Next works should present the necessary policy development, financial aspects and economic impact of geothermal projects, along with the geo-scientific assessment of geothermal resources.

2. Geothermal power plant technology

Based on the availability of exploitable hydrothermal resources, a large number of technologies and power plant configurations have been studied [14,26,35,36]. In general, researchers agree that five power configurations have been developed for geothermal plants: 1. dry steam, 2. single flash, 3. double flash, 4. binary (Organic Rankine - Kalina Cycle), and 5. advanced geothermal energy conversion systems (hybrid single-double-flash systems - triple flash, hybrid flash-binary systems, hybrid fossil-geothermal systems, hybrid other-renewable heat source-geothermal systems, and hybrid back pressure system) [24,37,38]. However, Valdimarsson [36] suggests that geothermal power plants can be classified into two groups, steam cycles for higher well enthalpies and binary cycles for lower enthalpies. This paper assesses the five configurations mentioned before.

2.1. Single-flash steam power plants

The single-flash steam power plant is a relatively simple geothermal energy–electricity conversion configuration when geothermal production wells are producing a mixture of steam and brine [14]. A cylindrical cyclone pressure vessel separates the mixture into two distinct phases, steam and liquid, due to their naturally large density difference [18,36,39]. DiPippo [14] and Valdimarsson [36] indicate that the term 'single' indicates a single flashing process in the geo-fluid (transition from pressurised liquid to liquid-vapour mixture), which is produced as a result of lowering the geothermal fluid pressure and occurs either in the reservoir, production wells or cyclone inlet. Five to six production wells and two to three re-injection wells distributed across the geothermal reservoir are typically required for a 30 MW single-flash geothermal power plant [14]. Piping systems are additionally used to gather and transport the mixture from production wells to the powerhouse, although the steam's pressure drop as a result of pipe friction is a critical concern in these gathering systems [40]. Due to the complexity and reliability needed to analytically predict the pressure loss, empirical correlations are required taking into account pipe diameter, length, piping configurations, density and mass flow rate of steam. These variables not only affect the efficiency of the energy conversion system, but also the cost of the power plant [14,40,41]. Once the steam and liquid are separated, the obtained steam (generally 99.995% dry) drives an assembled turbine-generator producing electricity [14]. Braun and McCluer [18] explain that a single-flash process is selected if the temperature of the geothermal fluid is greater than 260 °C, reaching a capacity factor of 95–100%.

Fig. 1 illustrates a schematic diagram of the energy conversion system of the single-flash process. The single-flash steam power process starts in station 1, where the geo-fluid enters the production well at the source inlet temperature. There is a pressure drop between station 1 and 2 producing that the fluid initiates to boil (mixture steam-liquid) before entering the separator in station 2. The separator divides the mixture fluid into steam (station 5) and brine (station 3) which is re-injected in station 4.

The steam, in station 5, enters the turbine which is coupled to a generator to produce electricity by induced movement from the turbine. Steam expansion is then produced through the turbine down to station 6 at condenser pressure. An air cooler condenser may be used to allow cooling air at station c1 and leaving at station c2 [14,36]. DiPippo [14], Yildirim [43] and Zarrouk and Moon [40] identify that certain plant equipment is necessary to run the single-flash steam geothermal power plant, as can be seen in Fig. 2. This power plant configuration does not require large amount of fresh water for cooling [14,44,45]. A portion of the condensed steam is used in the cooling tower to obtain cooling water, especially for dry regions with a lack of fresh water [40].

The conversion process of a single-flash steam geothermal power plant is best visualised using a thermodynamic state diagram, Fig. 3. Çengel and Boles [46] state that the analysis of the process using that diagram is conducted taking into account two fundamental thermodynamic principles, the principle of energy conversion and the principle of mass conversion. In Fig. 3, the T-s state diagram illustrates the

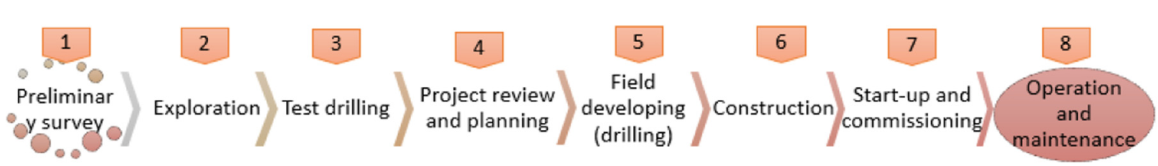
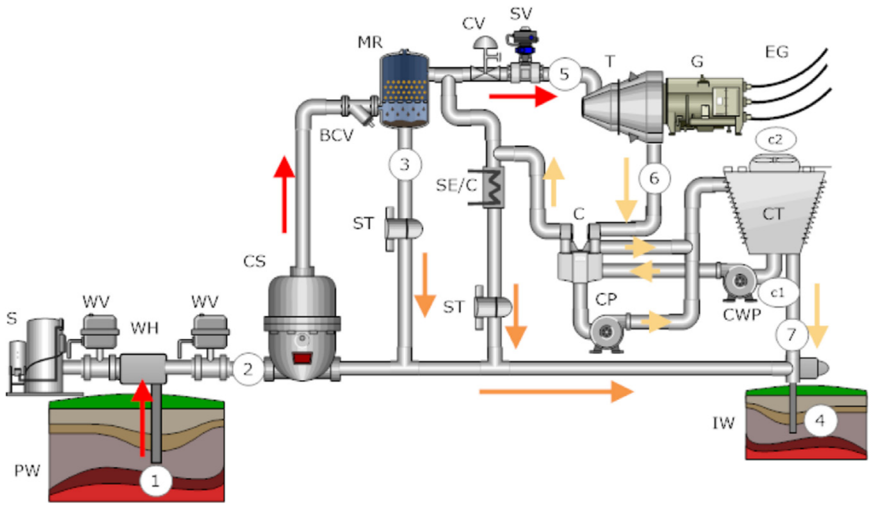


Fig. 1. Schematic representation of the eight stages of geothermal development by ESMAP-WBG [34].



PW	Production well	BCV	Ball check valve	SV	Stop valve
S	Silencer	MR	Moisture remover	SE	Steam jet ejectors
WV	Well valves	ST	Steam tramp	C	Condenser
CS	Cyclone separator	CV	Control valve	CP	Condensate pump
IW	Injection well	EG	Electric grid	CWP	Condensed water pump
G	Generator	T	Turbine	WH	Wellhead

Fig. 2. Single flash geothermal power cycle [14,36,42].

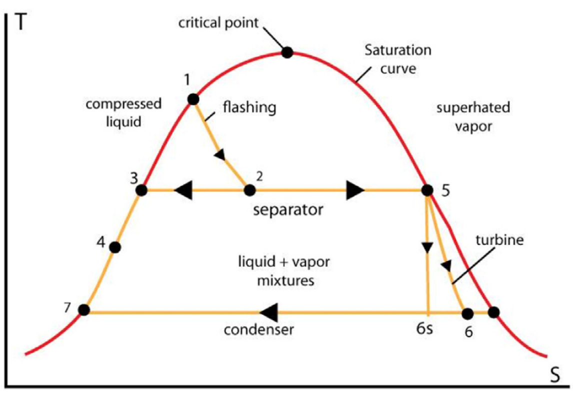


Fig. 3. General thermodynamic diagram, temperature-entropy (T-s), of a single flash cycle [14].

process for a single-flash power plant. At state 1, close to saturation curve, *the flashing process* takes place when the geothermal fluid under pressure initiates the process. In this state, the change in the kinetic or potential energy is neglected, and the enthalpy (h) is modelled as constant, $h_1 = h_{2,}$ Eq. (1), Table 1. *The separation process* takes place at state 2 after the flashing process and is modelled at constant pressure. In this state, a mixture of liquid plus vapour is presented determining the quality of the mixture. This quality is given by the dryness fraction (x_2) shown in Eq. (2). As a result, the steam mass fraction is given and represents the amount of steam going to the turbine. Then, *the turbine expansion process* produces work (w_1) between states 4 and 5, given by Eq. (3). In the thermal fluid entering and leaving the turbine, no heat losses are assumed and changes in kinetic and potential energy are neglected. The ideal process is from 4 to 5 s, thus, the isentropic turbine efficiency is defined by, η_t, the ratio of the actual work to the isentropic work as is illustrated in Eq. (4). The gross mechanical power ($\dot{W}_t$) developed by the turbine is represented by Eq. (5) and the electrical power ($\dot{W}_e$) is given by Eq. (6), which is equal to the generator efficiency (η_g) multiplied by the turbine's mechanical power. Finally, the condensing and cooling processes take place between state 5 and 6. The required flow rate of cooling water is given by Eq. (7) [7,36].

The Second Law of Thermodynamics is assessed in order to determine the entire plant performance [40]. This law compares the actual power output produced at the end of the single-flash steam process to the maximum theoretical power that the geothermal fluid could produce [14]. The specific exergy requires to be defined and modelled. The Second Law of Thermodynamics defines exergy as the energy that is available to be used; therefore, it is the potential to convert energy into work [40,44]. Exergy (e), of a geothermal fluid that has a temperature (T) and a pressure (P), under an ambient temperature (To) and ambient pressure (Po), is given by Eq. (8), Table 2. The multiplication of exergy by the total geothermal mass flow rate will result in the maximum theoretical thermodynamic power, also called the exergetic power (Eq. (9)). Lastly, the entire power plant efficiency is given by the ratio of the net power of the single-flash steam power plant to the exergetic power (Eq. (10)) [14,46].

Environmental impacts are potentially identified in specific places of a single-flash geothermal power plant at normal operation [14]. The main places where emission may occur are: at the wellhead (provides structural interface between wells and production equipment); at the silencers and mufflers; at the steam tramps; at the pipeline drains; at the ejector vents; and at the cooling tower [14,43,45]. Overall, DiPippo [39] identified that steam from geothermal reservoirs may contains a mixture of non-condensable gases, for example, carbon dioxide (CO_2), methane (CH_4) and hydrogen sulphide (H_2S). Commonly, these gases are isolated and treated before release to the atmosphere [47]. DiPippo [14] also clarifies that although CO_2 is released from a single-flash power plant, it constitutes an insignificant greenhouse gas source (0.06 kg/kWh) in comparison with a natural-gas-fired power plant (0.59 kg/kWh) or a coal-fired power plant (1.13 kg/kWh).

2.2. Double flash steam power plants

The double-flash steam geothermal power plant has been also developed for an energy–electricity conversion configuration when geothermal production wells are producing a mixture of steam and liquid [48]. DiPippo [14], pp. 112, indicates that 'the double-flash power plant is an improvement on the single-flash design' reaching up to '25% more power output for the same geothermal fluid conditions'. He also explains that although these kinds of plants are more expensive, more complex and require more operation and maintenance, the power

Table 1
Equations used for thermodynamic state analysis [14].

State	Main characteristics	Eqs.	
Flashing process	Constant enthalpy	$h_1 = h_2$	(1)
Separation process	Constant pressure; Mixture of liquid plus vapour	$x_2 = \frac{h_2 - h_3}{h_4 - h_3}$	(2)
Turbine expansion process	Constant entropy	$w_1 = h_4 - h_5$	(3)
		$\eta_t = \frac{h_4 - h_5}{h_4 - h_{5s}}$	(4)
		$\dot{W}_t = \dot{m}_s w_t$	(5)
		$\dot{W}_e = \eta_g \dot{W}_t$	(6)
Condensing process		$\dot{m}_{cw} = x_2 \dot{m}_{total} \frac{h_5 - h_6}{\bar{c}\Delta T}$	(7)

Table 2
Exergy equations and power plant efficiency [14,46].

Thermodynamic dimension	Eqs.	
Exergy	$e = h(T, P) - h(To, Po) - To[s(T, P) - s(To, Po)]$	(8)
Exergetic power	$\dot{E} = \dot{m}_{total} e$	(9)
Entire power plant efficiency	$\eta_u = \frac{\dot{W}_{net}}{\dot{E}} = \frac{\dot{W}_e}{\dot{E}}$	(10)

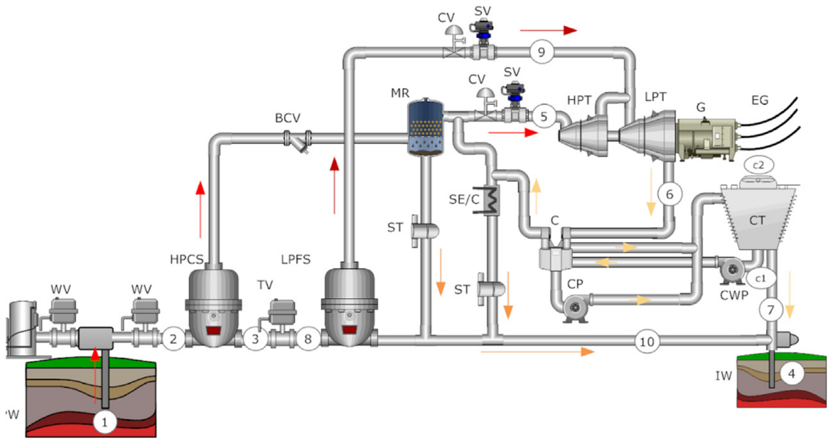
output justifies their installation. The addition of a secondary flash process is a significant improvement regarding the more efficient utilisation of the geothermal resource [39]. After the first pressure drop in the primary separator (single-flash process), a second pressure drop is applied in a second flash process (second separator) generating additional steam from the separated liquid leaving the first separator [14,39]. Then, lower-pressure steam is produced, which is admitted to the coupled turbine-generator at an appropriate turbine stage generating extra power [39] or to a different turbine depending on the configuration [43]. Chamorro, Mondéjar [45] indicate that this optimisation maximises the entire exergy efficiency of the double-flash power plant. The main component, therefore, is the geothermal steam-water separator. A complete design overview of horizontal separator and vertical cyclone separator for flashed-steam geothermal power plants has been conducted by Zarrouk and Purnanto [19]. Although the exergy efficiency is increased and is calculated differently compared with single-flash, other assumptions made in single-flash plants, such as calculations of turbine work, quality of the mixture and the entire power plant efficiency, are valid for double-flash designs [14,43,45].

In comparison with the single-flash system (Fig. 2), the main difference in the double-flash configuration (Fig. 4) is the addition of a low-pressure separator and the dual-admission turbine. The low-pressure steam is admitted to the turbine at an appropriate stage in order to produce a smooth combination with the expanded high-pressure steam [14]. Fig. 4 illustrates the energy conversion process of a double-flash steam geothermal power plant. The double-flash steam power process starts in station 2, where the geo-fluid enters the production well at the source inlet temperature. There is a pressure drop between station 1 and 2 producing that the fluid starts to boil (mixture steam-liquid) just before entering the separator in station 2. Then, the first flashed-steam process occurs. The separator divides the mixture fluid first into a high-pressure steam (station 5) and brine (station 3) which is throttled down to a lower pressure level at station 8. As a result, the second flashed-steam process takes place. The low-pressure separator receives the brine and by a second pressure drop a new mixture (steam-brine) is produced. The second new low pressure steam is transported to the turbine at the second steam admission at station 9. The first high pressure steam, at station 5, firstly enters the turbine at the primary steam admission. The dual-admission turbine is coupled to a generator to produce electricity by induced movement. Steam expansion is then produced through the turbine down to station 6 at condenser pressure [14,36]. Additionally, Valdimarsson [36] argues that the design process of the turbine requires having the same pressure difference on the first stage-admission of the turbine and the same pressure difference between the high and low separators. Therefore, a higher mass flow is required in the lower pressure stage than in the high-pressure stage. An air cooler condenser may be used introducing cooling air at station c1 and leaving at station c2 to condense the remaining hot fluids at station 6. Finally, the remaining brine from the second flashed process at station 10, along with the condensed fluid at station 7 are re-injected at station 4.

The thermodynamics of the energy-electricity conversion process of the double-flash geothermal power plant is better explained by using the temperature-entropy (T-s) diagram (Fig. 5). The striking characteristic of this process is the two flash processes taking place in 1–2 and 3–6 states, and these *double-flash process* are analysed individually as a single-flash process [14,36]. Eqs. (11)–(14), in Table 3 are used to determine the fractional amount of produced steam in the mixtures leaving the separators at each flashed process (x_2 in 1–2 state and x_6 in 3–6 state – the separation process).

In addition, four equations are implemented to determine the mass flow rates of the steam (state 2) and brine (state 6) produced in the separation processes at the high and low pressure stages respectively. The expressions are Eqs. (15)–(18). The produced steam mass flow rate at high pressure ($\dot{m}_{hps}$, at state 5) is given by Eq. (15) and at low pressure ($\dot{m}_{lps}$, at state 8) is given by Eq. (17), while the produced brine mass flow rate at high pressure ($\dot{m}_{hpb}$, at state 3) and low pressure ($\dot{m}_{lpb}$, at state 7) are given by Eqs. (16) and (18) respectively. At state 9, the two steams (high and low pressured) come together to the low-pressure turbine stage. Four values will be calculated by using Eqs. (15)–(18): the power produced in the turbine; the heat rejected in the condenser, and in the cooling water, and the disposed waste liquid.

Two *turbine expansion processes* can be described in this system. The *first turbine expansion process* produces work (w_{hpt}) between states 4 and 5, given by Eq. (19), and the *second turbine expansion process* produces work (w_{lpt}) between states 9 and 10, given by Eq. (26). Consequently, two isentropic turbine efficiencies are defined for the high-pressure process (η_{hpt}), Eq. (20), and low pressure process (η_{lpt}), Eq. (30). The power generated in the first turbine stage at high pressure is given by



PW	Production well	SV	Stop valve	MR	Moisture remover
S	Silencer	SE	Steam jet ejectors	ST	Steam tramp
WV	Well valves	C	Condenser	CV	Control valve
BCV	Ball check valve	CP	Condensate pump	TV	Throttle valve
IW	Injection well	HPT	High pressure turbine	G	Generator
CWP	Condensed water pump	LPT	Low pressure turbine	EG	Electric grid
HPCS	High pressure cyclone separator	LPFS	Low pressure flash separator	WH	Wellhead

Fig. 4. Double-flash geothermal power plant with a dual admission turbine [14,36,42,45].

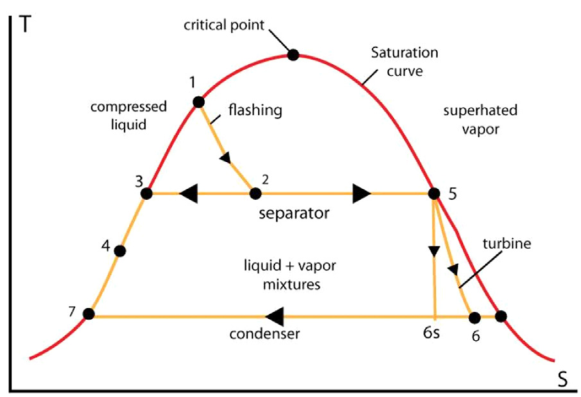


Fig. 5. Temperature – entropy process diagram for double-flash power plant with a dual admission turbine [14].

($\dot{W}_{hpt}$), Eq. (21), while the power generated in the second stage at low pressure is given by ($\dot{W}_{lpt}$), Eq. (27). The total power generated in the turbine ($\dot{W}_{total}$) is given by the sum of the power produced in each turbine stage, Eq. (31). Finally, the electrical power ($\dot{W}_{e,gross}$), Eq. (32), is affected by the generator efficiency (η_g). Similarly, the exergy of the incoming geothermal fluid, the entire power plant efficiency, the applied equipment and the environmental impacts are analysed as in the single-flash process DiPippo [39], and Valdimarsson [36].

2.3. *Dry-steam power plants*

Geothermal dry-steam reservoirs have been identified in many places worldwide, the two largest dry-steam reservoirs in Larderello, Italy, and in The Geysers, USA, while restricted dry-steam reservoirs have been recognized in Wairakei, New Zealand, Matsukawa, Japan, Kamojang, Indonesia, and Cove Fort, Utha, USA [14,39,40,47]. Zarrouk and Moon [40] explain that flashed generation systems are likely to convert into dry-steam in case the geothermal reservoirs dries. A study conducted by Chamorro, Mondéjar [45] reports that dry-steam geothermal power plants are the most efficient among the high enthalpy technology configurations. These configurations use vapour-dominant medium at high temperatures from hydrothermal reservoirs [39], and production wells directly deliver steam to the coupled turbine-generator to produce electricity [18].

DiPippo [39] stated that dry-steam plants convert 50–70% of the available work (exergy) of the geothermal heat flow into electricity. DiPippo [41] also demonstrated that even though the dry-steam plant is a simple concept in comparison with steam flashed process, it requires small centrifugal cyclone separators to eliminate particulate matter (rock bits, dust), drain pots to remove condensate from steam pipes, and a final moisture removal separator to ensure high quality steam in the turbine. DiPippo [14] additionally explains that a venturi meter is required to accurately measure the steam flow rate provided to the turbine.

Fig. 6 illustrates the energy conversion system of the dry-steam power plant process. The dry steam (geothermal heat flow) obtaining from production wells completes the power cycle reaching the turbine in the same way as single-flash steam power plants [14]. A particular characteristic is that the impulse-reaction blading turbine performs as a single pressure unit either with single-flow or double-flow for smaller or larger units respectively. As can be seen, Fig. 6 is very similar to Fig. 1 (single-flash) with a particulate remover instead of a cyclone separator.

The dry-steam process is shown in the T-s thermodynamic state diagram in Fig. 7. The process starts at state 1, where production wells provide saturated steam or slightly superheated steam. Between states 1 and 2, *the turbine expansion process* takes places, and then *the cooling process* is reached in process 2–3 releasing heat through the condenser. The thermodynamic analysis is the same as for the single-flash geothermal power plant process [14,45]; the Eq.s for analysing dry-steam power plants are restated in Table 4. DiPippo [14] also reports that the environmental impact is lower than flashed power plants since only steam is used in the process producing no mineral-laden brine to be disposed.

2.4. *Binary – Organic Rankine cycle and Kalina cycle power plants*

The binary geothermal power plant (B-GPP) uses a secondary separated system to produce electricity by which a working fluid is preheated and evaporated through transferring heat by making contact with the geothermal heat flow [18]. DiPippo [39] previously indicated that binary configurations are particularly appropriate for low temperature geothermal resources (120–150 °C), and that the avoidance of

Table 3
Thermodynamic equations for double-flash geothermal power plants [14,36].

State	Main characteristics	Equations	
Flashing process 1	Constant enthalpy	$h_1 = h_2$	(11)
Separation process 1	Constant pressure Mixture of liquid plus vapour	$x_2 = \frac{h_2 - h_3}{h_4 - h_3}$	(12)
Flashing process 2	Constant enthalpy	$h_3 = h_6$	(13)
Separation process 2	Constant pressure Mixture of liquid plus vapour	$x_6 = \frac{h_3 - h_7}{h_8 - h_7}$	(14)
Produced steam mass flow rate	High pressure	$\dot{m}_{hps} = x_2 \dot{m}_{total} = \dot{m}_4 = \dot{m}_5$	(15)
Produced brine mass flow rate	High pressure	$\dot{m}_{hpb} = (1 - x_2)\dot{m}_{total} = \dot{m}_3 = \dot{m}_6$	(16)
Produced steam mass flow rate	Low pressure	$\dot{m}_{lps} = (1 - x_2)x_6\dot{m}_{total} = \dot{m}_8$	(17)
Produced brine mass flow rate	Low pressure	$\dot{m}_{lpb} = (1 - x_2)(1 - x_6)\dot{m}_{total} = \dot{m}_7$	(18)
Turbine expansion process	High pressure stage (Eqs. 22 and 23 are the Baumann rule)	$w_{hpt} = h_4 - h_5$	(19)
		$\eta_{hpt} = \frac{h_4 - h_5}{h_4 - h_{5s}}$	(20)
		$\dot{W}_{hpt} = \dot{m}_{hps} w_{hpt} = x_2 \dot{m}_{total} w_{hpt}$	(21)
		$h_5 = \frac{h_4 - A\left[1 - \frac{h_7}{h_8 - h_7}\right]}{1 + \frac{A}{h_8 - h_7}}$	(22)
		$A = 0.425(h_4 - h_{5s})$	(23)
Turbine expansion process	Low pressure stage	$\dot{m}_5 h_5 + \dot{m}_8 h_8 = (\dot{m}_5 + \dot{m}_8) h_9$	(24)
		$h_9 = \frac{x_2 h_5 + (1 - x_2)x_6 h_8}{x_2 + (1 - x_2)x_6}$	(25)
		$w_{lpt} = h_9 - h_{10}$	(26)
		$\dot{W}_{lpt} = \dot{m}_9(h_9 - h_{10})$	(27)
		$h_{10} = \frac{h_9 - A\left[x_9 - \frac{h_{11}}{h_{12} - h_{11}}\right]}{1 + \frac{A}{h_{12} - h_{11}}}$	(28)
		$A = 0.425(h_9 - h_{10s})$	(29)
		$\eta_{lpt} = \frac{h_9 - h_{10}}{h_9 - h_{10s}}$	(30)
		$\dot{W}_{total} = \dot{W}_{hpt} + \dot{W}_{lpt}$	(31)
		$\dot{W}_{e,\ gross} = \eta_g \dot{W}_{total}$	(32)

contact between the geo-fluid and power production equipment may prevent scaling and corrosion effects. However, Dickson and Fanelli [49] emphasised that binary system designs can utilise a temperature range between 85 and 170 °C, stating that upper limited temperatures depend on working fluid thermal stability and lower limited temperatures on technical, financial and economic aspects. The secondary fluid (working fluid) in the binary system operates under a conventional Ranking cycle [50], and as the used working fluid is organic, the binary cycle is also known as the Organic Ranking Cycle (ORC).

The secondary cycle allows binary power plants to be versatile. Yari [44] exemplifies this versatility identifying various types of binary power plants configurations such as B-GPP using ORC with internal heat exchanger (IHE), B-GPP with regenerative ORC and B-GPP with regenerative ORC using IHE. Another technical variation in B-GPP was patented by Kalina Al in 1982; the Kalina cycle uses the thermodynamic properties of ammonia–water mixture as a working fluid allowing different binary configurations [51,52]. The remarkable feature of the Kalina cycle is the efficiency improvement in geothermal power cycles achieving between 30% and 40% more thermal efficiency than typical B-GPPs [50].

Fig. 8 exemplifies the energy conversion system of a basic binary geothermal power plant, which applies a closed loop of a thermodynamic Rankine cycle. Highlighting the main characteristics of the process, pumps (P) are used to extract the geothermal heat flow through the production wells (PW), and pass through different components of the primary cycle. The geo-fluid commonly undergoes sand removers (SR) to prevent scouring and erosion in piping and tubes. The fluid continues its flow through the evaporator (E) and preheater (PH), and finally an injection pump (IP) reinjects the geothermal heat flow into the reservoir by the injection wells (IW).

On the secondary cycle, the working fluid encompasses two heating-boiling steps: firstly, the working fluid reaches its boiling point in the PH, and secondly, emerges as a saturated vapour after making contact (a heat exchange process) with the E. Then, the resulting saturated vapour of the working fluid expands in the turbine, condenses and returns to the evaporator, closing the loop system and starting the process again [14,36,39,50,52]. DiPippo [14] explains that the geothermal heat flow is kept above the flash pressure point in order to avoid the breakout of steam and calcite scaling in the piping system. This binary-type energy conversion configuration permits the exploitation of low-temperature geothermal resources under many different technical variations depending on technical features in order to reach remarkably high plant efficiencies [53].

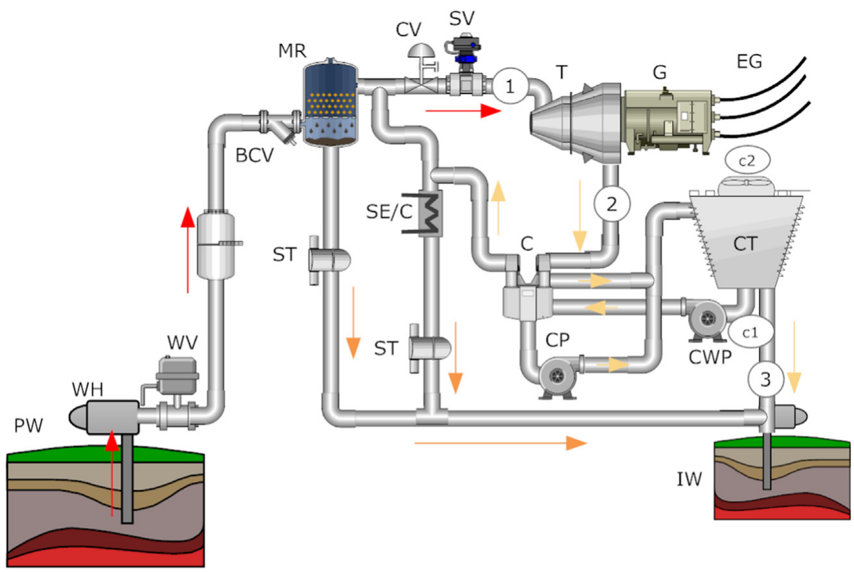
The main thermodynamic characteristics of the secondary working fluid in the Organic Ranking cycle are that, at low temperatures (85 and 170 °C), it has a low boiling point and high vapour pressure [50]. To explain these thermodynamic features, pressure-enthalpy and temperature-entropy diagrams are required (Fig. 9).

The thermodynamic process starts at state 1 where the working fluid at saturated vapour point enters the turbine expanding and producing work. The generator then generates electricity by using this work. The pressure and temperature of the saturated vapour decrease at estate 2 after turbine expansion. At constant pressure, the working vapour fluid goes into the condenser reducing its temperature and therefore condensing the fluid, at state 3. The cooling process of the working fluid takes place between state 3 and state 4 by using cooling water from the air-cooled cooling tower. This cooling stage changes the state of the working fluid from vapour to saturated liquid. Then, the working saturated liquid fluid is pumped back to the pre-heater (state 5) and evaporator (state 6), and the working fluid emerges as saturated vapour starting the cycle again at state 1 [14,36,50,54].

The thermodynamic analysis of the condenser, the turbine and the feed pump is the same as for flash or dry-steam plants. Table 5 summarises the Eq. to analyse a binary geothermal power plant. Eq. (37) calculates the work produced (w_1) in the turbine expansion process, while Eq. (38) analyses the isentropic turbine efficiency (η_t), and finally the turbine power ($\dot{W}_t$) and the generator power ($\dot{W}_e$) is calculated by Eqs. (39) and (40) respectively where $\dot{m}_{wf}$ represents the working fluid mass flow rate and η_g is the generator efficiency. In the condensing process, $\dot{Q}_c$ represents the rejected heat from the working fluid as a result of cooling. The power transferred from the feed pump ($\dot{W}_p$) to the working fluid is given by Eq. (42). Three assumptions are required to analyse the heat exchange process in the preheater PH and evaporator E: well-insulated PH and E; steady flow; and negligible potential energy and kinetic energy [14]. Then, the thermodynamic system is governed by Eq. (43) where '*a*' represents the geothermal heat flow inlet, '*b*' the geothermal heat flow after E and '*c*' after PH.

Eq. (46) analyses the evaporation heat transfer rate between both fluids the geothermal heat flow and the working fluid, where T_a is the known brine inlet temperature, T_b is found from the pinch-point temperature (minimum temperature difference between two fluids - given by the manufacturer) and the known T_5. Finally, the overall cycle can be analysed by Eqs. (48)–(50). The thermal efficiency of the entire cycle (η_{th}) represents in Eq. (48) in terms of the thermal power input ($\dot{Q}_{PH/E}$) and the thermal power rejected ($\dot{Q}_c$) [14,36,44,46,54].

The selection of the working fluid is the most important issue during the design process of a B-GPP, which must consider the thermodynamic properties of both geo-fluid and working fluid, health, safety and environmental impact [14]. The selection of working fluids defines the B-



PW	Production well	BCV	Ball check valve	SE	Steam jet ejectors
WH	Wellhead	MR	Moisture remover	C	Condenser
WV	Well valves	ST	Steam tramp	CP	Condensate pump
IW	Injection well	CV	Control valve	CWP	Condensed water pump
EG	Electric grid	SV	Stop valve	T/G	Turbine- Generator

Fig. 6. Dry-steam geothermal power plant [14,19,42].

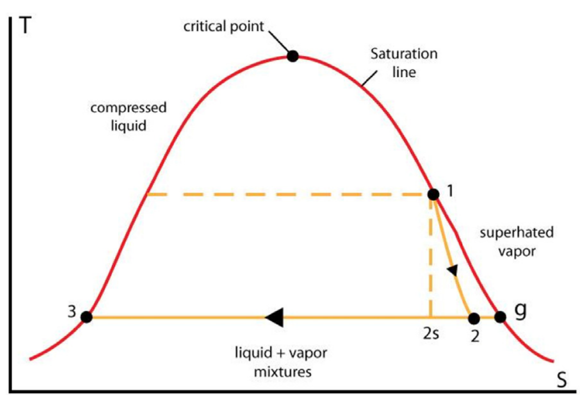


Fig. 7. Temperature – entropy (T-s) process diagram for a dry-steam power plant with saturated steam at the turbine inlet [14,45].

Table 4
Thermodynamic equations in dry-steam process [14].

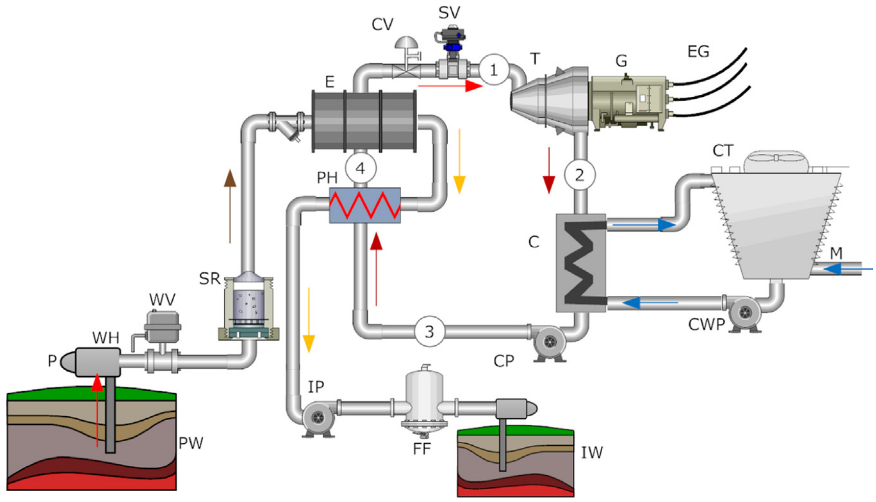
State	Equations	
Turbine expansion process	$w_t = h_1 - h_2$	(33)
	$\eta_t = \dfrac{h_1 - h_2}{h_1 - h_{2s}}$	(34)
	$\dot{W}_t = \dot{m}_s w_t = \dot{m}_s (h_1 - h_2)$	(35)
	$\dot{W}_e = \eta_g \dot{W}_t$	(36)

GPP system performance and economy [55]. Some working fluids are presented in Table 6, which clearly illustrates critical temperatures (CT) and critical pressures (CP) of working fluids are far lower than water. The versatile use of a secondary cycle in B-GPP has incurred in several variations of binary innovative systems, achieving improvements at higher efficiencies [14,25,44,56]. DiPippo [14], Yari [44] and Valdimarsson [27] explain different alternative configurations of the binary cycle such as the dual-pressure binary cycle, the dual-fluid binary cycle, the Kalina binary cycles and regenerative ORC.

A variety of approaches have been studied for working fluid selection in ORC-GPP. Quoilin, Declaye [57] presents a method which select the working fluid and an expansion machine in the same process. This tool selects the most suitable combinations of working fluid and expansion machine for a typical ORC systems. Mikielewicz and Mikielewicz [58] investigate 20 working fluids for ORC and conclude that R123 and R141b are the most suitable for small scale applications. Quoilin, Broek [59] additionally discuss the indicators that should be taken into account for selecting the most appropriate working fluid in a ORC: thermodynamic performance, isentropic saturation vapour curve, high vapour density, low viscosity, high conductivity, evaporating pressure, condensing gauge pressure, high temperature stability, melting point, low ozone depleting potential, low greenhouse warming potential, availability and low cost. Astolfi, Romano [60] conduct a detail study of Binary ORC power plants for the exploitation of medium–low temperature geothermal sources [61]. In part A, they investigate 54 working fluids in 6 different cycle configurations, concluding that, for low geothermal brine temperature (120 °C), the optimal fluid is decafluorobutane C_4F_{10}, and for higher temperature (180 °C), the optimal fluid is R236ea.

2.5. Advanced geothermal energy conversion systems – hybrid configurations

DiPippo [14] enumerates three well established advanced configurations of geothermal energy conversion systems: hybrid single-flash and double-flash systems, hybrid flash-binary systems and hybrid fossil-geothermal systems. Additionally, there is great interest in the development of hybrid power plants combining geothermal systems with biomass, waste-to-energy technologies, fuel cells and solar thermal systems [24,38,62–65]. Studies of Astolfi, Xodo [62], Peterseim, White [64] and Thain and DiPippo [24] seek to outline the main advantage of hybrid geothermal-other-renewable systems in aspects such as environmental impact, cost of electricity, exergy and plant efficiencies, turbo-machinery performance, techno-economic feasibility and investment risk. Regarding environmental impact of binary power plants, the geothermal heat flow is pumped and returned to the reservoir, and the working fluid never comes in chemical or physical contact with the



PW	Production well	E	Evaporator	CV	Control valve
P	Pump	PH	Preheater	SV	Stop valve
WH	Wellhead	IP	Injection pump	T	Turbine
WV	Well valve	FF	Final filter	G	Generator
SR	Sand remover	IW	Injection well	EG	Electric grid
C	Condenser	CP	Condensate pump	CWP	Cooling water pump
M	Make-up water	CT	Cooling tower		

Fig. 8. Basic binary geothermal power plant [14,36,42,45].

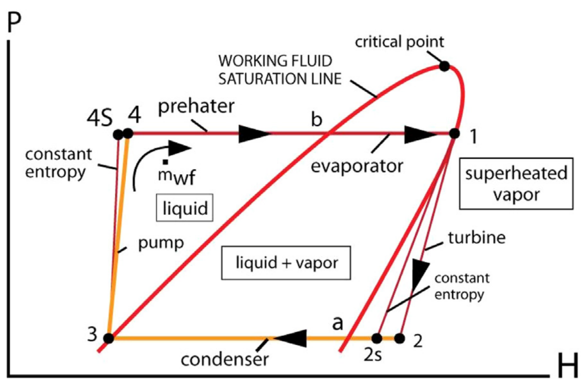


Fig. 9. Pressure-enthalpy diagram of a Binary geothermal power plant [14].

environment. Thus, thermal pollution is the only environmental impact, which takes place due to the heat rejected along with the cycle and is used for direct heating purposes [14,47].

Recent investigations are focusing on hybrid configurations of different thermal and non-thermal renewable with geothermal resources [24,38,62,66], although hybrid geothermal-fossil-fuels systems are not new [39,67]. Hybridisation of solar and geothermal energy in power plant configurations is current interest of research [68–75]. Jiang, Zhang [72] conduct a thermodynamic study of a Hybrid Solar-Enhanced Geothermal System Power Plant using CO_2 as working fluid in a supercritical CO_2 Brayton cycle. They conclude that the hybrid system has higher efficiency than the sum of the two stand-alone systems separately. While the geothermal cycle provides base-load electrical power, the solar system rises the capacity factor by generating additional electric power during peak demand hours. A recent study by Cardemil, Cortés [69] involved the performance analysis of a solar concentrating parabolic collector hybridised to a single and double-flash (triple flash) geothermal power plant for different geothermal reservoir conditions. Results demonstrate a 20% additional power output in the hybrid single-flash configuration along with 19% reduction on the consumption of the geothermal heat flow from reservoir in the hybrid double-flash configuration. Ayub, Mitsos [68] couple two existing models, an ORC geothermal model and a low-temperature solar system. Results show a 2% decrease in the levelized energy cost for the hybrid system and although optimizing the ORC geothermal configuration an 8% reduction in the levelized energy cost is observed.

Zhou [67] carries out fundamental studies on hybrid geothermal energy systems. The feasibility study on a solar-geothermal hybrid configuration demonstrates a 12.7% increase in the power plant performance in the net electrical output and a 7.5% increase in the thermal efficiency [76]. Another work by Zhou, Doroodchi [75] show that a 20% reduction in the cost of electricity production can be achieved by a hybrid solar-geothermal power plant instead of use a stand-alone Enhanced Geothermal System. Back pressure systems are the simplest and the lowest overall thermal efficiency of the geothermal power plants. These requires less investment in comparison with the other technologies. These technologies are largely used in multiple use applications such as combined electricity and hot water production. In the mineral mining industry, back pressure systems provide temporary power during resource development where energy efficiency has low priority. Hybrid technologies is the most common application of these systems. Stand-alone scope of uses covers a temperature range from about 320 °C to some 200 °C. Thermodynamically, with a solar exergy fraction of more than 66%, the annual electricity production increases 15% and 19% for a subcritical and supercritical ORC solar-geothermal plant, respectively [67,74,75].

For low-enthalpy geothermal resources, hybrid geothermal-fossil fuel power plant configurations offer another alternative to reduce fossil-fuel consumption and greenhouse gas emissions. Zhou [67] also studies a 500 MW hybrid geothermal-coal configuration with a 210 °C reservoir temperature and 400 kg/s brine flow rate. Results show savings of up to 0.3 million tonnes of coal per year and reductions of up to 0.72 million tonnes of GHE per year [77]. Furthermore, a decrease between 33% and 87% in electricity cost compared with a standalone geothermal power plant can be reached along with an increase of up to 19% in electricity production in comparison with a sole coal-fired power plant [67].

Oil and gas fields are also potential for power production and direct usage of geothermal heat [78]. Reyes [79] has studied 349 abandoned onshore oil and gas wells concluding that 1.7×10^9 kWh can be added to the New Zealand electricity network. Kurevija and Vulin [80] similarly analyse three gas fields in Croatia showing that geothermal energy

Table 5
Thermodynamic equations for binary geothermal power plants [14].

State	Equations	
Turbine expansion process	$w_1 = h_1 - h_2$	(37)
	$\eta_t = \frac{h_1 - h_2}{h_1 - h_{2s}}$	(38)
	$\dot{W}_t = \dot{m}_{wf} w_t = \dot{m}_{wf} \eta_t (h_1 - h_{2s})$	(39)
	$\dot{W}_e = \eta_g \dot{W}_t$	(40)
Condensing process	$\dot{Q}_c = \dot{m}_{wf}(h_2 - h_3)$	(41)
Feed pump	$\dot{W}_p = \dot{m}_{wf}(h_4 - h_3)$	(42)
Heat exchange process at E and PH	$\dot{m}_b(h_a - h_c) = \dot{m}_{wf}(h_1 - h_4)$	(43)
	PH:$\dot{m}_b \bar{c}_b (T_a - T_c) = \dot{m}_{wf}(h_5 - h_4)$	(44)
	E:$\dot{m}_b \bar{c}_b (T_a - T_c) = \dot{m}_{wf}(h_1 - h_5)$	(45)
	$\dot{Q}_E = \dot{m}_b \bar{c}_b (T_a - T_b) = \dot{m}_{wf}(h_1 - h_5)$	(46)
	$\dot{Q}_{PH} = \dot{m}_b \bar{c}_b (T_b - T_c) = \dot{m}_{wf}(h_5 - h_4)$	(47)
	$\eta_{th} \equiv \frac{\dot{W}_{net}}{\dot{Q}_{PH/E}}$	(48)
	$\dot{W}_{net} = \dot{Q}_{PH/E} - \dot{Q}_c; \dot{Q}_{PH/E} = \dot{Q}_E + \dot{Q}_{PH}$	(49)
	$\eta_{th} = 1 - \frac{h_2 - h_3}{h_1 - h_4}$	(50)

Table 6
Working fluids commonly used in binary geothermal plants [14].

Fluid	Formula	CT °C	PC MPa	PS @ 300 k MPa
Propane	C3H8	96.9	4.24	0.9935
i-Butane	i-C4H10	135.9	3.69	0.3727
n-Butane	C4H10	150.8	3.72	0.2559
i-Pentane	i-C5H12	187.8	3.41	0.0975
n-Pentane	C5H12	193.9	3.24	0.0738
Ammonia	NH3	133.6	11.63	1.061
Water	H2O	374.1	22.09	0.003536

production from abandoned gas fields could be economically feasible. Davis and Michaelides [81] found that up to 3 MW of electric power could be produced from abandoned oil wells in South Texas region. Similar studies can be found in [82–86].

Very little was found in the literature on the hybridisation of geothermal and biomass power plants. Thain and DiPippo [24] study the hybrid concept to achieve greater power output in a hybrid geothermal-biomass power plant. Results demonstrate that net power increases 32% in comparison with the operation of the two stand-alone power plants. Moret, Peduzzi [87] also presents the results of hybrid geothermal-biomass study. Overall, innovative hybrid geothermal-biomass systems show positive synergies by using geothermal heat to increase the biomass conversion processes efficiency.

The review of the up to date geothermal power plants has included the single-flash configuration, the double-flash configuration, the dry-steam configuration, the binary configuration and advanced hybrid configurations. All of these power cycles are capable of providing geothermal energy (geo-fluid) at lower temperatures for direct heat purposes after electricity generation. Next, the literature review explores the different configurations of direct uses of the geothermal heat flow after its use in the power plant known as cascade applications. This kind of geothermal development not only maximises thermal use of the geo-fluid by its use in electric and non-electric applications, but also the impact of the geothermal project in local communities.

2.6. General considerations

A single-flash plant requires approximately 1200 m^2/MW, while a coal-fired plant needs 40,000 m^2/MW and a photovoltaic plant needs 66,000 m^2/MW [14], which makes it an economical option in terms of land required [45]. There are other environmental concerns regarding geothermal power plants in general, for example, water pollution, noise and visual pollution, water and land usage, greenhouse gases, and loss of natural beauty [18]. However, Bayer, Rybach [47] argue that there are several methods to abate these environmental issues, such as re-injection for surface water pollution, the use of mufflers and silencers for noise pollution, air-cooled condensers for water usage, and avoiding developments in national parks. In general, geothermal power plants produce a lower land impact and greenhouse gases than fossil-fuel-fired conventional power plants.

Geothermal uses configurations typically look at cascade applications using the brine first in producing electricity and then to heating purposes [88]. In this regard, geothermal heat sources at temperatures higher than 150 °C are enable to combine heat and power generation [28]. So, the condensing temperature, generally above 60 °C, is suitable for district heating or other direct heat applications.

3. Geothermal direct use technology

Non-electrical applications use heat energy directly from the geo-fluid to complete an extensive range of applications, which usually require a temperature range between 10 °C and 150 °C approximately [88,89]. Also, known as direct uses (DUs), these applications overtake both the economic limit of geothermal power generation temperatures and the poor thermodynamic performance of fossil fuels used for heating resulting in improved use of geothermal energy resources [90]. As a result of the identification and development of direct heat applications worldwide, currently 82 countries report direct utilisation of geothermal energy with an estimated installed thermal power at 70.33 GWt globally, at a growth rate of 7.7% annually and capacity factor of 0.265 [28,31,91]. Lund and Boyd [28] assess the global thermal energy used, which reaches 587,786 TJ/yr (163,287 GWh/yr), growing at a compound rate of 6.8% annually and identifying nine categories of utilisation: geothermal heat pumps, space heating, greenhouse heating,

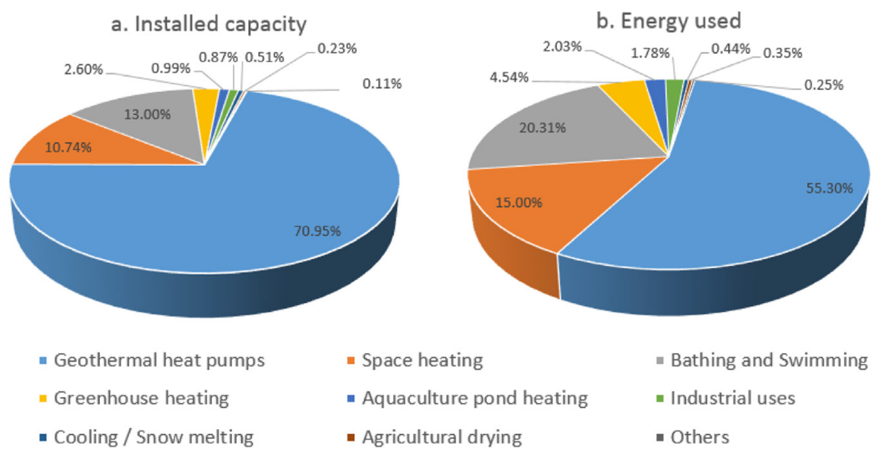


Fig. 10. Geothermal direct applications worldwide in 2015, distributed by a. Percentage of total installed capacity (MWt) and, b. Percentage of total energy used (TJ/yr) [28].

aquaculture pond heating, industrial uses, bathing and swimming, cooling and snow melting, and others (Fig. 10). The most striking finding is that, in 2015, 350 million barrels (52.5 million tonnes) of equivalent oil were saved and 148 million tonnes of CO_2 were prevented from being released to the atmosphere [28].

Fig. 11 summarises the DU of geothermal energy ranging from industrial applications at high temperatures, to aquaculture at very low temperatures. The versatility of DU can take advantage of the same resource to meet thermal requirements or to base combined heat and power configurations (CHP) [92]. In CHP, the thermal content, of either 'waste heat' or geo-fluid after the power generation process, is used to meet the required temperature in DU applications. Geothermal heat pumps play a vital role in space heating in cold zones [93–96]. Additionally, district heating by using low enthalpy geothermal resources is another very mature technology [97–101].

Recent research has demonstrated the positive impacts of cascade applications in geothermal development. The use of geothermal resources in cascade configurations include not only electricity generation but also direct use of thermal energy [4101–104], drying and dehydration processes [30,33], heat pumps [70,95,105,106], fish farming [102] and swimming pools for recreational activities [107]. Cascading systems allow multiple applications of CHP linked to the same geothermal resource [90]. In the cascade design, different temperatures of the same geothermal heat flow are used in staging and successive

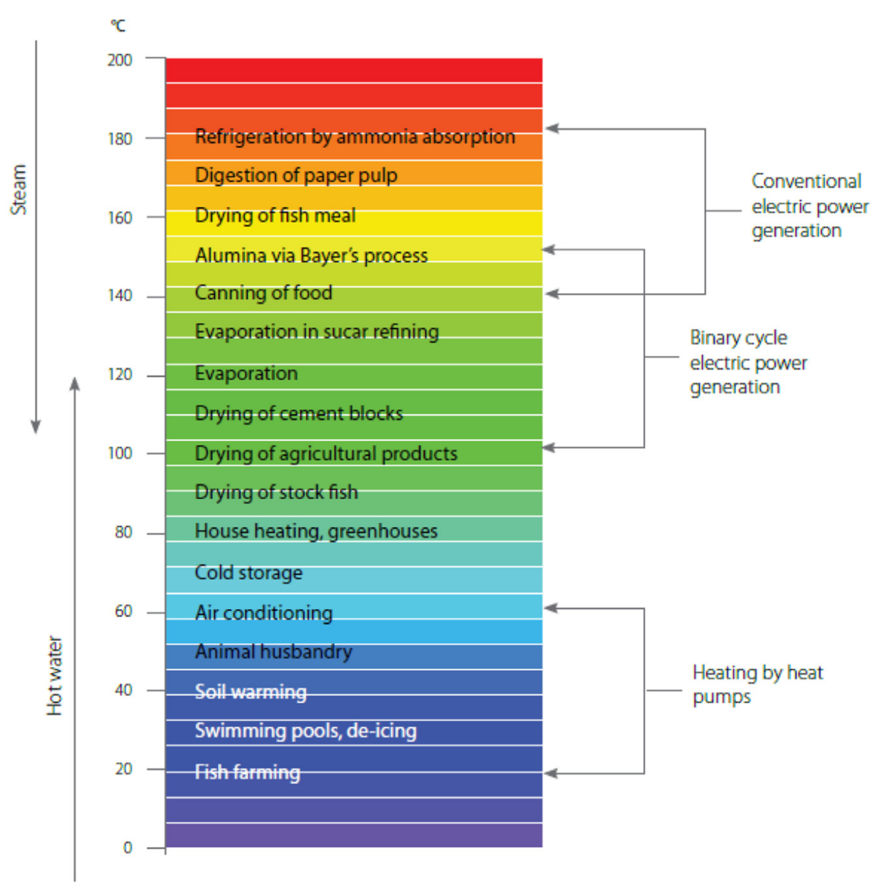


Fig. 11. Lindal diagram for direct geothermal applications [92].

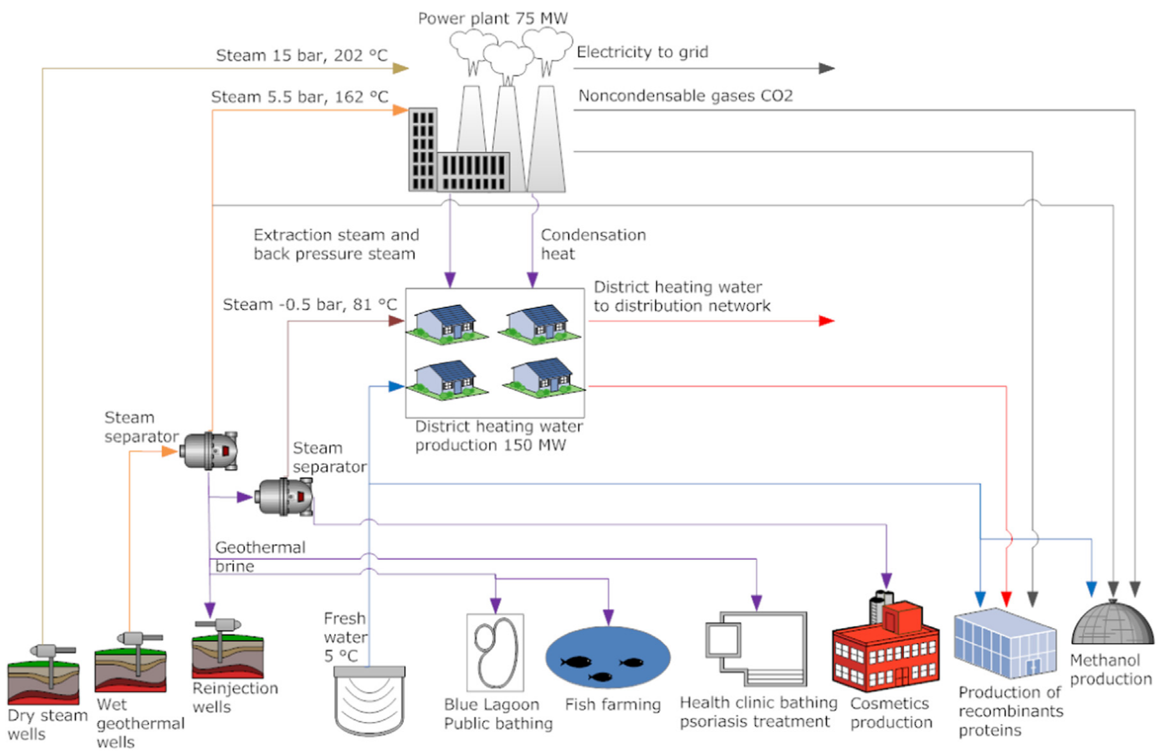


Fig. 12. Cascade application of geothermal resources, the example of the Blue Lagoon, Svartsengi Resource Park, Iceland [27].

applications in a sequence that requires lower temperatures downstream [26,89]. Gudmundsson [90] exemplifies the cascade system by a facility that uses the geo-fluid for different applications. The geo-fluid leaving the power plant at an optimum temperature is used to heat a cucumber and tomato greenhouse, then piped through cabbage, carrots and other vegetable fields. This an example of power generation, greenhouse and soil heating as cascading use. Bloomquist, Lund [26] reveal that considering individual direct uses and power generation projects may not guarantee an attractive investment return due to the high initial capital cost, whereas a multistage utilisation of the same geothermal heat flow maximises the socio-economic benefits of the development.

Fig. 12 provides an example of a combined heat and power configuration in a multipurpose cascade design. In this Fig., Valdimarsson [27] illustrates how the same geothermal heat flow (at 202 °C and 162 °C) is used to produce electricity, then, when it leaves the power plant (at 81 °C), is used for district heating purpose and finally at a lower temperature, the geo-fluid is applied in other different uses.

The US Agency for International Development (USAID) developed a ranking methodology of geothermal DU and described the socio-economic benefits of DU developments. The analysis of USAID [92] highlights eight factors for ranking geothermal DU applications allocating their weights: geothermal DU resource potential (20%), process energy requirements (15%), market demand (15%), investment potential (15%), employment potential (15%), socio-cultural fit (10%), environmental impacts (5%), and replicability potential (5%). Additionally, the USAID study identifies seven socio-economic and environmental benefits from the development of geothermal DU projects: product processing costs is reduced and product quality is improved; nutrition and household food security is improved; employment opportunities in rural areas are increased; incidence of rural poverty is reduced and family income is increased; employment opportunities for women and youth are enhanced; national capacity is strengthened through use of modern technologies and know-how; and environment is preserved through promoting the use of clean renewable energy [92].

4. Discussion and concluding remarks

From the review conducted, geothermal power plant technology and direct use applications are alternatives for decreasing worldwide fossil-fuel dependence and its environmental impacts. Stefansson [108] carried out a world geothermal resource assessment estimating a lower limit of geothermal potential for electricity generation at 1.5 TW. Stefansson also found that approximately 68% of the total geothermal resources are temperatures lower than 130 °C (mostly for direct heat applications) and the remaining resources are temperatures higher than 130 °C (suitable for electricity generation). Thus, Binary – Organic Ranking Cycle Power Plants might play a vital role in the exploitation of low temperature geothermal resources [109]. Furthermore, although hybrid geothermal-solar thermal configurations have been in-depth studied, there is a need for research in hybrid geothermal-biomass configurations. Both solar and biomass resources increase the energy output increasing the thermal efficiency and increasing the life of the geothermal reservoir. On the other hand, direct applications of geothermal heat present good opportunities for increasing the revenue of a geothermal project. Depending of the geographic zone, multiple direct uses can be achieved. Cascade configurations contributes to maximise the use of geo-heat contributing to increase the standard of living of the communities around the geothermal resource. Research opportunities are identified in hybrid configurations for poly-generation purposes including electricity along with heat, air conditioning, refrigeration, drying, evaporation, district heating among others.

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