Energy Strategy Reviews 39 (2022) 100735

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Geothermal wellhead technology power plants in grid electricity generation: A review

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ARTICLE INFO

Keywords:
Geothermal powerplants
Geothermal electricity development
Wellhead generators
Geothermal electricity projects
Geothermal energy technologies
Wellhead technology

ABSTRACT

Geothermal energy has a significant role to play in the global transition to renewable and low-carbon energy systems because of its ability to supply steady and flexible electricity particularly for baseload demand because of its cost competitiveness compared to fossil fuel energy options. However, geothermal faces a challenge of long project development times with conventional power plant taking an average of 5–10 years and with high risks associated with drilling of unproductive wells which discourage private investment and quick deployment. Although geothermal energy has a huge potential for power generation, it currently contributes less than 1% of global electricity generation capacity. The generation capacity grew from 8.7 GWe in 2005 to 15.61 GWe at the end of the year 2020, representing average annual growth of 4.01%. The overall objective of this study was to determine the potential, features and application of wellhead power plants in electricity generation both to complement and substitute central powerplants. It was established that wellhead power plants can be used on temporary basis during the project development or permanently as grid connected or off grid generation facilities. With current technology, wellhead generators of up to 15 MW capacity can be installed on well pads of production wells for temporary or permanent electricity supply. Wellhead generators can facilitate optimum resource utilization especially for wells with unique conditions like too high or too low pressure and temperature compared to others in the same steam. They are generally inferior to central power plants due to lack of economies of scale hence higher unit cost of power. Successful adoption of wellhead powerplants for faster electrifications calls for state support and incentives in terms of subsidies, development of electricity gid, attractive feed in tariffs and tax incentives without which they won't compete favorably against the conventional central powerplants. Generally, wellhead powerplants can make geothermal electricity projects more feasible with reduced barriers in investment and early electricity and revenue generation for investors. However, investment on temporary basis makes reasonable economic sense if the time between drilling the first productive well and completion of a central plant is more than one year. Incentives like high feed in tariffs and tax incentives may be necessary to make them competitive against the superior conventional powerplants.

1. Introduction

There is a global consensus and resolution to transition to renewable and low-carbon energy systems, which has generated interest in geothermal electricity particularly due to its ability to supply competitively priced electric power reliably and with desirable flexibility to meet base load steady energy demand and fluctuating demand for intermediate and base load energy demand compared with variable renewable sources like wind and solar PV depending on a power grid's needs [1]. The challenges of greenhouse gas emissions and climate change have generated significant interest and demand for renewable sources of energy like geothermal which has the ability to supply continuous and steady energy supply ideal for base load heat and power application [2,3]. It takes about 5–10 years from the time the first well drilled to the time of central geothermal power plant commissioning for operation and maintenance while wellhead powerplants take between 3 months and 6 months from the time of completion of well drilling and testing to commissioning time for power generation, operation and

Abbreviations: CHP, Combined heat and power; GWe, Giga-watt electricity; kWe, Kilowatt electricity; MWe, Megawatt electricity; KenGen, Kenya Electricity generating company PLC; NPV, Net present value; IRR, Internal rate of return; ORC, Organic rankine cycle; SSC, Specific steam consumption.

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https://doi.org/10.1016/j.esr.2021.100735
Received 30 June 2021; Received in revised form 28 September 2021; Accepted 12 October 2021
Available online 2 December 2021

maintenance of the plant [4–7]. In central power plant development, upon drilling the well, it must be shut in until enough wells are drilled and the powerplant is constructed ready for commissioning and operation [8,9]. Upon successful geothermal well drilling and testing in central powerplant development, it is possible to utilize these productive wells for electricity generation using wellhead generating unit (WGU) on temporary basis to supply power for field operations or to the grid until the powerplant is constructed and hence the need to connect it to the many production wells which would otherwise be idle, some for very many years [10].

The serious and interesting concern is why geothermal power generation has a very small contribution to the global electricity generation mix and why the average growth in capacity is very small compared to other renewable sources of energy like wind, solar and hydro, yet its potential is so big [11–13]. Geothermal electricity powerplants operate at high capacity factor of over 90% which allows them to supply steady and reliable electric power at low cost of electricity generated with high flexibility while offering energy security as the energy resource is natural, local and renewable and therefore protects countries against oil price fluctuation and supply instability and mitigates greenhouse gas emission from fossil fuel plants [14]. However, geothermal energy accounts for less than 1% of global installed electricity generation capacity [3,11]. This is because of the main challenges facing geothermal development that include limited resource availability and accessibility, limited access to capital due to high project upfront costs and risks involved and extremely long project development periods. Wellhead powerplants can provide quicker, less costly, and flexible means of geothermal electricity development [15,16]. Wellhead powerplants are smaller geothermal power plants that can be developed in a modular and simple construction mainly using mainly flash and binary technology and accelerate development of geothermal electricity [17].

Electricity supplies about 40% of combined global energy demand and consumption and remains a good measure and indicator of a country's socio-economic performance and progress [18]. As a polluter of the environment, electricity generation accounted for about 42% of the global carbon dioxide CO_2 production in 2013. This was followed by the transport sector which accounted for about 23% [19]. This environmental impact and concerns has led to a global rise in demand for clean, affordable, competitive, renewable and environmentally friendly energy resources for sustainable development [20,21]. These renewable sources of energy include geothermal energy, which is a form of energy stored in the earth as heat [22,23]. So massive is the geothermal potential that the global geothermal energy potential is about 50,000 times the global known oil and gas reserves with significant feasible use in electricity generation, direct heat and geothermal heat pumps [24]. Geothermal energy is attractive mainly because of its continuous availability making it ideal for reliable and stable base load electricity and heat supply [22].However, although geothermal energy resources are huge, geothermal contributes less than 1% of global electricity and records low annual growth rates compared to other renewable energy sources [23]. As an example, between 2005 and 2020, the average year to year annual growth in geothermal capacity was about 4.01% while in 2020, the growth in generation capacity was just 1.3% [25,26]. Geothermal power plants are operational in about twenty nine countries which had global installed power capacity of 15,608 MW by the end of the year 2020 [27,28].

The global transition to green and low-carbon electricity supply has increased demand for renewable energy sources for power generation. the main challenge is variability in supply of the major sources like hydro, wind and solar unlike geothermal which guarantees study supply [29]. The interest in geothermal energy as a renewable energy resource for power generation has increased the interest in wellhead technology as an alternative and substitute for conventional power generation systems [3]. Generally wellhead units are smaller than conventional plants but assume same shapes and configuration and often use steam from a single geothermal production well [23,30,31]. Where wellhead units are used on temporary basis, they are disassembled and moved to a new site upon the construction of a central powerplant [6]. Wellhead units vary in size based on the characteristics of the production well and technology used, but generally vary from 0.1 to 15 MW using present technology [3,9]. However according to Ref. [32] wellhead power plants are factory preassembled units that are road-transportable energy of capacity 1–15 MW, but most economical and commonly used sizes are 3–5 MWe based on socio-economic considerations [33,34]. It is therefore noted that wellhead generators have capacity ranging between 0.1 MW and 15 MWe and have several applications mainly in onsite power generation. This may however change with technology improvement through research and development [5,6].

In this study, the overall objective was to analyze the electricity potential of geothermal wellhead generators for faster development of geothermal electricity generation capacity by both on long term (permanent) and temporary (short term) installation. The focus of the study is use of wellhead powerplants as grid connected plants application. This study is a review of technical, environmental, and socio-economic aspects of wellhead power generation mainly as grid connected powerplants.

1.1. Problem statement

There is global increase in demand for renewable energy resources for power generation due to the concern over greenhouse gas emissions from fossil fuels and associated massive discharge of pollutants to the ecosystem and the serious threat of global warming [35]. Among renewable sources of energy like wind, solar, hydro and geothermal, geothermal energy has the advantages of higher reliability, sustainability of supply, greater capacity factor and less ecological impact [36]. Although geothermal electricity potential is large, it has an insignificant contribution to the global electricity generation capacity [37–39]. The global undeveloped geothermal electricity capacity is over 100 GW, yet it contributes less than 1% of the global electricity generation with limited growth with most electricity coming from central power plants of capacity between 50 and 100 MWe [5,23,32,40].

The earth has about 12.6 × 1024 MJ as the total heat energy content, of which about 5.4 × 1021 MJ is in the crust. Although this energy content is huge, its use is hampered by scarcity in exploitable resource and geological conditions which limit access to the geothermal resources like the need to allow liquid water or steam to transport the heat from deep hot zones to the surface for exploitation [19]. Today, the global growth in energy consumption is increasingly being met by solar PV and wind power projects [11,41,42]. The energy sector remains largely reliant on fossil fuels that are highly subsidized in many countries while these resources may be limiting in some countries, which is a major source of global energy insecurity [6,43]. Even where geothermal resources are available, their development is risky, expensive and time consuming hence limited growth in generation capacity. This is undesirable because 660 million people globally have no access to electricity, and this represents about 33% of the African population [24,44,45].

The global growth in geothermal electricity capacity remains low with average year to year growth of 4.01 between the year 2005 and 2020 [40,46]. The main challenge to geothermal electricity capacity growth is long project delivery period of between 5 and 10 years with huge capital requirement and high project risks [15,47,48]. Geothermal project development remains risky with no guarantee of getting feasible steam resources for power generation while the conventional project development requires tens of geothermal wells drilled one after the other. Successful wells are left idle, at times for many years while awaiting drilling of enough wells to sustain a central power plant. This is wasteful as it leaves useful energy idle after spending huge sums of money [3,4,6]. This problem of idle resources can be solved by use of wellhead generators to produce electricity on temporary basis instead of leaving wells ide for years, hence generating power for own use and sale to the grid and earn revenue for the developer [20,49,50]. Permanent wellhead generators for isolated wells and wells with unique chemical and thermodynamic properties compared with others in the same steam field should also be considered in mixed field development for optimum geothermal resource use [51,52].

1.2. Rationale of the study

There is a global shift from dependency on fossil fuels to renewable energy in electricity generation [53,54]. It is expected that by the year 2025, renewable sources of energy will account for 80% of the global electricity supply growth [53]. By the year 2030, it is projected that about 40% of global electricity supply all over the world will be met by renewables i.e., hydro, solar, wind, hydrogen, bioenergy and geothermal. Geothermal energy potential is so huge while its production and consumption in generation is stable unlike other renewable sources like wind and solar which are intermittent and at times unpredictable [16]. It is for this reason that geothermal energy has a very important role in the future global electricity mix. However, geothermal electricity project development is characterized by high development costs and long lead times which present challenges to geothermal energy and electricity development [11,55]. There is need to reduce this lead time, project cost and risks involved in geothermal electricity to realize faster growth and contribution to the global electricity generation mix. The wellhead technology promise to reduce the long wait to get both electricity and return on investment [32,56–59].

In geothermal project development process, well testing is done with discharge of steam to the atmosphere for a relatively long period of time. This practice is wasteful since no power generation or other useful application of the steam is exploited. The process additionally leads to environmental pollution [14]. The use of wellhead generators for power generation during well testing is an economical and environmentally benign use of geothermal energy resources [60]. In the conventional approach, once a well is tested, it is left idle awaiting development of more wells to provide enough steam for construction of a central power plant, and this waiting can take longer than 5 years. With wellhead plants, this steam can be used to generate electricity from individual wells using wellhead technology power plants for drilled and tested wells and during testing [3]. On average, drilling a geothermal steam well consumes about 350,000 liters of diesel fuel in diesel engine generator sets [5,57,61]. Therefore, installing a wellhead generator on productive wells prevents waste of steam through venting to open atmosphere and avoids pollution from diesel fuel used to run diesel generators to supply power for steam field development and export excess to the grid and for early revenue.

Geothermal energy has many benefits over other sources of renewable energy resources, such as hydro, wind, bioenergy, and wave energy. These advantages include high degree of availability (>98% and 7500 operating hours/annum common) hence suitable as base load power plants, have low land use requirements, limited liquid pollution if reinjection is applied, can reduce demand for imported fossil fuels for nonoil producing countries, it is more environmentally friendly and so can displace polluting fossil fuels, they are not affected by weather and climatic conditions, while geothermal powerplants operate with higher reliability, availability, and capacity factors than other types of power plants like diesel power pants [5,23,62–64].

2. Geothermal energy and electric power generation

The word geothermal is derived from the Greek word "geo" which means "earth" and "thermos" meaning [4,11], and therefore, geothermal means the thermal energy from the earth. Geothermal energy is heat derived from the earth's interior out of radioactive decay and is only useful if it reaches the earth's surface in sufficient quantities [65]. The heat from deep in the crust reaches the earth's surface for possible exploitation as heat and electricity by three important mechanisms and media. These are namely, ground water circulation, magma extrusion and crustal plate movement [65,66]. A heat carrier is needed to deliver the heat in convenient and enough to the surface of the earth, and is called a geothermal fluid [11,65,66]. As an energy resource, geothermal energy is renewable and ideal for supply of base load electricity and other direct uses sustainably while mitigating against greenhouse gas emissions from conventional energy sources like fossil fuels [62,64,67,68]. It has significant potential to supply long term, secure and reliable base load electricity and heat energy with low greenhouse gas emissions [69].

2.1. Heat content of the earth

Geothermal energy development and electricity production is a thriving international market with many players at various stages of the project cycle [11,38,70]. The earth has been radiating heat from its center for close to 4.5 billion years. It is estimated that at about 6437.4 km (4000 miles) in the interior of the earth's crust, the temperature is about 9932 °F (5500 °C) [11]. About 42 million megawatts (MW) thermal power flows from the Earth's interior, mainly by conduction. The mantle is estimated to have a temperature of between 300 and 350 °C and about 4000 °C at the base of the mantle. Assuming an average surface temperature of about 15^{O}C, the total heat content of the earth can be estimated at 12.6×10^{24} MJ while the crust has about 5.4×10^{21} MJ. This heat is huge but only a small fraction is exploitable due to several challenges and limitations [44]. Geothermal potential is considerable with the amount of heat within 10,000 m of the surface of earth alone having equivalent energy that is 50,000 equivalents of global oil and gas resources [11,71].

The thermal gradient of the earth on average is 2.5–3 °C/100 m [38,44,67]. This refers to the temperature rise per unit depth as you move deep into the earth's crust from the surface [11,72]. It is more feasible to exploit geothermal resources whose thermal gradient is above the average [6,73], with global average of above surface temperature about 15 °C [69]. At thermal gradient of 30 °C/km, it implies that at a depth of 5.5 km, the temperature is about 180 °C [11]. This is exploitable geothermal energy depending on availability of other enabling conditions for geothermal energy exploitation, especially the geothermal fluid and supporting rock structure. The advantage of geothermal energy is that it is technically inexhaustible having a constant heat flow for billions of years in the past and future. Fig. 1 shows the thermal gradient of the earth.

From Fig. 1, it is noted that the earth's temperature increases as the depth increases. It reaches about 5500 °C at about 6000 km deep.

A viable geothermal system consists of heat source, a permeable rock structure and has water as a heat or energy carrier. To establish the viability of a geothermal reservoir, resource developers must drill through the earth and test the resource temperature and geothermal fluid flow rate. A thermal aquifer shown in Fig. 2 is formed when rainwater or snow melts and feed the underground thermal aquifers with the water. Steam or hot water is the formed and trapped in cracks and pores embedded between a layer of impermeable rock structure, leading to the formation of a geothermal reservoir [11,55]. To exploit

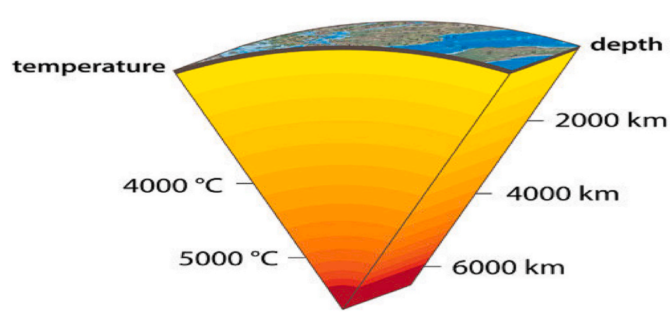

Fig. 1. The Earth's temperature [11].

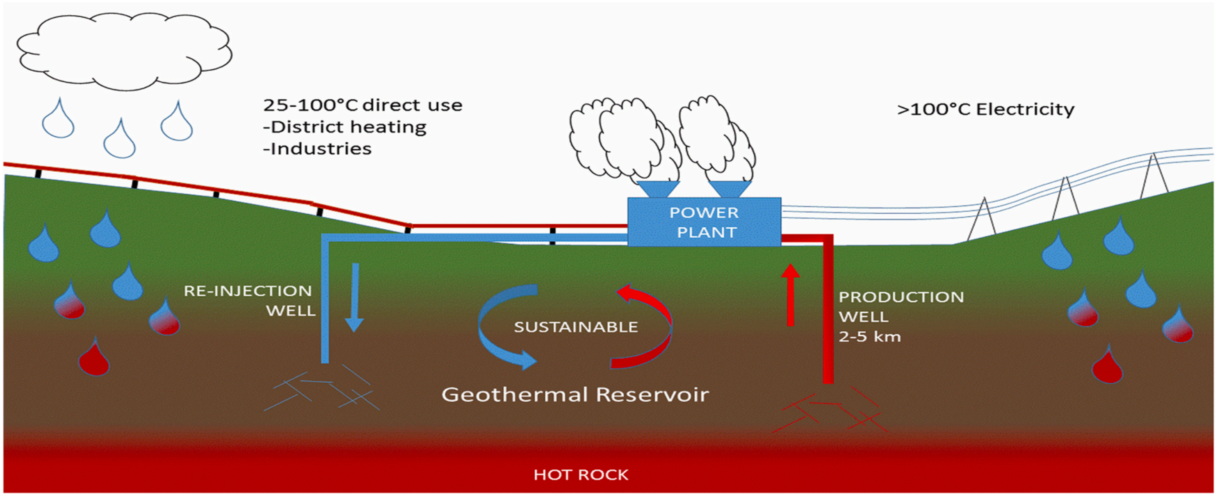

Fig. 2. The Formation of a geothermal reservoir [5,11].

this resources require drilling of wells into the reservoir to extract the fluid and drive it to the surface for power generation in central or wellhead powerplants [3]. In some cases, there is surface manifestations of the resource in form of hot water springs, geysers, and fumaroles [4, 11]. Fig. 2 below demonstrates the positional relationship between the critical elements of a geothermal reservoir.

From Fig. 2, it is noted that a geothermal reservoir has a hot rock as heat source, water source like rainwater, and a permeable rock structure between impermeable rocks.

The global geothermal potential is significant with about 99% of the earth having temperature above 1,000 °C, while 99% of the remaining 1% is hotter than 100 °C [68], hence they possibility of having low temperature geothermal resource [16]. This implies that geothermal energy alone has the capacity to meet the entire energy needs of humanity today [57]. Geothermal power plants have average system reliability of about 95% and load factor greater than 90% making them ideal for base load power generation and application [23,31]. Although electricity generation from geothermal energy resources is steady, continuous, and hence reliable, leading to higher electricity generation per MW of installed capacity, the global electricity generation remains low [23,66,69], and globally contributes less than 1% in terms of global electricity generation capacity from different sources [23,74].

In 2014 electricity generation from geothermal was 73.3 Terawatt-hr. (TWhr.) with production in 24. This grew slightly to 75 Terawatt-hour (TWhr) in 2015 which is a mere 2.3% growth in a year accounting for 0.3% of global electricity production in 2015 [23,27,66]. According to Ref. [66], global geothermal electricity generation capacity by the end of 2016 was about 12.7 GW (GWe). In the study by Refs. [28, 75] it was observed that in 2017, twenty four countries globally produced geothermal power with a combined installed power generation capacity of 13,270 MWe with about 14,165 MWe under development. By end of 2019, twenty nine countries globally had combined geothermal electricity generation capacity of 15.4 GW [25,27,28]. According to Ref. [76] geothermal capacity will be about 18.4 GW by 2021. The year to year geothermal electricity capacity growth between 2005 and 2020 varied between −1.09% and 5.4% growth and average growth in capacity of 4.01% [25]. The global economy was affected by the Corona virus pandemic in 2020 which realized a mere 1.35% growth in geothermal electricity capacity. This is quite low compared with the growth rates for wind and solar electricity generation.

2.2. Growth in generation capacity between 2005 and 2020

Geothermal electricity generation capacity continues to record low growth with nameplate global installed capacity reaching 15, 608 MWe by the end of the year 2020. Major geothermal electricity producers like Indonesia, Philippines, Mexico, Italy, Kenya and Iceland recorded nil growth in capacity for the year 2020 [77]. Table 1 shows geothermal generation capacity between 1960 and 2020 globally.

From Table 1 it is observed that geothermal electricity capacity has grown from 6.8 GWe in 1998 to 15, 608 GWe in 2020, representing about 4.01% average annual growth in generation capacity [3,11]. There was reduced geothermal generation capacity globally in 2011 while the least growth was realized in the year 2020.

2.3. Geothermal powerplants

Geothermal energy is a form of renewable energy with ability to supply reliable electricity for base load demand electricity and heat supply. Therefore they have a role to play in mitigation against greenhouse gas emissions through displacement of fossil fuel sources of energy in heat and electricity generation [78–81]. Geothermal energy potential is so huge with 99% of the planet earth being hotter than 1, 000 °C while 99% of the remaining 1% which has less than 1000 °C has a temperature greater than 100 °C [80]. Thermal energy stored in earth's crust has capacity to meet the entire energy needs of mankind today [82]. The most attractive features of geothermal powerplants is that they are highly reliable and operate at high load factor and high capacity factors, with system reliability averaging 95% as well as average load factor of more than 95% [3,11]. However, geothermal power plants

Table 1
Geothermal energy capacity and growth [3].

	YEAR	GLOBAL CAPACITY(MWe)	CAPACITY GROWTH(MWe)	PERCENTAGE GROWTH (%)
1	2005	8686	–	–
2	2006	8918	232	2.67
3	2007	9139	221	2.48
4	2008	9459	320	3.50
5	2009	9899	440	4.65
6	2010	10121	222	2.24
7	2011	10011	−110	−1.09
8	2012	10471	460	4.59
9	2013	10740	269	2.57
10	2014	11221	481	4.48
11	2015	11846	625	5.57
12	2016	12706	860	7.26
13	2017	13280	574	4.52
14	2018	14600	1320	9.94
15	2019	15400	800	5.48
16	2020	15608	208	1.35
TOTAL/AVE.			**461.60/YEAR**	**4.01%**

contribute less than 1% of global electricity capacity and register very slow rate of capacity growth compared to other renewable energy sources [4,6], for example, between the year 2005 and 2020, average annual capacity growth was just 4.01% [3,11]. High temperature and enthalpy geothermal resources can be used to generate electricity, but they require the extraction of the geothermal fluid from depths usually more than 3 km underneath the earth's crust. The conversion technology varies from steam field to steam field and for the case of wellhead power generation, it, may vary from well to another, based on well characteristics and application.

Upon successful drilling and testing of exploratory well, a decision must be made concerning the number of production wells to be drilled in a particular geothermal steam field to fully tap the available resource. For a vapor dominated geothermal system, production wells are drilled, tested, and connected to a common power plant through a network of insulated steam pipes to deliver steam to the powerplant. Generally, based on production well capacity, tens of geothermal wells may be connected to a line for a 50–55 MW unit, with additional one or two additional wells being left on standby [83]. Drilling wells is expensive and time consuming as wells are often drilled one or few at a time based on the number of drilling rigs [84]. This often leaves successfully drilled and tested geothermal wells idle while awaiting completion of other wells needed to sustain operations of a central power plant [4,5]. This creates an opportunity for temporary wellhead powerplant development.

2.4. Geothermal conversion technologies

There are three classes of geothermal powerplants based on the thermodynamic cycles and conversion technology. These are dry steam powerplants, flash powerplants and binary and hybrid or combination cycle power plants. The selection of the conversion technology is guided by the geothermal fluid conditions [16]. The conversion technologies adopted are common to both central powerplants and the wellhead power plants [4,11,16]. The geothermal resource fluid is divided into three major categories, high temperature resource if it is greater than 150 °C medium between 90 °C and 150 °C and low temperature if the resource temperature is below 90 °C [16]. Over 70% of global geothermal resources are in the form of low enthalpy geothermal fluid. These resources have temperature that is less than 150 °C hence the popularity of the organic Rankine cycles (ORC) systems as the ideal technology for conversion of the low-temperature geothermal energy to electricity [85,86].

The technology selection is guided by the thermodynamic properties of the steam or geothermal fluid [87]. The thermodynamic properties of the resource, especially temperature influences the resource application and energy conversion technology. The conventional Rankine cycle steam turbines normally operate at a temperature above 180 °C (350°F) while non-electrical applications can efficiently use geothermal resources with temperatures of 40°C–180°C or (100°-350°F), based on specific application [83,88]. The operational design of geothermal power plants is similar to fossil fuel and nuclear power plants which are based on the Rankine cycle except for the source of heat which is the geothermal fluid from earth delivered through production wells and a series of pipes [89,90].

2.4.1. Dry steam plants

For high enthalpy geothermal fluid normally with temperatures above 200 °C in saturated or dry state, the geothermal fluid is directly piped to a steam turbine via a strainer to generate electric power [91]. Dry steam geothermal plants are rare because the dry steam geothermal resources with such favorable conditions are scarce. Such resources are found at Larderello in Italy, The Geysers (USA), Old Faithful geyser at Yellowstone National Park in Wyoming (USA) which is in a protected area hence not developed and very few other known places globally [11,92,93], Lake counties in northern California [76], and the Kamojas in Indonesia [11,83,94].

2.4.2. The flash system

In a flash geothermal system, hot water, or wet steam is driven to the separator from the production well where it is flashed to steam at a lower pressure as the denser liquid settles in the flash tank base from where it is drawn out of the flash vessel under pressure normally to the injection well or other lower pressure and temperature thermal application, electricity generation or both before injection back to the reservoir. Pressure reduction to a level below vapor pressure of the fluid in the separator or flash vessel causes the geothermal fluid to flash or vaporizes, into dry steam which is directed to a steam turbine for power generation. The exhaust steam exiting the turbine is condensed and injected back to the reservoir [83]. The flash systems are equipped with a separator which causes pressure drop that causes steam to be separated from the water. Steam generated is directed to a steam turbine where it expands and condenses. The condensate is collected with the brine exiting the separator and reinjected back into the reservoir [26,91,95]. Flash systems can further be classified into single-flash, double flash or even triple flash based on the flashing stages adopted. The flash system remains the most appropriate system of power generation for liquid-dominated geothermal systems. The system capacities generally varied from 3 MW to 90 MW while the average capacity of 25.3 MW [96].

2.4.3. Binary powerplants

Binary cycles are used to convert medium-low temperature geothermal resources to electric power, mainly as binary and Kalina cycles [97]. Binary cycles use two fluids in a closed loop cycle, one being the geothermal resource fluid and the other an organic fluid [11]. The geothermal fluid is passed through a heat exchanger where it transfers heat to a low temperature boiling fluid which acts as a working fluid [4]. The working fluid vaporizes and expands through a turbine which rotates and turn a generator for power production. The working fluid is then condensed and recycled through the heat exchanger repeatedly. The geothermal fluid leaving the heat exchanger in a single pass is often reinjected back to the reservoir [83]. The organic Rankine cycle is identified as the best cycle for low temperature thermal energy sources [98,99].

There are various types of binary cycles used in geothermal power plants based on the selected working fluid. They are mainly classified into Organic Rankine cycles which use an refrigerants or organic fluid, Kalina and Goswami cycles which use ammonia mixtures [87]. In organic Rankine powerplants, the geothermal fluid heats up and pressurizes a low boiling temperature and pressure a secondary fluid like penta-fluoropropane and Isobutane which normally in a closed cycle and hence no mixing.

Binary plants are designed to operate with two thermodynamic cycles consisting of a geothermal fluid loop and a power cycle loop and are classified as either organic Rankine Cycle plants or Kalina plants based on the working fluid used [50]. Kalina cycles use a mixture of 70% ammonia and 30% water as the working fluid with higher efficiency and exergy potential compared to the Organic Rankine cycles [57]. The Kalina cycle is a modified Rankine cycle the uses a distillation separator and absorption recuperator. The cycle was invented by Alex Kalina in 1980s. These power plants are safer, have lower capital costs and are simpler with possible applications in both small and big powerplants sizes 50–100 MW [100,101].

More advanced forms of the organic Rankine cycles include the organic flash or regenerative cycle and the supercritical cycles.

i.) Organic flash cycle (OFC)/Regenerative cycles

An organic flash cycle (OFC) is a modified form of trilateral cycle that avoids the state of isothermal evaporation and the use of a two-phase expander in the cycle and as a result the organic flash cycle significantly reduces the irreversibility during the evaporation of the working fluid [21]. In this cycle, the working fluid is heated to saturation and flashed by throttling. The saturated vapor from the flash separator then expands through a turbine hence doing some work and rotating it. In a basic organic flash cycle, the working fluid in saturated form from the separator and turbine exhaust are responsible for the largest part of the total heat input. System performance can be improved by recovery of heat from the saturated liquid or the turbine exhaust to preheat the working fluid [102].

Organic Flash Cycles (OFCs) are used to achieve a good temperature match between the two fluids to minimize heat loss from a saturated liquid in the flash separator which reduces the cycle efficiency. Thermodynamic performance can be improved by regeneration through recovery of more heat from the saturated liquid to be used in preheating the working fluid [97]. In regeneration, the evaporation and flash temperatures are optimized for maximum net power generation for geothermal fluid temperatures between 120 °C and 180 °C having reinjection temperature of 70 °C. The optimal flash temperatures for organic flash cycle with regenerator (ROFC), the organic flash cycle with regenerator and organic flash cycle with internal heat exchanger (ROFC + IHE) as well as the modified organic flash cycle (MOFC) are low compared with that of a basic organic flash cycle (BOFC) because of the limits of the preheat load and the pinch point which lead to a higher vapor mass flow rates [97,103]. The net power output increase and the decreases in the evaporator exergy losses by ROFC, ROFC + IHE and MOFC compared with those of BOFC tend to decrease with increasing geothermal water inlet temperature. A modified organic flash cycle (MOFC) can produce maximum net power which is up to 66.2% greater than power from the basic organic flash cycle (BOFC) for a geothermal fluid temperature of 120 °C. The main limitation of the modified organic flash Rankine cycle (MOFC) is that it requires more evaporator area of about 51–78%, less condenser area by 13–42% to produce same power as the BOFC [97].

In the study by Ref. [102]involving the use of a double flash Organic flash cycle O(FC), a modified OFC, two-phase OFC and a 2-phase MOFC showed that modified OFC (MOFC) generated 10–12% extra power compared to a conventional ORC. To reduce throttling irreversibility, a two-phase expander was adopted in the place a high-pressure throttling valve in the two-phase OFC. A two-phase MOFC produced up to 20% more net power compared to an ordinary ORC [102]. In terms of thermodynamic efficiency and economics of OFC and regenerative cycles (OFRC) [103], established that the unit cost of the OFRC was reduced and the efficiency of a double-flash OFRC was better than that of conventional ORCs [104].

ii.) Supercritical Organic Rankine Cycles

In a supercritical Organic Rankine cycle, the evaporation pressure should be made greater than the critical pressure of the working fluid to avoid the isothermal evaporation. This helps to improve the temperature matching between the working fluid and the heat source fluid. However, higher turbine inlet pressure causes increase in pump power consumption, increases the investment cost, as well as operational safety requirements making the system more expensive. The use of a non-isothermal phase change of a zeotropic mixture allows for a good match of the temperature profiles in the process of evaporation and condensation. The main challenges of zeotropic mixtures are the uncertainty over the thermodynamic properties of the fluid which inhibits accuracy of computational models and efficient system design. Additionally, the heat transfer coefficients of zeotropic mixtures are lower hence require larger surface areas for adequate heat transfer. In a trilateral cycle, the liquid-phase working fluid absorbs heat from heating fluid in the cycle [35]. Use of this cycle leads to desired reduction in heat transfer irreversibility by adaptive temperature matching between the working fluid and the heat heating fluid. However, the design of two-phase expanders with high isentropic efficiencies is still challenging [98].

2.4.4. hybrid/combined cycles

These are integrated geothermal energy conversion systems i.e. combination plants or geothermal system in combination with at least one other different source of energy like solar, coal, etc. (hybrid plants) [105]. The overall objective in either arrangement is to achieve synergy and hence realize superior performance compared to separate or individual arrangements [105]. The benefits include higher utilization, higher thermal efficiency, increased net power output or more financial and economic benefits. Geothermal combined systems may consist of different types of flash-steam units and/or binary plants in an integrated combination that achieves advantages and benefits not realizable in separate units. Examples of hybrid systems include fossil-fueled plants, such as coal-fired central stations, gas turbines, biomass, or waste-to-energy plants, or concentrating solar thermal or photovoltaic plants working in conjunction with geothermal powerplant cycles like flash, binary or dry steam systems [105].

Combined cycles constitute a combination of two or more of the basic conversion cycles i.e., dry steam, flash, and the binary cycles [11]. The suitable combination is selected based on the steam temperature and pressure conditions, reservoir and fluid characteristics, investment cost, and application among others. Combinations include flash and binary, dry steam and binary, flash, and binary combined. Where a flash/binary hybrid plant is used, the fluid is first flushed to steam in a separator then steam is fed to the turbine as the separated liquid is directed to a binary cycle plant for extra power generation [76]. Other examples of combinations are single flash/binary, fossil/geothermal systems, etc. Any combination adopted should guarantee a higher efficiency, list cost and maximum power output [63,106].

i.) Flash/binary combined cycle

Depending upon of field characteristics, a geothermal powerplant design can be such that it starts with a flash followed by a binary unit which uses waste geothermal fluid to as the heat source and a secondary fluid on the working cycle to generate extra power. This will form a combined or hybrid flash-binary plant. In the first cycle, a flash plant is operated by geothermal fluid from the production well which acts as the working fluid and is directed to reinjection well after exiting the turbine but with possible heat recovery before it goes back to the reservoir [107,108]. The waste fluid leaving the separators can be sent directly to injection wells or can be send to the binary station for heat recovery. This improves overall generation since extra electricity is generated from the same geothermal fluid [90,106].

ii.) Solar-geothermal combination plant

An example of a combination plant is the Solar–geothermal plants whose main challenge in designing is how to manage the intermittent nature of solar energy versus the continuous nature of geothermal energy. Solar energy can supplement both geothermal binary and flash-steam plants by means of superheating and/or preheating of the working fluid. A basic binary cycle plant with a solar array of parabolic collectors is used to superheat the binary working fluid before it is fed to the turbine. The main challenge is the intermittence nature of solar availability and hence heating function [87,89,90].

In a more complex flash-binary plant with solar-brine heating, a moderate-temperature geothermal brine is heated with solar energy to the design flash temperature. The flash steam is then directed to a topping up back pressure turbine for power generation. The condensate or exhaust from the first turbine which is a back pressure turbine is used as feed to the condenser/preheater (C/PH) before being reinjected. Back to the reservoir. The hot-separated brine coming from the separator is then used to heat up the already preheated binary working fluid before it is mixed the steam turbine condensate before the mixture is reinjected to the reservoir [89,90].

iii.) Fossil-Geothermal powerplants

It is possible to develop a combination of fossil fuel powerplant and geothermal energy source for electric power generation [85]. This combination of geothermal energy and fossil fuels for power generation offers many thermodynamic advantages compared to individual technology approach. Different approaches that can be used include fossil superheating of geothermal steam, use of geothermal heat in preheating of fossil fuel powerplants feed water which then replaces some high grade steam which can be used for extra power generation [85,86], and development of a compound geothermal fossil power plants [85].

iv.) Combined Heat and Power/Cogeneration Cycles

Combined heat and power is simultaneous generation of electricity with heat or thermal applications which significantly improves the cycle efficiency [99,109]. Use of cogeneration systems leads to higher thermodynamic and environmental performance and reduction in unit cost of energy. CHP is increasingly used in geothermal energy exploitation as well as other renewable sources of energy like solar, wind and biomass. With huge quantities of low grade heat in geothermal fluid, cogeneration has a special role in geothermal energy utilization [109,110].

Cogeneration systems are classified into topping and bottoming up based on the sequence of energy exploitation adopted. In topping cycles, the energy supplied is first used for power generation followed by heat energy application, hence heat is a by-product of the cycle. Topping cycle is the most ideal for geothermal energy [111]. For a bottoming cycle, the energy is first used in thermal processes while rejected heat is used in power generation. These cycle are ideal in manufacturing like cement, iron and steel, ceramic production, gas production and petrochemical industries [90,111].

Therefore, there are various conversion technologies available for use in geothermal electricity generation applicable to both wellhead and conventional power plants. Selection of conversion technology should balance between efficiency, exergy, and cost optimization to ensure optimum geothermal resource exploitation. The factors considered in technology selection are efficiency, financial and economic factors and geothermal resource and reservoir characteristics.

2.5. Geothermal power project cycle management

A conventional geothermal power plant project is not a quick fix for anybody, organization or any country [5,6]. This is because it takes 5–10 years to complete a conventional geothermal power plant from project inception to powerplant commissioning and project handover for operation and maintenance. The project cycle has many phases, some being quite risky and expensive [112]. Geothermal project development is takes place in 5 major stages namely, exploration, full field development, power plant construction, power plant operation, and operations abandonment [83]. The execution of a geothermal project can also be broadly divided into two major parts namely, resource exploration and resource exploitation which are further divided into several phases. Resource exploration seeks to identify and locate the geothermal resource while exploitation part is concerned with resource development and exploitation of the geothermal resource which includes powerplant design, construction and operation [4,112]. The resource exploration part has significant financial risks as it involves huge investment capital without any guarantee of success as opposed to the exploitation stage has less project risks but has massive capital and technical requirements [113].

A conventional geothermal project has five major phases, which are geothermal resource exploration, resource feasibility assessment, design, and construction of the powerplant, powerplant operation and maintenance phase, and finally powerplant decommissioning phase. Specific steps and activities for the project, among others include desktop research and studies, field appraisal drilling, production well testing, production drilling, powerplant design, powerplant construction and commissioning and termination of the powerplant by forced or planned closure. However, just as many projects are, geothermal powerplant projects may be as unique as the projects and steam field characteristics are [114,115].

A seven-stage geothermal power project comprises of the following stages.

i.) Preliminary survey
ii.) Resource exploration
iii.) Geothermal well testing
iv.) Project planning and review.
v.) Construction of powerplant
vi.) Power plants start up, commissioning and handover of the project to operator.
vii.) Powerplant operation, maintenance, and reservoir management.
viii.) Power plant shutdown and abandonment/decommissioning [11, 112].

2.6. Wellhead power plants in geothermal project cycle management

Project management refers to the use of knowledge, application of skills, tools and techniques to project activities in a manner that meets or exceeds the expectations of stakeholders [21,116,117]. Project cycle management is should be applied in the design and realization of geothermal electricity projects as a way of delivering projects within cost and specification desired [23,31,115]. Project cycle management entails project planning, project organization, staff motivation, stakeholder engagement and control of the project. This is necessary to reduce risk of project failure or simply poor project delivery outside time, cost and scope [115]. Therefore managing a project an energy project like geothermal electricity projects involves directing and coordinating human capital, material resources and technology as a resource throughout the life of a project to deliver electricity within time, budget and scope [118]. Therefore, any project must pay attention to the cost, time, and scope for a project to meet expectations of stakeholders. The development of geothermal power projects should be in line with project management principles due to high upfront risks and costs involved in addition to huge capital requirements with long project delivery periods [116,117]. Fig. 3 below demonstrates project management scope which is useful in effective development of geothermal electricity projects.

Fig. 3 shows the three dimensions of a project; namely cost, time and scope. To successfully manage a project, its cost, duration and scope should be controlled to manage project quality and success. Therefore, wellhead power plants provide a strategy for successful delivery of geothermal electrity projects by reducing the time, cost and scope to deliver electricity from geothermal energy resources. There are three types of risks in the development phase of geothermal projects, namely;

i.) Resource risks which include difficulty in accessing geothermal resources and huge costs that do not necessarily lead to viable resource discovery

Fig. 3. Dimentions of project manegement [115].

ii.) Project delays and hence cost overun risks due to unexpected occurences during drilling and powerplant constructions phases.
iii.) Finacing risks associated with long lead times hence delayed cash returns and increased riks [43].

The use of a geothermal wellhead power plants in the project cycle will reduce scope and cost and hence the time needed to start generating electricity from a geothermal resource and improve the financial viability of the geothermal electricity project. As a project, geothermal power plant development needs adequate resources for its operation. Hence, technical feasibility of installing a power plant is highly depended on availability of adequate geothermal resource and lack of any restrictions to resource use and availability of project financing. Economic feasibility depends on electricity purchase price and availability of financial incentives. Environmental restrictions and policies will also influence successful approval and execution of geothermal wellhead power plants in terms of cost and technology to use [119]. The complex nature of geothermal electricity projects in terms of delivery period, risks involved, high capital require, high technical requirements and stakeholder interests calls for alternative options in the delivery, operation, and maintenance as well as application of geothermal power to realize high positive impact and project sustainability [14]. Wellhead power plants when used in the geothermal project cycle will reduce the scope by virtue of size and simplicity and overall project cost due to low delivery period and flexibility especially when used as temporary power plants [6,120].

2.7. Critical review

From the review of literature on geothermal power generation, it is noted that there exist many mature and efficient generation technologies like the dry steam technology, flash steam technology organic Rankine, Kalina, and hybrid technology. These technologies address the resource characteristics and efficiency of conversion, and they appear to serve the geothermal industry well in terms of energy conversion for different available geothermal resources. None of the technologies specifically addresses the main challenges facing geothermal capacity growth that have ensured that geothermal plays a minimal role and contribution to global electricity generation, yet geothermal potential is very large [25,30,121,122]. These challenges are high project cost, high upfront risks, and a very long project delivery period of 5–10 years [3,5,43]. Wellhead generators are modularized units [8,75], that can be quickly installed once a geothermal well is drilled and tested in the steam field development stage. This is to ensure that productive wells are not left idle in the process of developing a central power plant as more wells are drilled.

3. Wellhead power plants technology, design and construction

Wellhead powerplants are modular geothermal generating units that are factory designed and optimized for specific production well chemical and thermodynamic conditions and pre-assembled for specific site assembly [3]. According to [123], a geothermal power generating unit is "a modular miniature power plant installed close to the geothermal well pad." With power produced being supplied to the national grid, regional grid, off grid applications and cogeneration within business entities like flower farming and salt extraction. Therefore, Wellhead power plants are small geothermal power plants usually installed at the geothermal production well pad. They generally vary from 100 kWe and 15 MWe in installed generating capacity [5,9,124]. These power plants do not need extensive steam field development except for connections between the well and the plant on site [74], and usually make use of steam from a specific production well [39]. The wellhead generators can also be installed on a production well being tested after drilling, and upon completion so that besides being used to generate test data and reports, they can generate electricity for field use on temporary basis. This saves fuel needed to run diesel generators which are the main source of electricity for field development, mitigates pollution and can supply power to the local and public grid while project development is still underway [125]. Therefore geothermal wellhead generators put into useful application the idle wells between time of successful completion of production well drilling and completion of the central or conventional geothermal power plant, instead of plugging off a productive well for many years and months awaiting completion of a central power plant [23].

3.1. Technical characteristic features

The conventional geothermal power plants are generally large and therefore they enjoy economies of scale which leads to lower unit cost of electricity generation and higher efficiency, and better power plant performance indicators compared to the smaller power plants like the wellhead generators [99]. The main benefit of wellhead generators is probably their modularized design which increases their flexibility and facilitate quick project delivery at lower total costs compared to the large size central power pants. However the wellhead powerplants have a challenger of inferior performance in terms of specific steam consumption, which is steam used to generate a unit power output, lower plant thermal efficiency and therefore higher cost of power to consumers as compared to power from larger central powerplants [5,124].This is demonstrated in Fig. 4 below.

3.2. Relationship between steam mass flow rate and well head pressure

The wellhead generating plants are smaller equipment compared to central geothermal power plants [124]. Fig. 4 below shows the relationship between wellhead pressure and mass flow rate of steam from a geothermal well.

Fig. 4 shows the relationship between streamflow rate of a geothermal well and the prevailing wellhead pressure. If the steam pressure and the wellhead pressure is the same, then there will not be any steam flowing from the well to the powerplant.

There is maximum steam extraction for power generation if the net pressure on the wellhead is zero [74,124]. Therefore, wellhead power plants can produce optimum power from each well given steam characteristics are unique to each geothermal well. A geothermal well connected to a common separator will not contribute steam if the separator pressure is the same as the wellhead pressure. It is for this reason that in central powerplants, wells with pressure below separation pressure would be rendered unproductive while high pressure wells will be overloaded and forced to contribute the entire steam requirement at a lower power plant separator pressure. Therefore, there is need optimize the use of specific well character for maximum power production which is not possible in central power plants with a common separator and steam turbine.

3.3. Plant efficiency

Wellhead are smaller equipment compared with central power plants, which makes them less efficient, with higher specific steam consumption and less output from the same steam conditions compared to generation from central power plants [3,36,38]. This is the main limitation for wellhead power plants if all other factors are held constant [13,57]. The relationship between the geothermal fluid flow rate and turbine pressure for both central and wellhead power plants is illustrated in Fig. 5 below.

Fig. 5 shows the wellhead power plants have a higher mass flow rate of geothermal fluid/steam for similar turbine inlet pressure compared to large-scale central power plants. Therefore, on average, the wellhead generators have a higher specific steam consumption compared to the central powerplants.

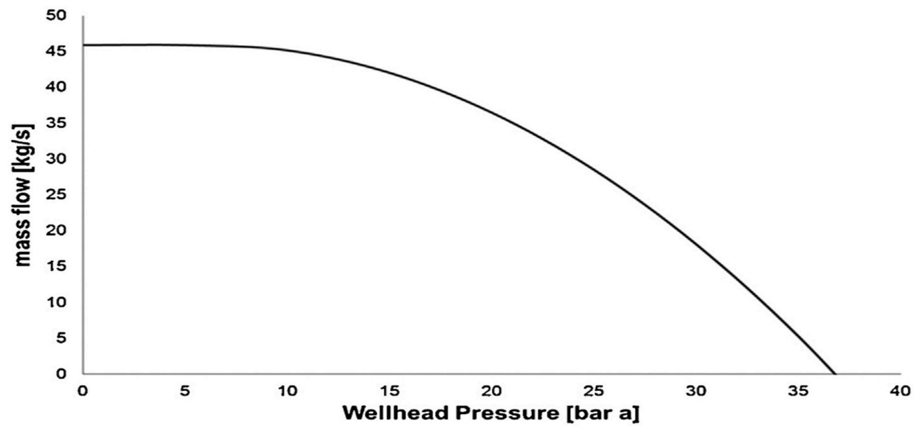

Fig. 4. Relationship between steam mass flow rate and pressure [74,124].

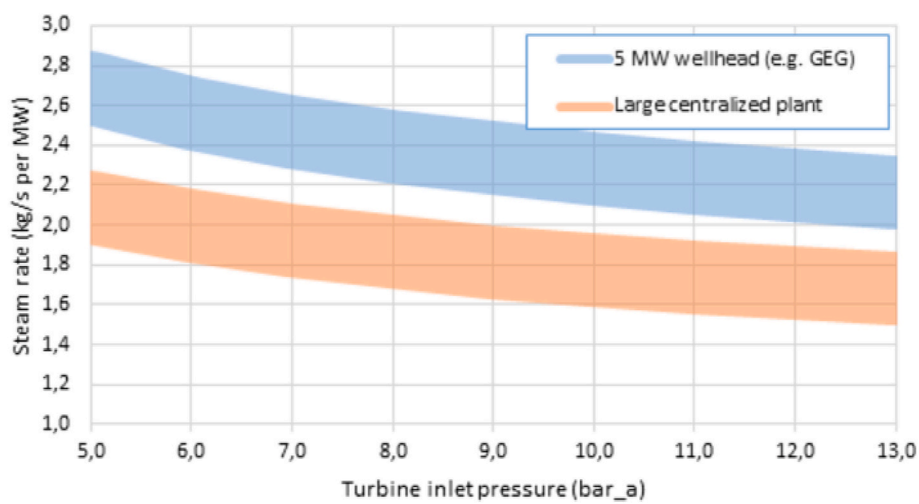

Fig. 5. Mass flow rate versus turbine inlet pressure for wellhead and centralized geothermal plants [3].

3.4. Well characteristics and optimization

In as much as central powerplants appear stronger and better in performance than wellhead plants, they have some limitations or own challenges worth noting. The steam separation pressure has an impact on the efficiency of the power plant equipment as discussed and demonstrated in Fig. 4 I section 3.2. The selection of separation pressure involves analysis of characteristic curves of individual geothermal wells to select the optimal separation pressure that yields the highest total output. In the process, a pressure is selected that may end up being too high or too low for specific well optimum operating conditions which will lead to reduced specific well generation and efficiency [5,126].

The geothermal fluid from different wells even in the same steam field are rarely identical in thermodynamic and chemical characteristics.

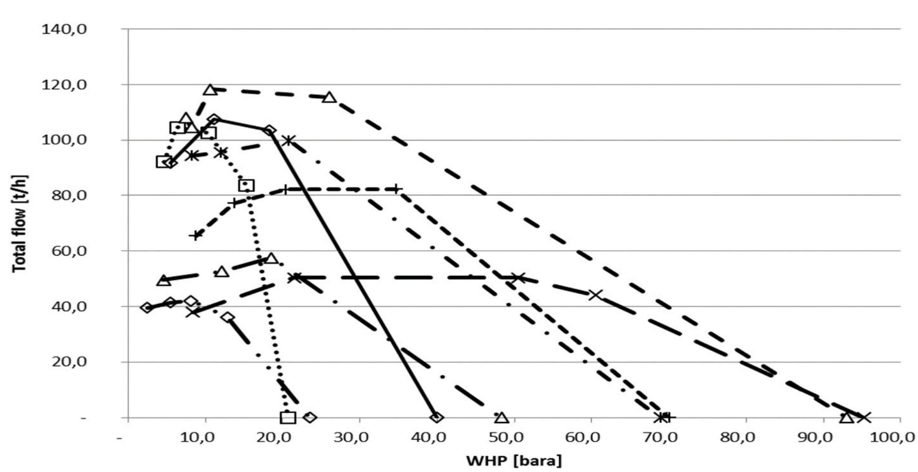

Fig. 6. Well flow rates versus steam pressure [74,124].

This implies that the characteristics of each well need to be established separately for development of optimal power generation option. With a single pressure system for central power plants, wells operate at combined optimal separator pressure conditions in terms of pressure and temperature [110,111]. As a result of this, some wells are rendered useless at the separation pressure for having pressure above their closing pressure. This leads to lost generation that can be as high as 5–20% of installed capacity [5,74,124]. Fig. 6 below shows production well steam flow as a function of steam pressure.

Fig. 6 above it is shown that selection of the separation pressure and hence powerplant design is an optimization process which should involve the analysis of each well characteristics separately. The figure shows individual well flow curves as a function of pressure and demonstrates that for wellhead power plants, individual wells can be independently optimized based on specific well optimal pressure to reduce losses and wastage. This approach would favor wellhead generators in fields where the geothermal fluid conditions like pressure, enthalpy and even chemical properties vary significantly [32,36].

Therefore, developing a geothermal steam field with wellhead power plants instead of a large-scale central power plant is worth considering. Since each geothermal field and geothermal well have different characteristics, it must be analyzed separately before design of the wellhead power plant. Having a mixture of wellhead plants for and central power plants in a mixed approach is another feasible alternative based on the steam field and well characteristics [5,74,124].

3.5. Complementary steam field development

In complementary development, the wellhead power plants are developed alongside a central power plant in the same steam field. Wellhead generation applies where the wells have high steam pressure or for the wells with lower steam pressure compared to others in the same steam field. The central power plants are developed for the majority wells with medium pressure wells with having a closer steam pressure range [14]. Fig. 7 below illustrates a complimentary powerplant development where a mixture of wellheads and central power plants are developed simultaneously.

Fig. 7 shows a complimentary development option where wells with higher pressure, low and intermediate pressure wells are connected separately within the same steam field. These leads to multiple power plants operating at different steam pressure levels in the same steam field.

3.6. Wellhead power generation systems

Wellhead and small geothermal plants are common features today and can operate as standalone plants or can be used within larger geothermal development program. According to Refs. [38,39,127], small geothermal power plants range from 100 kWe to 5 MWe. Other than electricity generation, small plants have other applications because of several desirable features which include cost effectiveness especially with diversified application of resources, can fit in the incremental project development strategy and can be installed early during site development.

It is possible to develop economically viable, small geothermal power plants with generation capacity of 100 kWe to 1000 kWe, using available technology for the production of electrical power [128]. According to Ref. [129], several other uses of small geothermal plants through development of topping and bottoming cycles. With advancement in geothermal electricity generation technology from low and moderate temperature geothermal resource with temperature of 100–150^{O}C, it is now common to find geothermal power projects below 5 MWe with integrated applications. Most wellhead geothermal power plants use binary or flash technology, but hybrid technology is also in use. There are cases where the power plants are used in cogeneration mode in which turbine exhaust steam or waste steam is put into direct thermal applications like horticulture, fish farming, process heating, and milk production among others [9,60,129].

3.6.1. Flash systems

The flash system can be in condensing or non-condensing turbine configurations. In non-condensing system, steam is exhausted from the turbine to the atmosphere either directly as shown in Fig. 3 below or an exhauster [9].

i.) Back pressure wellhead plants

In the back pressure or non-condensing system shown in Fig. 8, the system has no condenser. The back pressure wellhead power plant is like the condensing power plant, except that it has no condenser and cooling system. Back pressure system is simple in construction, and cheaper but has lower thermal efficiency. It is the simplest and by far the cheapest wellhead power plant design as shown in Fig. 8 below.

Fig. 8 shows the main elements of a backpressure/noncondensing turbine generator system. The main parts of the plant are the production well which delivers steam to the plant for the reservoir-injection well which takes brine back to the reservoir, flash tank or separator to separate brine ad steam and the turbine generator [4,5,9], steam separator, the turbine with electric generator. In wellhead units, the exhaust is normally blown to the atmosphere.

The back pressure plant is usually applied where the resource temperature is between 200 °C and 320 °C. The exhaust steam pressure is more than atmospheric pressure and the steam is not condensed at the exhaust [9,25,124].

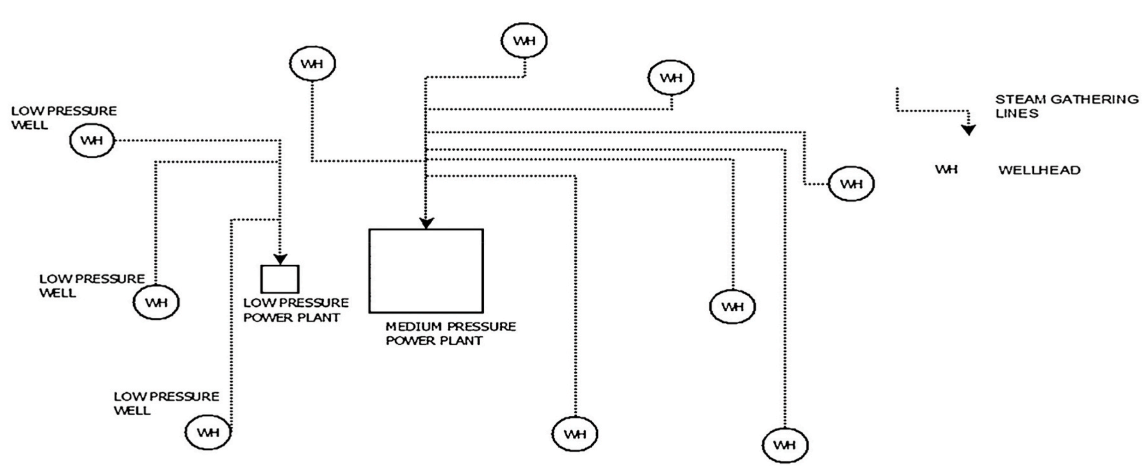

Fig. 7. Complimentary steam field development [14].

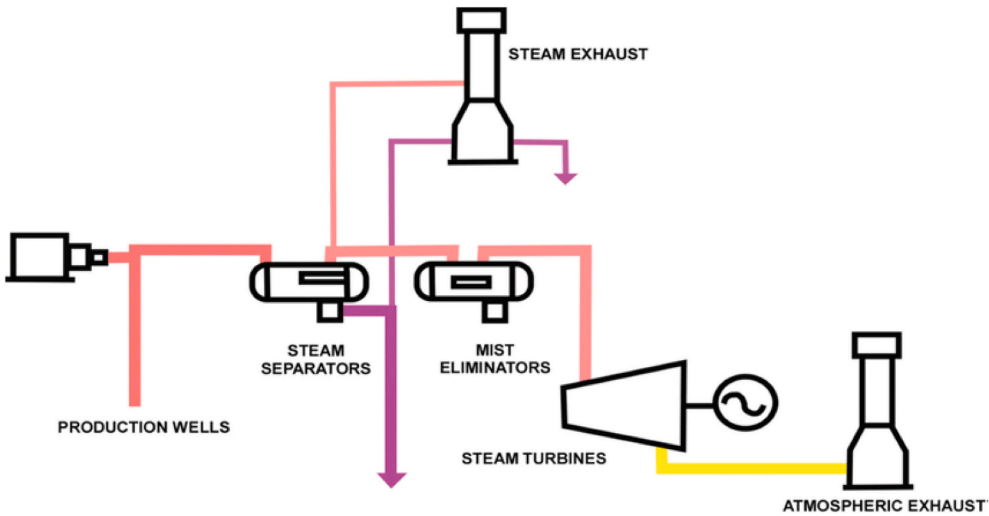

Fig. 8. Non condensing wellhead system with direct atmospheric exhaust [9].

The main advantage of back pressure units is that they are cheaper condensing power plant and binary plants, are simple in construction and are quick to construct and disassemble. On efficiency, since steam is not condensed, it has much more energy at turbine exit hence lower conversion efficiency [124]. Therefore back pressure wellhead power plants are the list efficient, cheapest and have multiple applications in supply of field development power, cogeneration, well testing, and hybrid generation [20].

The main feature of the backpressure turbine system is the release of the turbine exhaust to the atmosphere through an atmospheric exhaust device/system. In addition to the basic elements, a steam exhaust vessel through which non condensable gases and exhaust steam are vented off from the turbine. The system may also be equipped with other elements like the mist eliminators or dryers after the separator [99]. Venting is also provided at various points to remove the non-condensable gases. The main disadvantage of back pressure/noncondensing systems is that they have high steam requirements for similar power output compared to the condensing units. However they are the cheapest and are very attractive for use in geothermal well testing during steam field development [4,9,25].

ii.) Condensing turbine flash system

The condensing systems are equipped with a steam condenser to which the turbine discharges its exhaust steam. The condenser normally has pressure below atmospheric like 0.12 bars-a in some systems to facilitated efficient condensation. These power generating systems also yields greater power output for condensing systems compared with the back pressure systems for similar geothermal steam conditions and properties [9]. The system is illustrated in Fig. 9 below.

From Fig. 9 above, it can be noted that the condensing system has a cooling tower, condenser and cooling water pump which are not in the back pressure system. The common elements for both include the production well, reinjection well and the turbo-alternator [4,9,25].

3.6.2. Binary system

For binary cycle wellhead powerplants, the geothermal resource fluid from the production well is used to heat up the secondary working fluid by means of a heat exchanger between them. The working or power is expanded through the turbine to perform work which turns a generator for power generation. The system is applicable on low and medium temperature geothermal fluid [16]. The secondary fluid used can be ammonia, or refrigerants like Freon, pentane, butane, propane, Isopentane. The cycle adopted can be organic Rankine cycle, Kalina or Goswami cycles. The fluid coolants used are often coolers [4,9,34].

The organic Rankine cycle consists of four main parts, namely the turbine, evaporator, the condenser, and a feed pump. The working fluid is vaporized in the boiler before it produces mechanical work by expanding through a turbine. The rotating turbine then rotates a generator coupled to it for power generation. The turbine exhaust goes to the condenser where it forms a saturated fluid which is directed to a feed pump. The pump compresses it to the evaporator where the closed cycle is repeated [84]. Fig. 10 below is an illustration of a binary plant.

From Fig. 10, main features being the steam turbine generator,

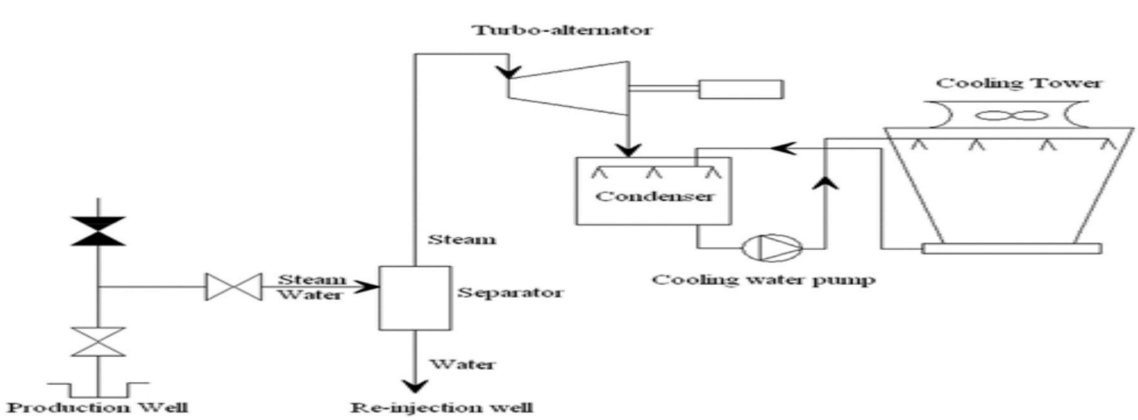

Fig. 9. The condensing wellhead power plant system [9].

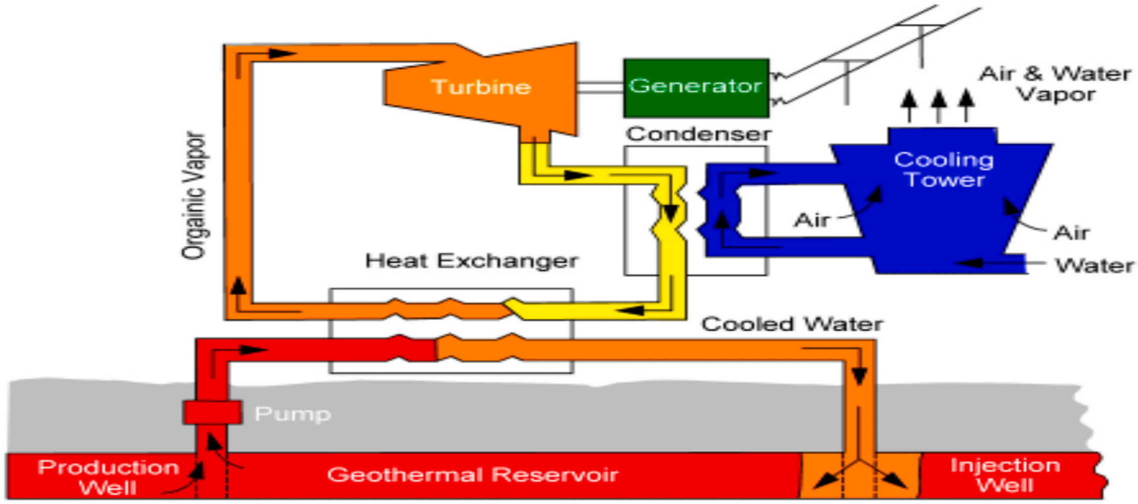

Fig. 10. Binary wellhead system [9].

production and reinjection wells, cooling tower, condenser, heat exchanger, cooling water pump and feed pump for the working fluid.

3.6.3. Cogeneration/combined geothermal heat and power plants

This is not a unique power conversion system, rather a generation arrangement that incorporates electricity generation and geothermal heat application, hence can be applied on all the generation technologies by exploiting the heat energy in brine after power generation. The integration of wellhead power plants with direct heat application for activities like crop dehydration, milk processing, greenhouse agriculture, fish farming, etc. facilitates off grid generation and diversification for better return on investment and hence viability of wellhead power plants [9]. An example of a practical cogeneration or combined geothermal heat and power is at Paratunka, Kamchaka in Russia which operated between 1960s and early 1970s [129]. This plant consisted of a binary plant producing 680 kWe with wastewater being used in a greenhouse. At Oserian in Naivasha at the Kenya's Olkaria steam field, a power plant producing 2 MW power also supplies heat for greenhouse flower farming [121,129]. The main objective of combined heat and power is to facilitate more efficient use of the geothermal resource. Low temperature geothermal electricity generation has low efficiency below 150 °C with net plant efficiency being between 7% for about 90^{o}Cand 12% for 150 °C [129].

The use of small geothermal powerplants in agriculture and industry has gained popularity especially with increased use of low to medium geothermal fluids below 150 °C in power generation. The waste steam is used to provide heat for agriculture, horticulture, fish farming, distilleries, dehydration and other process applications [130]. The Waste steam after expansion or from flash tank can be used to heat an organic fluid which then gets superheated and is used to run a steam turbine to generate electricity [57]. Heat in condensate and brine can be used for heat application via appropriate heat exchangers before reinjection to the steam field Fig. 11 below illustrates a combined heat and power plant where the waste heat from a wellhead unit is used for district heating.

Fig. 11 shows district heating and power generation arrangement from the same geothermal fluid which increases efficiency. Therefore, wellhead power plants can be used in combined heat and power where electricity is generated using a steam turbine and exhausted for process heating.

Integration of electricity generation in agricultural business and other direct geothermal activities can improve economic viability of low temperature geothermal resources and lead to higher overall efficiency for standalone wellhead power projects [9,49]. Other applications are agribusiness and agriculture production, industrial process steam/heat applications, distillation e.g., alcohol production, dehydration operations and milk processing.

This shows that wellheads and other small geothermal projects can

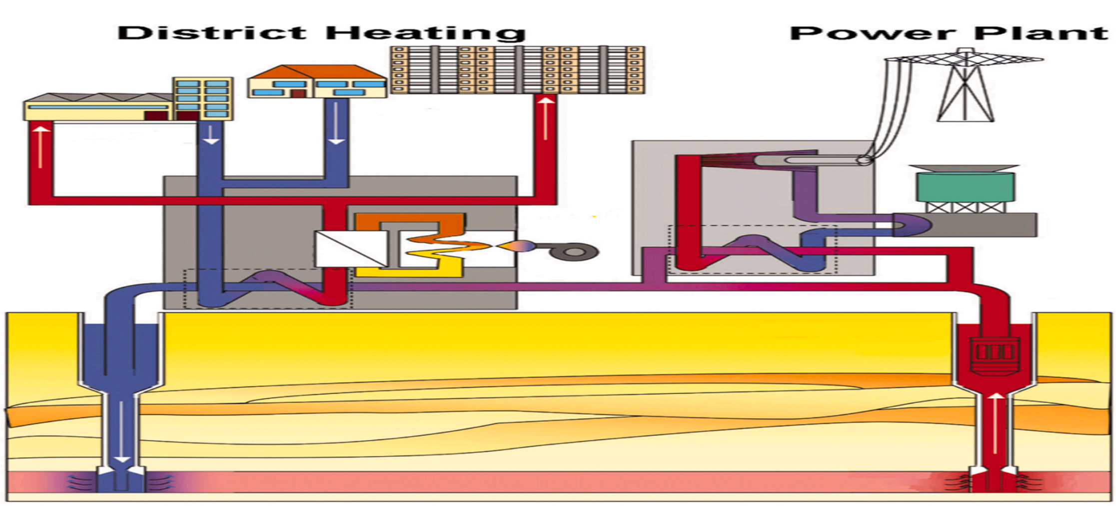

Fig. 11. Combined heat and power cycle. 150 °C [129].

be widely used not just for electricity generation but for heat application too. Several small geothermal power plants have been commissioned since 1904 but the focus is not grid electricity supply even though sufficiently excess power for export can be produced, which is the focus of this study. Table 3 below summarizes some of the small geothermal projects globally and their characteristics.

3.7. Construction of wellhead power plants

The generator units have of several parts and systems which include the fluid collection system, control system, grid connection system, and brine disposal system.

3.7.1. Well head power plant description

Wellhead power plants consist of four main systems, namely: the hot end or steam system, the cold end also called the condensing system, turbine unit, electric generator set and electrical & control systems. The turbine system often operates on back pressure and condensing system [4]. Fig. 12 below shows the main components of a well head power plant.

Fig. 12 above demonstrates the main features of a wellhead power plant which includes the separator, turbine, condenser, cooling towers, the control container as control room, silencer, generator, the production well and connecting steam piping. Fig. 13 below shows a photo of Olkaria geothermal wellhead plants in Kenya.

Fig. 13 above is a picture of showing five geothermal wellhead generators manufactured by GEG (Green Engineering Group Ltd.) on well pad WH-914, at Olkaria, near Naivasha in Kenya, with combined installed capacity of 27.8 MWe. The plants are assembled close to one another making it possible to have coordinated operation for all the units by same staff.

For wellhead powerplants the generator is located just next to the well and therefore it requires very minimal piping. This reduces the impact from visual effect, cost of piping and steam transmission losses [23]. The geothermal fluid the case of some wellhead plants like Eburru is disposed of in open pits. Reinjection of the fluid means each well will have own reinjection system or used fluid is collected from all or several plants and reinjected through a common well which makes reinjection system expensive to design and develop [5,126].

The operation and even maintenance of wellhead powerplants where a steam field is developed with wellhead generators is more complex and expensive since every wellhead wll have its own separate operations and controls besides common controls and management for the entire field [5,23,74,124]. Where electricity evacuating and transmission is done at low voltage distribution grids, the consumer behavior or trend may influence the operation of plants as they are affected by the demand trends with cases of frequent trips recorded at Eburru wellhead powerplant in Kenya [47]. Many transmission lines across a steam field where wellhead generators are used will have the challenge of visual effect from the many power lines crisscrossing the steam field for power transmission [5,126]. The solution in this case could be use of underground cables. On emissions, carbon dioxide and hydrogen sulphide are the most common emissions for both wellhead and central power plants and quantities as well as composition is not a function of whether or wellhead or central power plants are used [5,74,126]. For temporary application of wellhead powerplants, important consideration is ease of shut down and relocation in terms of time is important. The downtime and relocation time is influenced by the technology used and hence complexity of the power plant.

3.7.2. Wellhead decommissioning and relocation process

Wellhead decommissioning and relocation involves several activities. The process involves the following activities, removal of power evacuation and transmission equipment, removal of internal wiring in cubicles and generators, removal of pipes and flanges, removal of all insulations, connection or are cut into smaller portable pieces for welding at the new site and transfer to new sites. It is important to examine the steam supply for structural integrity so as to avoid use of faulty devices or parts from the previous installation especially parts like the control valves which are often affected by brine action [14,23,74,124] include:

The time required to relocate a wellhead power plant of 5 MW is as follows for three basic generation technologies summarized in Table 2 below [14].

From Table 2 above, it is noted that the backpressure plants are simplest and fastest to relocate followed by condensing and binary cycle generating units, respectively. The assumption is that the design is maintained and hence no changes during relocation, hence no need for modifications on layout and design [5,23].

3.7.3. Elements of the geothermal wellhead power plant

A wellhead power plant design is a modular design with standard components. The plant may operate independently for each geothermal well or arranged in a power farm in a way that substitutes central power plants or mixed central and independent plants. The plant is generally supplied in 40 ft ISO containers to the site with standardized key components to enable quick installation and dismantling [23,74,125].

According to Ref. [123], the layout is comprised of the following components:

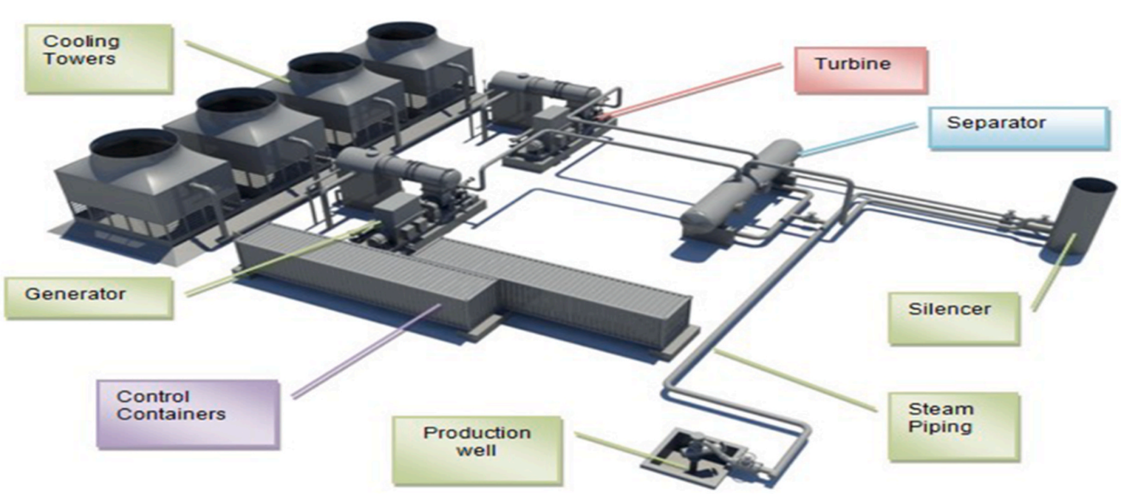

Fig. 12. Wellhead plant [8].

Fig. 13. Photo of five Olkaria geothermal wellhead plants in Kenya [131].

Table 2
Technology Comparison [5,14,74].

Generation Technology	Relocation time (Months)	Downtime (months)
Condensing generator units	6 months	3 months
Backpressure generator units	4 months	2 months
Binary generating units.	7 months	4 months

i.) The steam gathering system consisting of wellhead assembly, pipes, valve, steam separator, brine disposal system, pressure regulation system, brine level control system, flash water collection and delivery system.
ii.) A turbine with a generator unit, including their auxiliary devices.
iii.) Condensers, well pump, cooling towers, water circulation pump
iv.) An extraction system for non-condensable gases
v.) Electrical systems for power evacuation including transformers.
vi.) Instrumentation and control systems.

3.8. Characteristics and benefits of wellhead plants

Wellhead power plants possess attractive characteristics and applications as electricity generation system in the quest to increase the contribution of geothermal to the global electricity mix. These characteristics are as follows.

i.) They are easy to start compared with central powerplants and do not need auxiliary sources except for battery banks which are needed for instrumentation and control purpose.
ii.) They guarantee quick return on investment with less capital requirement making investment attractive.
iii.) They facilitate optimized geothermal resource use as they are designed to suit specific well thermodynamic and chemical characteristics, hence maximum possible generation is possible from a production well.
iv.) With quick installation of factory preassemble units, wellhead power plants are a solution to the long wait to realize electricity and revenue from geothermal by quick delivery of power generating units even before the steam field is fully developed.
v.) With small plant sizes and phased development with low capital requirements, wellhead powerplants reduce the risks involved in geothermal electricity project execution.
vi.) With optimized generation, the cost per unit generation can be reduced through maximum generation from a geothermal well as opposed to centralized power generation which can render some wells unproductive while some are underutilized depending on the common separation pressure selected for central power generation.
vii.) Since field operations are often powered by diesel generators, wellhead powerplants can be used to substitute the diesel plants hence this reduces cost of fuel and environmental impact. As an example, the development of Menengai well 03 and 04 in Kenya spent US $ 1.2 million in form of diesel power generation cost which was whopping 25% of the cost of the well drilling and development.
viii.) The development of wellhead powerplants offers flexibility that allow incorporation of other economic activities like combined heat and power to make better use of lower temperature brine or geothermal fluid.
ix.) Wellhead power plants have better powerplant performance indicators compared to the variable renewables like wind, solar and hydropower in terms of plant availability, capacity factor, reliability and in some cases, the unit cost of power [3–6,43].

Most of the wellhead plants are either binary, flash or hybrid of both flash and binary. In some applications, dry steam technology is used like the Geysers in the USA. With integration of wellhead/small power plants with other economic activities, the project's overall viability is increased making wellhead generation sustainable and competitive compared to centralized power generation. Small power plants consist of both single units and a combination of several small units. Technologies commonly used are flash, organic Rankine, combined cycle based on resource conditions. Most small geothermal plants are designed for waste steam use [19,32,36].

Research on the feasibility of wellhead power plants in Kenya showed that in cases where the wellhead power plants are connected to low voltage distribution grid network, their operations are unstable because they are often affected by the consumer trends, behavior, and activities. This leads to frequent trips as observed at Eburru wellhead power station in Kenya [4,6]. The overall effect of these trips and fluctuations is reduced plant availability, load factor and capacity factor and lead to negative environmental effect from the steam venting and blow offs. The studies further showed that wellhead power generation can realize availability of about 77.7%–92% and average load factor of 0.726, and capacity utilization of 81.1%, based on the performance analysis of the Eburru wellhead power plant. These parameters are lower than observed values of corresponding performance indicators for central power plants [4–6].

3.9. Qualitative differences between central and wellhead systems

There are significant differences between geothermal wellhead powerplants and the conventional or central power plants. These differences are summarized in Table 3 below.

Table 3 shows that the main differences between power generation from wellhead generators and the central power plants on the project duration, number of wells, operational capacity factor, efficiency and generation and delivery voltage, specific steam consumption and plant flexibility. The common features include the emissions and the steam characteristics.

The most significant physical feature of wellhead generators in geothermal power generation is their modular construction in which the parts are assembled on a single skid at the manufacturing and assembly facility for assembly on a specific site or location. The wellhead powerplants are also simple in construction because they need fewer permanent civil works, having already been assembled in the factory prior to transportation for site installation [8]. This makes geothermal electricity development projects simple, cheap, and quicker to execute as it takes between 3 and 6 months to assemble and commission. Customization of wellhead units to specific production well conditions make it possible to optimize generation from a given production well hence with maximum power generation. Therefore, use of wellhead generators ultimately mitigates the limitations of traditional methods of geothermal electricity development like long gestation periods of up to 10 years, high risks and costs and waste of steam from low pressure wells and higher steam pressure wells in each steam field.

Table 3
Conventional Versus Wellhead Power plants [5,23,74,124,125].

	PARAMETERS	CONVENTIONAL POWERPLANTS	WELLHEAD POWERPLANT
1	Set up period	The plant construction takes more than 2 years to complete and commission	The installation and commissioning generally take between 3 and 6 months
2	Customization	The plant design is not specific well dependent.	Wellhead generators are designed for a specific production well conditions
3	Production wells needed	Central power plants receive steam from multiple wells	Often use steam from a single production well
4	Power plant capacity factor (CF)	The conventional powerplants enjoy higher capacity factor	The wellhead generators operate at a lower capacity factor compared to central powerplants
5	Unit cost of power	Central powerplants enjoy economies of scale hence enjoy lower unit costs	Wellhead powerplants have higher unit cost of power since they do not enjoy economies of scale
6	Electricity evacuation and transmission	Usually at high voltage to grid transmission system	Can be evacuated at lower voltage and connected to distribution grids
7	Non condensable gases	Specific well dependent	Specific well dependent
8	Power plant Flexibility and mobility	Central power plants are fixed and rigid in design	Wellhead generators are flexible and can be relocated to different sites
9	Generation specific steam consumption (SSC)	The central powerplants operate at a lower specific steam consumption hance have better steam economy	Wellhead powerplants have a higher specific steam consumption hence consume more steam for same output
10	Power plant availability	Higher availability factor	Lower plant availability

4. Impact of conventional and wellhead power generation

The future of geothermal energy will be influenced by the degree to which geothermal power plants are sustainably and economically deployed [2]. Geothermal electricity projects generally take a long time, and often encounter delays before completion and commissioning. The projects are also associated with economic, social, technical and environmental challenges [132]. Geothermal resource development is risky and requires huge financial resources and technical capacity [4]. It is therefore necessary to do a careful feasibility study that covers technical, environmental, electricity demand, financial/economic, legal, and socio-economic aspects [6,132].

4.1. Economic impact of geothermal technology

Geothermal electricity development and power generation has a series of successive phases whose costs are affected by several factors and parameters. They include site, characteristics of the geothermal resource, powerplant type, design and size, as well as several prevailing market conditions like availability and cost of capital [133]. Geothermal electricity projects are often financed by a mixture of equity and debt. The normal financial structure which is often a requirement by financiers consist of 25%–30% equity with about 18% internal rate of return and 70%–75% debt financing with average of 7% interest rate. Most project developers prefer equity financing of projects, but commercial banks often require a minimum of 25% as equity financing [133,134]. Geothermal electricity generation cost is generally competitive with fossil fuel options. It has a levelized cost of electricity of about 9–13 USDcts/kWh, which places it among the cheapest renewable energy solutions. Therefore, geothermal energy provides low-cost, reliable, low-carbon and flexible grid electricity, but with the challenge of low rate of deployment [1].

Energy systems should be economically or financially sustainable. Economic and financial sustainability and progress requires that investors and financiers get expected cash inflows and return on investment [21]. The main advantage of geothermal energy is its steady availability for 24 h per day, 7 days per week, and 24 h per day compared to solar and wind whose availability is intermittent and unpredictable. This makes geothermal power plants operate at high load factors, high availability and hence ideal for baseload electricity supply. The unit cost of geothermal electricity from conventional powerplants is between US$0.05 and US$0.12/kilowatt-hours, making it competitive enough compared to fossil fuel sources like oil and coal [132]. The main limitation of geothermal power development is high initial investment cost in form of facility cots, infrastructure development costs, and very high risk in resource exploration and development [102]. It costs on average US$4 to US$8 million to drill a geothermal production well and reinjection well with no guarantee of discovering viable wells making the investment risky [4–6,132].

The development of geothermal energy resources yields significant social, economic and employment benefits with multiplier effects particularly in rural areas where most of the projects are located [24]. The exploitation of geothermal energy resources adds some value to the rural economies of the host community. A study by Ref. [135] in Poland covering the years 2005 and 2018 showed that geothermal related activities had a multiplier effect of 2.5, which implied that for every 1 US$ dollar invested, the result was US$ 2.5 in the value of economic activities. This implies that economic activities are increased by a factor of 2.5. Mankind is faced with decreasing environmental quality and increasing danger of driving the biosphere into a state that cannot sustain human life and civilization [21,136]. Additionally, humanity encounters social sustainability challenges like decreasing level of trust, reducing cohesiveness, and significant ecological challenges. This is often associated with increase in financial impact of social and ecological systems resulting from civilization and increasing demand for energy generation and use [136]. The economic significance of wellhead powerplants has been demonstrated by Kenya which was the first country to utilize wellhead technology for temporary and permanent grid power generation [11]. As a result, the country realized faster development of geothermal power with over 75 MW grid connected wellhead powerplants. This improved the revenue base of the Kenya Electricity Generating Company (KenGen), more jobs, more green or renewable energy for the national election grid by utilizing steam that would have otherwise remained unutilized or waste while awaiting development of central power plants and wells that would have been difficult to connect to the central powerplants [137].

The conventional geothermal projects take a very long period of time and are capital intensive which makes them unattractive to investors and financiers with regard to the time value of money borrowed [4,21,23]. In the study by Refs. [14,138] it was established that drilling a geothermal well takes 37–50 days, however in another study by Ref. [14] where drilling was assumed to take a normal distribution curve, the duration was found to be about 3 months or 90 days. The construction of a conventional power plant takes about 2 years to complete, while wellhead generators on the other hand take between 3 and 6 months to install after well drilling and testing and offer significant flexibility. This makes them attractive to both investors and developers as they guarantee quick return on investment and early electricity generation [4,23,74].

Geothermal investment costs are divided into surface costs which are related to steam development and subsurface costs which are related to resource development [2]. For conventional powerplants with capacity between 5 and 150 MW, a flash and dry steam powerplants cost between US$ 1000 and 2000/KW [2,139]. For a binary power plant of capacity 1–35 MW will cost between US$ 2285 and US$3000/kW [2,140]. For wellhead powerplants, the cost of a 5 MW condensing technology wellhead generator is about 1700 USD/KW while a 5 MW binary technology wellhead generator is about 2300 USD/KW. The cost of 5 MW back pressure wellhead technology powerplants is the lowest at estimated cost of 1500 USD/KW. These cost estimates include the main elements of wellhead generators i.e., the team separators, piping and elements for well connection, civil construction works, mechanical fittings and electric installations, control switches and systems, electric generator and all other necessary plant accessories [138]. The main cost element in subsurface geothermal resource development is drilling and testing. There is exponential increase in drilling cost with drilling depth [141]. For engineered geothermal systems, there is need to account for reservoir or well stimulation, which is about US$ 2.4 million per well stimulation, regardless of the drilling depth [2,142]. Other than capital or investment costs, operation and maintenance costs are very important in determination of the cost of power as well as the economic feasibility of a geothermal project. The operation and maintenance (O&M) costs are generally proportional to the amount electricity generation, but exponential decline with increasing plant capacity of the power plant [2,143]. In the research by Ref. [2] it was noted in his model that the cost of operation and maintenance decreases from 20 US$/MWh for a 5 MWe plant to 14 US$/MWh for a bigger 150 MWe geothermal power plant. Job creation is very important socioeconomic benefit of any capital investment. Geothermal power projects generally create 26 jobs per MW capacity which implies that a 50 MW geothermal power plant would create about 1300 jobs compared to 6 to 8 jobs for natural gas power plant projects. Which is significant contribution to the income and economic performance [24]. Security of electricity supply is an important social, political, and economic aspect of electricity generation. Since geothermal energy is generated from local resources, electricity from geothermal will reduce a country's dependence on imported energy resources and improve the energy security of a country [6,84]. Geothermal electricity improves on the trade deficits of a country by avoiding import expenditure. With wellhead power plants, these benefits are realized quickly at a lower risk [4,24,33].

Therefore, both wellhead and central power plants contribute to the economic development through generation and supply of electricity, which is a critical input for economic development, early return on investment, stimulation of the rural economies, direct and indirect employment, and taxes to central and local governments to varying degrees based on the size, number and types of power plant technologies used. In the study by Refs. [4–6], on the geothermal wellhead power plants in Kenya, it was demonstrated that wellhead power plants have high profitability with gross profits as high as 65% of the gross revenue from geothermal wellhead electricity sales to the grid. This implies that wellhead power plants have low operational costs and higher return on investment compared to central power plants. The average payback period of 4.4 years was observed for wellheads owned by Kenya Electricity Generating Company (KenGen), and this could be reduced to 3.4 years with tax incentives like tax reliefs and high grid electricity feed in tariffs for investors [4].

In another study by Ref. [43] it was noted that using wellhead power plants in the early stages of project development, was economically viable only if installed as a strategy for early revenue generation, continuous well testing and attracting private investors in geothermal power plant development. The study further showed that wellhead units increase the Net Present Value (NPV) and revenue of the project rather than waiting for many years to develop a central power plant. This study was based on a 5 MW wellhead power plant, with effective electricity prices of $0.088/kWh, had revenue projection of $4.5 million for time intervals (TI) of 3 years 6 months and $6.3 million for total time interval (TTI) of 5 years and 6 months, respectively. This study also showed that a 5 MW wellhead powerplant positive gives a Net Present Value (NPV) of +4 with the Internal Rate of Return (IRR) of 17% during its economic life but the parameters turn negative over total time interval (TTI = 5.5 years). The total capital outlay is estimated at US$ 15,000,000.

Therefore, wellhead power plants have significant economic and financial impact in terms of early revenue, jobs, multiplier effect to rural economies, less financial risks, early return on investment and makes investment in geothermal electricity more viable and hence attractive to investors and financiers. However, the overall benefit versus the central powerplants needs further investigation and detailed research.

4.2. *Environmental impact of geothermal power plants*

In the geothermal electricity project cycle, the environmental impacts begins to be severe during and after the exploratory with activities like drilling and well testing taking place among others [83]. Geothermal energy resources are often located in environmentally sensitive areas for example the Olkaria in Kenya is in the middle of a protected national park while the surrounding area is highly productive agricultural farmland with high population density; many human settlements and related socio-economic activities [48]. It is therefore necessary to control and manage geothermal activities to ensure less or no negative impact to the neighborhood and environment [5,11,48]. The environmental impact caused by geothermal energy is a function of the conversion technology applied and application of geothermal with direct application having the least negative effects. Geothermal powerplants do release some amounts of sulphur dioxide, carbon dioxide and hydrogen sulphite to the environment. The powerplants emit 97% less acid rain-causing sulphur compounds, and 99% less carbon dioxide compared to fossil fuel power plants of similar size. Reinjection of geothermal fluids reduces emissions and helps in resource renewal. Hydrogen sulphide naturally exists in geothermal reservoirs and can be reduced by scrubbing [144].

Geothermal energy resource exploitation cause causes several environmental effects of like changes in land use because of exploration and geothermal power plant construction, noise pollution, visual effect, discharge of water and gases, generation of foul smell, and soil subsidence. Modern technology available today mitigates most of these effects and minimizes the impact on the physical environment [145]. The greenhouse gas emissions and global warming potential is a very important consideration when considering energy options [146].The global concerns over high greenhouse gas emissions and global warming as well as other environmental challenges and impacts like acid rain has set in motion a global transition to a green and low carbon energy future [21,99]. In this transition, geothermal energy has a significant role to play [147]. However, like all other energy sources, wellhead power plants and other geothermal powerplants have several negative environmental effects that should be considered and mitigated. Successful utilization of geothermal resources for electricity generation is dependent upon availability of almost zero emissions and efficient heat/steam to electricity conversion technologies [50].

The growing need for energy system decarbonization has created high demand for renewable sources of energy. However, the main sources with greatest potential, solar and wind are intermittent in supply are difficult to control [148]. This makes geothermal energy a very attractive source of renewable and low carbon power [12]. The energy sector is the largest contributor to the greenhouse gas emissions, for example in 2010, it accounted for 35% of the total anthropogenic greenhouse gas emissions [149]. Carbon emissions grew by an annual average of 1.7% between 1990 and 2000 and increased to average of 3.1 between 2000 and 2010 [21]. To stabilize these greenhouse gases at low levels require a transformation of energy supply systems which includes substitution of fossil fuels sources with low carbon sources like geothermal, wind and solar [149].

There is a general consensus that geothermal energy is a clean source of energy [23,150]. A common feature in all geothermal powerplants is that most of them emit varying quantities of hydrogen sulfide (H_2S) which may or may need some special equipment for treatment to meet environmental regulations. The e Geysers in US have 0.15% hydrogen sulphide by weight. Current methods of treating non-condensable gases can reduce the composition of hydrogen sulphide (H_2S) by 99.9% [24]. In a study by Ref. [151], it was demonstrated that based on an Eco-Point single score calculation, wind energy is the best technology with a value of 0.0012 Eco-points/kWh followed by photovoltaic plant which had 0087 Eco-points/kWh just before geothermal power plants that achieved a value of 0.0177 Eco-points/kWh. This is lower than many national energies mix Eco-points/kWh which has an average value of 0.1240 Eco-points/kWh. Geothermal energy like all other forms of electricity and heat generation, whether renewable or non-renewable, have both environmental impacts and benefits [52,152].

The positive impact of geothermal energy is avoiding generation of polluting sources like diesel and coal power pants which emit CO_2, SO_2, NOx, ash and other pollutants in relatively larger quantities [52]. However, geothermal power generation, whether wellhead or conventional technology has some negative impacts to the environment in form of gaseous emissions, liquid effluents like brine spills or overflows, and other undesirable audio-visual effects including steam blow offs, noise pollution and interference with animal and plant natural habitats. According to Ref. [124] steam pipelines and power transmission lines have visual impacts while Carbon dioxide (CO_2 and hydrogen Sulphide (H_2S) emissions are same for a geothermal well regardless of the generation mode adopted. However, for wellhead power plants, the emissions are distributed over a wider area hence reducing the intensity over the generation area, but similar quantities of emissions are expected from wellhead and central geothermal powerplants. The level of emissions from geothermal fluid is a function of the fluid chemistry and conversion technology used, with the organic Rankine cycle technology offering the best solution in terms of minimizing the non-condensable gas emissions, whether used for wellhead or central power plants [4,5,11,74].

Geothermal wellhead plants have some negative, environmental consequences just like the central power plants. According to Ref. [47] venting of geothermal fluid from production well especially upon plant tripping is one of the challenges of wellhead generation like for the cases of Eburru EW-01 production well. This venting leads to silica deposits on neighboring crop farms leading to protests and demand for compensation by farmers in 2012. The main reason for frequent venting of wellhead well was high proportion of water in the steam from the production well and frequent electricity power line tripping due to overload since it is connected to low voltage electricity distribution network.

The potential for surface instability is one of the serious environmental concerns of geothermal power plants. This is because geothermal plants extract geothermal fluid from reservoirs within the earth crust, which can make the land above to sink over time [25,94,153]. To reduce this risk, geothermal fluid reinjection into the earth via re-injection well is done to reduce the risk of land subsidence. Induced seismicity is another consequence associated with geothermal energy exploitation. This may happen when large quantities of geothermal fluid is extracted and injected below the earth's surface [24]. Several wellhead powerplants do not have reinjection wells to create this massive recirculation, although this practice is not a sustainable way of using geothermal energy resources and instead enhances the risks of getting land subsidence. Geothermal energy is only regarded as renewable and resource use sustainable, only if the rate of geothermal fluid extraction is less than the rate of recharge [21].

All power plants have some land requirements, environmental consequences, and impacts. Geothermal power plants have a low carbon foot print and require between 1 and 8 acres of land per MW compared to 5–10 acres for nuclear and 19 acres per MW for coal power plants [24]. Since wellhead power plants have no steam field pipe networks and are located just next to geothermal well pad, the land requirements are significantly lower and related environmental impact of geothermal power plants include land subsidence and micro seismicity which may be influenced by the nature of the steam field, steam extraction and power generation technology adopted. According to Ref. [154] geothermal power plants can be sited or located within farmlands and protected areas since they have less land requirements and generate minimal solid waste.

During exploratory drilling as well as field development, environmental impacts include soil erosion, dust release and depositions, emissions and effluent from drilling and diesel generation and related emissions, and noise from the construction of the access road and drilling pad, air pollution from release a non-condensable gas in steam, steam venting, and related noise and visual effect, brine contamination of soil and surface water sources, among others. At the Geysers in US, about 75–80% of steam going to the power plant is emitted to the atmosphere. With the smaller remainder being condensed and reinjected into the reservoir. The non-condensable gases in steam are a major air pollutant. The common non condensable gases in geothermal fluid are carbon dioxide, methane, hydrogen sulfide, ammonia, hydrogen, nitrogen, argon, and radon. The most hazardous non condensable gas is hydrogen sulfide which has a characteristic "rotten egg" smell [83]. Hydrogen sulfide concentration as low as 0.03 parts per million by volume can be detected by the sense of smell [4,6,83].

Geothermal development as well as operation activities like geothermal well drilling, drilled well testing, cleanout and engineering construction of plant and steam pipelines are noisy and can be nuisance to nearby human settlements and animal habitat in protected areas. The main threat to water from geothermal development is of streams from soil erosion arising from earth work, spillage of drilling fluids condensate from powerplant operations. Soil from earthwork is also a threat to the geyser due to sedimentation. There are also cases of geothermal well casings failure from corrosion, blow-out, tool damage, as well as land slippage which can lead to possible contamination of the groundwater resources. Therefore, geothermal operations have negative impact to the environment during development as well as operation and maintenance and is common to wellhead and central powerplants [54,155].

4.2.1. Environmental impact of wellhead power plants

The operation of wellhead powerplants encounters several notable challenges. These challenges include plant trips during operation which causes steam blowing, noise and deposited of brine on nearby farms. Non-condensable like hydrogen sulphide and carbon dioxide gases present a significant environmental challenge except for organic

Rankine technology where they remain confined in the working fluid loop and re-injected through the injection well. To control the non-condensable gases, a gas extraction system should install [50]. In the study by Refs. [46,156] on environmental impact of Eburru wellhead power plant in Kenya, it was established that the local community has been impacted negatively with high levels of hydrogen sulphide, higher ambient noise levels, high boron concentrations and other negative environmental impacts. These effects are discussed below.

i.) The chemistry of brine effluent exceeds recommended requirements for effluent discharge to the environment in terms of total dissolved solids, pH, electrical conductivity, chlorides, Boron, and Barium.
ii.) The hydrogen sulphide in the atmosphere away from the power plant exceeded the tolerant limits of 0.0355 ppm as far a 100 m in the northern direction of the power plant.
iii.) The ambient noise levels exceeded tolerable limits of 35 dB [A] as far as 1100 m from the power station although the level is not too high to cause hearing impairment.
iv.) The commissioning of Eburru wellhead power plant, brought conflicts between the local community and the power plant owner/operator. Notable environmental issues include crop damage due to venting of geothermal fluids resulting from several trips of the plant.
v.) Between July 2014 and December 2015, Eburru wellhead plant realized 383 trips which led to venting of the plant with serious environmental implications.
vi.) Heat or thermal pollution in form of hot geothermal fluid is a common scenario whenever the geothermal fluid is not reinjected back to the steam field. This hot water causes damage to flora and fauna and can also cause accidents if not well secured.
vii.) In Philippines, it was observed that atmospheric venting of production wells produced brine spray that defoliated up to 100 m of dense forest from the geothermal production well [25,125].

According to Ref. [157], there is use to sustainably exploit geothermal resources by extracting and reinjecting the geothermal fluid in right quantities to avoid environmental disasters like land subsidence and disappearance of land manifestation features like the geysers. This was experienced in New Zealand. In Kenya, blow offs occasioned by frequent trips of Eburru Wellhead Plant leads to conflicts with local farmers due to brine deposits from geothermal well [47].

Several environmental challenges related to geothermal resource exploitation from wellhead power plants have been noted. The challenges include pollution from brine where there is no brine injection, noise pollution and repugnant smell mainly from hydrogen sulphide (H_2S) gaseous emissions and deposits of brine on crops and neighboring settlements [61]. With many trips experienced at Eburru wellhead technology, the environmental and technical sustainability is subject to further investigation while their suitability to supply base load power like the conventional powerplants needs further investigation. This is because base load plants should be reliable with high-capacity factor and power plant availability [4,11,52,76,152]. The negative environmental impact of wellhead power generation is summarized as follows.

i.) Water is often emitted to the atmosphere as steam and in the process, releases hydrogen sulphide, carbon dioxide, methane, and other dissolved substances from the geothermal system.
ii.) Vegetation is destroyed initially during field development while during wellhead operation phase, deposits of geothermal fluids cause damage to natural and crops.
iii.) Noise pollution from cooling towers, steam blowing, turbine operation and initially during drilling and power plant construction.
iv.) Negative landscape effect because of development of high voltage transmission and distribution powerlines, road networks, plant and machines and related auxiliary equipment during development and operation phase.
v.) The absence of reinjection wells for most geothermal wellhead power plants can trigger surface subsidence and localized earthquakes over time for example in Switzerland, geothermal development at Basel and St. Gallen was suspended after hydraulic simulation triggered earthquakes.
vi.) Long term use of wellhead power plants can lead to drying up of surface water springs and well, drop in levels of water aquifers due to continuous extraction of geothermal fluid with less or no reinjection [4,5,11,74,123,152,155].

4.3. Social impact of geothermal electricity projects

Generally, investment in geothermal energy projects adds societal value in terms of direct and indirect employment. However, geothermal energy related activities in general offer less jobs than the traditional energy sectors of the economy [135]. All electricity generation projects are to some degree associated with conflicts between the community, investors and project developers [5,74]. Investors in wellhead geothermal plants should engage the local community as early as possible for the project to be executed with minimal resistance. According to Ref. [47], experience by Kenya Electricity Generating Company PLC. (KenGen) demonstrates the need for an inclusive environment and social impact assessment. This is necessary to facilitate early engagement of the community which yields better results and should therefore be encouraged for all projects [11,46,116].

The best way to achieve social acceptance of a geothermal project is through participation. The principal parties in the participation are who should engage seriously are the resident or the local community and the project managers [158]. Stakeholders should be engaged using various approaches like through workshops, consultative meetings, site exchange visits, public presentations and hearing, and participatory research. These will facilitate two way communication between the project developers or government and the local community to gain project acceptance [23,47]. Successful engagement requires proper stakeholder identification so that the right stakeholders and issues are addressed [4,116,117]. The main stakeholders in development of geothermal wellhead power plants include; the local community who constitutes neighbors of the power plant, the regulatory authorities including the environmental management authorities, the donors or financiers who provide funding for the projects, consultants for the project employers and the government, various contractors and subcontractors, the project commissioner or investor, government officers from respective line ministries and agencies, local administrators as well as NGOs (Non-Governmental Organization), CBOs (Community Based Organizations) and other members of the civil society.

A study by Refs. [23,48,52,156] showed the following socio economic impacts of both central and wellhead power plants based on studies carried out at Olkaria geothermal fields;

i.) The local benefit through use of facilities developed by the geothermal electricity companies like water supply, shops, and the schools.
ii.) Very few of the locals are employed mainly on casual and manual jobs like security guards, messengers, cleaners, laborers, and contracted services like carpentry.
iii.) Fear of effect of increasing dust levels and repugnant smell the project could bring if it expands towards their homesteads.
iv.) Increasing cases of respiratory diseases especially asthma, eye problems, colds, and flu's which locals attribute to the emissions from the geothermal power plants
v.) The Maasai community who resided in the vicinity of the power plants claimed that they were displaced/resettled from their homes without compensation as they were simply told to move from the project sites.

vi.) Reduction in land size(s) as the project expands which negatively affects their main economic activity which is raring cattle and other livestock as grassing land is taken away.
vii.) Geothermal projects led to reduction in family size due to the gradual reduction in community land which affects their cultural heritage.
viii.) The local community complains about incidents of miscarriages and children being born with deformities or retarded. They attribute this to existence of the geothermal electricity activities.
ix.) The local community complains of foreign cultural attitudes penetrating their culture and causing cultural conflicts because of interaction with outsiders.
x.) Unsustainable exploitation of geothermal resources can lead to the reduction of water levels and eventual drying of natural water springs, wells and rivers which provide fresh water to local communities and wildlife.
xi.) The local communities like the Maasai have limited access to electricity and rely on firewood as the source of energy even when they live next to the geothermal power stations.
xii.) Extensive pipelines which are a major feature with traditional geothermal power plants and less with wellhead power plants can interfere with the migratory paths of wild animals hence negatively impact on natural habitat as most of these geothermal resources in Kenya and Japan and many other countries are in protected natural habitats like game parks.

These studies show widespread negative perception of geothermal power generation activities by local communities. With proper project planning and execution, the general environment of surrounding communities can be protected. Project acceptance can be improved through participation in the project planning and execution. The natural habitat should also be protected by sustainable resource use e.g. use of reinjection wells and protection and securing of wildlife migratory paths and keeping a safe distance between the community and the power plants activities [4,21,23,48,156]. According to Ref. [48] socio economic impacts are unavoidable in all geothermal power plant projects, but the impact can be reduce by consulting the affected community and individual and application for the most effective methods and technologies [4,11,23,48].

Geothermal wellhead generation has been associated with conflicts which similarly arise in development of conventional geothermal power plants, although to varying degrees in a number of environmental aspect [47]. They include failure to implement agreed actions and responsibilities to the community by the developer, for example the Kenya Electricity generating company failed to honor agreed compensation made in 1980 leading to mistrust between the developer and the community [47]. Cases of the host community trying to get unfair benefits have also been encountered. An example is false claims of damage by the community to investors which is exploitative and dishonest [47]. Conflicts also result from incitement by politicians and other interest groups seeking support from the community by magnifying real or imagined impacts and challenges of the projects [47]. In another example of conflicts reported in New Zealand, where historical conflicts between Maori and European immigrants made gaining trust from Maori difficult for geothermal developers yet it is quite essential [157].

To solve conflicts, a geothermal wellhead project should have a stakeholder committee to represent the interests of all project stakeholders [4,116,117]. Stakeholder committee should have local administrators like the area local chief and assistant chief for the area, elected chairperson, liaison officer representing the investor and representatives of each administrative unit like villages [47].

4.4. Technical and operational factors and indicators of geothermal energy

Various technical parameters and factors are used to measure the performance of geothermal powerplants. They include heat extraction rate, conversion efficiency, well productivity, electric power generation capacity and output, capacity factor, reinjection, reservoir lifetime, and resource reinjection [2]. The capacity factor for most modern central geothermal powerplants is between 90 and 95% [2,159]. In the study on the performance of wellhead powerplants in Kenya, it was established that the capacity factor for operating wellheads varied from 70% to 90% [4–6]. Geothermal fluid reinjection in geothermal power generation is a long-time practice which ensures that often more than 95% of the geothermal fluid is reinjected back to the geothermal reservoir. This helps to limit loss of pressure and ensures that a heat carrier i.e., the geothermal fluid is always present. By design practice, reinjection wells are usually located at the lower elevation relative to the production wells. This makes the use of reinjection pumps dispensable. Where this is not possible, then the use reinjection pumps become necessary design requirement [2,139]. As opposed to the central power plants, studies by Refs. [3,4] point out lack of reinjection for the wellhead powerplants at Olkaria and Eburru in Kenya and many other cases. This raises questions over the long-term technical sustainability of geothermal wellhead power generation.

The reservoir Operating time is an important consideration in geothermal powerplant design and operation. This time is influenced by the extraction rate and recharge rate either through natural means or through reinjection or both. The higher the rate of extraction, the higher the lower the reservoir operating life, but this can be extended by reinjection of used geothermal fluid. This implies that a lower leads to longer lifetime and increased production. Depending on the natural recharge, this value can be significant [2].

5. Results and discussion

Geothermal powerplants have several benefits compared to fossil fuel sources like supply of power with high load factor and availability but they also have challenges like high upfront costs, risks in resource development and limited availability of feasible resources [102]. Geothermal wellhead generators are small geothermal power plants with capacity generally between 0.1 and 15 MW that are installed at the well pad of a geothermal production well. Their design can be optimized to a specific well condition by avoiding interconnection of wells with steam at different pressure to a common separator which can render some low-pressure wells unproductive and those and unique high enthalpy will remain underutilized for the pressure far greater than the common separator pressure which is wasteful. Through wellhead power plants, the design operation pressure is specific to a specific well since wells even from the same steam field often have different thermodynamic, physical, and chemical properties. For example, if 3 wells one at 18, 15 and 6 bars are connected to a separator pressure of 10 bars, the well at a pressure of 6 bars won't contribute while the well at 18 bars will have underutilized capacity. To facilitate temporary application and relocation t new sites, wellhead generators can be made modular to allow for easy relocation to another well when needed [3,4,124].

The main environmental effect of geothermal powerplants is realized in air quality including noise, pollution, land pollution which includes soil erosion, land subsistence, seismicity, interference with wildlife natural habitat, visual effect, and contamination of natural water bodies with brine. Since central powerplants and wellhead powerplants use the same well conditions, technology adopted influences the extent of environmental pollution, for example use of extraction systems for non-condensable gases, use of organic Rankine cycle and injection wells are some of the measures that can be put in place to limit pollution in both central and wellhead powerplants. The energy conversion technology adopted has no bearing on the chemistry and thermodynamic properties of the geothermal fluid or brine.

5.1. Advantages of wellhead power plants

Based on application and steam field as well as specific production well characteristics, wellhead generators have several benefits or advantages when used in geothermal electricity generation[160]. The various advantages are discussed below.

i.) Wellhead power plants are ideal for countries with strict environmental regulations which make development of central power plants restrictive. An example is Japan where almost all geothermal resources are in restricted national parks while environmental regulations are relaxed for all power plants of capacity less than 7.5 MW. Therefore, it is wellhead powerplants that provide generation option for these restricted areas.

ii.) Some cities in several countries have transport restrictions for heavy loads making it difficult to develop large power plants in some locations which favors small wellhead plants that are light and easy to transport without breaking the law.

iii.) It is possible to connect wellhead generators to distribution grids instead of the transmission grid which effectively reduces transmission losses and distribution losses. This further reduces the cost of power to consumers.

iv.) The use of wellhead plants facilitates simultaneous electricity generation wd wellhead testing to establish the steam field characteristics and performance ahead of full-scale resource development without waste of steam.

v.) Since wellhead generation plants do not need auxiliary power source except a battery for instrumentation systems, the plants can be in remote locations without grid power supply. This makes them ideal for remote locations and even off grid electricity applications.

vi.) The investment in wellhead generators enables investors to realize early revenue and electricity supply which improves the financial viability of geothermal energy and electricity projects. This is because of the short lead times of 3–6 months after drilling a production well.

vii.) With wellhead power plants, it is possible to optimize generation from a specific production well because the wells operate in isolation and are not affected by neighboring wells which often have unique geothermal fluid conditions.

viii.) Wellhead generators are portable and easy to move from one location to another which makes them ideal plants for use as mobile power plants especially for geothermal development field operations and other remote operations within geothermal fields.

ix.) The wellhead plants have very little steam piping requirements making them easy and cheaper to install and with little environmental impact compared to large power plants used in central stations.

x.) Wellhead power plants have fewer financial requirements and investment risks compared to other large scale power plants making them more attractive to investors and project financiers.

xi.) It is easier to take advantage of unique characteristics of each well and select optimum points on the load curve for use by the well head hence optimum output can be realized for individual well characteristics. It also eliminates redundancy of low-pressure wellheads and waste of steam from high pressure steam wells which are well above the separator pressure.

xii.) Wellheads have attractive feed in tariffs in many countries e.g., Kenya hence offer better and quick returns to investors in most countries with geothermal resources.

xiii.) Wellheads are less complex and hence easy to operate and maintain thus guarantee high profit margins and electricity availability. This guarantees higher returns on investment.

xiv.) Data on the geothermal resource can be gotten simultaneously with electricity generation hence early determination of site-specific chemistry problems ahead of the development of a central power plant. This contributes to reduced project delivery periods.

xv.) A wellhead power plant reduces investment risks since the cost of the unit is amortized over the lifespan of the unit rather than the entire geothermal energy project.

xvi.) Wellhead plants get brine from one or two wells thus eliminating the challenge of mixing brine from different wells. Mixing brines may result in troublesome precipitation like in the case of Cerro Prieto since brine from different wells may have different chemistry.

xvii.) It is possible to make additional increments of generation easily and quickly than in central plants and hence cover any electricity shortfalls and emergencies. Therefore, wellhead power development facilitates phased delivery of geothermal power from a geothermal field which reduces financial pressure and failure risks. Phased implementation and successes give confidence in the geothermal field, and this forms the basis for bigger investment.

xviii.) Wellhead power plants present an opportunity for a user to lease a unit and hence become his own developer or investor during geothermal project implementation.

xix.) A wellhead generator and equipment are reusable and can be moved from one geothermal field to another [5,8,23,47,74].

5.2. Limitations/disadvantages of wellhead plants

There are several obstacles in the development of conventional powerplants which have increased the demand for wellhead powerplants [14]. They include large capital requirements, difficulty in raising project capital, long project duration and resource scarcity and variation in resource characteristics [14,60]. The use of wellhead powerplants fully or partly solve some of these challenges [4]. However, the use of geothermal wellhead plants faces several challenges which include:

i.) Developing a steam field with wellhead generators means many similar parts is needed for many wells in a steam field which increases installation, operation, and maintenance costs.

ii.) Wellhead power plants have challenges of handling brine and effluents since most wellhead units have no reinjection wells which increases environmental impact from brine/geothermal fluid and unsustainable resource exploitation.

iii.) Wellhead generators need many electrical transformers and transmission networks elements from a given geothermal steam field compared to central powerplants because of each operates as a standalone plant unit. This also has a negative impact to the environment in terms of visual effect causes by the many electricity transmission and distribution lines cross the steam field.

iv.) The long-term viability is yet to be established since for now they are commonly used for short term applications during steam development stage. Little data is available for permanent wellhead units.

v.) There are queries on reliability and long-term economic viability of geothermal wellheads power plants due to several missing parts or equipment like reinjection systems although some are designed with these systems [4,43,120].

The main advantage of using wellhead powerplants is the quick delivery of electricity but have several limitations like compared to the traditional plants. These limitations include some limitation of capacity and hence the plants miss out on the benefits of economies of scale as compared with the central plants. If a wellhead or mixed development mode is adopted, the development requires multiple equipment like transformers for each generating unit and a local network of evacuation powerlines which cause an irritating visual impact like the one caused by the wide pipe network connecting wells and the powerplant in a central power plant which in some cases traverses a wildlife and human habitat causing undesirable interference and also translates to increased land requirement and logistical challenges in evacuation of power from the many units wellhead units in a geothermal field. With the technology being new in the market, grid connected wellhead power generation comes along with technical and operational challenges and need to train staff to acquire new skills. The technology also requires special treatment like tax and investment incentives with higher feed in tariffs to compete with the superior and established central power generation. Since wellhead powerplants are designed for a specific well, any challenge affecting one well will paralyze operations unlike the central powerplants where some wells can be isolated as operations continue with or without derating of capacity [160].

5.3. Application of wellhead plants

Geothermal wellhead powerplants have been in use for several years in geothermal project development. Several other feasible applications have been identified over time [14]. According to Refs. [9,32], the applications include;

i.) They can be installed as grid connected permanent power plants.
ii.) Wellhead powerplants can be used for onsite industrial applications where they supply power to rural or remote industries located close to the geothermal steam field or reservoirs.
iii.) Wellhead power plants can be used as peaking units for large installations where they supply peak power in addition to the base load supplied by the central units or other powerplants.
iv.) The wellhead units can be used alongside the central power plants. Can be used as standby generating units for the main central power plants where they supply electricity to auxiliaries during startups or when they are shut down for maintenance.
v.) The wellhead plants can be used for off grid power supply in remote and isolated areas without grid power connectivity like military bases, remote villages, mines, isolated towns etc.
vi.) The wellhead generator units are used in well testing to ascertain the characteristics of a specific geothermal production well. The most used Wellhead power plants for well testing are the back pressure steam turbines with open air exhaust.

Table 4
Results of the study [2,8,23,31,34,47,74,142].

ASPECT OF COMPARISON	PARAMETER	CENTRAL	WELLHEAD	REMARKS
Economic	Cost of powerplant	US$ 1000–3000/KW	US$1500–2300/KW	Central powerplants enjoy economies of scale hence have a lower cost of plant per unit capacity.
	Total Cost of power	0.05USD/kWh to 0.12USD/kWh	0.08 to 0.15 USD/kWh	The wellhead generators are cheaper and simple in construction since they use smaller and fewer parts that are installed as factory preassemble units.
	Operation and maintenance cost	US$ 14/MWhrs	US$20/MWhrs	Central powerplants enjoy economies of scale and hance have lower operation costs per unit output.
	Cost of geothermal well drilling	US$ 4–8 million	US$ 4–8 million	Wellhead powerplants are installed on normal production wells meant for central power plants
	Drilling duration per well	44–90 days/well	44–90 days/well	The time taken to drill a production well is independent of the conversion technology
	Project delivery period	2–10 years	3–6 months	This is based on duration after first well drilling. Wellhead powerplants can guarantee faster delivery of electricity
	Economic multiplier effect	2.5	≤2.5	The multiplier effect of conventional geothermal projects is higher than that due to wellhead generators
	Payback period	≥10 years	≤4.4 years	Investment in wellhead powerplants guarantees early return on investment with a shorter payback period.
Technical	Size	0.1 KW- 15 MW	Size influenced by techno-economic size. Generally, above 20 MW	Wellhead generators are meant to produce electricity from a well or few hence limited capacity and size of plant compared to conventional powerplants. Current wellhead technology allows up to 15 MW
	System reliability	95%	70–90%	Wellhead powerplants ten to have higher outages and hence lower system reliability
	Powerplant load factor and capacity factor	90–95%	70–90%	Operational challenges tend to reduce the load factor hance often operate below their optimum rating
	Reinjection of geothermal fluid	Design requirement	Often missing	A number of wellhead powerplants have no fluid reinjection which is a threat to the long-term sustainability of resource use
	Conversion technology	Use dry steam, flash, binary and hybrid conversion technologies in permanent and fixed construction	Use similar technology as the central powerplants but on a smaller scale. Turbine system used are condensing, back pressure and extraction type based on application and cost	Technology used is determined by application, resource conditions and affordability based on cost and technology.
Environmental	Pollutants	The main challenge is emission of non-condensable gases like CO_2, H_2S, NH_3, N_2, Argon, radon. Also, water, land or soil pollution and noise.	The main challenge is emission of non-condensable gases like CO_2, H_2S, NH_3, N_2, Argon, radon. Also, water, land or soil pollution and noise.	Pollutant type and quantities are influenced by the characteristics of the reservoir and not the conversion technology. However binary cycles result in least pollution since the geothermal fluid is confined in the closed loop. Conventional and wellhead powerplants have similar environmental impact based on conversion technology and brine chemistry.

vii.) Wellhead power plants can be used in during geothermal steam field development to supply power for drilling and other field operations to substitute diesel powerplants. They can also be used to generate power during well testing instead of blowing steam to the environment.

5.4. Summary of wellhead features and characteristics

This study demonstrates the significant potential and benefits of the use of wellhead generators in geothermal electricity. The results of this research on the characteristics and the role of wellhead powerplants in geothermal electricity generation is presented in Table 4 below.

From Table 4, it is shown that geothermal wellhead power plants are attractive and competitive geothermal electricity generation facilities and so can be used to accelerate geothermal electricity generation using existing conventional technologies in smaller scale but are faster and cheaper to execute.

5.5. Research findings

The study showed the following major findings about geothermal wellheads power plants in grid electricity generation.

i.) Because of their limited size and hence lack of economies of scale, the unit cost of power from Wellhead powerplants is more than central power plants, and the wellhead plants technically less efficient than central having a higher specific steam consumption (ssc) compared conventional. This implies that a steam field developed with wellhead powerplants alone will yield less power for the same steam use assuming other factors remain constant i. e., the plants have same flash pressure and standard steam conditions.

ii.) For optimum use of steam from wells with significant variation in steam conditions, in the same geothermal steam, wellhead powerplants will give better performance as each well will be operated at its optimum conditions not average conditions as in central power plants.

iii.) In cases where most wells have similar steam characteristics but a few, it may be more feasible to have those with too high or too low pressure and temperature operated separately as wellhead powerplants while those with similar characteristics can be connected to a central geothermal power plant. Therefore, wellhead generators are installed on wells with lower and higher wellhead pressure, while wells with intermediate pressure with similar characteristics are connected to a central power plant.

iv.) Wellhead conversion technology can be selected based on cost or efficiency based on the geothermal fluid conditions. The back pressure wellhead units are the cheapest, but they are the least efficient power plants, followed by the condensing power plant, but the available power output is lower than and less efficient than the condensing and then ORC power technology plants are the most expensive but also the most efficient units ideal for medium and low temperature geothermal fluids. The back pressure units are also the simplest in construction and ideal for temporary applications in steam field development including well testing.

v.) Emission of non-condensable gases mainly in form of carbon dioxide (CO_2) and hydrogen Sulfide (H_2S) emissions are well specific and are not a function of the conversion technology. However, the use of Organic Rankine cycle technology for wellhead units will limit emission to the environment as the geothermal fluid is only used in heat transfer in a closed loop. The flash system and back pressure systems release huge quantities of condensable gases to the atmosphere. However, both central and wellhead units have similar emission activities except that in wellhead units, the emissions are widely dispersed in the steam field away from a central generating plant area.

vi.) Some countries have strict environmental regulations which prohibit large installations in protected zones. Unfortunately, most of the geothermal resources are in protected areas as in Japan. Under such like conditions, wellhead provide the only feasible way of exploiting the geothermal resources in protected land. A large network of hot pipelines needed for central power plants may interfere with wild animals' migratory paths which is an interference with the natural habitat.

vii.) Developing a field with wellhead generators increases cost of operation and maintenance since each wellhead generator has got own operation and controls in addition to combined controls for several wellheads units or the entire steam field. .

viii.) Developing a steam field with many wellhead power generators leads to a network of many power lines crossing the field causing visual effect and interference with animal migratory paths.

ix.) There are various applications for wellhead generators and can be used on permanent or temporary basis. In the case of temporary applications, important factors to consider are relocation time and cost of installation as well as complexity. Back pressure turbines have the least assembly and relocation time requirements.

x.) In general, wellhead generator units can be found in sizes of 0.1–15 MW. However, the most common and more cost-effective size is 3–5 MW. The optimum size is based on prevailing wellhead and fluid characteristics of the specific production well. Other factors to consider are costs involved and operational requirements like venting and separation pressure.

xi.) The is a challenge of resource use sustainability and pollution from brine or geothermal fluid where wellhead power plants are not developed with reinjection wells. Where they are used, each my need own reinjection if they are widely spaced making the investment expensive.

6. Conclusions

Geothermal energy has a significant role to play in the global transition to renewable and low-carbon energy systems because of its ability to supply steady and flexible electricity particularly for baseload demand because of its cost competitiveness with fossil fuel energy options. However, geothermal faces a challenge of long project development times with conventional power plant taking average of 5–10 years and with high risks associated with drilling and unproductive wells which discourage private investment and quick deployment. Although geothermal energy has a huge potential for power generation, it currently contributes less than 1% of global electricity generation capacity. The generation capacity grew from 8.7 GWe in 2005 to 15.61 GWe in 2020, representing average annual growth of 4.01%. Wellhead and central geothermal powerplants can adopt various conversion technologies that are common to both although to different sizes. The main reason why geothermal generation growth is low and hence limited contribution is that it takes a very long time between the time the first viable resource is established and the time to construct and operate a central powerplant which exerts financial pressure to financiers and developers. It is this challenge that wellhead generators can be used to address by putting to immediate use the wells that have been drilled and tested. The main difference between wellhead power plants and the conventional powerplants is that wellhead power plants often use steam from one or in some cases few closely located geothermal production wells with limited steam pipeline connections and steam field development.

Wellhead power plants have generated interest because of their modularity and simplicity which facilitate faster construction, commissioning and power generation leading to shorter lead times of about 6 months compared to the conventional central geothermal power stations which take many years, generally between 5 and 10 years. With the current technology and existing geothermal resources, it is possible to sustainably develop wellhead power plants with capacity ranging between 100 kWe to 15 MWe. However, we have some incidents where wells with significant pressure and capacity have been drilled, signifying the need to further develop the technology for such wells and steam fields. The plants can be developed for temporary or permanent applications. With proper design and execution, wellhead power plant technology can reduce project lead times, early electricity generation for field development and grid connection, off grid application and faster return on investment and hence reduce project risks and enhance access to financing.

Technically, the central power plants enjoy economies of scale compared to wellhead powerplants and therefore are superior to wellhead powerplants in many powerplant performance indicators which include capacity factor, availability, load factor, unit cost of power generation, among others. On the other hand, the wellhead power plants possess unique and desirable characteristics like quick project delivery and short lead times, optimal use of specific geothermal wellhead thermodynamic conditions like temperature, pressure, and brine characteristics for maximum power generation by optimization of flash pressure and temperature as well as well flow characteristics which influence the installed capacity and technology selection as opposed to central powerplants whose design and operation is guided by average parameters of the entire steam field and all connected wells. Selection of the flash pressure often leads to underutilization of high enthalpy wells and even cutting out of low enthalpy and low-pressure wells. Both wellhead and conventional power plants. Selection of conversion technology should balance between efficiency, exergy, and cost optimization to ensure optimum geothermal resource exploitation. The available geothermal energy to electricity conversion technologies includes dry steam, flash steam, binary, combined and hybrid conversion technologies. The factors considered in technology selection are efficiency, financial and economic factors and geothermal resource and reservoir characteristics.

Some desirable economic features of wellhead generators include reusability hence savings on initial cost, lower investment capital requirements, flexibility and portability of generators, and faster electricity generation capability. There is need to carry out detailed socioeconomic studies to establish economic viability of wellhead power plants ahead of implementation to guarantee viability. Overall, wellhead powerplants have significant economic and financial impact in terms of early revenue for investors, early electricity for steam field development, hence savings on conventional energy since diesel powerplants are often used to power rigs and other field operations that need electricity. Jobs created and power generated in the early stages of the projects in temporary application as well as including aft multiplier effect to rural economies, less financial risks, early return on investment permanent applications enhances decentralized generation while boosting rural economies with stable electricity and revenue to local authorities and communities. This further adds value and makes investment in geothermal electricity more competitive and viable and hence attractive to investors and financiers. However, investment in wellhead generators make economic sense when the time difference between the instant the wellheads start generating and the time the traditional powerplants start generating is more than one year but required adequate economic evaluation ahead of investment.

. On the environment, geothermal energy exploitation does not cause serious negative impacts to the environment compared to fossil fuel. The main challenge with most wellhead generators is lack of used fluid injection well hance the challenge of disposal causing brine related pollution. This also hampers the sustainability of resource use as lack of reinjection limits the replenishment of the geothermal resource in the reservoir. Therefore, geothermal fluid reinjection should be considered as a necessary measure for sustainable geothermal resource use especially where the wellhead power plants are installed on permanent basis for sustainability purpose even though it will increase the installation cost. Common environmental issues from operating wellhead powerplants include noise pollution and steam blowing especially during plant trips and brine pollution where reinjection is not practiced. Participatory techniques should be applied to mobilize the local community and resources to guarantee social sustainability of the wellhead powerplant projects. Participatory research can be used to generate facts on effects of geothermal on the environment and hance develop mitigation strategies. This strategies and measures can enhance project acceptance and increased social value of wellhead power generation.

Despite the limitations highlighted, wellhead power generation promise to be a viable solution to the many challenges facing geothermal electricity generation namely high risks and slow rate of project development due to long delivery times and huge capital requirements for conventional or central geothermal powerplants. The wellhead power plants should be incorporated in geothermal electricity generation projects both for temporary and permanent application. Generally, wellhead powerplants can make geothermal electricity projects more feasible with reduced barriers in investment and the commercial operation date.

7. Policy and general recommendations

This study has demonstrated the significant potential of wellhead power plants in the faster and economical realization of geothermal electricity either as temporary, permanent, or mixed wellhead and central power plants. Policy recommendations suggested including the need to give serious consideration for brine reinjection for geothermal powerplants. Policy incentives include tax holidays and reliefs for wellhead plant equipment and attractive electricity feed in tariffs.

Disclosures

Funding

There is no funding provided for this research by any third party.

Availability of data

The authors provided all available data and information for this research but welcome any clarifications and additional information through email or other forms of communication available and accessible to them.

Authors contribution

The first author developed the manuscript draft under the guidance of the second author who provided editorial and technical guidance as research advisor. The authors jointly agreed on content and format and submission for peer review and publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors wish to acknowledge various leading companies for their continuous innovation and development of wellhead geothermal systems.

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