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Review on life cycle environmental effects of geothermal power generation

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ABSTRACT

A comprehensive overview of potential environmental effects during the life cycle of geothermal power plants is presented using widely scattered available information from diverse literature sources. It is shown that so far only few studies provide quantitative estimates on both direct and indirect environmental consequences. Life cycle assessment (LCA) studies on geothermal electricity production are scarce and typically country- or site-specific with a focus on the geothermal fields in the western USA. In fact a general assessment is challenging due to the dissimilar nature and maturity of currently applied geothermal power plants, the influence of site-specific characteristics, and uncertainty in long-term productivity. Especially life cycle fugitive emissions, the thread from geological hazards, and water and land use effects are highly variable and may even change with time. Based on our survey, ranges are provided for emissions and resource uses of current worldwide geothermal power generation. We also define an approximate universal case that represents an expected average. The collected data is suitable to feed life cycle inventories, but is still incomplete. Potential emissions of critical toxic substances such as mercury, boron and arsenic and their local and regional environmental consequences are particularly inadequately addressed on the global scale.

Contents

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1. Introduction

Geothermal energy is thermal energy generated and stored in the earth. Ninety-nine percent of the earth's volume has temperatures $>1000\ ^{\circ}C$, with only 0.1% at temperatures $<100\ ^{\circ}C$. The total heat content of the earth is estimated to be about 10^{13} EJ and is therefore immense. The main sources of geothermal energy come from the residual energy available from planet formation and the energy continuously generated from radionuclide decay. Planet earth can afford to give away heat to the atmosphere, with a thermal power of 40 million MW_t (equivalent to the thermal power of about 13,000 nuclear power plants of the 1 GW_e class) without any cooling. Thus, the geothermal resource base is sufficiently large and basically ubiquitous. Geothermal resources consist of thermal energy stored within the earth in both rock and trapped steam or liquid water. Utilization is in two main categories: electricity generation and direct use (for space heating, balneology, greenhouses, etc.). In our contribution we exclusively focus on high-enthalpy geothermal energy use for power generation [1–3]. For direct use and low-enthalpy technologies such as ground source heat pump (GSHP) and groundwater heat pump (GWHP) systems the reader is referred to recent comprehensive reviews [4–8].

Geothermal energy is counted among renewable energies, with a long tradition, experience and great potential for the future [9–14]. As for all other alternative environmentally favorable power generation options, the life cycle of such technology is also associated with environmental impacts. The objective of this study is to provide a structured review on life cycle environmental effects of geothermal power generation. These include emissions, energy and resource usage, as well as social consequences. The compiled information is intended as a basis for a life cycle assessment (LCA), which is a standard and normed procedure to reflect and assess all environmental effects during the life cycle of a service or product.

In the following, first the standard geothermal plant types are shortly described. Then, in a comprehensive review of heterogeneous available information sources, environmental consequences during the life cycle of geothermal power generation are categorized with a qualitative and when possible quantitative discussion. These consequences include land use, geological hazards, noise, emissions to atmosphere, soil and water, energy and water use. Then the findings from the few available life cycle assessment studies are compared, and as far as possible a state-of-the art data inventory is consolidated.

2. Technology description

Geothermal power plants take hot geothermal fluid (or steam) from depth and convert their heat to electricity; the conversion efficiency depends mainly on the fluid's heat content/temperature. The temperature commonly decreases with depth, and is different between geologically active and young areas, in comparison to older and “cooler” regions. Thus, most attractive for this technology are those few geologically young areas worldwide, where very high geothermal gradients are found. This means that in a few hundreds or even thousands meters depth abnormally high temperatures are present, and ideally productive reservoirs with high volumes of stored geothermal fluids and/or steam exist. In contrast to these hydrothermal geothermal reservoirs, petrothermal production is focused on geothermal reservoirs with no or marginal water (hot dry rock, HDR). The latter are typically created through mechanical or chemical stimulation and counted among engineered geothermal systems (EGS). These represent a category of rather new plant types that generate electricity from greater depth and thus can also be applied in other areas of normal geothermal gradient. For example, at the scientific pilot EGS project at Soultz-sous-Forêts (France), the installed capacity is now 1.5 MW. However, EGS still have only a marginal share in the worldwide installed capacity with 10.9 MW in 2010 [2] and accordingly are not further discussed in the present study.

Geothermal power plants consist of numerous components such as production/reinjection boreholes, connecting/delivery pipelines, intermediate equipment like silencers/separators, power house (including turbines/generators, controls) and cooling towers. Each of them has environmental effects and adds to life cycle contributions, some of them only temporary (e.g. during construction), some of them lasting (e.g. silencer noise). These effects and contributions are treated in subsequent chapters “Direct environmental impacts” and “Review of Life Cycle Assessments”; here the various power plant components are briefly described.

Since it is not practical to transmit high-temperature steam over long distances by pipeline due to heat loss, most geothermal plants are built close to the resource. Given the required minimum spacing of wells to avoid interference (typically 200–300 m) and the usual capacity of a single geothermal well of 4–10 MW_e (with some rare, spectacular exceptions), geothermal power plants tend to be in the 20–60 MW_e range, even those associated with large reservoirs. The current (2012) largest geothermal power plant operates with a capacity of 140 MW_e at Nga Awa Purua, Rotokawa geothermal field, New Zealand and is fed by only six production wells. Much smaller plants, in the range of 0.5–10 MW_e, are common as binary-type plants. Below the main geothermal power plant types are briefly described, mainly after DiPippo [1,15], where more details can be found. We can distinguish different technologies, with a current worldwide share in electricity produced as shown in Fig. 1. Average capacity and energy produced

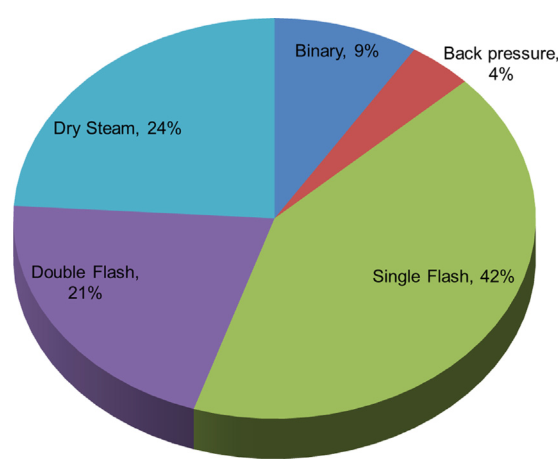

Fig. 1. Share of different geothermal plant technologies in global electricity production (after Bertani [2]).

for major plant types (hybrid excluded) are about 5 MW/unit (binary, back pressure), 30 MW/unit (flash plants) and 45 MW/unit (dry-steam) [2].

Dry-steam plants are used at high temperature (> 200 °C), vapor-dominated (or dry-steam) reservoirs. Dry-steam reservoirs are rare, the only known major fields being Larderello in Italy and The Geysers in California, USA. Dry, saturated or slightly superheated steam is produced from wells. The steam carries non-condensable gases (NGC, mainly CO_2 und H_2S) of variable concentration and composition. Steam from several wells is transmitted by pipeline to the powerhouse, where it is used directly in turbines of the impulse/reaction type. In some countries, back-pressure, exhausting-to-atmosphere operation is possible in accordance with local environmental standards (=back pressure plants). Because of NGC found in geothermal steam (typically 2–10% by wt of steam, but sometimes higher), the gas extraction system is a critical plant component.

Usually, 2-stage steam ejectors with condensers are used, but in some cases vacuum pumps or turbo-compressors are required. The condenser can be surface-type or (more often) direct contact-type. The former is preferred whenever the NCG stream must be treated or processed before release to the atmosphere, e.g. whenever emissions limits for hydrogen sulfide (H_2S) would be exceeded. In such cases, an elaborate chemical plant must be installed to remove the hydrogen sulfide. The steam condensate is not recirculated to a boiler as in a conventional power plant and is available for cooling tower makeup. In fact, an excess of condensate (typically, 10–20% by wt of the steam) is available and is usually injected back into the reservoir. Mechanical induced-draft cooling towers, either counterflow or crossflow, are mostly used for wet cooling systems, but natural-draft towers are selected at some plants.

The most common type of geothermal reservoir is liquid-dominated. For artesian-flowing wells, the produced fluid is a two-phase mixture of liquid and vapor. The quality of the mixture (i.e. the weight percentage of steam) is a function of the reservoir fluid conditions, the well dimensions, and the wellhead pressure, which is controlled by a wellhead valve or orifice plate. Typical wellhead qualities may range from 10% to over 50%.

The conventional approach is to separate the phases of the two-phase flow and use only the vapor to drive a steam turbine. Since the wellhead pressure is fairly low, typically 0.5–1.0 MPa, the liquid and vapor phases differ significantly in density ($\rho_l/\rho_v = 175$–350), allowing effective separation by centrifugal action. The liquid from the separator may be injected, used for its thermal energy via heat exchangers for a variety of direct heat applications, or flashed to a lower pressure by means of control valve or orifice plate, thereby generating additional steam for use in a low-pressure turbine. Plants in which only primary high-pressure steam is extracted are called single-flash plants; plants utilizing both high- and low-pressure flash-steam are called double-flash plants. About 20–25% more power can be generated from the same geofluid mass flow rate by using double-Flash technology than by single-flash. The two-phase flow from the well(s) is directed horizontally and tangentially into a vertical cylindrical pressure vessel, the cyclone separator. The steam transmission lines are essentially the same as in the case of dry-steam plants and are usually fitted with traps.

Binary plants are employed for low geofluid temperatures below about 150 °C, or for geofluids with high dissolved gases. In a binary plant, the thermal energy of the geofluid is transferred via a heat exchanger to a secondary working fluid for use in an Organic Rankine Cycle (ORC) or Kalina Cycle [1]. The secondary working fluid with low boiling temperature evaporates and drives the turbine. There is a wide range of candidate working fluids, such as hydrocarbons with low boiling temperatures (e.g. isobutane, isopentane, propane). The geofluid itself does not contact the moving parts of the power plant, thus minimizing, if not eliminating, the adverse effects of erosion. Most binary plants operate on pumped wells and the geofluid remains in the liquid phase throughout the plant, from production wells through the heat exchangers to the injection wells. Binary plants are well suited to modular power packages in the range 1–3 MW per unit. Standardized, skid-mounted units can be factory-built, tested, assembled and shipped to a site for rapid field installation. A number of units can then be connected at the site to match the power potential of the resource.

Either water or air may be used for cooling depending on site conditions. If wet cooling is chosen, an independent source of make-up water must be found, since (geo)steam condensate is not available as it is in the case of direct- or flash-steam plants. Due to chemical impurities, the waste brine is not generally suitable for cooling tower make-up.

3. Emissions and environmental impacts

Current installed capacity worldwide is around 13 GW, and by the year 2010 totally 24 countries have been generating geothermal power [2]. Of these 24 countries, USA, Philippines, Indonesia, Mexico, Italy, Iceland, New Zealand, and Japan produce more than 90% (Fig. 2). This reflects the focus of geothermal power plants at specific locations of high geothermal gradient, such as geologically young and active volcanic areas. Here, geothermal reservoirs can be accessed in shallow depths of usually less than 2000 m. Even if engineered geothermal (EGS) systems are slowly on the rise, they require deep wells of several thousand meters depth. This makes them technologically more demanding and economically less attractive. Still, substantial growth rates are predicted for the next decades, e.g. [2,11,12]. In the following, standard geothermal power production, especially in the USA, is taken as a reference. Many environmental threads and direct emissions are described independent from plant type. Finally, for the Life Cycle Inventory (LCI), emissions, resource and energy use associated with flash-steam and binary plants are scrutinized in more detail.

3.1. Direct environmental impacts of geothermal projects

The environmental effects from geothermal electricity production are commonly categorized based on safeguard subjects, type and pathway of stresses and emissions. A variety of publications by different authors is available that share a similar perspective, e.g. [16–19]. Most of these categories emphasize environmental burdens, but apart from the provision of renewable energy, geothermal activities are also sometimes associated with secondary benefits. Fig. 3 illustrates life cycle environmental effects of geothermal power generation, which are subsequently discussed in detail.

3.1.1. Land use

In this general category we include use of land, changes to landscape and to natural features. Land surface is needed during the different life cycle stages of a geothermal power plant, and this may be temporal (mainly during construction, reclamation) or permanent (mainly during operation) [20]. Geothermal energy production is focused at the resource below the subsurface and thus the manipulation, alteration and depletion of the geothermal reservoir is associated with the use of underground. Equivalent to the assessment of fossil fuel or open pit mining, however, this is not considered a critical environmental issue.

Probably the most detailed distinction of land use phases is provided by the Bureau of Land Management, BLM ([21]; Table 1). Here "land disturbances" mean land use in the western USA, and thus may be used to feed the Life Cycle Inventory (LCI). BLM [21]

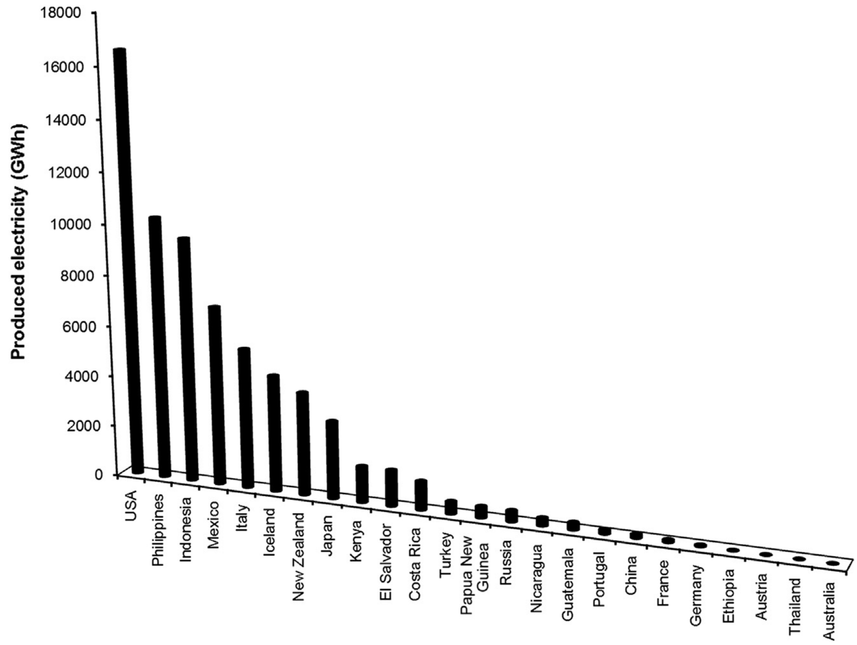

Fig. 2. Generated electricity (GW h) from geothermal power plants in 2010 (based on data from Bertani [2]).

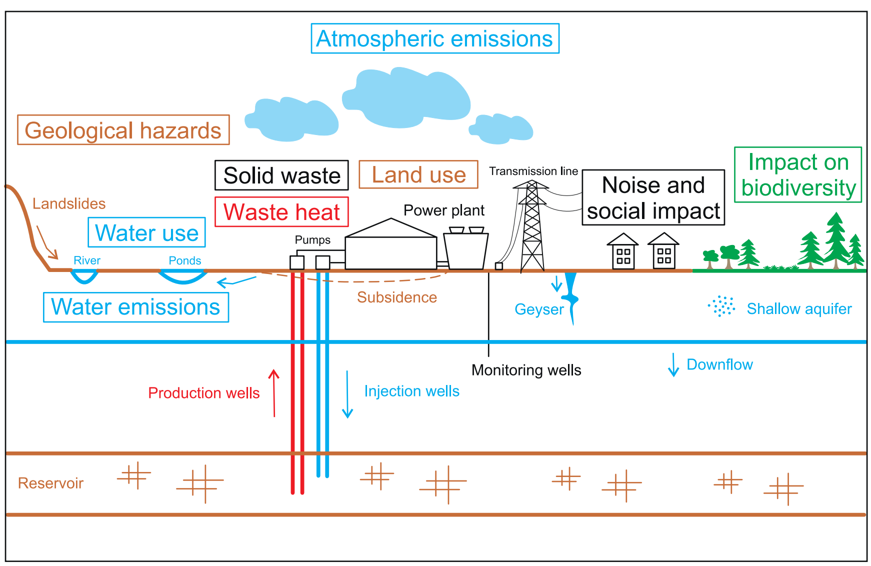

Fig. 3. Direct life cycle environmental impacts of geothermal power production.

emphasizes the uncertainty in the listed values, which stems from uncertainty about timing, location, distribution of the geothermal resource(s), as well as type of geothermal plant. Since part of the land (exploration, site preparation) is only used temporally, permanent land use during plant operation is estimated smaller, although no exact numbers are given. They estimate an average value of "land disturbance" during the construction of a 50 MW power plant of 0.85 km^2. The studied scenario applies six well pads (with single and multiple wells, e.g. by employing advanced directional or slant drilling technology), about 0.4 km road per well, and 8–80 km long transmission lines (about 15 m corridor). However, a 50 MW power plant could also involve up to 25 production and 10 injection wells. During drilling, holding ponds for temporary discharges can be sizeable, although their contribution to the land footprint is judged minimal [11]. The complete surface facility includes power plant, as well as cooling towers, auxiliary buildings and substation. Geothermal plants with super-saline brines require huge vessels to process the brine. Tester et al. [11] estimates 75% higher land use for such plants. During the last phase of reclamation and abandonment, it is expected that removal of the power plant, plugging, capping and reclaiming the wells, and regarding the site and access roads will facilitate natural restoration [21]. At Larderello (Italy), the exploited area with 22 dry-steam power plants and a total installed capacity of 595 MW covers an area of 250 km^2 [2], which is depicted in Fig. 4.

As revealed by the ranges given in Table 1, estimated maximum values for the entire land disturbances are about a factor of 7 higher than the minimum. The installation of transmission lines plays a substantial role in this, whereas the power plant buildings only cover about one tenth of the entire land footprint on the average. This is also reflected in the alternative land use estimates for parts or full geothermal applications estimates as listed in Table 2. Without wells and transmission lines, reported values reach 1.2–2.7 tm^2/MW. Lower land footprints per MW are given for high capacity flash-steam plants, ideally with reinjection of the extracted geofluids. Small-size binary power plants with cooling towers increase the footprint. Without transmission lines, the land use range captures values reported in other sources (Table 1). A land use of 2.3–9.7 tm^2/MW is estimated for different sites, technologies and plant capacities. Tester et al. [11], for example, suggest a value of 7.5 tm^2/MW for flash–cycle rankine-cycle power plants. The entire Cerro Prieto field covers 540 ha (as reported by Hunt [22]). Taking this area yields 30 tm^2/MW, which is the highest value computed and about equal to the maximum estimate from BLM [21], see Table 1. Hunt [22], however, emphasizes that this overestimates the true land use. Land may be disturbed, divided up into small parcels, but not lost.

Still, the role of the power transmission line is never accounted for. Geothermal power plants are restricted to active geothermal areas, which may be remote, nearby recreational parks and not often industrialized and have low population. Thus, transmission lines often have to be relatively long. Sometimes geothermal plants are strategically installed together with energy intense industries, such as aluminum melting in Iceland. Generally valid numbers can hardly be obtained, but 8–80 km length as used in Table 1 [21] is a reasonable range. Ultimately, whether they should be included or not will depend upon the boundary settings for the life cycle assessment (LCA).

Table 1
Typical land disturbances ($\times 1000\ m^2$) during geothermal resource development of a 30–50 MW power plant (after BLM [21]).

Exploration	**8.1–28.3**
Geologic mapping	Neglible
Geophysical surveys	
Gravity and magnetic surveys	
Seismic surveys	
Resistivity surveys	
Shallow temperature measurements	
Road/access construction	4.0–24.3
Temperature gradient wells	4.0
Drilling operations and utilization	**206.4–1416.4**
Drilling and well field development	20.2–202.3
Road improvement/construction	16.2–129.5
Power plant construction	60.7–101.2
Installing well field equipment including pipelines	20.2–80.9
Installing transmission lines	97.1–971.3
Well workovers, repairs and maintenance	Negligible
Total	**214.5–1485.2**

Some discussion can be found on the land quality in geothermal areas. Goldstein et al. [12] note that new development options in countries such as Japan, Indonesia, the USA and New Zealand are constrained by land use issues in or in the vicinity of national parks and tourist areas. Often, such environments are unique, e.g. [23,24], with their own vegetation and special geothermal subsurface phenomena. In some cases, the productivity and value of such land is economically low-rated (e.g. at the Wairakei geothermal field in New Zealand, [22]), in other cases of high cultural value or agriculturally highly productive (e.g. Imperial Valley in California). Other prominent examples are geothermal power generation in Japan and Indonesia. Land use issues here are often of high relevance as many geothermal resources are located in forest conservation areas and national parks [25,26]. Hunt [22] summarizes that the impact of land use is not only influenced by the type, extension of the development, but also by its original use.

Changes to the original landscape as a consequence of geothermal development are often seen as serious problems. The visual intrusion from surface installations often disturbs or destroys locations of great scenic quality [18,21]. During the drilling and site construction, visual disturbances are most pronounced, for instance, when tall drill rigs are installed. Facilities, such as buildings and pipelines used during the operation, can be painted to blend with the neighboring environment [21,27]. While the models built in the early days were massive, nowadays smaller and more inconspicuous installations are deployed [20]. Still, flexibility in adjusting surface constructions to the landscapes or locating at low-value land is limited, since geothermal power plants need to be built on the site of geothermal reservoirs [22].

Typical surface manifestations of geothermal processes or discharges are hot or steaming ground, hot springs and pools, mud pools, fumaroles, geysers and deposits of sinter of sulfur and other minerals [24]. These geothermal features are special, natural wonders and restricted to only a few areas, often fragile and not resilient to human intervention, and are thus of high environmental value. DiPippo [27] stresses that, usually, care is taken to preserve these manifestations when they serve as tourist attractions. However, the consequences of large-scale and long-term geofluid

Fig. 4. Dry-steam plant, installations and transmission lines at Larderello (Italy) with a total exploited area of around 250 km^2.

Table 2
Land use values and ranges ($\times$ 1000 m^2/MW installed capacity) for geothermal power production at specific locations and provided as generalized values.

Plant type and specifications	1000 m^2/MW	Data source
181 MW Cerro Prieto field (Mexico), only wells	0.7	Hunt [22]
Drill site including surface disturbances caused by excavation, construction and new roads	0.2–2.5	Ármannsson and Kristmannsdóttir [113]
110-MW flash plant, excluding wells	1.3	Tester et al. [11], Goldstein et al. [12]
20 MW binary, excluding wells	1.4	Tester et al. [11], Goldstein et al. [12]
49 MW flash-rankine, e.g. Salton Sea Calif., excluding wells	2.3	Tester et al. [11], Goldstein et al. [12]
Single-flash plant, excluding wells	1.2	DiPippo [27]
Binary plant, excluding wells	2.7	DiPippo [27]
Geothermal plant, not specified	1.4	Brophy [16]
56 MW flash, including wells, pipes	7.5	Tester et al. [11], Goldstein et al. [12]
50 MW, no transmission line	2.3–10.3	BLM [21], Table 1
50 MW, all installations of geothermal plant	4.3–29.7	BLM [21], Table 1
Range for entire geothermal field, not specified	4.1–32.4	US DOE [114]
180 MW Cerro Prieto field (Mexico), entire field with wells and power station	30	Hunt [22]

extraction are often hard to predict. This inevitably causes impacts, e.g. through the permanent extinction of geysers. For example, in New Zealand, more than 100 geysers disappeared, which is mainly influenced by geothermal developments, and recovery appears hardly possible [24,28]. Thus, the total land use is often more extensive than the occupied land by the power plants and installations. Barrick [29] reports geothermal well withdrawal radiating many kilometers on geysers extinction. These lateral effects from geothermal reservoir exploitation are also critical for any other competitive economic, touristic, or cultural uses of geothermal features. Spas, for example, make use of hot water and are often in conflict with geothermal energy use [12,30]. Sometimes, however, such as the Blue Lagoon in Iceland, geothermal power production creates new features of high touristic value [18].

3.1.2. Geological hazards

Geothermal energy production is associated with extensive extraction or circulation of geofluids and/or steam, large-scale and local manipulation of the shallow and deep ground. Consequently, a range of geological consequences represent critical hazards, often unique for geothermal activities, such as induced seismicity, e.g. [31,32]. General indicators and quantities, however, to describe these environmental effects, are not available. The highly case-specific characteristics and diversity of the associated geological hazards hamper a generally valid ranking. The subsequent list therefore is only exemplary and not a complete compendium of all phenomena.

The steep, volcanic terrain, where geothermal facilities are commonly built, is a main factor for the frequent occurrence of slumps or landslides [33,34]. In 1991, for example, a moderate-sized landslide occurred at the Zunil I geothermal field in Guatemala with an estimated volume of 800,000 m^3 killing 23 people [19,35]. Landslides may also be stimulated by the change in the regional water and heat flow, and when unconsolidated sediments, such as pumice, are destabilized. Construction of road access in undeveloped natural, often rugged terrain accelerates erosion and causes loss of vegetation [36].

Ground deformations are often observed as a consequence of reservoir pressure decline after fluid withdrawal. Subsidence is accentuated by compressible rock formations in the upper part or above a shallow reservoir, which is drained and compacted after pore pressure decline. They are more common for liquid dominated fields, which are often located in young unconsolidated volcanic rock [22,37]. For example, the subsidence rate at Wairakei geothermal field reached 45 cm/year, at Larderello (Italy) 25 cm/year, and at Svartsengi (Iceland) 1 cm/year [18,38,39]. Subsidence is often most pronounced in the early reservoir depletion stage. This locally means a loss of land through flooding and a change in contour [24], and the regional hydrological flow regime might be altered; other consequences can be damages to buildings and infrastructure, including the pipelines, drains, roads and well casings of the plant [33]. Boothroyd [23] also mentions a positive effect of subsidence when local wetlands are created that develop new habitats. Subsidence can be mitigated by the reinjection of spent fluids, e.g. [40]. Ground deformations entail sometimes the creation of surface-near tensile fractures and fissures in the surrounding [41], which offer new pathways for gas and water circulation. Pasvanoğlu et al. [42] even report formation of an extensive sinkhole as a consequence of intense hydrothermal water abstraction in a karst regime at the Kozakli geothermal field in Turkey. As another extreme, reinjection triggered ground inflation in some cases [43].

Under extraordinary conditions, hydrothermal explosions and well blow-out may occur when steam pillows develop above the lowered groundwater surface [1,18,27], or due to sudden release of overburden pressure caused for example by an earthquake [44]. However, nowadays, these are rare with the gathered experience and technological improvements. Geothermal activities are concentrated at seismic active zones, and the natural seismicity is often changed. Microseismicity, due to fluid injection, is reported for several applications [20,22,31,32].

In summary, the geothermal energy production is commonly focused in geologically young and active, fragile and sensitive environments, which are often pristine and hard to access. Under such conditions, relatively high efforts are necessary in development of geothermal fields, and the risk of geological hazards is higher than elsewhere. These hazards not only threaten the geothermal installations, but also local vegetation and often specialized ecosystems, as well as the natural hydrological conditions.

3.1.3. Waste heat

All heat-power conversion systems produce waste heat, which can attain significant portions (Fig. 5). This applies to geothermal power generation as well. The waste heat fraction depends on the conversion technology/power plant type. Geothermal power plants release considerably larger waste heat quantities, due to the lower conversion efficiency, than other power plant types. On the other hand, the geothermal cooling facilities, like cooling towers are, related to unit capacity (MW_e), significantly larger than for other technologies. For geothermal power plants, the waste heat is released at the plant site, into the atmosphere, into ponds or natural water bodies [45].

As outlined in the technology description above, the heat-power conversion efficiency depends mainly on the temperature of the produced geothermal fluid. Due to the considerably lower conversion efficiency of binary power plants, the latter have

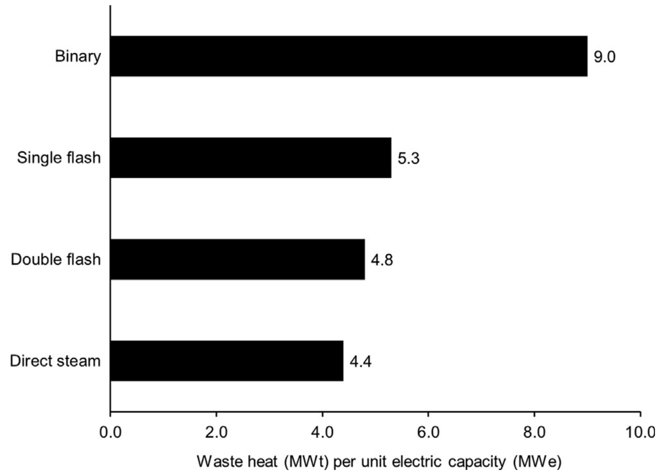

Fig. 5. Waste heat (MW_t) per unit electric capacity (MW_e) of different types of geothermal power plants (after DiPippo, [27]).

comparably high amounts of waste heat, whereas direct-steam and flash-steam plants emit less heat. When the waste heat is utilized for direct heating purposes (e.g. to feed it into district heating networks), not only the economy of geothermal development is increased, but a significant environmental benefit would also result due to the avoidance of waste heat emission to the plant surrounding.

3.1.4. Atmospheric emissions

During the life cycle of geothermal power plants, typical atmospheric emissions are from exhaust associated with transportation, application of diesel engines during roads, wells and plant construction. In many cases, however, exhaust emissions are relatively small in comparison to fugitive emissions. The permanent steam release during operation is of paramount importance for atmospheric emissions, which is common for flash- or dry-steam plants. Geothermal gases with specific environmental threats, such as H_2S, CO_2, and CH_4, are often discharged. These non-condensable gases (NCG) are released from flash-steam and dry-steam power plants, because in comparison to the steam, they do not condense at the turbine outlet [46]. Trace amounts are reported for Hg, NH_3, Rd, and B. Downstream abatement systems are often installed to decrease most critical compound concentrations, such as of H_2S. A minor source may be cooling tower drift, which was an issue for example at the Coso site in California. If geothermal fluid is (additionally) used for cooling, potential hazardous fugitive substances may be released. This was the case with boron at the Coso plant [47], where, however, no negative effects were identified.

The released mixture concentrations vary substantially among the different locations, within a geothermal field and even during the lifetime of a power plant. For example, H_2S increases more than CO_2 during production, as demonstrated for power plants in Iceland [18]. In the course of operation, a steam cap may evolve below the surface and temporally release high gaseous concentrations [48]. Measured, estimated, and indirectly derived numbers are mixed in the literature, with sometimes different underlying assumptions. For example, Bloomfield et al. [46] point out that calculated CO_2 emissions from the content in the primary steam may overestimate emission factors, since fractions partition in the condensate, and reinjection of spent fluids that also carry CO_2 contents is sometimes ignored.

Reported direct carbon dioxide, CO_2, emissions from geothermal power plants span a broad range. This greenhouse gas originally stems from degassing magma, more rarely from decomposition of organic sediments and metamorphic decarbonization [48]. The most cited global survey on this topic is the one for the International Geothermal Association (IGA) by Bertani and Thain [49], who derived a range of 4–740 g/kW h for a large number of power plants that constitute 85% of the 2001 geothermal capacity (6648 MW), and weighted average of 122 g/kW h. This is very similar to the earlier estimate by Fridleifsson [50], who provided a range of 3–380 g/kW, with more details on the underlying assumptions. Often much more optimistic estimates, mostly without further background details, can be found in the literature. A range of 50–80 g/kW h is given by DiPippo [1], Kagel et al. [47] assume 44 g/kW h, GEA [51] lists 0–40 g/kW h, and Bloomfield et al. [46] provide a number of 91 g/kW h, which is also a weighted average for geothermal plants in the USA. For New Zealand the total geothermal electricity was about 13 PJ [52], and annual CO_2 emissions from geothermal power production of 301,000 t are reported [53,54]. This yields an emission factor of 83 g/kW for CO_2, which is comparable to the NZ average stated by Rule et al. [55] (80 g/kW h, range of 30–570 g/kW h). For power plants in Iceland, Ármannsson et al. [48] provided values of 152 (Krafla), 181 (Svartsengi) and 26 g/kW h (Nesjavellir) for the year 2000. According to the US DOE [56], dry-steam plants at The Geysers (California) produce about 41 g/kW h and flash plants generate about 28 g/kW h. Binary plants ideally represent closed systems and no steam is emitted. A very high CO_2 content in the produced geofluid at the Kizildere geothermal power plant (Turkey) is used for producing industrial grade CO_2 [57]. The weight ratio of NCG is about 13%, with more than 96% CO_2. With the steam consumption of 10.96 kg/kW h CO_2 emissions at Kizildere would reach more than 1300 g/kW h [58].

Emissions of CO_2 occur naturally in geothermal regions. Special interest is therefore on the change of CO_2 emissions through geothermal energy use and stimulated additional or potentially accelerated CO_2 release to the atmosphere. Bertani and Thain [49] emphasize the observed decrease of natural CO_2 emissions in the Larderello field, Italy, since power plant operation. While, for example, for Larderello it is assumed that the anthropogenic emissions are equivalent to the original geogene emissions, in Iceland, power plants are considered as contributors by 8–16% to the national CO_2 emissions in the year 2002 [48]. Still, natural geothermal CO_2 emissions are high and remain high even when power plants are in operation. Dereinda and Armannsson [59], for example, find that natural release of CO_2 from of the geothermal field is about three times higher than from the vented steam from the Krafla geothermal plant in Iceland. Fridriksson et al. [60] anticipate a six fold increase of CO_2 emissions by operation of the Reykjanes power plant in Iceland. In New Zealand (NZ), at the Ohaaki hydrothermal field, after 20 years of geothermal power production, soil degassing was intensively measured [41]. Main findings are that due to low-permeability of the reservoir spatial extent and magnitude of natural CO_2 emissions have not changed. In contrast, at Wairakei, NZ, Sheppard and Mroczek [61] concluded, that the emissions, based on heat flow measurements, have even doubled as a consequence of geothermal energy production. For Wairakei, Rule et al. [55] report a value of 40 g/kW h CO_2 emission associated with the binary Wairakei power plant. Bertani [2] expects that the emission factor (per kW h) will decrease with time.

Among the sulfur bearing gaseous emission primary sulfur dioxide (SO_2) is only a minor constituent. Kagel et al. [47] report small values of 0.159 g/kW h for flash-steam, liquid-dominated, and 9.8×10^{-5} g/kW h for hydrothermal dry-steam at The Geysers. In contrast, hydrogen sulfide, H_2S, is the most dominant non-condensable gas (NCG) in geothermal fluids, and reaches on the average about 90% in the NCG content [49]. It is often subject of local environmental concern, because of its smell and toxicity. However, odor nuisances appear early before toxic concentrations.

When dissolved in water aerosols, H_2S reacts with oxygen to form more oxidized sulfur-bearing compounds such as SO_2. Kristmannsdóttir et al. [62] observed that H_2S is washed out by precipitation and only a small fraction ends up as SO_2. Thus, local effects of H_2S will be triggered by land use, rainfall, wind pattern and topography. As an example, in 2011, the 213 MW Hellisheidi power plant in Iceland emitted 13 kt/year H_2S into the atmosphere (6.96 g/kW h) and reinjection measures are under way. The emissions are suspected the reason for a 140% increase of sulfur pollution in the area of Reykjavik (30 km distance) [63,64]. Further values in a range of 0.5–6.4 g/kW h reported in the literature (in 1991 and 1992) are listed by Hunt [22]. Bloomfield et al. [46] estimate as a weighted average for geothermal power plants in the USA a smaller value of 0.085 g/kW h, where apparently abatements systems reduce the emitted fraction. Kagel et al. [47] emphasize that, despite the incline in geothermal use, since the 1970s total H_2S emissions have continuously decreased by about one order of magnitude. This reflects the increased application of efficient abatement technologies, e.g. [2,65].

Methane (CH_4) occurs at low concentrations in geothermal steam, but is of particular interest due to its high global warming potential (GWP). Taking again the 2007 New Zealand total geothermal electricity production of about 13 PJ [52], and reported annual CH_4 emissions from geothermal power production [54], an emission factor of 0.85 g/kW for CH_4 is obtained. This is consistent with the 0.75 g/kW given by Bloomfield et al. [46] as a weighted average for all geothermal power plants in the USA. Alternative emission factors are not found, and methane emissions are seldom in the focus. They tend to be higher in systems with marine sediments [36].

Generalized or averaged values for further compounds are scarce. For ammonia (NH_3), Bloomfield et al. [46] report a weighted USA average of 0.06 g/kW h. Nitrogen oxide (NO_x) and particulate matter emissions from geothermal power plants are rated negligible. However, NO_x may be generated in abatement systems, which are common for H_2S oxidation. For example, Kagel et al. [47] provide a value of 4.58×10^{-4} kg/MW h for The Geysers dry-steam field, which stems from the burning process applied in some plants with abatement [11]. Another rare case is that of proximal silica deposition that has led to forest damage at Wairakei [9].

Boron, B, ammonia, NH_3, arsenic, As, and mercury, Hg, in the atmosphere are leached by rain, which threatens soil and surface water in the surrounding of power plants. Often, geothermal or volcanic areas are naturally burdened by deposition of pollutants, and thus, the comparison to the undisturbed natural state is important to judge the net impact of steam plant operation. Boron, which exists as boric acid in the steam, is a critical compound from the emissions at various locations, such as Larderello in Italy, and Kizildere, Turkey [36]. Case studies reveal elevated Hg concentrations in vegetation, fish, surface waters, and the atmosphere in the surrounding of geothermal plants [36,66]. Mercury pollution in the vicinity of Larderello has been measured for decades, for example, by Baldi [67], who observed up to 1.8 μg/g in mosses in a distance as far as 0.6 km. For example, Bacci et al. [66] found emission rates of 3–4 g/kW h of Hg at the Mt. Amiata geothermal power plant in Italy. Arnórsson [36] states that Hg contents may be as a high as 0.5 ppm in geothermal steam.

A main determinant of the total direct emissions of a geothermal plant not only is the geological regime, but the core plant technology used, its life cycle and the application of additional procedures, such as abatement, cooling and reinjection technologies. Steam is released from flash-steam or dry-steam facilities, but through reinjection with spent fluid, after compression of NCGs, their atmospheric release is minimized. Reinjection is considered favorable [27], but it is still not routine practice [43]. There are some reservoirs where full reinjection has been achieved, but often, partial reinjection to support and maintain the productivity is conducted. Gas compression and injection will cost additional energy, which may rate the entire system uneconomical.

Already during initial testing, spray is often released that could damage vegetation in the surrounding area [18]. In contrast to steam-based technologies, binary cycles are considered "closed systems". However, they use low-boiling fluid/gas, such as commonly isopentane (R-601a) with a global warming potential (GWP) of about 11. Similar to the working fluid of low-enthalpy geothermal heat pumps, it may escape in slow fractions over time [6,22,68]. Finally, air emissions also accompany well drilling, bleeding, clean-outs and testing, as well as discharge, can occur from line valves and waste drilling mud degassing [20]. Exhaust is emitted from machinery during all life stages, especially during site preparation, road construction, drilling, and plant dismantling.

Microclimatic effects can occur at sizable power plants or geothermal fields with substantial discharge of warm water vapor. Increased rainfall and fog are therefore rare [33]. However, plumes of steam are part of the visual appearance of a site ([17]; Fig. 3).

3.1.5. *Solid waste, emissions to soil and water*

Especially in liquid-dominated high-temperature geothermal fields, the extracted volumes of geothermal fluids and of the resulting waste can be significant. Separated and condensed fluids often accumulate in steam-based plants. Similar to gaseous emissions, geothermal fluids are diverse, with many specific constituents and compositions depending on geological setting, production mode, time and technology. Concentrations rise with about the square of the salinity. For instance, the Salton Sea field (USA) is hosted by evaporate deposits. Geofluids here are highly saline (Cl~155,000 ppm). In contrast, the alkaline fluids of the Krafla, Námafjall, and Nesjavellir fields (Iceland) are of very low salinity (Cl~100 ppm; [69,70]). Critical contaminants of steam emissions, such as hydrogen sulfide (H_2S), boron (B), ammonia (NH_3), mercury (Hg) are also characteristic compounds of the fluids, with additional accumulation of metals such as arsenic (As), lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), antimon (Sb), lithium (Li), barium (Ba) and aluminum (Al) [17,18,27]. Geothermal fluids or brines can accrue in large amounts, and ideally they are fully reinjected. For technical or economic reasons this is often not done and decontamination is necessary before discharge or spill to (mostly) surface water bodies. There are numerous scenarios where insufficient control of geothermal fluids causes substantial local environmental problems, particularly when the very harmful compounds, such as Hg and As are discharged. Goldstein et al. [12] note that surface discharge of separated brines or fluids has been a problem at a few sites in the past but nowadays occurs only rarely (e.g. Wairakei, NZ, [24]) and is prohibited by environmental regulation. Robinson et al. [71] investigated arsenic emissions in the Wairakei river and in most cases found aqueous concentrations of > 10 μg/l, the WHO standard, and around 30 μg/g in sediments. The Wairakei and Ohaaki power stations are identified as major sources for the pollution. Similarly elevated arsenic concentrations were measured in the reaching rivers downgradient of the Mt. Apo geothermal field in the Philippines [72], but here they are interpreted as elevated natural background concentrations, i.e. released from hot springs. In their worldwide overview, Kaya et al. [43] present a comparison of waste fluids discharged to surface water bodies at twelve plant sites (Fig. 6). When quantified as emissions per produced energy, at these plants several liters (i.e. kilograms) per produced kW h are released. As an extreme, fluid discharge rates of 323.5 kg/kW h are calculated for Nagqu in Tibet.

Hunt [22] estimates annual mercury (Hg) emission of the Wairakei geothermal field into the Wairakei River of 50 kg. Discharge from the Kizildere power plant, Turkey, leads to regional pollution of a

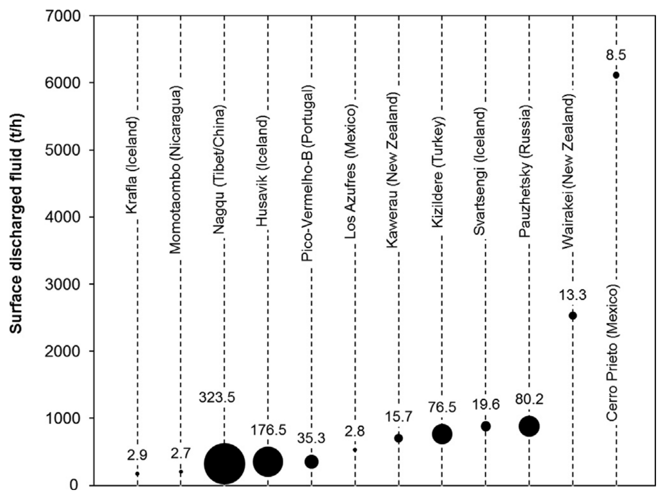

Fig. 6. Fluid discharged to the surface from selected geothermal fields (after data provided by Kaya et al. [36]). Graph shows total hourly discharge (*t*/*h*) on vertical axis and visualized by circle size the relative waste water release (kg/kW h).

downstream river catchment and the connected aquifer over an area of more than 100 km^2. As a consequence of agricultural use of polluted water for irrigation, boron (B) accumulates in soils and it threatens natural vegetation and fruit crops. Often natural background concentrations, such as of boron in the Kizildere surrounding are elevated, and hence accelerated deposition from geothermal development yields more easily to harmful concentrations [73]. Koç [73] reports an amount of about 194 kt B per year, emitted from anthropogenic (and natural sources), which negatively affect the environment. At the Balcova geothermal field, Turkey, both faulty reinjection, as well as discharge to surface waters threatens the environment due to high concentrations of B, as well as of As, and Sb [74]. Similarly, thermal waters from the Yangbajing geothermal field in Tibet carry high concentrations of B and As (and F) into a downstream river. Guo et al. [75] measured concentrations of up to 3.8 mg/l B and 0.27 mg/l As in the river, and observed health problems among inhabitants. Sometimes pollutants are retarded through storage in holding or evaporation ponds, from which they can leak in surface water bodies [17].

Reinjection can contaminate fresh water aquifers [17,74]. They are also threatened by drilling fluids and infiltration of geothermal fluids in case of well casing failure. Waste fluids from drilling and testing can cause gullying [33], and depending on the composition lead to contamination of freshwater bodies.

Generally, the total amount of solid waste is considered small and not of environmental concern. Solid waste can be grouped as follows [9,16,17,20,36]:

- Drilling waste such as cuttings, cement residues, drilling muds (such as bentonite),
- Chemical deposition in pipes and vessels of the plant, scale residues with accumulated As and heavy metals,
- Sediments in cooling towers, possibly with Hg contamination,
- Waste material, deposits, activated carbon, from treatment and abatement systems,
- General waste associated with commercial operation.

Besides the limited effects of solid waste there are also benefits: extraction of metals and minerals as byproducts can be profitable during geothermal energy extraction, whether it is for power or direct use applications. This is highly case-specific, and depends on the primary mineral concentrations in the geothermal fluids. The ability to remove silica can allow for added energy extraction, reduce operation and maintenance cost and open the way for the recovery of such metals as zinc, lithium, manganese, cesium, rubidium and even precious metals such as gold, silver and platinum. In the early history of geothermal resource development, boric acid, sulfur, potassium and ammonium salts were recovered commercially until they lost economic competitiveness to other mining processes [76]. Clark et al. [77] gives an overview on byproduct recovery projects, and though rate current interest in mineral extraction from geothermal fluids low. Most projects have been abandoned after pilot scale applications.

The mineral resources that have the greatest potential to be economically extracted are silica, lithium, and zinc. Producing a silica by-product is one possible option to address scaling issues. Silica extraction is reported, for example, from the power plants in Wairakei, New Zealand, Mammoth Lake and Coso (both California, USA) and Steamboat Springs, Nevada, USA [78]. Lithium removal from geothermal fluids is realized at Hatchobaru, Japan and at Wairakei. One of the most metal-rich geothermal fluids in the world exists near the Salton Sea in the Imperial Valley of southern California, USA. The geothermal fluids have been mined for their zinc content [78], but this was stopped after a short period, because it turned out unprofitable [77].

3.1.6. Water use and consumption

Geothermal power plants, installation and operation can require a considerable amount of water. The use of freshwater depends on the size of the plant, the technological variant, the working temperatures and cooling mechanism, and the availability of alternative salt, sewage (i.e. "grey") or geothermal water. Geothermal fluids are not fresh water. They are extracted in a range of roughly 150–1000 m^3/well and hour [21]. Clark et al. [77] list production rates in the range of around 60–80 m^3/MW h for binary and 15–27 m^3/MW h for flash-steam power plant, which are originally from the California Division of Oil, Gas and Geothermal Resources. More conservative estimates of 96 and 74 m^3/MW h are then taken for their hypothetical scenarios. It is an exception that spent geothermal fluids or condensed water is used as potable water or for agriculture [12,21]. Mostly they are (partially) reinjected, treated, ponded and/or discharged.

Geothermal reservoirs are often overlain by shallow groundwater. Pressure drop in the deep reservoir may stimulate cold downflow, especially when connecting flow paths, such as fractures and faults, exist [33,79]. This means an indirect depletion of the freshwater hosted in the local shallow aquifer. Reinjection of spent geothermal fluid is a common means to avoid substantial pressure drop.

Water is consumed from the very beginning in large quantities of up to 1000 m^3/d for drilling. Clark et al. [77] estimates the total water consumption for 1 m well construction of around 5–30 m^3, depending on geology, technology, number of liners and depth. This means for a 2 km well a water use of around 8000–55,000 m^3.

During operation, water in small amounts is consumed to minimize scaling and to manage dissolved solids [77]. A main determinant for water use and consumption will be the cooling technology, with a predominantly evaporative water consumption that is dependent on geofluid/steam inlet and outlet temperature. Binary power plants use a small amount of water (Fig. 7), and through only air-cooling water is saved. Water-cooling is often applied, is water intense, and is a dominant factor when freshwater from rivers or aquifers is withdrawn. Due to the comparably lower steam and the higher fluid outlet temperatures, water based cooling is rated less demanding than for alternative power plants, such as those using nuclear of fossil fuel based boilers [21]. This is not supported by works that compare operational water consumption of different power plant types; e.g. [80]. Fthenakis and Kim [81] add to this discussion, that geothermal power plants need more “water” (i.e. geofluid?) than conventional steam plants, because of the lower heat electricity conversion efficiency (8–15%).

In flash-steam plants, cooling of steam to the fluid state for reinjection is needed. About 15–20% of the withdrawn geothermal fluid may discharge as water vapor into the atmosphere after flashing to steam and evaporation from cooling towers or holding ponds [21]. This, however, is not crucial for the freshwater consumption of a plant, as long as no additional freshwater is needed as balance.

A recent report by Macknick et al. [80] reviews values for different US American geothermal plant and cooling technologies (see Fig. 7), partly based on the data provided by Clark et al. [77]. A critical point of their comparison between per MW h consumed water or fluids volumes (see Fig. 7) is the compilation of data from different sources, partly from the 1970s, and without further details on the underlying assumptions. For example, it is not clear why flash-steam plants have close to zero water consumption, even of water is used for cooling. Generally, the given ranges are in a similar order of magnitude as those by Clark et al. [77]. Air- and hybrid-cooled plants consume water in a range of 0–1.5 m^3/MW h. Water cooling means an increase of up to 14 m^3/MW h. In comparison, Fthenakis and Kim [81] report a broad range of about 0–7.5 m^3/MW h for dry-steam plants (depending on cooling system) and 2.3–15 m^3/MW h (withdrawal and consumption) for liquid dominated systems. The upper limit is similar to the value listed by Adee and Moore [82] for the water-cooled Salton Sea binary plant, which is about 17 m^3/MW h

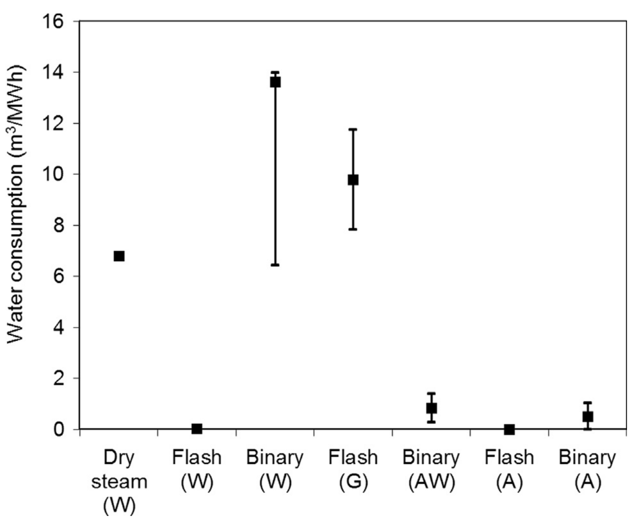

Fig. 7. Comparison of operational water consumption for different geothermal power plant and cooling technologies (W: water, A: air, G: geofluid, AW: hybrid) (based on data for US plants collected by Macknick et al. [80]). Median values and ranges are shown.

Often make-up water is periodically utilized to make up for blowdown losses and balance evaporative geofluid/steam deficit (e.g. from flashing, cooling). In some cases, water is added to the reinjected steam condensate, such as at The Geysers, Darajat and at Laradello [43]. Make-up water does not need to be fresh water, but low-quality water requires more frequent cycling and thus larger volumes [21]. For example, grey water is injected at The Geysers to mitigate gradual productivity loss [83]. Rybach [20], Franco and Villani [84] and Goldstein et al. [12] point out that nowadays, spent geothermal fluids and/or steam condensate is preferably employed for (partial) cooling of steam type power plants. Once used, cooling water is reinjected or discharged to evaporation ponds or aquifers, with elevated salt concentrations.

Table 3 shows examples of production, injection, make-up and geofluid loss fractions for several Californian geothermal power plants [77,85]. The freshwater volume that is ultimately consumed will be determined by the makeup water consumption per electricity generated. For the exemplary four Californian plants a range of 0.01–0.86 m^3/MW h and a weighted mean of 0.1 m^3/MW h for water consumption through makeup is calculated.

Two scenarios on total water consumption of geothermal plants are inspected by Clark et al. [77], with operational make-up water dominating. They calculate water consumption of 1 m^3/MW h for an air-cooled 10 MW binary and 0.04 m^3/MW h for a wet-cooled 50 MW flash-steam plant, assuming that the geofluid/steam condensate is employed. A geofluid loss rate of 10 m^3/MW h is assumed, but the effect of long-term decrease of reservoir pressure was not further scrutinized. The relatively high water consumption by the binary plant stems from switching to wet-cooling during hot summer daytime operation (hybrid cooling), and maintenance of reservoir pressure.

The US EPA [86] calculates a range of about 0.75–1.15 m^3/MW h of total water volume consumed for electricity generation from geothermal resources [21]. James [87] provides a life cycle “water” withdrawal and consumption rate of 38 m^3/MW h for a flash-steam plant. However, he considers all geothermal fluid consumption due to vapor losses during flashing of the geofluid. A critical aspect here is that apparently geofluids, which are often brines, are equated with water, and the role of reinjection, discharge and evaporation is roughly considered. The use of freshwater, which is of prime interest within LCA, is not distinguished, and in some cases low quality water may be applied to support cooling and/or as make-up.

3.1.7. Impact on biodiversity

A short verbal assessment of potential biodiversity impacts is favoured, because generally applicable indicators can hardly be quantified with the scarce information available on this topic, e.g. [88]. Geothermal environments, their intrinsic species and populations of plants, animals and micro-organisms and the dependent ecosystems are often unique, considered fragile and sensitive, e.g.

Table 3
Geofluid extraction, injection, loss and makeup water volumes for selected Californian geothermal power plants [85]. Makeup water is approximated by Clark et al. [77] and calculated per unit energy generated based on production values given by Kaya et al. [43].

Site	Category (majority generator type in case of different technologies)	Electricity production MW	Production (geofluid) 1000 m^3/d	Injection (spent geofluid, makeup) 1000 m^3/d	Loss (geofluid: evaporation, discharge) 1000 m^3/d	Makeup (water) 1000 m^3/d	Makeup (water) m^3/MW h
Casa Diablo	Binary	40	54.2	52.9	2.1	0.83	0.86
East Mesa	Binary	79	177.5	167.3	8.5	0.77	0.41
Heber	Binary	85	133.9	125.4	8.6	0.08	0.04
Coso	Multi-flash	274	95.4	49.6	45.8	0.23	0.03
Salton Sea	Multi-flash	336	202.0	165.3	36.5	0.06	0.01

[24]. In several cases, endemic organisms are reported [89,90]. Thus, even if geothermal power generation plays only a minor role for electricity generation worldwide, local effects on biodiversity may be substantial. Another point is the typically partial land use over great areas. Fragmentation of land and forest lowers species number and changes community composition, e.g. [30]. Furthermore, toxic air and aquatic emissions can pose a threat on adjacent habitats. For example, small to moderate biodiversity impacts caused by mercury and hydrogen sulfide releases have been reported by Loppi et al. [91] in the geothermal fields of Bagnore and Piancastagnaio in the area of Mt. Amiata.

3.1.8. Noise and social impact

During the life cycle of a geothermal power plant, potential sources for noise are the building and drilling activities, plant operation and any destruction work during land reclamation. While noise from construction and reclamation is considered standard noise, high noise levels of around 120 dB (muted around 85 dB) are reported for drilling [20]. During well testing, high pressure steam is released through a silencer with noise levels of 70–110 dB (muted). The cumulative impact will depend on the total number of wells under testing, over periods of commonly several months. Construction and demolition noise is mostly caused by trucks, bulldozers, graders and cranes for the time of road and power plant construction and dismantling, e.g. [18,92]. During routine operation, cooling towers, transformer and power house are main sources for noise. Water-cooled towers are more sizable with higher noise emissions than air-cooled condensers [11].

A general assessment of social impacts is hardly possible. Geothermal energy production often is concentrated in regions with extraordinary landscapes, which are touristic attractions with mud pools, geysers, fumaroles and steaming ground, and are often remote and pristine, e.g. [93]. By extinction of geothermal surface features, and industrial development in such regions, there is a high risk that land of high social value is lost. This includes the prominent role of such landscapes and geothermal features for indigenous people, ethnic, religious and social groups that have traditional ties to the land, such as in New Zealand [24], or the Maasai community in Kenya [94]. In Bali, Indonesia, geothermal development is limited due to severe religious, cultural, as well as environmental concerns by the public. Currently, for example, the Balinese community, religious leaders and the local government do not accept a planned 163 MW plant at Bedugul in Bali [95]. Some followers of traditional Hawaiian religious practices are convinced that geothermal power is harmful [96].

Whereas many natural beauties in nature parks and other protected areas can be excluded from geothermal development, thermal springs (mainly their flow-rate) are often influenced by nearby geothermal fluid production wells. Frequently, the effects become visible only after a certain time [20]. Large-scale hydrogeological effects from geothermal power generation may mitigate the productivity of hot springs, and thus it competes with the tourist sector. In few cases, however, such as at the Blue Lagoon in Iceland, new tourist attractions are fortuitously created. Iceland is a good example for critical social activity groups (e.g. SavingIceland), which excoriate geothermal power production for direct environmental and health impacts and also social consequences. A main factor, however, in this country is the attraction of energy-intense industries (such as Aluminium melting), which build or plan their facilities close or in combination with geothermal power plants.

Noise emissions are most critical during exploration and well drilling. Since the installation of wells is often not finished when geofluid production starts, and during operation new ones are continuously drilled (to increase or maintain production level, for injection, etc.), temporal noise problems are potentially present during the entire life cycle of a plant. Aside from this, the increased risk of seismic events, land subsidence or lifting, may be also seen as a local social threat.

The provision of energy to remote areas, and creation of job opportunities are the positive effects. Local communities, however, typically have only a marginal direct employment benefit, since mostly specialized people are needed for exploration, drilling and plant operation, e.g. [94]. Instead, retail trade, health care and social assistance, accommodation and food services sectors often provide potential new sources of jobs for local communities [21]. An example of a very detailed discussion on such socio-economic issues, consequences of geothermal development in less developed regions and successful mitigation of potential problems can be found in a report of the development of the Las Pailas geothermal field in Costa Rica by Barrantes Víquez [30]. Focus is set on public acceptance of the project and integration of new workers in the existing indigenous social community. This also shows the specific nature of potential social impacts.

4. Review of life cycle assessments

4.1. Constraints

In summary, life cycle assessment (LCA) studies on geothermal power production are rare (Table 4). One primary reason is that environmental impacts from certain plants are often very local and case specific, and thus generally valid conclusions from single studies can hardly be drawn. Standard geothermal power plants necessitate abnormal geological conditions, which exist only at a few places. These conditions are mainly a high geothermal gradient, which is found in geologically young and/or active volcanic areas, and the existence of a substantial and accessible reservoir of geothermal fluid and heat beneath. The case-specific characteristics of the potentially affected local environment, and the focus on exceptional and sometimes remote places, makes it hard, if not impossible, to come up with a generally valid assessment of environmental impacts as common in LCA studies on other more industrial based renewable energy technologies.

Second, the effect of geothermal power plants on local and regional water quality, the induced change of the hydraulic regime and hazardous geological consequences are always unique. At the same time, the potentially threatened environments are unique. The value of the safeguard subject, which is not always clear, is a basis for proper assessment of environmental impacts. On the one hand, the affected regions are the home of highly specialized flora and fauna, the often rough and pristine landscapes are considered of high value, specific and sensitive features, such as geysers, are often erased, and the resilience potential is typically low. On the other hand, undeveloped or undevelopable land, and in some cases conditions hostile to human life, often located far away from civilized places are found. As a consequence, environmental assessments sometimes conclude that these environments deserve small or no protection.

A third point is that during the last decades geothermal energy production has evolved, and International Geothermal Association (IGA) president Horne [97] even identifies a “geothermal renaissance”. This is mainly contributed to the evolution of engineered geothermal systems (EGS), which essentially stands for geothermal power plants that extract energy from much deeper, basement type geological formations and thus are applicable under common geological conditions. Aside from this, new combined cycle plants and hybrid technologies evolve. Cogeneration of heat is often standard. Geothermal and solar thermal hybrids are just one example of innovative applications. Also the efficiency of geothermal electricity production has increased. Instead of 1970–2000 “standard” 55 MW single-flash plants with inlet pressure of about 600 kPa and steam

Table 4
Overview of life cycle assessment (LCA) studies of geothermal power systems.

Source	Technology			Environmental impact categories	Specific impacts and emissions	Country
	Dry steam	Flash steam	Binary-cycle			
Sullivan et al. [101,105], Clark et al. [112]		×	×	1 2 3 4	Consumption of aluminium, concrete, cement, bentonite, diesel, iron and steel	USA
Clark et al. [77]		×	×	4	Water use	USA
Fthenakis and Kim [81]	×	×	N/A	4	Water use	USA
Hondo [100]		×		1		Japan
James [87]		×		1 2 5 6 7 8 9 10 11	Water use, Pb, Hg, NH_3, CO, NO_x, SO_2, VOC	USA
Rule et al. [55]			×	1 2		New Zealand
Karlsdottir et al. [107]		×		1 2 3 4 5 6 7 8 9 10 11		Iceland
Pehnt [99]			× (EGS)	1 2 3 5 8 11	Iron ore, bauxite consumption, CO, NO_x, NMHC, HCl, NH_3, benzene and benzopyrene emissions	Germany
Frick et al. [106]			× (EGS)		Water use	Germany

Impact categories: (1) CO_2 emissions, (2) Global warming, climate change, (3) Cumulative energy demand, total energy demand, primary energy, energy payback time/ratio, (4) Abiotic depletion, resource requirements, material intensity, non-renewable resource depletion, (5) Acidification, (6) Ozone depletion, (7) Human toxicity, (8) Particulate matter formation, particles/dust, (9) Ecotoxicity, freshwater and marine aquatic ecotoxicity, sediment ecotoxicity, terrestrial ecotoxicity, (10) Photochemical ozone creation, photochemical oxidation, photochemical ozone formation, photochemical oxidant formation, smog, (11) Eutrophication, nutrient enrichment.

consumption of 8–10 kg/kW h modern technologies work with up to 2550 kPa and consume as low as 5 kg/kW h steam. A general LCA that evaluates current geothermal power production would need to include the different types and efficiencies, and even then would not be prospective enough to judge the environmental effects of the technologies used in the future.

The dynamic technological innovation and gradually increasing efficiency is hard to capture, as is the characteristic time-dependent performance of power plants. Lifetimes given for existing plants are diverse, from 30 to 80 years, and performance declines are frequently reported [43]. Counter-measures, such as reinjection, may partially overcome this, and long-term sustainable power production over decades is possible, e.g. [98]. Apparently, this is very case-specific, and is difficult, due to the uncertainty in the geological description, to predict on the long term.

For making future predictions, a critical point is that new geothermal power plants will compete for the limited number of productive and accessible hydrothermal reservoirs. While prominent and highly productive locations, such as The Geysers and Wairakei, are already well developed, new plants have to find new “second choice” places. This may balance the benefit from more efficient production.

Finally, environmental awareness is increasing. Contrary to common practice decades ago, reinjection is much more common now, air-cooling is favoured when possible, waste water is sometimes remediated and steam emissions, especially those that carry hydrogen sulfide, are decontaminated. As welcome as these facts may be, life cycle thinking means that the often existing long-term impacts from the less controlled past have to be reflected in a life cycle inventory. Further, steam emissions are especially hard to quantify based on literature studies only. Carbon dioxide, for instance, is mostly unregulated as a pollutant and hence, estimates rather than reliable values are found. The latter also refers to methane, and much more critical substances such as mercury, arsenic and boron.

4.2. Overview of existing studies, system boundaries and methodologies

There are many different categories of studies. A considerable number is dedicated to an often qualitative description or analysis of environmental burdens and benefits [1,17,18,20,22], as well as guidelines for remediation, regulation or for countermeasures are provided. Some of these are in the framework of environmental impact assessments, e.g. [33,92], and many of them distinguish the effects associated with different technological variants. Among the existing LCA studies, more than a few are streamlined LCA concepts, for example, when comparing different renewable energy technologies, e.g. [99], and geothermal electricity production is often included for completeness. Another category of LCA-type work concentrates on a part of LCA, such as a global warming potential, e.g. [55,100], water use, e.g. [77,81], or on a selected life cycle stage e.g. [101]. In several cases, sufficient background information and complete inventory data is lacking or not easily accessible, e.g. [87,100,102,103]. In some cases, standard life cycle inventory databases, such as the GEMIS database [104], provide life cycle generic or site-specific information on direct emissions. Most comprehensive and complete LCA and qualitative studies on environmental emissions and resource use through geothermal power production are those by [55,77,101,105–107].

Pehnt [99], Frick et al. [106], Lacirignola and Blanc [108], and Gerber and Maréchal [102] examined EGS. Hence, their findings are not representative for standard geothermal electricity production. Gerber and Maréchal [102], for example, studied hypothetical geothermal cogeneration systems in Switzerland. German binary EGS plants are in the focus of Frick et al. [106], which provide a comprehensive prospective analysis of hypothetical installations under different geological conditions, taking 1 kW h net power at the plant as functional unit. The results are highly dependent on the geological conditions (such as temperature of geothermal fluid, reservoir depth and technical life time). Their system boundaries contain drilling/construction, operation and decommissioning, and they provide a detailed insight into the inventory data and sources, e.g. [109]. Heat cogeneration is accounted for in different scenarios. As impact categories, demand of finite energy resources (cumulative energy demand), global warming (GWP100), acidification, and eutrophication potential are chosen.

Hondo [100] compares the carbon footprint of geothermal electricity production with other power generation technologies in Japan. A double flash-steam plant (55 MW, 60% capacity) is selected, and five exploration wells (1500 m), 14 production and 7 reinjection wells (1000 m), as well as additional wells each year over a total lifetime of 30 years are assumed. For the functional unit of 1 kW h electricity production, carbon dioxide emissions for the full life cycle of 15 g/kW h are quantified. Fugitive emissions, however, are not accounted for by this value.

The recent work by Sullivan et al. [101] from the US Argonne National Laboratory represents a comprehensive comparison of geothermal to other power generation alternatives in the USA. In detail, hypothetical EGS, binary and flash-steam plants are investigated, and the "plant cycle", i.e. indirect burdens from construction, material and energy provision for drilling, stimulation, construction and operation, is covered for a lifetime of 30 years (95% capacity factor). As references, however, real cases were selected and average numbers representative for the US were collected. Focus is set on carbon dioxide emissions per capacity (MW) from drilling, plant and surface construction, as well as operation. The objective is to arrive at a generally valid comparison to other power generation technologies. This study provides detailed information on materials consumed for drilling and construction. This includes aluminium, concrete, cement, bentonite, diesel, iron and steel. Sullivan et al. [105] address, as an extension to their 2010 work, among others, hybrid geo-pressured gas and electric wells. Furthermore, direct burdens and emissions from well-field exploration, well material and fuel requirements, on-site plant construction activities, as well as GHG emissions, are accounted for. As functional unit the unit provision of energy is selected, with special focus on GHG emissions and embodied energy. In Clark et al. [77], the same authors calculate ranges of water use for the system boundaries as defined in Sullivan et al. [101]. Similarly, in another study, Fthenakis and Kim [81] compare water use rates in US electricity generation.

The work by Sullivan et al. [105] is the first life cycle based study that combines the burdens from the plant cycle with direct (fugitive) GHG emissions, which stem from natural gas release of the flash-steam plant. However, they also emphasize the problem in defining generally valid ranges, mainly due to the diversity and often anonymous sources of reported values.

In their comparative study on life cycle GHG emissions and embodied energy of renewable energy generation technologies in New Zealand, Rule et al. [55] calculate based on the conditions at Wairakei power station (drilling, plant construction and 100 years plant operation) a small value of 5.6 CO_2/kW h, but they also discuss fugitive emissions from geothermal steam release. As operational emissions that would occur naturally anyway, they suggest excluding them in the carbon footprint calculation of their study. The presentation by James [87] compares cost and environmental impacts of different power generation technologies in the US, including a 50 MW flash-steam geothermal plant. GHG emissions, water consumption and further air emissions are reported for construction and operation of a facility summarized for the entire lifetime with respect to MW h produced. CO_2 emissions (214 g/kW h) and water use (38 m^3/MW h) are dominated by fugitive gas and vapour loss from the flashing of the geofluid. Hunt [22] mentions that IAEA reviewed three studies from 1989 to 1992 on full-energy emissions from geothermal electricity provision. He refers to a range of 20–57 g/kW h, but no further details are given.

Karlsdottir et al. [107] give insight into their LCA study on the geothermal combined heat and power production of the double-flash Hellisheidi plant in Iceland. Focus is set on the GWP (CO_2, Methane) and cumulative energy demand that are associated with construction and operation, ignoring energy and material flows due to construction and equipment maintenance. Electricity production is estimated to account for 35–45 g/kW h in total. For the fraction of primary energy demand, a bulk value range of 0.1–0.2 is given. Further preliminary results are reported for a number of further standard Life cycle impact assessment (LCIA) categories.

5. Method and data for life cycle inventory (LCI) compilation

5.1. Description of chosen technologies

We define two reference cases, which are oriented at the hydrothermal geothermal power plant variants distinguished by Sullivan et al. [101,105] and Clark [77] in the reports by the Argonne US National Laboratory (Table 5):

- Binary: A binary plant with 10 MW net power output
- Flash: A flash-steam plant with 50 MW net power output

Table 5
Specification of two geothermal power plants following the settings provided by Sullivan et al. [101,105] and Clark [77].

Name	Binary	Flash
Number of turbines	Single	Multiple
Generator type	Binary	Flash
Cooling	Air	Evaporative
Net power output, MW	10	50
Plant lifetime, years	30	
Producer-to-injector ratio	3:1 and 2:1	
Temperature, (°C)	150–185	175–300
Thermal drawdown, % per year	0.4–0.5	
Number of production wells (average)	3	14.6
Number of injection wells (average)	1.2	6
Well replacement	1	1
Exploration wells	1	1
Well depth, (km)	<2	1.5 <3
Flow rate per well, (kg/s)	60–120	40–100
Pumps for production	Lineshaft or submersible	None
Distance between wells, (m)	800–1600	
Location of plant in relation to wells	Central	

Both cases are oriented at south western US conditions, and operate for a lifetime of 30 years. Underlying data is collected from experts in industry and US national laboratories. We complement these two base cases with data ranges from other studies, and try to determine roughly averaged emissions and use of resources for a third "universal" case. All is expressed for the standard functional unit, which is provision of a unit (here: 1 kW h) electrical energy from a high enthalpy geothermal resource. System boundaries include exploration, drilling, well installation, surface plant construction with all buildings, operation for 30 years, and plant decommissioning and recycling. For most of these stages, Sullivan et al. [101] offer modelled life cycle metrics, which cover energy, GHG emissions, and selected "materials used in significant quantities", such as steel, aluminium and concrete. While in the Argonne reports, the plant fence line (incl. background processes for material and energy provision) literally represents the system boundary, we try to discuss further implications from geothermal plant within the land use category, and water and air emissions. Pipelines that connect plants with consumers, energy demand for plant construction on site, and materials transportation are not considered. For the latter, which is highly site-specific, no representative data could be found.

We include cooling facilities, but exclude cogeneration of heat, which may play an important role in some places, and will improve the overall environmental performance of a plant. EGS or hybrid technologies are not considered, since these do not represent current standard technologies.

5.2. Material, water and energy requirements

The materials consumed for exploration, drilling and construction are adopted from Sullivan et al. [101], Clark et al. [77] and Rule et al. [55]. The latter is oriented at the Wairakei field in New Zealand, with different assumptions for system lifetime, well number, and well depth. They define a lifetime of the power plant of 100 years, and well lifetime of 17 years, which means 4–5 new sets of wells (average depth of 660 m) drilled within the total operation time. Sullivan et al. [101] compare their results, given as mass per power output (i.e. per MW), with those by Rule et al. [55]

Table 6
Materials and resource consumption for exploration, drilling and plant construction for binary and flash plant scenarios (Table 5), Wairakei case study by Rule et al. [55], and an approximate average (universal).

Material		Binary				Flash				Wairakei	Range (rounded)	Universal
		Plant	Well	Well-to-plant	Total	Plant	Well	Well-to-plant	Total	Total		Total
Aluminum	(g/kW h)	0.18	N/A	N/A	0.18	N/A	N/A	N/A	N/A	0.02	0.02–0.18	0.1
Concrete	(g/kW h)	1.75	N/A	N/A	1.75	0.61	N/A	N/A	0.61	2.15	0.6–1.8	1
Cement	(g/kW h)	N/A	0.27	0.06	0.33	N/A	0.83	0.06	0.88	0.89	0.3–0.9	0.6
Bentonite	(g/kW h)	N/A	0.13	N/A	0.13	N/A	0.29	N/A	0.29	N/A	0.1–0.3	0.2
Diesel	(l/kW h)	N/A	1.5×10^{-4}	3.9×10^{-5}	1.9×10^{-4}	N/A	1.9×10^{-4}	3.8×10^{-5}	2.2×10^{-4}	2.4×10^{-4}	$1.9–2.4\times10^{-4}$	2.2×10^{-4}
Iron	(g/kW h)	0.016	N/A	N/A	0.02	0.01	N/A	N/A	0.01	N/A	0.01–0.02	0.015
Steel	(g/kW h)	0.88	0.41	0.06	1.35	0.10	0.97	0.05	1.12	0.65	0.6–1.4	1
Water	(l/kW h)	N/A	N/A	N/A	4.0×10^{-3}	N/A	N/A	N/A	4.0×10^{-3}	N/A	N/A	4.0×10^{-3}

Table 7
Water and energy use of binary and flash scenarios (Table 5), ranges and approximate average (universal) values during geothermal power plant operation.

Process and type of use	Unit	Binary	Flash	Range	Universal
Transport (construction)	Fraction of total embodied energy	N/A	N/A	5–10%	6.8%
Water use (full life cycle)	l/kW h	1	0.04	0–17	1
Auxiliary energy use (operation)	Fraction of generated electrical energy	N/A	N/A	1–2%	1.5%
Abatement technology					Case-specific

and Frick et al. [106]. Substantial differences with the latter in the material and water consumption are attributed to the different plant types, because Frick et al. [106] inspects the life cycle of EGS.

In summary, Table 6 values display no significant differences between the studies and technologies. Most striking is the high steel consumption for the binary plant. This stems from the large air-cooling structure that is needed for this variant. In contrast, producing high temperature steam is expected to be more demanding for the deeper wells. Further details on specific trends can be found in Sullivan et al. [101] and are not discussed here in more detail. We obtain roughly averaged values for our universal case, which may be significantly different for specific locations. We expect that representative average values may be slightly higher. Main reasons are the defined system boundaries and excluded assets, such as facilities for waste water treatment, on-site energy and material consumption, potential failure (of drilling), as well as rudimentary reflection of the exploration phase. Further, proper definition of capacity factors and system lifetime is crucial, but their values can hardly be generalized. Hondo [100], for example, assumes a capacity factor of only 60%, in comparison to 93% in the work by Rule et al. [55] and 95% in the Argonne reports. Fridleifsson et al. [10] estimate an average global capacity factor of 75%, and it is anticipated that this will increase to 90% in the near future [2]. Finally, transportation is not or only partially included, which will increase the Diesel consumption per kW h. Contrarily, including recycling credits for steel, for example, by including dismantling of the power plant, would reduce the calculated net consumption.

Sullivan et al. [105] point out that life-cycle construction information for power plants is hardly available. This includes activities such as earth moving, operation of cranes, etc. Direct energy burdens that are associated with plant construction activities (on-site) and transport of material to the site are estimated to be roughly 6.8% of the embodied energy (plant cycle energy). While this quantifies the energy consumption for on-site activities and materials transportation, transportation of workers is neglected. We also follow their suggestion, and assume a fraction 6.8%, which is made up by 25% from electricity and 75% from diesel (Table 7).

Material, energy and water use during operation are very site-specific, mostly incompletely reported and often have to be guessed or predicted. Still, operational material consumption (except for re-drilling of wells) is expected to be relatively small, for example for maintaining plant pipes, dealing with corrosion and scaling, maintenance of wastewater treatment or abatement systems (e.g. for removal of H_2S from exhaust steam), heat carrier fluid in binary cycle, etc. Therefore, these are neglected in the overall analysis (see Table 7). Assets of higher priority are expected to be:

– Auxiliary energy for operation of pumps (extraction, circulation, reinjection)
– Water use for makeup, cooling, and treatment

Operational energy consumption is not covered by the Argonne reports. For the flash plant, only injection devices are assumed, whereas, for the binary system, extraction as well as injection pumping has to be considered. In Sullivan et al. [101], the equipment is roughly included (based on steel mass) in the well implementation expenditures as aggregated in Table 6. However, operational energy consumption is ignored. Frick et al. [106] describe in detail the relevance of feed and down-hole pump operation for binary EGS systems that circulate fluids at much greater depth than standard geothermal plants (3.8–5 km). For example, a 10% capacity fraction of energy that is consumed by feed pumps (0.18 MW), and a full auxiliary energy need of 0.5–3 kW h/(m^3/h) for running the geothermal fluid cycle are assumed. Applying the lower range to the binary plant as configured in Table 5, an auxiliary power need of about 1.5% of the generated electricity is obtained (Table 7). This is also an average value (for range 1–2%) as provided by Karlsdottir et al. [107].

For quantifying water use by geothermal plants, some fundamental assumptions are necessary. First, here, water use only refers to the consumption of freshwater, e.g. [110,111]. Geofluids from geothermal reservoirs or geothermal brines are not commonly fresh water. Thus, for example, vapour discharge from flash steaming is not accounted for. During the life cycle, water is used directly for well and plant construction, as makeup water to balance geofluid deficits and to increase reinjection volume, and (partial) cooling. Indirect effects are all those associated with change of the hydro(geo)logical flow regime, and downflow water loss from upper freshwater aquifers. The latter can hardly be generalized, are rudimentary covered in the LCA literature and accordingly, are neglected within the scope of this study.

In general, the plant technology and even more the cooling type will determine total water consumption. Even air-cooling and steam condensate-based cooling will require (mostly) fresh water supply, and thus the water consumed for cooling or to balance evaporative water and geofluid loss will dominate the overall consumption. Even for low-water flash-steam cooling, Clark et al. [77] shows that drilling fluid requirements are only responsible for 14% of the necessary life cycle water volume. The Argonne report by Clark et al. [77] is dedicated to the water use of US geothermal power plants. We adopt their values for the full life cycle, which are 1 l/kW h for the air-cooled (water-cooling in hot summer) 10 MW binary plant, and 0.04 l/kW h for the 50 MW flash plant using wet cooling through the steam condensate. The latter is at the lower limit in comparison to other reported values, and taking the US EPA range of 0.75–1.15 l/kW h as another reliable reference, 1 l/kW h appears a good rough average estimate (Table 7). This value is even conservative when comparing it to the ranges given by Fthenakis and Kim [81], which are at least 2.3 l/kW h for binary plants. In contrast, air-cooled modern facilities in the relatively cold Icelandic climate may need lower volumes.

5.3. Land use

The land use according to BLM [21] ranges from 4200 to 29,300 m^2/MW capacity (Table 1). Lower values denote conditions, where only the power plant facilities are considered, whereas wells and conduits, land use from exploration activities and road construction are not included. For the boundary conditions of the scenarios given here, i.e. 30 years of operation and a capacity factor of 95%, land use is 1.7×10^{-5}–1.2×10^{-4} m^2 per kW h produced. An average value of 7×10^{-4} m^2 per kW h is obtained (Table 1).

Main questions are, when, if, through which effort and to what extent restoration will be possible after use. Even if "only" 30 years of operation are considered, as in the given scenario, long term consequences remain. Most precious geothermal features, such as geysers and fumaroles can be lost permanently, land and aquifers are potentially contaminated, and roads remain. Land use per kW h may be less for long-term operation over, for example, 90 years as indicated by the Wairakei case study by Rule et al. [55]. However land use may be more intense particularly when far reaching effects, such as from subsidence, extinction of geysers, etc., are included.

5.4. Emissions

Most relevant direct emissions during plant operation originate from geothermal steam release. While such fugitive emissions may be close to zero for closed cycles, such as binary plants, non-condensable gas (NCG) release from vapour-based plants is common. Based on the literature as described in detail in previous chapters, ranges and "averaged" values for hydrogen sulfide, sulfur dioxide, carbon dioxide, methane, and ammonia emission rates are listed in Table 8. An underlying assumption is that even if geothermal plants "accelerate" release of GHGs through geofluid and steam extraction, short term natural release rates are not significantly altered. This is in line with observations from recent measurement campaigns, e.g. [41]. Long term decrease of natural GHG emissions through the surface are not accounted for. This is equivalent to the boundary conditions applied for environmental assessment of carbon sequestration technologies.

Methane is a frequently ignored compound, which is often released at small rates. However, it increases the GWP by more than 15% as opposed to considering carbon dioxide only. In comparison, the GEMIS database [104] estimates full life cycle direct emissions (incl. well drilling) as high as 122.4 g/kW h CO_2 and 2.7 g/kW h for SO_2. This is based on a flash-steam geothermal plant with a reservoir at 1000 m depth that is located in the Philippines. The first value compares well to our universal value and apparently reflects the weighted mean from the survey by Bertani and Thain [49]. SO_2 emissions are much higher than estimated in Table 8, and this may reflect that the given value cumulates the full life cycle, and that secondary oxidation of H_2S is quantified in SO_2 equivalents.

Table 8
Atmospheric emissions from geothermal plants: main pollutants with ranges from literature and estimated universal reference values.

Substance		Range	Universal
H_2S	(g/kW h)	0.085–7.0	0.1
SO_2	(g/kW h)	0.0001–0.16 (−2.7)	0.001
CO_2	(g/kW h)	4–740	122
CH_4	(g/kW h)	0.75–0.85	0.8
NH_3	(g/kW h)	N/A	0.06
NO_x	N/A	N/A	Negligible
Particulate matter	N/A	N/A	Negligible
B, Hg, etc.	N/A	N/A	N/A

Abatement technologies may generate secondary emissions such as nitrogen oxides and additional sulfur oxide. However, even though considered standard for geothermal plants, general impacts associated with steam clean-up have not been studied, yet. Therefore, we judge the listed atmospheric emissions as optimistic values. In principle, critical substances, such as mercury or boron, as well as high hydrogen sulfide emissions (no treatment), and secondary release of nitrogen oxide, sulfur dioxide, etc. (treatment) should be also accounted for. For mercury, which is a very toxic compound, the value of 0.5 ppm as suspected by Arnórsson [36] could be added to Table 8.

Due to the scarcity of reported data, and the very case-specific variability, further emissions are not included in this study. This is especially conservative for aquatic emissions, which have led to contaminated land, surface and groundwater bodies at many locations (e.g. Kizildere, Wairakei, Cerro Prieto, Yangbajing). Discharge of separated brines is considered a problem of the past, e.g. [12], but the early years of geothermal plants are also part of the life cycle we look at from today's perspective. The highly toxic substances such as mercury, arsenic, boron, etc., which can stay as permanent contamination in natural water bodies and soil are of particular relevance.

6. Overall assessment and technology-specific issues

Power generation by using near surface high temperature reservoirs is an appealing, economically attractive, technologically established, but locally limited renewable energy variant. A general overall assessment is ideally based on a representative universal case, which averages the different geological, thermal, technological and local environmental conditions. Even if different technologies such as binary and flash-steam plant types are distinguished, however, site-specific factors will govern their ultimate environmental performance.

There are two extremes. One is a modern binary plant, with high capacity of over 10 MW and a capacity factor of more than 90%. A low number of e.g. 3 wells for production and 2 for injection are drilled, with a small number of new installations during the time of operation. The circulated geothermal fluid shows little temperature decline, and make-up water is grey water that does not stress local water bodies. A modern air cooling facility is applied, and due to the moderate climate, hybrid use of water cooling is not necessary.

Maybe cogenerated heat supplies a local community, fish farm or desalination facility. The plant is located in well-developed or (environmentally) low value land, and can sustainably be operated for far more than 30 years. This one ideal case is the environmentally benign variant, where direct emissions into the atmosphere are very small, closed system operation is well controlled and efficient, and water, as well as precious land use is minimized. The life cycle impacts will be dominated by the resource, energy use and interference with the regional hydrological regime from drilling and operating wells. Material and energy consumed for plant construction, as well as for auxiliary devices, such as circulation pumps, will play the most dominant role. Life cycle GHG emission will be in the range of a few tens of CO_2 equivalents per kW h, we estimated a standard value of 1–2% embodied energy, and impact in further categories will be uncritical.

The other extreme is a flash-steam plant with relatively low capacity and capacity factor of 20 MW and 60% for example. The geothermal reservoir is deep (2000 m), and performance of the plant continuously declines. To overcome this, new wells are repeatedly drilled, reinjection is partially employed, but it creates productivity problems (temperature decline, thermal breakthrough, pressure drop). The steam released is rich in CO_2. Abatement systems to reduce concentrations as well as of toxic metals and boron are not very efficient. Potentially H_2S and NO_x could be released as secondary products from steam oxidation. Even if discharge of used fluids and brines to surface and groundwater bodies is minimized or buffered by ponds, uncontrolled and accidental aquatic emissions have contaminated the adjacent freshwater bodies. In the hot climate, air-cooling, at least temporally, has to be switched to water-cooling, and including the consumed make-up water, life cycle water use reaches several litres per kW h. Finally, the region the plant operates hosts many unique geothermal surface features, is habitat of special endemic organisms and the land is of high environmental and cultural value. Certainly, this worst case extreme is very rare. Here, environmental effects will probably be dominated by climate change impacts due to the high CO_2 content and volume of the released steam. Possible values of more than 500 gCO_2/kW h are reported. Thus, this variant is close to modern fossil fuel based plants. Furthermore, contamination and destruction of precious natural fresh water bodies and pristine land is often mentioned as a consequence of geothermal energy production, and in the extreme case substantial local problems are generated especially with respect to human and ecotoxicity, land and water use.

Our "universal" case is somewhere between these extremes, and in comparison a conservative variant that benefits from the lessons learned through the experience from the past. For example, it presumes that water-cooling is mitigated, abatement technologies are standard and (partial) reinjection is applicable. Finally, main determinant for the climate change impacts will be the direct steam release, its composition and the volumes. If this factor is not relevant then the environmental performance of geothermal plants with respect to this category is excellent. Relevant contributions to other impact categories will be site specific, such as ecotoxic effects from release of metals and boron, and land use. Water use can hardly be ignored for such applications, since make-up water is typically necessary, which may be significant, if reinjection has to be supported. Even if water cooling is not standard anymore in the future, often it has been applied in the past life cycle of today's plants, and hybrid cooling applications are often selected instead of exclusive air/steam condensate based techniques. A critical assumption, which is necessary for life-cycle based quantification of environmental effects, is the time of operation. Ranges from a few to nearly 100 years are reported or anticipated, and of course this parameter will determine the relative contribution of operational effects versus those from power plant implementation and dismantling. Despite this, it is assumed that wells are not only installed during the initial construction phase but new wells are repeatedly drilled. Fugitive emissions per kW h do not depend on power plant life time given an averaged performance and capacity factor. As a consequence, major environmental burdens, as associated with the universal case, will not fundamentally change with assumed lifetime of the plant.

7. Conclusions

The presented overview of potential life cycle environmental effects from geothermal power plants tries to bring together scattered available information of reports and related studies. In fact, life cycle assessment (LCA) studies on current geothermal electricity production are rare, and mainly through the recent work by the US Argonne National Laboratory [77,101,105,112], specific data is available that could also be utilized in our study. A crucial point is that general assessments are hard to make. Many technological, economic and environmental aspects of geothermal plants are fundamentally controlled by geological and local factors. The latter are always unique, site-specific, they can span a broad range, and often even their effects are uncertain. For example, the trend of long-term productivity of geothermal reservoirs is often unknown, concentrations of compounds in geosteam or -fluid are highly variable and they may change over time. Even without the uncertainty in geotechnological performance, the case-specific variability of fugitive emissions, water and land use effects, the different plant types in use, as well as the improvements during the last decade make it virtually impossible to define a typical plant case with representative life cycle inventory. Finally, many environmental effects cover sensitive information that is hardly available or often only anonymously reported. This is especially problematic for atmospheric and aquatic emissions, which are sometimes discussed, but can hardly be generalized per kW h based on local information only. Previous work on water often does not distinguish between consumption and water throughput, and it is also hard to quantify the ratio of fresh water in comparison to low-quality grey or brackish water that may be employed.

In view of these prerequisites, data presented here is highly dependent on the reliability of a few previous studies, from which the USA perspective dominates. This also means that conditions in other countries that play a prominent role in geothermal power generation, such as the Philippines or Indonesia, are barely reflected. It is questionable, if environmental regulations in these countries and their interpretation in practice are similar. In spite of this, we tried to define a streamlined universal case, with ranges and approximate average inventory data. It is meant as an average of current geothermal power generation, without a prospective view on future improvements and possible EGS spread.

A main conclusion is that, in general, environmental effects are mostly associated with emissions at the site, rather than, for instance, hidden in the manufacture process of plant components or governed by drilling activities. Atmospheric emissions, especially of fugitive greenhouse gases via steam release, are very critical, and apparently often underrated. For example, since the USA have not signed the Kyoto protocol, CO_2 emissions from geothermal plants are not regulated yet in the USA. This should be kept in mind, when Tester et al. [11] concluded in their prominent MIT report, "it is highly unlikely that any geothermal power plant will be a threat to the environment anywhere in the United States, given the comprehensive spectrum of regulations that must be satisfied." Other aquatic and atmospheric emissions may carry toxic concentration levels of other critical compounds such as of mercury, boron and arsenic. Despite the often only local effects in the vicinity of the plant, accidental or permanent release can represent a significant threat to the environment. More research and surveys, however, are necessary to obtain a more general picture on worldwide average emission rates and consequences.

We excluded release of these potentially critical toxic substances in the tabulated inventory due to the lack of general data. Furthermore, abatement systems are often operated to minimize emission of polluted steam or water. They add another unknown component, which is ignored here. Contrarily, cogeneration of heat or minerals is neglected and this may play an interesting role at some places. In summary, even if major environmental determinants are identified and their effects are quantified, the provided data is far from being precise or complete. We suspect that the full environmental burden of worldwide geothermal power generation is somewhat higher than what is estimated by our data. The relevance of neglected threats, the more success-story focused available literature, and the life cycle burden of environmental damages from the past are the main arguments for this conjecture. Still, this critical perspective and the claim for a more comprehensive view on life cycle burdens is not intended as an argument against this technology. It is meant as invitation for more transparent reporting and assessment of local and regional environmental consequences, in order to demonstrate the green side of this large potentially renewable energy source. At the small number of geothermal fields worldwide, this way of electricity generation is technologically, economically and, in principle, environmentally the best if not the only game in town.

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