Streamlining Energy Sprawl: Assessment of Geothermal Impacts on Public Lands

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ABSTRACT

Renewable energy power generation, including geothermal, solar photovoltaics (PV), and wind, can have significant land use impacts depending on the technology and the size of the facility. At the same time, innovations across these renewable technologies are working to improve plant efficiency per acre of disturbance. Through a survey of satellite imagery and other sources, this analysis reevaluates the impact of geothermal power generation and examines the variations in land use for different geothermal technologies (binary, flash, and dry steam). Geothermal operations on Bureau of Land Management (BLM) sites serve as the focus for this analysis – i.e., only active sites with federal mineral ownership for which the BLM receives royalties from power production. The results show significant variation in direct land disturbance across the operations sites and across these three geothermal technologies. Although there is variation across plants within the same geothermal technology category, dry steam plants (The Geysers) were shown to have the lowest impact, in acres per megawatt capacity and acres per gigawatt-hour generation, followed by flash steam and binary plants. Overall, direct land impacts relative to capacity and generation have declined 16-27% for facilities constructed since 2000 as compared to those constructed prior, even though most new facilities are binary plants (which traditionally had higher land disturbance). Additionally, capacity factors based on actual net production data were found to average only 50% across all operations sites, suggesting that previous estimates based on nameplate capacity only may lead to an undercounting of generation-based land disturbance metrics. Should the geothermal industry capture additional market share, improving land disturbance metrics through accurate net production and capacity data and further minimizing impacts will be increasingly important as competition over land use intensifies.

1. Introduction

United States electricity consumption is expected to increase 1% annually from 2018 – 2050. New power generators will be required to meet this additional demand while also replacing existing generators that are planned for retirement. Renewable technologies such as solar photovoltaics (PV), wind, and geothermal are expected to support a growing portion of electricity demand nationwide (U.S. Energy Information Agency (EIA), 2019a). This expected increase is a function of the declining costs of renewable energy technologies (especially wind and PV) as compared to conventional fossil fuel generators, as well as the presence of favorable policies that support renewable energy markets, including state-mandated Renewable Portfolio Standards (Barbose, 2019; Lazard, 2019).

Although renewable energy technologies can provide a variety of economic and environmental benefits, these facilities can also have significant land use impacts (Denholm et al., 2009; Fthenakis and Kim, 2009; Heath et al., 2012). Land use impacts can be evaluated in several ways, including assessments of the surface area impacted, the duration of the impact, and the quality, type, and intensity of the impact (Koellner and Scholz, 2008). Although a comprehensive assessment of land use impacts might address all three categories, this type of analysis requires an in-depth, case-by-case ecological evaluation, making rapid cross-site and cross-technology comparisons more difficult.

In the context of power generation, research has focused on assessments of land area impacts in order to understand both the potential scope of impacts across different uses and historical trends (Denholm et al., 2009; Heath et al., 2012). Here, land use impact is categorized using both direct area (physically disturbed land) and total area (land associated with a project). Direct area impacts are the most significant because the land typically cannot be used for other purposes and may require reclamation to return it to its previous state. Thus, duration and quality of the impact in these directly impacted areas is likely to be more significant than throughout the remainder of a project’s total area (i.e., leased land).

Meeting future electricity demand with new renewable energy projects will inevitably have land use impacts. Understanding these potential impacts is critical for identifying potential environmental issues and possible mitigation measures (Trainor et al., 2016). At the same time, land use impacts are evolving with technology innovation, so historical analyses of these impacts represent snapshots in time as opposed to accurate projections of future land use (Heath et al., 2012).

This study focuses on geothermal land disturbance, given that geothermal deployment could potentially increase 2,600% by 2050 with the possible deployment of up to 60 gigawatts (GW), including both conventional hydrothermal and Enhanced Geothermal Systems (EGS) (U.S. Department of Energy (DOE), 2019). Should deployment continue to increase, these new projects may have significant land use impacts, and it is unclear whether land disturbance metrics for geothermal have improved since the last historical analysis completed by Heath et al. in 2012. Through a survey of satellite imagery and other sources, this study reevaluates the impact of geothermal power generation and reexamines the variations in land disturbance for existing geothermal technologies (i.e., binary, flash, and dry steam).

2. Literature Review

2.1 Understanding Land Use Impacts

All land uses – whether agriculture, forestry, mining, or power generation – have substantial impacts on an area's environment and biodiversity (Canals et al., 2007). Quantifying impacts and comparing them across land uses can be challenging because different lands can have varying human or ecological benefits that can be valued differently based on the analysts' judgments (Canals et al., 2007). Although the field is working to develop a comprehensive method to conduct land use assessments, this work is still ongoing (Teixeira et al., 2016). Thus, in-depth analyses of land use impacts are typically completed on a case-by-case basis. For example, federal agencies in the United States determine allowable land uses via large-scale resource management plans under the Federal Land Policy and Management Act of 1976, and then conduct case-by-case environmental / land use impact assessments for development of specific parcels as required by the National Environmental Policy Act of 1969.

To begin to compare land use impacts across different uses, locations, and technology configurations, scholars have focused on a more rudimentary assessment: land area impacted. Although this approach is less sophisticated, it can identify the areas where direct impacts may have the largest effect on environmental indicators, such as biodiversity and ecological services. Therefore, these assessments serve as a critical foundation for subsequent analysis on impacts and can provide a metric for comparing potential impacts across land uses and time.

2.2 Renewable Energy Land Use Impacts

All power generation sources have land use impacts which vary with both the technology and plant configuration (Trainor et al., 2016). Even so, direct impacts are typically associated with the same general land use categories, such as power generation equipment / facilities, access roads, and transmission infrastructure. These land uses result in physical disturbance of the impacted land (Heath et al., 2012; Kagel et al., 2007).

Heath et al. (2012) produced the first comprehensive comparative assessment of three renewable energy technologies' land disturbance impacts (geothermal, PV, and wind). The focus of the analysis was on utility-scale projects across the United States. Heath et al. (2012) provide estimates of total and direct land area impacted by each of the technologies. To normalize the data, the land area is compared to project capacity and estimated power generation.

Heath et al. (2012) concluded that the total land areas required for geothermal and PV technologies were comparable on a capacity-weighted average (8 – 10 acres/megawatt [MW] of nameplate capacity). In comparison, wind's total land area impact is much higher at 89 acres/MW. When considering direct impacts (i.e., physically disturbed land) geothermal and wind projects use comparable sizes of land, 0.7 acres/MW and 1.0 acres/MW, respectively. In contrast, PV's direct impacts occupied 5.9 – 7.2 acres/MW. When comparing direct land area impacts as a function of power generation, geothermal projects were found to require the least land (0.13 acres/gigawatt hour [GWh]), followed by wind (0.19 acres/GWh), and then PV (3.5 acres/GWh).

2.3 Why Revisit Geothermal?

Although Heath et al.'s (2012) seminal work provides much to the literature, the study also stresses that frequent updates may be essential to track the changes from technology innovation on land use impacts over time. This is certainly true in the context of geothermal energy, where the industry has conducted a wide variety of research and development into exploration and drilling activities to reduce unsuccessful drilling (i.e., dry holes) and maximize production (U.S. Department of Energy (DOE), 2019). These innovations can have a direct effect on land use requirements by reducing the number of wells and associated pads, pipelines, and other infrastructure needed to produce geothermal energy.

Six geothermal projects have also been built on federal land since the publication of Heath et al.'s 2012 study, five on new sites and one redevelopment on a previously inactive site.[1] These projects could demonstrate the breadth of innovation that has occurred in the geothermal industry and provide a more accurate depiction of how land disturbance impacts have evolved in the last decade. These revised land disturbance assumptions can then serve as the foundation for subsequent forward-looking analyses of geothermal deployment impacts.

Such analysis may be especially valuable, given that the geothermal industry is ripe for expansion through 2050 (U.S. Department of Energy (DOE), 2019). Geothermal energy has a variety of benefits as compared to other technologies, both fossil and renewable, which make it attractive in the market. Like other renewable energy technologies, geothermal energy has emission reduction and fuel security benefits over fossil fuels. Historically, geothermal has also had an advantage over variable renewables such as PV and wind, because geothermal can provide always-on, reliable electricity. As a result, the economic value of geothermal power stays relatively constant as deployment increases, while the value of PV and wind systems may decline when considering the requirements of operational flexibility (Orenstein and Thomsen, 2017). While the recent trend of decreasing cost and increasing deployment of energy storage for new or retrofitted PV and wind systems gives these technologies greater flexibility and reliability, geothermal still provides a valuable part of the energy portfolio to balance the grid and provide consistent reliable electricity.

Looking forward, there are a wide variety of innovation pathways that can revolutionize geothermal energy development, drive down geothermal costs, and maximize deployment, with pathways that range from technology improvements (i.e., improved geothermal drilling and wellbore integrity) to regulatory process optimization (i.e., streamlined permitting). Given these benefits and opportunities – and particularly with the continued development of EGS technologies – the U.S. Department of Energy concluded that geothermal energy can support about 8.5% of the total national electricity demand by 2050, compared to the 0.4% of total generation it provides today. To meet this demand, many new geothermal projects will need to be sited, including the drilling of hundreds of new wells, to deliver up to 60 GW of geothermal capacity to the electrical grid (U.S. Department of Energy (DOE), 2019).

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[1] The new sites include: Lightning Dock in New Mexico and Don Campbell, McGinness Hills, Patua, and Tungsten Mountain in Nevada. In Utah, Cove Fort was originally developed in the 1980s with a smaller generation unit but was permanently shut down in 2003. As such, it was excluded from analysis by Heath et al. (2012). The older plant was later decommissioned, and the site redeveloped with new, larger binary plants that began operation in 2013.

This study will serve a critical role in providing the field with a better understanding of how land use impacts have evolved in the geothermal industry, thereby providing a foundation to consider the extent of impact from subsequent geothermal projects.

3. Methods

This study evaluates the direct surface disturbance (direct impact) associated with BLM-managed geothermal activities on federal public lands (BLM also manages operations on U.S. Forest Service Land, which are also included here). For each geothermal site, geographical information system (GIS) mapping was developed of disturbances from wells, pads, pipelines, roads, and power generation equipment. Direct impact was then measured on a surface area basis (square meters or acres) and land disturbance metrics were created by normalizing it by the generator nameplate and net capacities (MW) and annual production (GWh) for each site. These metrics allow for the comparison between geothermal technologies and with other forms of power generation.

Uniquely, this study utilizes annual net production data for each unit at each site, allowing for comparison by actual performance of the units and geothermal resources rather than through assumed capacity factors. The study also examines the difference between nameplate and net capacity metrics for each site, providing an additional comparison based on the actual current performance of each site.

3.1 GIS Mapping of Land Disturbance at BLM Geothermal Sites

GIS mapping of surface disturbance was performed for all active geothermal operations on federal public land – i.e., those in which BLM is receiving royalties from power production. GIS mapping of each site was performed on Google Earth Engine (GEE), an online platform for geospatial analysis and visualization. GEE offers imagery base maps sourced from Digital Globe that provide sub 1-meter resolution. However, in some cases, the imagery was outdated and failed to show recent site construction (especially development at the Tungsten Mountain and McGinness Hills geothermal fields). In these cases, estimates of disturbance locations were gleaned from site visits and alternative mapping sites (Bing Maps).

Surface disturbances were mapped as one of several categories: generation pads (cleared areas for well pads or other equipment), pipelines, roads, or equipment (generation, cooling, or ancillary / other). Shapefiles were created for each category at each geothermal site and uploaded in QGIS, an open-source GIS application with spatial analysis capabilities. Line segments for pipelines and roads were widened to create areas representative of their actual size: 1m width for pipelines, 3m width for roads. QGIS then calculated the area for each disturbance type. A total disturbance area for the geothermal site was also determined by merging the separate disturbance type shapes into a total impact footprint.

A count of large-bore (production and injection) wells at each site was taken from Geothermal Prospector, a geothermal mapping tool developed by the National Renewable Energy Laboratory (NREL). These well lists were confirmed and updated during onsite visits as well as through review of databases from California Geologic Energy Management Division (CalGEM, formerly DOGGR) and the Nevada Department of Minerals (NDOM).

3.2 Capacity & Generation by Project Site

Land disturbance metrics for each geothermal site were calculated by normalizing the total site disturbance by the nameplate capacity, net capacity, and annual generation for each.

This study also emphasizes the important difference between nameplate and net capacity for these metrics. While power generators are sized by nameplate capacity, this value does not accurately represent power generation available for export to the grid. Parasitic losses at geothermal plants can be significant, often 10-30% or more of gross generation. These losses include the energy required to pump the geothermal fluid from production wells, reinject it after use, and run cooling equipment such as air fans or water pumps. Additionally, resource limitations such as potential variation or decline can also decrease gross generation capabilities below the nameplate capacity and thus further decrease net capacity, especially at long-established sites such as The Geysers and Coso (Brophy et al., 2010; Coso Operating Company, LLC, 2020; Richter, 2012). Current net capacities for generation at these sites may be half of the original nameplate capacity of the installed equipment.

Given this reality, this report utilizes both nameplate and net capacity for each power generation unit at a site. Sources examined included: U.S. Energy Information Agency (EIA) data (form 860), public filings and news releases from the geothermal operating companies, previous Geothermal Resources Council or other publications, and reports from state energy or other agencies. In the case of source discrepancies, precedence was given to official filings from operating companies or state agencies. Lower reported values in other sources were assumed to approximate net capacity. Publicly available sources for capacity values at each site are presented in the Appendix.

Annual production for each unit and site were developed from EIA data, namely Form 923. Monthly and yearly generation totals from EIA for each unit were checked against those published by the California Energy Commission and the Nevada Division of Minerals (NDOM). A typical annual production value (in GWh) for each geothermal site was estimated by averaging the yearly totals from EIA for 2012 through 2018, or fewer years if the facility had a modification that influenced net capacity (adding, repowering, or removing units).

4. Results

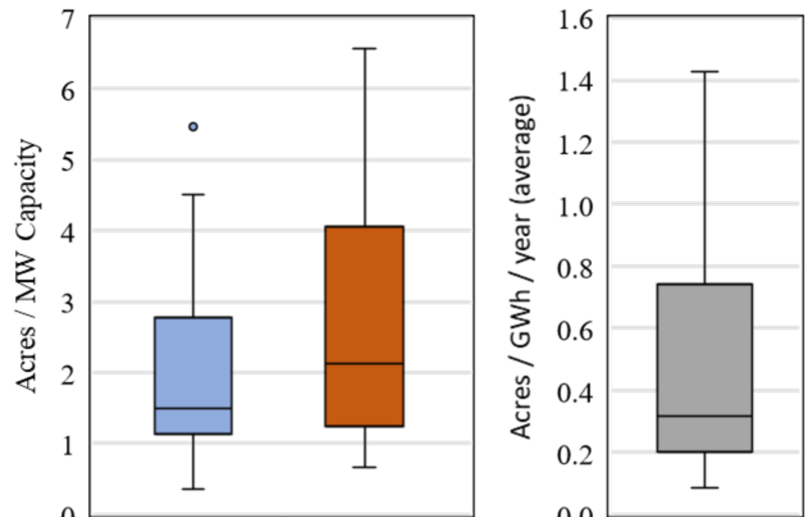
4.1 Direct Land Disturbance

Consistent with the literature, total project area is not an ideal metric for evaluating land impacts associated with geothermal projects (Heath et al., 2012). As with wind projects, geothermal land disturbance is dispersed across total project area (i.e., leased land). Additionally, active geothermal operations may only occur on portions of owned or leased areas, while tapping larger area geothermal reservoirs underneath the surface. As a result, direct land disturbance for geothermal operations usually accounts for only a small fraction of the total acreage associated with the site – for instance, average direct land disturbance for projects in this study averaged only 1.1% of total site acreage.

For the area directly impacted, generation pads (well pads and cleared areas for other equipment) account for most land disturbance, averaging 71% of the mapped land disturbance for all sites. Roads make up much of the remainder, averaging 20% of the mapped disturbance, with some variation due to those sites that leverage pre-existing or public infrastructure, followed by pipelines at 5% and generation equipment at 4%.

4.2 Land Use Metrics

To normalize and compare direct land disturbance across geothermal facilities, land disturbance was assessed as a function of nameplate and net capacity along with average annual production (GWh).[2] The overall results are shown in Figure 1 (results by site are presented in the Appendix). As seen, there is a skew to the distribution of site metrics, with a long tail of sites with higher relative disturbance and one outlier – Patua.[3] For other sites with higher relative disturbance (East Mesa, San Emidio, Soda Lake), the variation can be explained by the closure of older generating units and the loss of their capacity while environmental reclamation or repowering is still ongoing. At the other end, the high capacity and power density of the dry stream plants at the Geysers pulls down the overall capacity-weighted averages of the study. Exclusion of the Geysers from the analysis results in a much closer alignment between the medians and capacity-weighted averages for the remaining sites.



	Acres / MW Nameplate	Acres / Net MW	Acres / GWh / year
Median	1.49	2.12	0.32
Capacity Weighted Average	0.90	1.48	0.20
Avg w/o Geysers	1.59	2.33	0.34

Figure 1: The direct land disturbance metrics calculated by this study.

[2] Total land disturbance and metrics for each site are presented in the Appendix.

[3] Satellite imagery for Patua shows large additional generation pad, likely from a planned second geothermal unit that was never constructed and possibly later used as staging for the nearby solar PV farm. The PV generation was not included in the overall site capacity. PV generation and disturbances at Stillwater were similarly excluded, though Stillwater's metrics are much closer to the medians.

Some of the variation in land disturbance metrics between sites can also be attributed to the total number of active and inactive wells at each (most large-bore wells are situated on disturbed pads). While not an exact relationship, most better performing sites (for land disturbance metrics) also tended to have a relatively smaller number of wells – i.e., fewer wells per MW capacity and/or GWh production. Sites with relatively fewer wells often tended to fall at or below the medians for each land use metric. For example, McGinness Hills has 10 times the capacity and generation per drilled large bore well as compared to East Mesa or San Emidio. Likewise, McGinness Hills is also second lowest for all land disturbance metrics (after the Geysers), whereas East Mesa and San Emidio are above the third quartiles for each metric.

The impact of the Geysers facility on the Figure 1 medians demonstrates the importance of assessing variation across geothermal technologies. Table 1 and Table 2 summarize these direct impacts by technology and compare with the results of Heath et al. (2012), for both capacity (nameplate and net) and generation metrics respectively.

Overall, the nameplate capacity-based metrics from this study follow the same land disturbance by technology conclusions found by Heath et al. (2012). Dry steam (The Geysers) shows the lowest land disturbance due to its higher energy density; binary plants have the highest land disturbance due in part to their lower brine temperatures (and thus enthalpy); and flash plants fall in the middle. Unlike Heath et al. (2012), this study also examined plants utilizing a combination of both flash and binary technologies – often, an older flash plant that was later supplemented by a more recent binary unit. On average, these dual-technology plants had somewhat higher relative land disturbance than flash-only plants, but the metrics for these were comparable to binary-only plants and all fell within the interquartile ranges Figure 1 (i.e., they were not part of the long tail of the skewed distribution).

Despite this similarity, Table 1 shows the differences between nameplate capacity metrics across the two analyses. This study found slightly lower (-13% to -19%) relative land use by technology, as well as a slightly lower (-11%) overall average, than Heath et al. (2012). These differences can be generally attributed to variations in disturbance tracing.[4]

This study goes further than Heath et al. (2012) by also assessing land use impacts as a function of net capacity. As expected, relative impact increases for all geothermal technologies, as net capacity is often significantly lower than nameplate capacity due to parasitic loads and / or resource limitations. Table 1 shows this increase as compared to the nameplate capacity metrics from Heath et al. (2012), both by technology (+14% to 41%) and in the overall average (+39%). Resource limitations at both the Geysers (dry steam) and Coso (flash) result in the largest change between the nameplate versus net capacity metrics (Brophy et al., 2010; Coso Operating Company, LLC, 2020; Richter, 2012). In fact, this significant net capacity decrease at Coso drives the average land disturbance metric for flash plants above that for both binary and dual-

[4] For example, this study found a lower impact for dry steam plants at The Geysers despite the loss of some 100 MW of capacity since 2012 due to plant shutdowns. Likely, these differences are due to disturbance tracing method – this study only mapped disturbances directly attributable to the geothermal operations and the connecting roads between disturbance features. Thus, this study generally excluded other pre-existing or public roads, earthworks, or other clearings within the leased area that lacked clear connection to the geothermal operations. This difference in metric values is found even if the metrics are calculated using only the geothermal plants evaluated by Heath et al (2012).

technology flash-binary plants. While the net capacity values for each geothermal plant in this study may be approximate, they represent a more accurate description of actual production capabilities and a better metric of land disturbance for each site.

Table 1: Direct land disturbance metrics on a capacity basis for each geothermal technology from this study as compared to Heath et al. (2012).

	Heath et al (2012)	This study			
Technology	**Acres / Nameplate MW**	**Acres / Nameplate MW**	**% diff.**	**Acres / Net MW**	**% diff.**
Binary	1.9	1.63	-16%	2.18	+14%
Flash	1.6	1.41	-13%	2.52	+45%
Dry Steam	0.44	0.36	-19%	0.67	+41%
Binary + Flash	*	1.69		2.47	
Total Average	**1.0**	**0.90**	**-11%**	**1.48**	**+39%**
Avg w/o Geysers	*****	**1.59**		**2.33**	

**Not evaluated by Heath et al. (2012)*

The most valuable land disturbance metric, and the largest difference between this study and Heath et al. (2012), is based on annual power production (Table 2). This difference (+32% to 41% depending on the technology) is primarily driven by the use of actual annual production data in this study. This increase suggests that production-based land disturbance metrics have previously been significantly underestimated. For instance, Heath et al. (2012) approximated annual production as a fixed percentage of the nameplate capacity, choosing a capacity factor of 85% to capture the high online times for baseload geothermal plants. However, as previously discussed, parasitic losses often account for 10-30% of gross generation, while resource limitations may further limit gross generation below nameplate capacity. Thus, an assumed 85% capacity factor based on nameplate capacity is likely too high for many (or even most) geothermal plants, thus explaining the significant difference between these two studies.

In fact, the calculated capacity factor based on actual net generation averaged only about 50% of nameplate capacity across all the sites in this study – significantly lower than the previously assumed 85% value. If capacity factors are instead calculated from approximate net capacity, the values are much higher, averaging 83% across all sites (78% if the Geysers are excluded). These differences reinforce the sensitivity of overall generation and associated land disturbance metrics to capacity factor assumptions and demonstrate the importance of actual production data. Without it, evaluations of land disturbance metrics may be inaccurate and impair comparisons across renewable energy technologies.

While this study identifies that generation-based land disturbances are higher overall than those determined by Heath et al. (2012), land disturbances for geothermal have also declined at most newer facilities (Table 3). In the table, geothermal sites are compared based on whether the site was developed before or after 2000. As seen, the high-power density of the dry steam plants at the Geysers, which were developed starting in the 1960s, again skews the results. Excluding the Geysers, direct disturbances for newer plants have decreased by an average of 16-27% for all metrics. Moreover, relative disturbances for the six binary sites developed after the publication of Heath et al. (2012) show even further average decline. Excluding Patua (see Footnote **Error! Bookmark not defined.**), the other newest plants show a 52-59% decline in all land disturbance metrics as compared with sites commissioned before 2000 (e.g., 0.16 acres/GWh/year compared with 0.37 acres/GWh/year). Comparison with only the pre-2000 binary plants shows a similar decline for all metrics (64-73%).

Table 2: Direct land disturbance metrics on a generation basis for each geothermal technology from this study as compared to Heath et al. (2012).

	Acres / GWh / year		
Technology	**Heath et al (2012)**	**This study**	**% diff.**
Binary	0.26	0.36	+32%
Flash	0.21	0.32	+41%
Dry Steam	0.06	0.09	+35%
Binary + Flash	*	0.35	
Total Average	**0.13**	**0.20**	**+44%**
Avg w/o Geysers	*	**0.34**	

**Not evaluated by Heath et al. (2012)*

Table 3: Historical trends in relative land disturbance, pre- and post-2000, along with the metrics for only the six newest plants developed since Heath et al (2012).

	Acres / Nameplate MW		**Acres / Net MW**		**Acres / GWh / year**	
	Pre-2000	**Post-2000**	**Pre-2000**	**Post-2000**	**Pre-2000**	**Post-2000**
Total Average	0.80	1.42	1.39	1.90	0.19	0.29
Avg w/o Geysers	1.69	1.42	2.59	1.90	0.37	0.29
New since 2012*		1.24		1.64		0.25
New w/o Patua**		0.80		1.07		0.16

** I.e., sites not evaluated by Heath et al. (2012): Don Campbell, McGinness Hills, Patua, and Tungsten Mountain in Nevada; Lightning Dock in New Mexico; and Cove Fort in Utah.*
*** Patua is excluded from the average due to outlier status. See Footnote* **Error! Bookmark not defined.**

Conclusions

Geothermal power has the potential to expand dramatically to meet increasing demand and clean energy targets in the coming decades. This expansion is not without its challenges, as geothermal and other renewable energy technologies can have significant land use impacts. Previous work has sought to quantify and compare these impacts by each technology at that time. However, continued innovation and development work has also sought to improve land use efficiency and decrease impacts (disturbed acreage) for these technologies. Thus, historical impact studies cannot always be simply extrapolated to estimate future impact for all technologies.

This study offers updates to previous geothermal work by utilizing actual net generation and net capacity data for disturbance metrics and by evaluating new facilities developed since 2012. Overall, this study found that relative land disturbances for geothermal projects are generally declining, with most new binary plants outperforming older plants by a significant margin. This study also found that land disturbance impacts for geothermal may also have been previously underestimated through the use of nameplate capacity values and assumed capacity factors. Net capacities and actual production data provide a much more accurate picture of technology performance, particularly for these land disturbance metrics.

While this study does improve on previous research, limitations in its scope also provide opportunities for future work. This study only examined geothermal operations located at least partially on public lands in the United States, representing only about 70% of the geothermal capacity currently installed in the country and less than 20% of existing global capacity (Richter, 2019). Evaluating a larger number and variety of geothermal plants could provide a more comprehensive assessment of current and future land impacts. Doing so could also help determine whether the environmental protection standards required for geothermal plants on U.S. public land drives them to more efficient land use and / or lower direct impacts. Additionally, while this study investigated the land use performance for the newest generation of binary plants, it did not examine innovations in other geothermal or renewable energy technologies, limiting its ability to make an updated cross-technology comparison. These limitations should be addressed in future work.

Given the rapid innovation and deployment of new energy technologies, evaluations of their performance and environmental impact can only be snapshots in time. Frequent updates and more expansive evaluations are critical for monitoring geothermal technology performance and improvements relating to land use, especially given its potential for significantly increased deployment across the globe. This study’s findings of generally decreasing land disturbances for geothermal power projects suggest a trend that is essential to the prospects of geothermal development in an era of growing demands on land use for energy and other priorities. Even so, continued work to evaluate, monitor, and decrease these land use impacts may be critical to maximize power generation in a future with growing land constraints.

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APPENDIX

Table 4: Capacity (Nameplate and Net MW) and annual production (average GWh / year) values and sources used to calculate land disturbance metrics for each site. Capacity and production values are evaluated through the end of 2018. Only BLM-managed operations on federal public land were included in this analysis.

BLM geothermal site			2018 Capacity [1]		Production	
State	**Site**	**Startup Year**	**Nameplate MW**	**Net MW (approx.)**	**Average GWh / year***	**Other Sources**
CA	Casa Diablo / Mammoth	1984	40	29	211	[5]
CA	Coso	1987	270	145	1,197	[6]
CA	East Mesa / Ormesa	1986	68	39	287	[5]
CA	Geysers	1971	1,535	833	6,444	[7, 8, 9]
NM	Lightning Dock	2013	15	10	13	[10]
NV	Beowawe	1986	19	17	103	[11]
NV	Blue Mountain	2009	50	38	239	[12]
NV	Brady Hot Springs	1992	30	27	77	[5, 11]
NV	Desert Peak	1986	26	23	86	[11]
NV	Dixie Valley	1988	67	61	487	[11]
NV	Don Campbell	2013	40	39	341	[5]
NV	Jersey Valley	2010	23	10	74	[5]
NV	McGinness Hills	2012	170	120	741	[5]
NV	Patua	2013	30	25	115	[13, 14]
NV	Salt Wells (Enel)	2009	23	18	103	[15]
NV	San Emidio	1986	13	11	73	[5]
NV	Soda Lake	1987	23	16	66	[16]
NV	Steamboat Complex	1988	125	65	541	[5, 14]
NV	Stillwater	1991	47	33	130	[14, 15]
NV	Tungsten Mountain	2017	37	27	213	[5]
UT	Cove Fort	2013**	25	20	152	[15,16,17]
UT	Roosevelt / Blundell	1984	38	33	255	[18]
	Total		**2,712**	**1,639**	**11,948**	
	Total w/o Geysers		**1,178**	**806**	**5,504**	

**Based on the average of 2012-2018 production, or of production with currently existing capacity. Yearly production values are taken from EIA [2] and checked against those reported by the California Energy Commission [3] and the Nevada Division of Minerals [4].*

*** Cove Fort was originally developed in the 1980s with a smaller generation unit but was permanently shut down in 2003. As such, it was excluded from analysis by Heath et al. (2012). The older plant was later decommissioned, and the site redeveloped with new binary plants that began operation in 2013.*

[1] (U.S. Energy Information Agency (EIA), 2019b)
[2] (U.S. Energy Information Agency (EIA), 2019c)
[3] (California Energy Commission, 2019a)

[4] (State of Nevada Division of Minerals (NDOM) and Price, 2019)
[5] (Ormat Technologies, Inc., 2019)
[6] (Coso Operating Company, LLC, 2020)
[7] (Brophy et al., 2010)
[8] (California Energy Commission, 2019b)
[9] (Calpine, 2019)
[10] (Turboden, 2017)
[11] (Benoit, 2014)
[12] (Richter, 2010)
[13] (Fasano, 2017)
[14] (Shevenell, 2015)
[15] (Enel Green Power, 2019)
[16] (Benoit, 2016)
[17] (Bureau of Land Management (BLM), 2015)
[18] (John W. Lund, 2004)
[19] (Allis and Larsen, 2012)

Table 5: Land disturbance metrics calculated from GIS mapped direct impact and capacity / generation for each BLM-managed geothermal site.

BLM geothermal site		Direct land disturbance (acres)	Land disturbance metrics		
State	**Site**		**Acres / MW Nameplate**	**Acres / Net MW**	**Acres / GWh / year**
CA	Casa Diablo / Mammoth	52	1.29	1.78	0.25
CA	Coso	391	1.45	2.70	0.33
CA	East Mesa / Ormesa	209	3.07	5.35	0.73
CA	Geysers	556	0.36	0.67	0.09
NM	Lightning Dock	11.4	0.76	1.14	0.88
NV	Beowawe	17.1	0.90	1.00	0.17
NV	Blue Mountain	74	1.50	1.95	0.31
NV	Brady Hot Springs	80	2.68	2.98	1.04
NV	Desert Peak	57	2.20	2.49	0.66
NV	Dixie Valley	130	1.94	2.13	0.27
NV	Don Campbell	48	1.21	1.24	0.14
NV	Jersey Valley	42	1.88	4.22	0.57
NV	McGinness Hills	81	0.48	0.68	0.11
NV	Patua	164	5.47	6.57	1.43
NV	Salt Wells (Enel)	72	3.14	4.00	0.70
NV	San Emidio	57	4.51	5.20	0.78
NV	Soda Lake	93	4.06	5.83	1.41
NV	Steamboat Complex	81	0.65	1.24	0.15
NV	Stillwater	70	1.47	2.11	0.54
NV	Tungsten Mountain	45	1.21	1.66	0.21
UT	Cove Fort	45	1.79	2.24	0.29
UT	Roosevelt / Blundell	55	1.43	1.65	0.21
Total average		**2,431**	**0.90**	**1.48**	**0.20**
Total w/o Geysers		**1,875**	**1.59**	**2.33**	**0.34**