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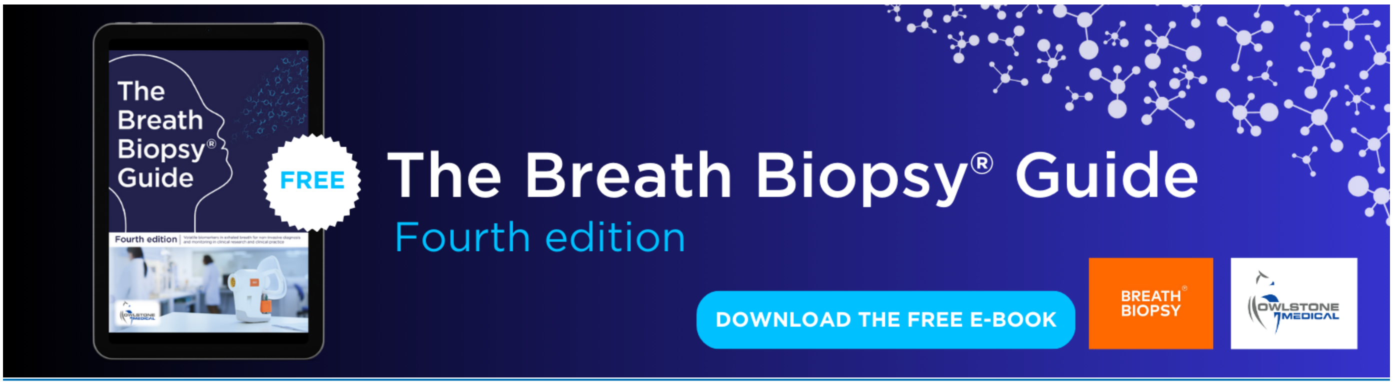

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Realizing the geothermal electricity potential—water use and consequences

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Abstract
Electricity from geothermal resources has the potential to supply a significant portion of US baseload electricity. We estimate the water requirements of geothermal electricity and the impact of potential scaling up of such electricity on water demand in various western states with rich geothermal resources but stressed water resources. Freshwater, degraded water, and geothermal fluid requirements are estimated explicitly. In general, geothermal electricity has higher water intensity ($l\ kWh^{-1}$) than thermoelectric or solar thermal electricity. Water intensity decreases with increase in resource enthalpy, and freshwater gets substituted by degraded water at higher resource temperatures. Electricity from enhanced geothermal systems (EGS) could displace 8–100% of thermoelectricity generated in most western states. Such displacement would increase stress on water resources if re-circulating evaporative cooling, the dominant cooling system in the thermoelectric sector, is adopted. Adoption of dry cooling, which accounts for 78% of geothermal capacity today, will limit changes in state-wide freshwater abstraction, but increase degraded water requirements. We suggest a research and development focus to develop advanced energy conversion and cooling technologies that reduce water use without imposing energy and consequent financial penalties. Policies should incentivize the development of higher enthalpy resources, and support identification of non-traditional degraded water sources and optimized siting of geothermal plants.

Keywords: enhanced geothermal systems, water intensity, energy water nexus, renewable energy, sustainability

S Online supplementary data available from stacks.iop.org/ERL/6/034023/mmedia

1. Introduction

Geothermal electricity, which is generated by utilizing the Earth's internal heat, has received attention from policy makers, regulators, researchers and investors because of its potential to provide as much as 10% of US baseload electricity demand by 2050 [1]. Further, geothermal electricity overcomes some of the intrinsic disadvantages of other renewable electricity pathways, especially intermittency issues typically associated with wind and solar.

Traditional geothermal resources—hydrothermal resources which produce dry steam, hot water, or a combination of both—currently account for nearly all the geothermal electricity generated globally. Such resources have limited potential for growth—the US Energy Information Administration expects the share of such resources to rise from 0.35% of total US electricity production in 2009 to around 0.6% by 2035 [2]. Instead, growth is expected from unconventional resources called enhanced geothermal systems (EGS). Such resources have high temperature but are likely to contain little

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or no naturally occurring geothermal fluid, and may not have sufficient permeability to sustain production. To exploit such resources, a permeable reservoir must be created by hydraulic fracturing. Energy is then extracted from the reservoir by pumping fluid from the surface through the induced fractures, collecting it in production wells, circulating it through power-generating turbines and re-injecting it [3]. This process is also known as heat mining.

To appropriately develop such resources, water requirements of geothermal electricity should be established to guide identification of sites where power generation can be developed with minimal impact on local water resources. However, to our knowledge there has never been published a peer-reviewed comprehensive analysis of the water use of electricity from geothermal resources. Water use could be derived from the detailed specifications and performance of a number of geothermal power plants across the globe available in the literature [4–8]. Kutscher *et al* [9] estimated the impact on efficiency and water requirements of equipping a pilot plant in Nevada, US with evaporative cooling. Clark *et al* [10] estimated the water required during plant/well construction and operation under four specific scenarios involving hydrothermal and EGS resources. However, none of the studies developed a methodology to estimate and compare water requirements of plants using different types of conversion and cooling technologies, and across a range of resource enthalpies. More importantly, no study to date has analyzed the impact of potential scaling up of geothermal electricity on water resource demand. Such an effort could inform research priorities for minimizing water use, which will support efficient resource development.

This study aims to fill this gap. It compares the estimates of water intensity—water requirement per unit of energy produced—with other fossil fuel and renewable electricity generation technologies, and provides a sense of how much water will be needed, should such technologies be developed on a large scale. This information will provide critical information to planners and policy makers regarding the potential impacts and limitations of future development of geothermal technology. Given that water can be a limiting resource in many areas of the country and world, and given the growth in competing demands for its availability, care must be taken to ensure geothermal development takes place such that alternative water uses are adequately taken into account. Section 2 briefly describes geothermal technology and its water resource requirements in general terms. In section 3, we describe our methodology for estimating water demands, and the results are discussed in section 4. We discuss future research needs in section 5.

2. Water types used in geothermal electricity generation

Our research tracks the requirements for freshwater, degraded water and geothermal fluid, and estimates withdrawal and consumption volumes for each of these three categories. Water withdrawal is the removal from a surface water body or aquifer. The water withdrawn is used both consumptively and non-consumptively. Water consumed is not immediately available for use by humans and the ecosystem in the watershed from which water is originally withdrawn [11, 12]. Water used non-consumptively is released back to the environment with or without change in quality, usually in the form of cooling tower blowdown and is available for alternative uses in the same watershed.

'Freshwater' is defined as water that has total dissolved solids (TDS) concentrations of less than 1000 mg l^{-1} [13]. Geothermal power plants require freshwater for cooling. We define 'degraded' water as water that has more than 1000 mg l^{-1} TDS. Such water includes contaminated groundwater, treated municipal effluent, industrial process water or wastewater, irrigation return water, storm water runoff, brackish water, and other types of water impacted by human activity. Much naturally occurring water also falls into this category [14]. Degraded water may be used for heat mining as well as for injection into a geothermal reservoir to prevent decline in pressure and, hence, production. Degraded water may also be used to replace fluid lost during power generation. Examples of degraded water use include the dry steam geothermal resources in Geysers, California, where storm water runoff from power plant sites and treated municipal effluent are injected to maintain pressure [15, 16] and at Larderello, Italy where sea water is injected to enhance dry steam production [17].

For EGS resources, degraded water is required for the initial stimulation of the geothermal reservoir to enhance permeability and establish a circulation loop for heat mining. Once power generation is underway, incremental water injections are required to compensate for fluid losses resulting from leakage from the fracture system to the surrounding rocks.

Geothermal fluid is naturally occurring subsurface water that is withdrawn for heat mining. Depending upon local geological conditions, such fluids may have high concentrations of salts—chlorides, sulfates and bicarbonates; and dissolved gases like ammonia and methane [18]. An extreme example is the hydrothermal resources at Salton Sea in California where the TDS is around 240 000 mg l^{-1} [19]. The volume of fluids withdrawn per unit of electricity generated primarily depends upon the fluid temperature, the power-generating technology and to a lesser extent on the ambient temperature and efficiency of the power plant technology. To the extent possible, geothermal fluids are collected and re-injected, but losses through several parts of the power generation cycle are inevitable. In flash power plants, for example, some or all of the geothermal fluid flashes to steam as it ascends from depth and enters the turbine. In the generation process, some of the fluid in the vapor state condenses to form high quality water with very low mineral content, which can then be used for cooling purposes. Evaporation of this water for cooling purposes is counted as geothermal fluid consumed. It is not considered freshwater consumption because it is not sourced from a body of freshwater. This escaped vapor also represents the amount of supplemental degraded water that needs to be injected into the geothermal resource to maintain pressure.

3. Methodology

We developed an Excel®-based model that provides first-order annual average estimates of water requirements based on plant configuration, cooling system technology, and geothermal resource enthalpy. The methodology and thermodynamics behind the model, assumptions, and data sources are detailed in [18]. Our model relies upon an extensive literature review conducted to determine factors that affect water use intensity—for example the relationship between energy conversion efficiency and temperature of inlet geothermal fluid, differences in efficiency of various power plant technologies or configurations, and the impact of cooling technologies such as wet re-circulating cooling systems (WRCS) or dry-air-cooled condenser (ACC) on power plant efficiency.

Since there are wide variations between sites in the environmental conditions, input variations, plant design and operation conditions, the relationships identified in this study have been generalized to encompass a broad set of conditions or scenarios. It should be noted that water consumption of power plants will depend upon a large number of factors that the model currently does not consider—mineral content of the geothermal fluid, ambient temperature and humidity, specific design parameters of the power plant, and dissolved solids and chemical composition of freshwater withdrawn from ground or surface sources. In addition, water intensity will vary due to fluctuations in ambient temperature and humidity, and in the temperature of the geothermal fluid. We emphasize that our estimates are annual averages and are not intended to capture diurnal or seasonal fluctuations.

3.1. Water requirements of low enthalpy resources

For geothermal resources with a wellhead temperature of less than 200 °C, binary or Organic Rankine cycle (ORC) plants are most appropriate. These plants are very similar to Rankine cycle coal or nuclear plants, but use an organic fluid like iso-pentane instead of water as the working fluid. To assess water use of ORC plants, we estimated the thermal energy input to the ORC cycle based on the calculated resource enthalpy. The net power output is based on the plant's thermal or first-law thermodynamic efficiency, which is assumed to correlate linearly with resource enthalpy [20]. Efficiency depends upon the exact ORC configuration—our results are based on ORC plants with recuperated cycle or an internal heat exchanger (IHE), which are currently the most prevalent type [21]. Freshwater is required for evaporative cooling of the power plant and for dissipation of waste heat. A simplified representation of freshwater requirements is given below:

$$\dot{w}_{\mathrm{f}} = (\dot{Q}_{\mathrm{in}} - \dot{W}_{\mathrm{gross}}) f_{\mathrm{latent}}/h_{\mathrm{vap}} = (\dot{Q}_{\mathrm{in}} - \eta_{\mathrm{th}} \dot{Q}_{\mathrm{in}}) f_{\mathrm{latent}}/h_{\mathrm{vap}} \quad (1)$$

where $\dot{w}_{\mathrm{f}}$ is freshwater consumed in kg s^{-1}; $\dot{Q}_{\mathrm{in}}$ is thermal energy input to the power plant in kilowatt; $\dot{W}_{\mathrm{gross}}$ is the gross electricity produced in kilowatt; f_{latent} is the fraction of total heat rejected by latent heat transfer, i.e. evaporation of water, and ranges from 0.65 to 0.9 for WRCS [22] and 0 for ACC; η_{th} is the thermal efficiency of the ORC plant; and h_{vap} is the latent heat of vaporization of water and equal to 2270 kJ kg^{-1}.

While WRCS depends almost entirely on evaporative cooling, dry and hybrid cooling systems dissipate waste heat either entirely or partly directly to the ambient air and hence require less freshwater. Such dry and hybrid systems function at a lower efficiency, especially in hot and dry weather conditions. We have not modeled open-loop once-through cooling systems which are unlikely to be adopted because of environmental impacts and consequent regulatory challenges in the US [23].

The quantity of geothermal fluid withdrawn is represented below and is related to the resource enthalpy and the efficiency of the conversion process—the higher the enthalpy of the resource, the smaller the volume of geothermal fluid that must be withdrawn to provide a unit of thermal input:

$$\dot{w}_{\mathrm{geo}} = \dot{Q}_{\mathrm{in}}/(C_p(T_{\mathrm{geo,in}} - T_{\mathrm{geo,out}})) \quad (2)$$

where $\dot{w}_{\mathrm{geo}}$ is volume of geothermal fluid withdrawn in kg s^{-1}; $T_{\mathrm{geo,in}}$ is the inlet temperature of the fluid in degrees Celsius and proportional to resource enthalpy; $T_{\mathrm{geo,out}}$ is the temperature of fluid re-injected to the ground after exiting the power plant; and C_p is the specific heat capacity in kJ kg°C^{-1} of the geothermal fluid.

For EGS applications, the degraded water requirement is also related to the magnitude of geothermal fluid lost due to leakage from the fractures to the surrounding rocks—the larger the leakage, the larger the volume of degraded water that is required to maintain reservoir pressure. The extent of losses will depend upon site specific conditions such as the permeability of the rocks, depth of the reservoir, and age. Losses are also a function of injection pressure; Tester *et al* [1] note that high-injection pressures extend the fractures and increase permeability which in turn can lead to an increase in flow losses. Fluid losses are expressed as a percentage of the circulation rate of geothermal fluid and are assumed to be 2% in this study [1, 17, 24, 25]. Therefore, degraded water consumed is given as:

$$\dot{w}_{\mathrm{d}} = 0.02 \times \dot{w}_{\mathrm{geo}} \quad (3)$$

where $\dot{w}_{\mathrm{d}}$ represents the degraded water requirements. We assume that the portion of $\dot{w}_{\mathrm{d}}$ is met through WRCS blowdown, which is accounted for under freshwater consumption.

3.2. Water requirements of high enthalpy resources

For geothermal resources with a wellhead temperature higher than 175–200 °C, flash power plants are most appropriate. As mentioned above, most or nearly all the makeup water for cooling is provided by steam condensate. Additional water may be required during summer, reflecting the effect of higher ambient temperatures on water evaporation. The steam condensate also represents the amount of geothermal fluid consumed and hence the amount of degraded water that has to be sourced from external sources and injected to compensate for loss of geothermal fluid. Degraded water is also required for injection to account for fluid losses from the geothermal resource resulting from leakage from the fracture system to the surrounding rocks.

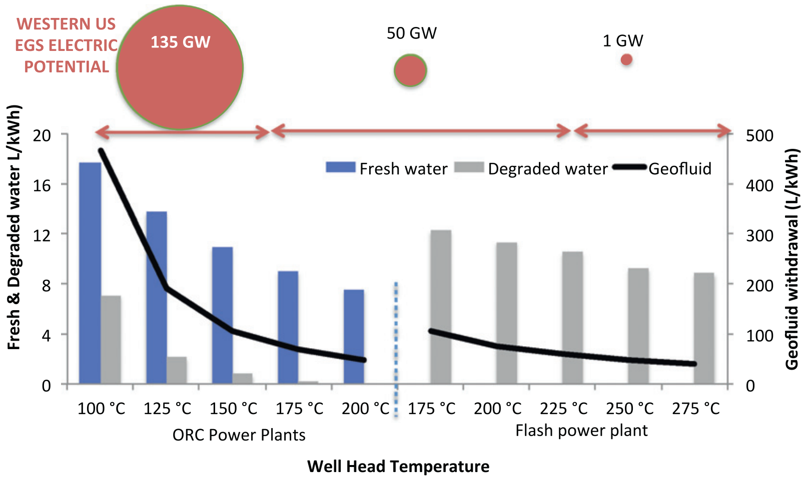

Figure 1. Water requirements of geothermal electricity from EGS resources. An ORC cycle with IHE and WRCS is assumed for low to medium enthalpy (<200 °C) resources; and single flash with WRCS is assumed for medium to high enthalpy resources (>175 °C). Potential geothermal electricity generation capacities in the contiguous western US states are also shown. Since cooling tower blowdown is injected to sustain EGS resource pressure, freshwater withdrawal volume equals consumption. Degraded water withdrawal and consumption volumes are assumed to be equal in our model.

4. Results

4.1. Water demand for individual plants

Figure 1 summarizes the water withdrawal and consumption requirements of electricity from EGS resources. Thermal efficiency of ORC power plants is linearly and positively related to the resource enthalpy represented by the wellhead temperature. Consequently, any increase in geothermal resource enthalpy reduces water requirements. The increase in efficiency and corresponding decrease in water requirements is quite significant—water requirements for electricity generation from a resource at 200 °C are less than half of those required to produce electricity from a resource at 100 °C (figure 1). Note that the relationship between resource temperature and water use is non-linear, due to the non-linearity of temperature vis-à-vis the heat content of water. An ACC reduces freshwater requirements to zero but increases geothermal fluid withdrawal by 12% and degraded water consumption (for EGS scenario) by a factor of three or more. Hydrothermal resources require somewhat lower volumes of freshwater than EGS resources, and do not require degraded water. These additional results are summarized in the supplementary material (SM) (available at stacks.iop.org/ERL/6/034023/mmedia).

For resources with a wellhead temperature above 175 °C requiring flash power plants for energy conversion, the reduction in water requirements with increase in enthalpy is not as steep as in the case of ORC plants. Unlike ORC plants, efficiency of flash plants (second law or 'exergy' efficiency) is independent of resource enthalpy [5].

Figure 1 also summarizes the geothermal electricity potential based on resource estimates for the continental western US up to a maximum depth of 6 km [1]. The western US has the biggest temperature gradients and hence offers the largest resource base for EGS electricity, which can be potentially scaled up to a level to substantially displace thermoelectricity [1]. Economic and technological constraints dictate a maximum drilling depth of 6 km; experience in drilling wells for EGS resource development to depths of approximately 5 km already exists [26]. The electricity potential of around 185 GW may be compared with a current thermoelectricity capacity throughout the entire US of 730 GW [23]. We believe that the above estimate is quite conservative; a recent US Geological Survey (USGS) study estimated an electricity potential of 345 GW from EGS resources in the western US with a 95% certainty [3, 26]. The USGS study assumed a higher thermal recovery rate—the fraction of subsurface reservoir thermal energy that can be extracted sustainably at the wellhead of the geothermal well—of 8–20% compared to only 2% assumed by [1].

Two significant conclusions may be drawn from figure 1. First, preferential development of high enthalpy resources, which constitute around 28% of the geothermal electricity potential as shown in figure 1, will put relatively lower pressure on the already stressed water resources of western states. Second, most of these high enthalpy resources, being in the 175–225 °C range, necessitate a choice between ORC or flash conversion technology. The former requires freshwater while the latter requires degraded water albeit of higher volumes. These differences in water requirements should be considered in economic and environmental cost benefit analysis.

We compared the water consumption intensity of geothermal electricity with that of fossil thermoelectric and solar thermal electricity, assuming that all plants use a WRCS. For thermoelectric plants, upstream water requirements for feedstock mining/extraction, coal beneficiation, and natural gas processing were also considered. We express water requirements from an end user's perspective, thus electricity losses during transmission and distribution of 8% are considered. Our analysis indicates that water requirements of electricity from geothermal resources are substantially

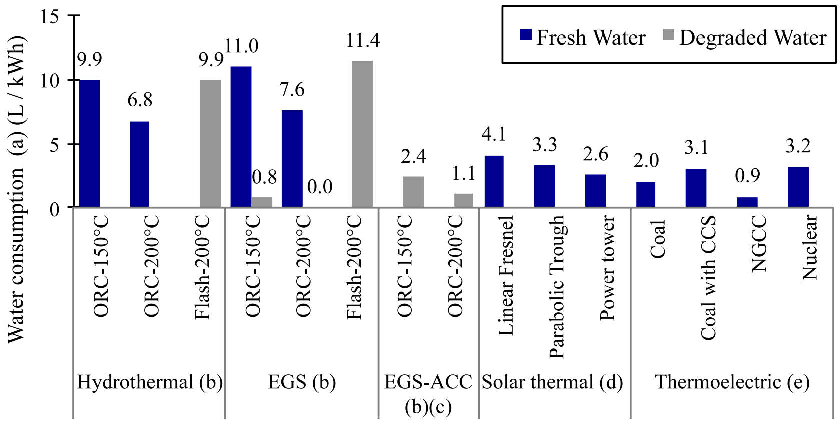

Figure 2. Comparison of water consumption intensity of electricity from various pathways. (a) Water consumption based on WRCS for all power plants except (c); T&D losses of 8% assumed. (b) Geothermal fluid withdrawal requirements not shown, (c) dry cooling assumed, (d) source: modeling by DOE [27], (e) source: [28]. Includes water for coal mining and beneficiation, uranium mining and enrichment, and natural gas extraction. Water withdrawal intensities are compared in the SM (available at stacks.iop.org/ERL/6/034023/mmedia).

higher than those of both thermoelectricity and solar thermal electricity.

Figure 2 indicates that, for the assumptions outlined above, water requirements of (delivered) electricity from geothermal resources are substantially higher than those of thermoelectricity and solar thermal electricity using the same WRCS cooling technology. This explains, at least partly, why 78% of the net capacity of ORC plants in the US use ACC [7, 29], in comparison to only 1% of thermoelectricity [23]. This despite the fact that there is a higher energy penalty for dry-cooled ORC plants than for similar thermoelectric plants, resulting in less efficient production. For example, power output for a plant can decrease by up to 50% from winter to summer [30, 31]. In contrast, air-cooled thermoelectric plants suffer a much lower drop in performance in summer [32, 33]; usually around 10% or less. Diurnal fluctuations may also be significant: DiPippo [5] reports that the power output of the air-cooled bottoming binary cycle in Brady, Nevada was 33% lower at 6 pm than at 6 am in the morning, based on observations over ten days in September 2002. Average ambient temperatures were 30.1 °C and 16.8 °C at 6 pm and 6 am respectively.

4.2. Water demand for large-scale production

We conducted a scenario analysis to examine the aggregated water demand of increased geothermal production and the impact of displacement of thermoelectricity by geothermal electricity on state-wide water requirements. The reference scenario (RS) represents the water required by thermoelectricity generated in 2005 [34]. WRCS account for 95–100% of all thermoelectricity in these states, except California and Colorado where once-through cooling systems using sea water and freshwater dominate respectively.

Two alternative geothermal-based scenarios were envisaged. In the geothermal baseline scenario (GS-BL), the penetration of WRCS in ORC plants (wellhead temperature less than 200 °C) is at the same level as for thermoelectricity today. In the water efficient scenario (GS-WE), we assume that 78% of the ORC plants use dry cooling, as is the case today. All flash plants are assumed to use WRCS in both scenarios. In both scenarios, the geothermal electricity generated from EGS resources is based on electricity potential as summarized in figure 1 and based on an additional subjective assumption of 5% economic viability. The potential electricity generated from EGS up to 6 km ranges between 6 TWh in Utah to 11 TWh in Nevada. The proportion of thermoelectricity displaced by EGS electricity (D) varies more significantly given the differences in thermoelectric production in 2005—D ranges from 8% in Arizona to 1500% in Idaho where hydroelectricity constitutes nearly all the electricity generated in the RS.

Figure 3 compares the water consumption requirements of the three scenarios. Displacement of thermoelectricity by geothermal electricity with evaporative cooling (GS-BL) will lead to an increase in freshwater requirements of 41 billion liters per annum (10%). However, in the GS-WE scenario, changes in freshwater requirements are small in all states except Idaho where electricity generated in GS is 16 times the thermoelectricity in RS, and in Oregon where the geothermal energy within 6 km depth is largely low enthalpy. All states require additional degraded water in GS except California (not shown) where a transition away from thermoelectric plants using once-through cooling reduces withdrawal of seawater.

Our analysis aims to provide a broad overview of the impact of geothermal electricity scale-up on water use. Since water availability and scarcity are more logically characterized at the watershed level [35] than at the state-level, our analysis may be extended to provide actionable knowledge to policy makers and industry participants. Further, volumetric estimates of water withdrawal and consumption may be converted using regionally differentiated characterization factors to provide 'stress-weighted' water intensity estimates that will allow comparison across regions and support decisions involving trade-offs across regions [36, 37].

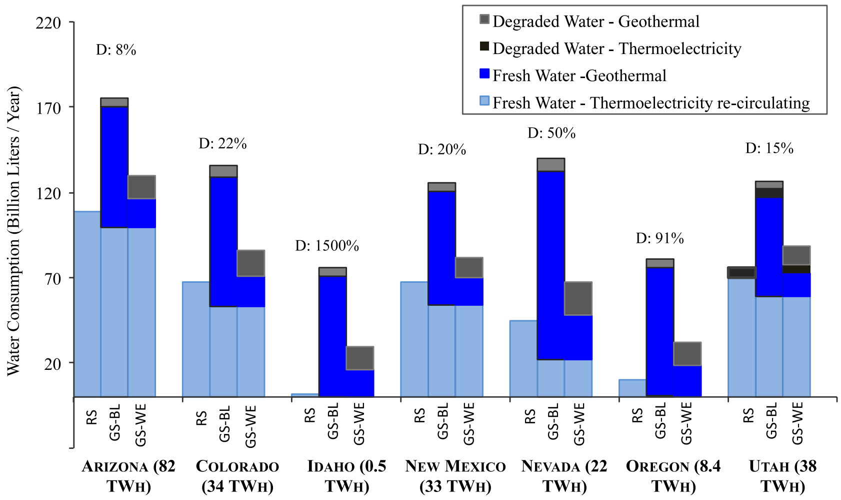

Figure 3. Impact of displacement of thermoelectricity by EGS electricity on consumptive water requirements. 'D' represents the percentage of thermoelectricity produced in the reference scenario (RS) and displaced by electricity from EGS resources in geothermal scenario (GS). Two geothermal sub-scenarios are envisaged—the baseline (GS-BL) and water efficient (GS-WE) scenarios. Detailed assumptions as well as a comparison of withdrawal water requirements are given in the SM (available at stacks.iop.org/ERL/6/034023/mmedia).

5. Discussion

Our results indicate that generating electric power from geothermal resources can lead to increased use of fresh and degraded water relative to that of other traditional power-generating technologies using comparable cooling technologies. Given that water can be a limiting resource in many areas, and in light of the growth in competing water use demands, care must be taken to assure geothermal development takes place in ways in which this resource competition is adequately taken into account. Current mitigation efforts have primarily focused on dry cooling systems at hydrothermal generation facilities. While such systems significantly reduce water consumption, the consequent energy penalty during summer imposes a financial penalty and moderates geothermal electricity's key advantage over other renewable electricity pathways—baseload dispatchability without storage.

To address this trade-off between water use and energy penalty, we suggest a research and development effort to identify every instance in which water is used and evaluate potential for improved efficiency. We note that, for example, hybrid and water-enhanced dry cooling reduce freshwater requirements significantly below WRCS without large energy penalties [27]. Such systems depend upon air cooling for the most part and on evaporative cooling in periods of high ambient temperatures. Research by the Department of Energy [27] indicates that appropriately designed hybrid systems consuming 1% of the water requirements of wet re-circulating systems can halve the energy penalty vis-à-vis dry cooling for a solar thermal plant. These cooling systems have witnessed limited development in their application to thermoelectric power plants, but have substantial potential to reduce water use in geothermal generating facilities. Such advanced cooling systems have higher capital costs than ACCs, which in turn are more expensive than WRCS [28]. This highlights the need for regulatory incentives to spur widespread adoption. Adding to these hybrid systems the capability for 'smart technology' to self-regulate water use, and the ability to load follow, would reduce freshwater consumption substantially. Improving efficiency necessarily cascades benefits to other parts of the system, resulting in diminished demand for heat mining and consequently reduced demand for degraded water.

If geothermal potential is realized, as indicated in figure 3, demand for degraded water will grow, even with an emphasis on dry cooling. This highlights the need for expanding the availability and identification of degraded water resources for power generation purposes. Research in this area has already been initiated [38–40] resulting in the identification of several potential degraded water reservoirs that are currently either unused or need to be treated before release to the environment. Additional work, focusing on the identification of non-traditional local and regional degraded water sources, could be beneficial.

A third area of research should focus on cascaded applications, in which warm water from the cooling cycle is heat-mined before re-injection. Such cascaded applications could include agricultural, manufacturing and processing uses that require low-grade heat resources. Such systems could displace some of the load imposed on existing power generation systems. However, thorough analysis of the impact on this increased cooling would be required to establish the consequences for reservoir lifetime if lower temperature fluids are re-injected into the subsurface.

Geothermal power production has many advantages over both conventional thermoelectric and renewable technologies. Among these are reduced or eliminated atmospheric emissions, a smaller spatial footprint, no intermittency and no fuel cycle with concomitant fuel processing costs. Further, geothermal resources are large enough to provide a substantial portion of the electricity requirements in the US and elsewhere. Further research on the topics outlined above can accelerate the deployment of this technology to areas that currently would have difficulty deploying it due to water scarcity.

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