Global Inventory of Dissolved CO_2 Sequestration Potential in Geothermal Systems

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ABSTRACT

Geothermal electricity generation has low carbon emissions compared to hydrocarbon alternatives. Nevertheless, recent attention on emissions of magmatic CO_2 and other non-condensable gases (NCG) has prompted interest in their capture and reinjection. The geothermal industry is uniquely placed to effect CO_2 sequestration due to existing reinjection infrastructure (e.g., wells, pipes, pumps) and detailed characterization of the subsurface resource.

Dissolving CO_2 into reinjected fluid is one way to dispatch emissions without creating a buoyant free phase in the reservoir. The CO_2 can be sourced as NCG capture from the produced geothermal fluid or from a hybrid fuel energy scheme like bioenergy carbon capture and sequestration (geothermal-BECCS). The latter approach allows for CO_2 concentration in the reservoir to be increased beyond the natural state, turning the geothermal system into a carbon sink. Depending on the local context, spillover benefits could include increased electricity generation, derisking of marginal wells, and additional revenue from CO_2 emission offset schemes.

In this study, we develop first-order estimates for the global CO_2 sequestration potential of installed geothermal power plants retrofitted for geothermal-BECCS. We estimate the potential carbon dioxide removal (CDR) rate ($MtCO_2/yr$) on a plant-by-plant basis using a mass and energy balance model with fluid throughput rates inferred from plant capacity, technology, and resource temperature. We also calculate potential revenues from CO_2 removal and boosted electricity.

We estimate that existing geothermal systems have the potential for 60 million tonnes of CO_2 removal annually ($MtCO_2/yr$) at a value of $6 billion. On average, hybridized cycles generate about 30% more electricity at a value of $3 billion annually. However, biomass fuel requirements to realize this scale CDR are 37 Mt/yr and may represent a key bottleneck for many countries. The United States had the highest potential CDR rate at 21.6 $MtCO_2/yr$, followed by Indonesia, the Philippines, and Turkey with 6-7 $MtCO_2/yr$, and other countries (New Zealand, Italy, Kenya, Mexico, Iceland, Japan) in the range of 2-3.5 $MtCO_2/yr$. Herein, we discuss the caveats, limitations and risks that geothermal-BECCS would need to overcome to realize these benefits.

1. INTRODUCTION

As countries seek to decarbonize their economies, geothermal electricity and direct heat will play a key role. The geothermal industry has enjoyed renewed interest and growth in the last decade, with installed capacity increasing by 30% between 2015 and 2020 (Huttrer, 2021). However, the most attractive geothermal resources have shallow, high-temperature reservoirs, which are mainly restricted to volcanic regions in a handful of countries. Many of these fields have already been developed or placed into protective status. In the future, we will need innovative technologies that can better utilize low-temperature resources, either by mitigating their poor conversion efficiency (Zarrouk and Moon, 2014) or by finding complementary revenue streams that increase their economic performance.

This paper focuses on one such technology: geothermal generation hybridized with bioenergy and carbon capture and storage (geothermal-BECCS; Titus et al., 2023a). The deployment of negative emissions technologies like BECCS feature prominently in the Intergovernmental Panel of Climate Change's AR6 report to counter hard-to-abate CO_2 emissions and limit global warming to below 1.5°C (IPCC, 2022).

1.1 Hybrid fuel cycles

One way to increase the efficiency of electricity generation from low temperature geofluids is to hybridize with a second fuel cycle. Solar-geothermal hybrids studies have considered superheating geothermal water using parabolic mirrors to concentrate sunlight (Manente et al., 2011) or by using a second heat exchanger to increase working fluid temperature in a binary cycle (Greenhut et al., 2010). However, the seasonal and diurnal intermittency of solar radiation influences energy delivery to solar-hybrid schemes. Hybridizing with a fossil fuel cycle can avoid the intermittency problem because the additional fuel energy is 'on demand' (DiPippo, 2016; Kestin et al., 1978). However, this introduces dependencies on the cost and availability of fuel as well an increasing overall emissions profile. Hybridizing with a biomass fuel cycle significantly abates the emissions penalty but has the same issues with fuel cost and scarcity.

Thain and DiPippo (2015) studied geothermal-biomass hybrids in some detail. They considered introduction of a steam superheater at the 29 MWe Rotokawa geothermal field, New Zealand, which would theoretically increase output a further 8.5 MWe. For the biomass feedstock, they proposed to use forestry waste from the nearby Kaingaroa Forest; in New Zealand, major forestry and geothermal resources are co-located in the Waikato and Bay of Plenty regions. CO_2 emission from biomass combustion is considered carbon neutral over the life cycle of the fuel because any liberated carbon was earlier sequestered from the atmosphere.

A geothermal-bioenergy cycle has been implemented at the 20 MWe Cornia-2 facility (Dal Porto et al., 2016) in the Larderello geothermal field in Italy. Here, combustion of a local biomass source is used to superheat steam to 370°C for a further 6 MWe of power. Hybridization was a relatively straightforward retrofit of the underperforming plant with a biomass boiler and heat exchanger being inserted directly in the steam line. Titus et al. (2023a,b) have considered other retrofit configurations that may be feasible depending on the configuration of the initial plant.

1.2 Reducing geothermal emissions

Although it has low emissions compared to thermal alternatives (e.g., natural gas, coal, petroleum), geothermal electricity generation nevertheless has a non-zero footprint. Geothermal emissions primarily derive from the discharge of NCGs that are co-produced or exsolved from the hot geofluid. Bertani and Thain (2002) calculated a global MW-weighted average emissions intensity for geothermal of 122 gCO_2/kWh with a wide range of individual values, 4–740 gCO_2/kWh. These estimates are for fuel cycle emissions only and do not consider the full lifecycle of a geothermal plant, including construction and decommissioning (McLean and Richardson, 2021). Some geothermal plants in Turkey produce fluids from carbonate reservoirs and these can have particularly high emissions intensities exceeding 1000 gCO_2/kWh (Fridriksson et al., 2017).

Recent efforts to reduce geothermal emissions have focused on the capture and reinjection of NCGs. Since 2014, the CarbFix project at Hellisheidi, Iceland has been injecting ~15 000 tCO_2/yr using a downhole bubbler to dissolve emissions into reinjected fluid (Gíslason et al., 2018). The dissolved CO_2 is reactive with basalt formations, rapidly precipitating carbonate minerals that provide long-term trapping. Marieni et al. (2018) have suggested the method could also be applied for reinjection into silicic rocks that dominate in other geothermal provinces, e.g., rhyolite deposits of the Taupo Volcanic Zone, New Zealand. Indeed, since 2021, the Ngatamariki geothermal power plant in New Zealand has been trialing NCG reinjection of ~8000 tCO_2/yr (Ghafar et al., 2022). For the 2022 carbon price of 80 NZD/tCO_2 that would ordinarily be levied on these emissions, this reinjection represents an abated liability of 0.64 million NZD/yr. Such schemes are a promising step towards carbon dioxide removal from the atmosphere with permanent storage (e.g., in underground reservoirs).

1.3 Geothermal-BECCS

Bioenergy Carbon Capture and Storage (BECCS) is a CDR-based electricity cycle that involves the combustion of a biomass feedstock followed by capture and permanent storage of exhaust CO_2 (Fridahl and Lehtveer, 2018). The concept has several parallels with some of the innovative techniques pioneered in geothermal in the last decade, notably the use of a biomass feedstock (e.g., Cornia-2 at Laderello, Italy) and emissions capture and storage (e.g., CarbFix at Hellisheidi, Iceland). Geothermal-BECCS is a specific class of BECCS and CDR that increases power output and offers negative carbon emissions compared to a traditional geothermal development (Titus et al., 2023a).

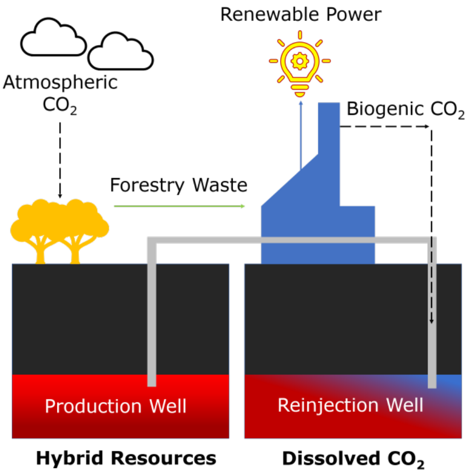

Figure 1: Process cycle schematic of a geothermal-BECCS system. From Titus et al. (2023b).

Previous studies have considered aspects of geothermal-BECCS in a New Zealand context. For instance, Titus et al. (2023a) presented the thermodynamic basis for hybridized geothermal and bioenergy generation for both flash and binary configurations. They also quantify the negative emission intensities of these cycles, which range from -131 to -922 gCO2/kWh. Titus et al. (2022) quantified the economic performance of such combined geothermal-bioenergy hybrids, testing sensitivity of levelized electricity costs (LCOE) to feedstock (forestry waste) costs and the price of carbon on the New Zealand market. They suggested LCOEs between 0.16 and 0.20 NZD/kWh under 2022 conditions, dropping to 0.03 to 0.06 NZD/kWh for anticipated reductions in gate cost and increases in carbon price. Finally, Titus et al. (2023b) considered the practicalities of retrofitting existing plant infrastructure to geothermal-BECCS. This may be the most cost-effective implementation of geothermal-BECCS in the near term, as it leverages existing (and expensive) reinjection apparatus' that exist at most geothermal systems (Kamila et al., 2021).

Our goal in this paper is to quantify the potential of geothermal-BECCS systems beyond New Zealand. Unfortunately, it is not practical to replicate the case-by-case detail of prior geothermal-BECCS studies for each of the hundreds of installed geothermal generation units around the world. Instead, we have categorized the existing generation by technology and resource temperature, and estimated the order-of-magnitude sequestration potential for each.

This high-level approach does not consider two elements that would be essential to assess the feasibility of a specific site: (i) economic performance, including anticipated expenditures, levelized costs and payback period, and (ii) reservoir performance, including chemical breakthrough, permeability decline through mineralization and CO_2 breakout. Nor does it consider the potential of new builds at undeveloped low-temperature resources. Rather, the goal here is to bound the potential benefits of geothermal-BECCS for the global geothermal industry at the present time.

2. METHODOLOGY

2.1 Description of Data

For information on global installed geothermal generation capacity, we used the Geothermal Power Plant Map compiled and published by ThinkGeoEnergy (Richter and Schneider, 2020). This database includes the location, country, installed capacity (in MWe), and technology type of 359 geothermal generation units (Table 1, Figure 2). Fields can have multiple generating units, which may or may not be of different technology types. The top 10 countries account for 93% of all installed generation. Binary plants make up about a quarter of total generation, with the balance produced through various steam turbine configurations. To account for realistic downtime rates, when calculating potential carbon sequestration, we discounted the installed capacity by the global average capacity factor between 2015 and 2020 of 80% (IRENA, 2021).

Table 1: Summary of installed capacity compiled from the Geothermal Power Plant Map (Richter and Schneider, 2020).

Country	Total Installed Capacity (MWe)	Number of Generating Units
United States	3658	77
Indonesia	2027	25
Philippines	1932	24
Turkey	1586	60
New Zealand	1009	22
Italy	936	36
Kenya	861	16
Mexico	775	12
Iceland	753	9
Japan	601	31
Other countries	1029	47
Total	**15 167**	**359**

Technology Type	Total Installed Capacity (MWe)	Number of Generating Units
Single Flash	5311	95
Binary	3605	165
Double Flash	2967	36
Dry Steam	2914	54
Triple Flash	195	2
Back Pressure	175	7
Total	**15 167**	**359**

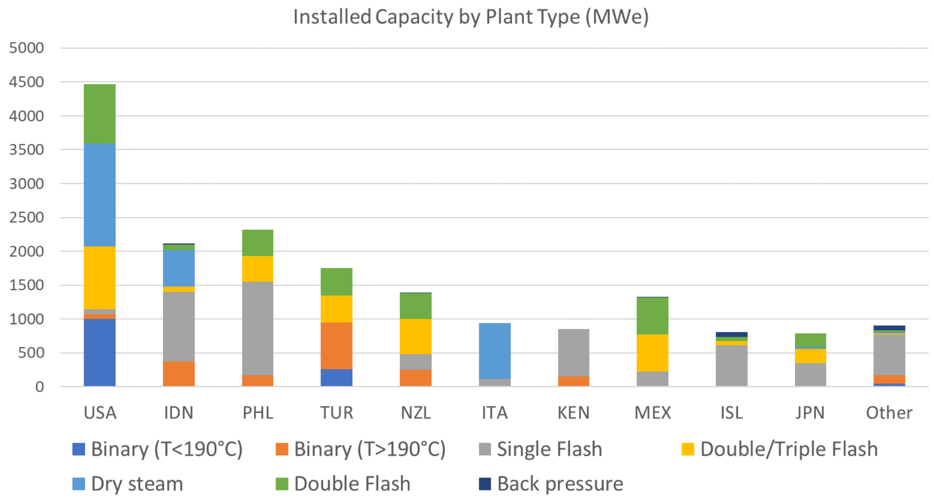

Figure 2: Summary of total installed capacity by country and technology type.

To approximate geothermal-BECCS retrofit performance for each generating unit, we needed to know the approximate resource temperature. For most installations, we were able to infer an approximate geothermal system temperature using data compiled by Wilmarth et al. (2021; their figure 2). In some instances, we grouped generating units that were geographically close and likely to be within the bounds of the same geothermal system, e.g., The Geysers, California, and then assigned a single resource temperature. This approach is not wholly satisfactory as individual generating units may access reservoir compartments or system areas with disparate temperatures. One way to improve this would be to obtain a mass-weighted production temperature for each of 359 generating units, however, this may be difficult as that information is often proprietary.

In cases where system temperature information could not be obtained from Wilmarth et al. (2021), we supplemented with literature sources (Simsek, 1985; Armannsson, 2008; Asturias, 2008; Caranto et al., 2010; Capuno et al., 2010; Ayala, 2014; Mertoglu et al. 2015; Akin, 2017; Eneva et al., 2019; Mulyani et al. 2019; Ayling, 2020; Tosti et al., 2020; Hamdani et al., 2020; Alfiady et al., 2021). For 77 generating units, we could not find any information confirming the resource temperature and therefore left these out of the geothermal-BECCS calculations. Individually, these omitted units were quite small, collectively comprising 3.2% (479 MWe) of the total installed capacity in the database.

2.2 Geothermal-BECCS Retrofit Models

To minimize the amount of new infrastructure required, geothermal-BECCS retrofits in this study were divided into two categories: (1) in systems likely to contain a component of geothermal steam, we assumed a biomass boiler was inserted to superheat the steam prior to turbine expansion; and (2) for binary cycles with no steam separation, the vaporization step in the binary cycle was re-assigned to a biomass heat exchanger with a reduced mass of geothermal brine relegated to preheating.

Category 1 is reminiscent of the Cornia-2 power station where the turbine inlet temperature was significantly increased over the original plant (156°C to 375°C) through biomass superheating. In contrast, with the energy load shared between the biomass heat exchanger and geothermal brine for the working fluid cycle, Category 2 requires less geothermal fluid extraction. This could correspond to fewer wells, reduced resource consents, or reduced mass takes from existing wells.

From a hybridization standpoint, Category 1 is optimal when an existing plant is operating below design capacity. Category 2 may be preferred to delay the drilling of replacement wells to replace declining assets. Table 2 summarizes the retrofit categories assigned to the different geothermal plant types in the database. It includes the key assumptions required to analyze these plants in aggregate. We accept that some of these retrofit assumptions may not be appropriate on a case-by-case basis, with plant components and configuration often tailored to the specific production temperatures, chemistry, or layout of a geothermal system. Nevertheless, they ought to provide order-of-magnitude estimates of key energy cycle quantities: hybrid power output and CO_2 injection rate. Specific details of the mass and energy balance calculations are given elsewhere (Titus et al., 2022, 2023a, b).

Table 2: Summary of geothermal-BECCS retrofit approach and assumptions by plant type.

Geothermal Plant	BECCS Retrofit Category	Key Assumptions
Single Flash	Category 1: a biomass superheater is placed between the separator and turbine to heat separated steam to 400°C.	▪ A maximum steam superheat temperature of 400°C is selected due to high corrosive potential of geothermal steam. ▪ The condenser temperature is 46°C. ▪ Biogenic CO_2 was dissolved in separated brine, not steam condensate.
Double Flash/Triple Flash	Category 1: a biomass superheater is placed between the 1st separator and the high-pressure turbine to heat separated steam to 400°C.	▪ The enthalpy of steam entering the low pressure (and/or intermediate pressure) turbine remained unchanged. ▪ Biogenic CO_2 was dissolved in the remaining brine after the second (or third) flash.
Dry Steam	Category 1: a biomass superheater is placed between the production well and turbine to heat dry steam to 400°C.	▪ The reservoir is 50 bar and at vapor saturation. ▪ Plants have surface condensers, as steam condensate was the only vehicle for sequestration, to avoid contamination by oxygen and subsequent corrosion. ▪ The turbine inlet pressure is 10 bar.
Low Temperature Binary (<190°C)	Category 2: a binary geothermal-BECCS plant using biomass heating applied to the same amount of working fluid. This requires less overall geothermal fluid.	▪ The working fluid is isopentane. ▪ The final temperature of the working fluid exiting the preheater is no greater than 10°C cooler than the incoming geothermal fluid. ▪ A downhole pump is used to transport geofluid from the production well to the plant as a saturated liquid. ▪ The brine reinjection temperature is 95°C.
High Temperature Flash-Binary Hybrid (>190°C)	Category 1: 2-phase geothermal fluid is separated, with brine sent to a binary cycle and steam sent to a biomass superheater prior to turbine entry	▪ The superheater location is in the steam-line only (requires the least modification) and the two-phase fluid flows unassisted. ▪ A maximum steam superheat temperature of 400°C is selected due to high corrosive potential of the geothermal steam. ▪ The working fluid is isopentane. ▪ The working fluid turbine inlet pressure is equal to the separator pressure. ▪ The final temperature of the working fluid exiting the evaporator is no greater than 10°C cooler than the incoming separated brine temperature. ▪ The brine reinjection temperature is 95°C.

2.3 Economic and Environmental Benefits of Plant Retrofits

We calculate several performance metrics to quantify the potential costs and benefits associated with geothermal-BECCS.

2.3.1 Boosted power output

We benchmark our retrofit calculation against the installed generation capacity at each site, denoted W_0. After retrofit, the new generation capacity is W_{net}, which accounts for the parasitic load to compress exhaust CO_2 to the dissolution pressure. We then calculate the percentage increase in power output as $(W_{\text{net}} - W_0)/W_0 \times 100$.

We estimate revenue from saleable power on an annual basis assuming a reference wholesale electricity price of \$100/MWh and a capacity factor of 80% (IRENA, 2021). For different power pricing schemes, these estimates are straightforward to rescale using a preferred electricity price.

2.3.2 Carbon dioxide removal

A key output of the geothermal-BECCS calculation is the annual rate of dissolved CO_2 reinjection, Q_{CO2}, usually measured in millions of tonnes of CO_2 per year ($MtCO_2$/yr). The ratio of CO_2 injection to hybridized generation capacity, W_{net}, gives the emissions intensity of the system, EI, measured in grams of CO_2 per kilowatt hour (gCO_2/kWh). This calculation assumes that all CO_2 emissions from the produced geofluid were captured and added to the biomass exhaust for reinjection (à la CarbFix).

We estimate potential gross revenue from carbon dioxide removal, C_{CDR}, on an annual basis assuming a reference carbon price of \$100/tCO_2. Actual revenues would depend on an individual project's ability to take advantage of local or global carbon markets, and net revenue would need to account for the cost of fuel, CO_2 storage monitoring and audit. The annual rate of biomass feedstock required, Q_{BIO}, is proportional to sequestration rate using a factor of 1.6 tCO_2 per tonne of forestry waste (Puettmann et al., 2020) (tBIO = tonne of biomass).

2.3.3 Reduced field mass take

For low temperature binary systems, the retrofit approach fixes the working fluid mass of the binary cycle and instead substitutes part of the geothermal energy input with the biomass source. As a result, the same power output ($W_{\text{net}} \approx W_0$) can be realized with a smaller mass of geofluid. This could prolong the life of the resource or infrastructure through reduced pressure drawdown and scaling rates. For these systems, we have calculated a percentage reduction of the geothermal mass flow rate.

3. RESULTS

Tables 3 and 4 summarize the performance geothermal-bioenergy hybrid systems by plant type and country, respectively. For plants that separate and transmit a dry steam component to a turbine, steam superheating results in an average 30% increase in generation (ranging between 13 and 42% for different plant types). In contrast, for low-temperature binary systems, the additional energy from biomass combustion offsets energy derived from geofluid. As a result, mass takes from the geothermal system are about 45% lower than the pre-hybrid configuration.

The emissions intensity for steam superheating configurations has a MW-weighted average of -446 gCO_2/kWh. These hybrid configurations remove CO_2 from the atmosphere at a similar (kWh levelized) rate that natural gas turbines emit. Low temperature binary systems have a much larger negative emissions intensity of -1830 gCO_2/kWh because, compared to flash plants, they typically had a lower ratio of plant nameplate capacity to geothermal fluid take. Additionally, flash plants are unable to use steam condensate as a CO_2 injection medium as we assumed the plant lacked a surface condenser.

Table 3: Summary of geothermal-BECCS performance by plant type.

	Binary		**Single Flash**	**Double/Triple Flash**	**Dry Steam**	**Back Pressure**	**All**
	(T < 190°C)	**(T > 190°C)**					
Generating units	42	59	87	38	53	5	284
Installed capacity W_0 (MWe)	1307	1844	5293	3162	2914	168	14 688
Hybrid capacity W_{net} (MWe)	1331 (+1.8%)	2611 (+42%)	7403 (+40%)	4228 (+34%)	3291 (+13%)	238 (+42%)	19 102 (+30%)
CDR rate Q_{CO2} ($MtCO_2$/yr)	17.1	7.0	18.5	9.5	6.7	0.9	59.6
CDR revenue C_{CDR} (B\$/yr)	1.7	0.7	1.8	1.0	0.7	0.1	6.0
Fuel rate Q_{BIO} (Mt/yr)	10.7	4.4	11.6	5.9	4.2	0.5	37.3
Emissions Intensity* EI (gCO_2/kWh)	-1830	-384	-356	-321	-290	-522	-446

*MW-weighted average of individual units

Table 4: Summary of geothermal-BECCS performance by country.

	USA	IDN	PHL	TUR	NZL	ITA	KEN	MEX	ISL	JPN	Other
Generating units	66	25	22	44	20	36	13	12	6	20	20
Installed capacity W_0 (MWe)	3595	2027	1932	1351	1009	936	854	775	747	582	880
Hybrid capacity W_{net} (MWe)	4205	2663	2649	1839	1362	1081	1209	1041	1036	794	1221
CDR rate Q_{CO2} (MtCO$_2$/yr)	21.6	6.3	6.0	6.8	3.0	2.2	3.4	2.2	2.6	1.9	3.7
CDR revenue C_{CDR} (B$/yr)	2.2	0.6	0.6	0.7	0.3	0.2	0.3	0.2	0.3	0.2	0.4
Fuel rate Q_{BIO} (Mt/yr)	13.5	3.9	3.8	1.2	1.9	1.4	2.1	1.4	1.6	1.2	2.3
Emissions intensity* EI (gCO$_2$/kWh)	-734	-335	-324	-526	-315	-295	-398	-300	-352	-339	-665

*MW-weighted average of individual units

Total CO$_2$ removal across all generating units is just under 60 MtCO$_2$/yr, ~60% of which comes from low temperature binary and single flash systems. However, this requires more than 37 Mt/yr of biomass feedstock (fuel) to be secured and delivered to the plants. At a reference price of \$100/tCO$_2$, the total value of sequestration is \$6 billion annually, or about \$400 000 per installed MWe. For comparison, additional saleable power from biomass boosting at a reference price of \$100/MWh has an annual value of about \$3 billion (total boosted power value is ~\$13 billion annually).

The country with the largest potential for geothermal-BECCS is the United States, with an estimated possible carbon removal rate of 21.6 MtCO$_2$/yr across its 66 generating units and 3595 MWe capacity (Table 4, Figure 3). The next closest country, Indonesia, manages only 6.3 MtCO$_2$/yr of CDR. The main reason for the United States' outsized performance is the preponderance of low-temperature binary systems, which are well-suited to CDR due to their high negative emissions intensity. For reference, the potential CDR of conventional BECCS in the United States is estimated between 100–110 MtCO$_2$/yr when accounting for spatial constraints between feedstock availability and reservoir suitability (Galik, 2020). Geothermal reservoirs might therefore unlock considerable additional storage potential.

Indonesia, the Philippines, and Turkey have the next highest CDR rates ranging between 6.0 and 6.8 MtCO$_2$/yr. An important caveat for Turkish geothermal systems is that several have extremely high dissolved CO$_2$ concentrations, which contributes to large positive emissions intensities (>1000 gCO$_2$/kWh; Fridriksson et al., 2017). For such systems, geothermal-BECCS may not confer net negative sequestration when accounting for these natural emissions, whether they are captured or not.

The other countries in the top ten - New Zealand, Italy, Kenya, Mexico, Iceland and Japan – each have potential CDR rates of several MtCO$_2$/yr.

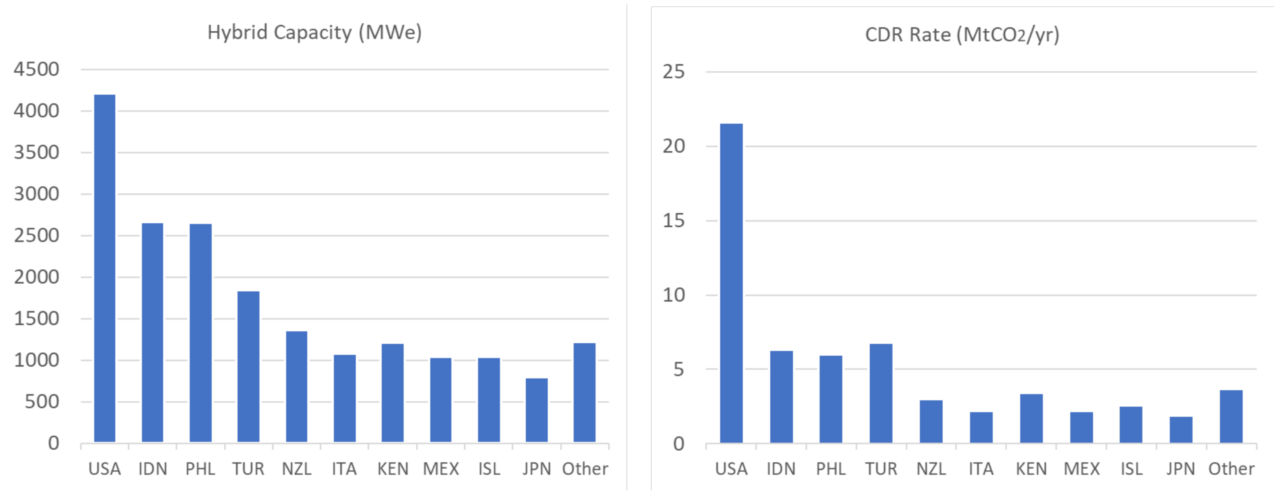

Figure 3: Summary of total hybrid generation capacity (left) and carbon dioxide removal (CDR, right) by country.

4. DISCUSSION

4.1 Biomass Feedstock Availability

Securing enough low-cost biomass fuel is an important bottleneck that developers would need to eliminate before deploying geothermal-BECCS at scale. For example, in New Zealand, we calculate that full hybridization of the geothermal generation sector would require 1.9 Mt/yr of biomass. However, competitively priced, regionally available forestry residues only total 1.0 Mt/yr (MPI, 2020; Titus et al., 2022) suggesting that other sources may need to be sought, e.g., municipal solid waste, energy crops.

Similarly, most of the low-temperature systems in the United States are in Nevada's Basin and Range province. Nevada is the 6th lowest ranked state by forest cover (Vogt and Smith, 2016) suggesting that power plants are unlikely to be co-located with sources of forestry residues. Developers would instead need to explore alternative feedstocks or pursue biomass supply agreements with adjacent states. Providing distances are reasonable (<200 km), transportation emissions can be less than 10% of total CO_2 removal. Forested landscapes are also notably scarce in Iceland.

In contrast, Indonesia and the Philippines are densely forested, with geothermal systems often located in remote volcanic terrain. However, this old-growth rainforest is not likely to be a preferred biomass feedstock due to its high value as an existing carbon sink and for the unique ecosystems and threatened species it supports (e.g., Orangutan, Sumatran Elephant.)

Assessing biomass availability would be the first step in deciding whether geothermal-BECCS or, alternatively, direct air capture and sequestration (DACS) is more suitable for CDR retrofits, though the latter would be unable to boost the electricity generation of the plant. To compare geothermal-BECCS with geothermal-DACS on an even playing field, the levelized cost of carbon abatement (LCCA, Friedman et al., 2020) may be a more appropriate tool.

4.2 CDR and Reservoir Management

The large-scale, long-term injection of dissolved CO_2 in the subsurface is an activity that requires careful planning and handling. On a field-by-field basis, developers must consider the risk of chemical breakthrough, wherein a plume of water with elevated CO_2 concentration encroaches on the production wells. If this occurs, additional NCG capture and reinjection would be needed to maintain net CDR rates. Furthermore, CO_2 breakout in two-phase or low-pressure production zones could increase NCG concentrations in pipelines and plant machinery, requiring intervention. In the first instance, CO_2 breakthrough risks should be managed through standard reinjection practices designed to limit thermal breakthrough, e.g., tracer testing, reservoir modelling. To this end, the existing placement and operation of reinjection assets in fields – presumably designed to minimize thermal breakthrough risks – may also confer some protection from chemical breakthrough. Reservoir managers may further look to high-CO_2 Turkish fields for experience managing similar fluid environments.

A second consideration is whether induced mineralization in the reservoir would lead to long-term permeability declines in the reinjection area. Understanding this risk is likely to require laboratory and in situ geochemical studies on a field-by-field basis, taking the specific reservoir mineralogy and fluid composition into account (Matter et al., 2016; Marieni et al., 2018). We suggest that some decline in the reinjection assets may be acceptable providing that any interventions or expansions this necessitates are offset by the value of carbon removed.

4.3 Estimating the potential for geothermal-BECCS new builds

Hybrid geothermal-BECCS plant designs have several advantages that may improve the economic prospects of marginal, low-temperature resources that have been so-far undeveloped. These advantages include complementary revenue streams (CDR) and energy boosting that derisks low-temperature aquifers or wells on field margins. However, we have not here estimated the potential of geothermal-BECCS new builds at undeveloped systems. To do so would require a database of field prospects, matched by estimates of resource temperature and sustainable production rates. If these were furnished, the rest of the analysis could proceed as detailed in this study, ideally with uncertainty analyses to provide P10, P50 and P90 estimates.

Some notable countries with low temperature geothermal resources (<160°C) and an abundance of potential biomass feedstock include Canada (Giuntoli et al., 2021; Hickson et al., 2021), Germany (Toselli et al., 2019) and France (Chavot, 2019; Galiègue & Laude, 2017). France in particular has already investigated the capture of CO_2 from sugar-beet fermentation in low temperature geothermal brines to offset fossil-boiler emissions as part of the CO_2-dissolved project in the Paris basin.

5. CONCLUSION

We have derived order-of-magnitude estimates for the global potential of dissolved-CO_2 injection at existing geothermal plants. Our approach has considered a specific retrofit strategy based on hybridization of geothermal plants with bioenergy carbon capture and storage (geothermal-BECCS). We used publicly available databases to characterize existing geothermal installations by country, technology type, and resource temperature. Then, we applied a power plant systems model to estimate potential energy boosting and carbon dioxide removal (CDR) under certain retrofit assumptions. Finally, the gross revenues associated with the retrofit systems.

We estimate that existing geothermal systems have the potential for 60 million tonnes of CO_2 removal annually ($MtCO_2$/yr) at a value of $6 billion. On average, hybridized cycles generate about 30% more electricity at a value of $3 billion annually. However, biomass fuel requirements to realize this scale CDR are 37 Mt/yr and may represent a key bottleneck for many countries. The United States had the highest potential CDR rate at 21.6 $MtCO_2$/yr, followed by Indonesia, the Philippines, and Turkey with 6-7 $MtCO_2$/yr, and other countries (New Zealand, Italy, Kenya, Mexico, Iceland, Japan) in the range 2-3.5 $MtCO_2$/yr.

The goal of our study has been to develop first order estimates of the potential for atmospheric CO_2 removal and storage in geothermal systems. This required assumptions about retrofitting that may later need to be varied on a case-by-case basis depending on the individual character of a field or a plant's configuration. Furthermore, an individual feasibility study would need to quantify both life-cycle financial performance and confirm a practicable reservoir management strategy, which we have not done here. Nevertheless, we hope that the high-level analysis provided herein may be useful for industry and government as they weigh the challenges of global decarbonization.

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