An Analysis of High Opportunity Geothermal Leasing Areas on BLM and USFS Lands

Faith Martinez Smith, Jonathan Ho, Whitney Trainor-Guitton, Sophie-Min Thomson, Ligia E. P. Smith, and Donna Heimiller

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List of Acronyms

ATB	Annual Technology Baseline
BLM	Bureau of Land Management
CONUS	Conterminous United States
DOE	U.S. Department of Energy
EGS	enhanced geothermal system
EPAct	Energy Policy Act of 2005
GDR	Geothermal Data Repository
GETEM	Geothermal Electricity Technology Evaluation Model
GSA	Geothermal Steam Act of 1970
GTO	Geothermal Technologies Office
GW	gigawatt
JEDI	Jobs and Economic Development Impact Models
KGRA	Known Geothermal Resource Areas
km	kilometer
LCOE	levelized cost of energy
NOI	Notice of Intent
NREL	National Renewable Energy Laboratory
ReEDS	Regional Energy Deployment System Model
reV	Renewable Energy Potential Model
SAM	System Advisor Model
SMU	Southern Methodist University
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

Executive Summary

The Biden administration set a goal to have a clean electricity sector by 2035 and a net-zero emissions economy by 2050 (United States Department of State and the United States Executive Office of the President 2021). In addition, the Energy Act of 2020[1] set specific renewable energy deployment targets on federal land, including seeking to permit more than 25 gigawatts (GW) of utility-scale wind, solar, and geothermal energy no later than 2025. Geothermal energy can play a significant role in reaching both the clean electricity sector and Energy Act of 2020's goals. This analysis focuses on the role that geothermal electricity can play within these renewable energy deployment targets for Bureau of Land Management (BLM) administered subsurface mineral estates. This includes United States Forest Service (USFS) managed land where the BLM administers the subsurface mineral estate.

This analysis conducted by the National Renewable Energy Laboratory (NREL) with support from the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO), models potential geothermal deployment on BLM and USFS land for different combinations of geothermal resource depths and technologies for future power systems, through the year 2050. This report identifies high opportunity geothermal leasing areas based on available data for geothermal resource potential, natural resource conflicts, and transmission access.

This analysis considers the impacts of the Energy Policy Act of 2005's (EPAct 2005's) default competitive leasing provisions, specifically the impact these may have had on geothermal resource discovery outside of Known Geothermal Resource Areas. This report builds upon work in the *GeoVision* report and the associated *GeoVision Analysis Supporting Task Force Report: Barriers* by increasing our understanding of high opportunity areas available for geothermal leasing on federal managed lands in the Conterminous United States (CONUS) (DOE 2019; Young et al. 2019).

Table ES-1 illustrates the breakdown of available economically deployable resource capacity on BLM and USFS lands into three potential deployment categories (i.e., illustrated in Table ES-1's rows) for each of the three geothermal resource depths and technology combinations (i.e., illustrated in Table ES-1's columns). The geothermal resource depths and technology combinations are modeled independently: there is no direct competition for new capacity between geothermal resource depths and technology representations. The deployment categories are broken down by *Best*, *Middle*, and *Least* economical resources for each geothermal depth and technology type based on the Regional Energy Deployment System (ReEDS) analysis.

- *Best* economical geothermal sites: The best third of the deployed resource at each depth and technology combination scenario represents the portion of the selected resource most favorable for development based upon ReEDS analysis.
- *Middle* third economical geothermal sites: The middle third of the deployed resource at each depth and technology combination scenario, represents the second group of geothermal resources to see deployment based upon ReEDS analysis.

[1] The Energy Act of 2020 is the short title of Division Z – Energy Act of 2020 of the Consolidated Appropriations Act, 2021.

- *Least* economical geothermal sites: The final third of the deployed resource in a geothermal resource depth and technology scenario, and represents the last group of geothermal resources to see deployment based upon ReEDS analysis.

A key advantage of this approach is that it allows us to consider competitive sites on BLM and USFS land that are more economical, factoring in the resource costs and the value of the services delivered by a plant, which are included in the modeling (described in detail in Section 3).

The total geothermal resource is substantial with 3.9 TW of Hydrothermal and 8.8-15.4 TW of EGS in CONUS. Of this available geothermal resource 1.4 TW (36%) of Hydrothermal and 2.8-5.9 TW (32-38%) EGS is on BLM and USFS land. Only a small fraction of the developable capacity is deemed economical, roughly 2.3% of hydrothermal resources and 0.8-1.4% of EGS resources. The highest opportunity portion of geothermal resources on BLM and USFS land is 2.2% for hydrothermal and 1.8-2.7% for EGS.

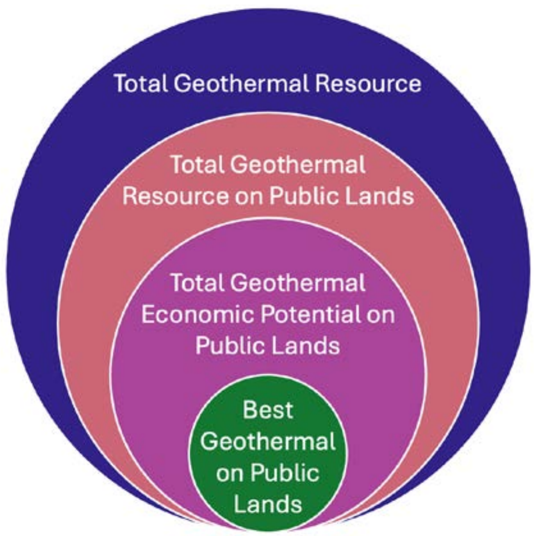

Figure ES-1. Nested plot distinguishing geothermal resource and economic potential on public lands. Plot is not to scale; it is purely illustrative.

The results show the total available resource for selected sites based upon downscaling of ReEDS investment decisions. Geothermal depths and technologies in Combinations 1 and 3 have a similar overall distribution by deployment category with the *Best* deployment category representing between 27% and 26% of the prioritizable resource of the federal mineral estate, in contrast to Combination 2 with 16% belonging to the *Best* economical geothermal sites. Moving from Combination 1 to 3, the total leasable BLM and USFS land fraction consistently increases, as the geothermal resource gets deeper and hotter. It should be noted that the hydrothermal results are overly optimistic as no permeability estimates are available at the same scale and scope as the estimates of temperature.

Table ES-1. Available Geothermal Resource Capacity on BLM & USFS Lands (GW)

Deployment Category	**Combination 1** **Hydrothermal Binary Deployment Capacity (GW) at 3.5 km depth**	**Combination 2** **Enhanced Geothermal System (EGS) Binary Deployment Capacity (GW) at 4.5 km depth**	**Combination 3** **EGS Flash Deployment Capacity (GW) at 6.5 km depth**
Best	8.5 (27%)	12 (16%)	28 (26%)
Middle	10 (32%)	35 (45%)	33 (30%)
Least	13 (41%)	30 (39%)	48 (44%)
Total	**31**	**77**	**109**

The map in Figure E2-1 illustrates the total combined identified leasing areas for geothermal depth and technology combinations 1 and 2; however, it is not broken down into the deployment categories described previously. The remaining maps (Figure ES-3 through Figure ES-5) illustrate the breakdown of these deployment categories for each geothermal depth and technology combinations.

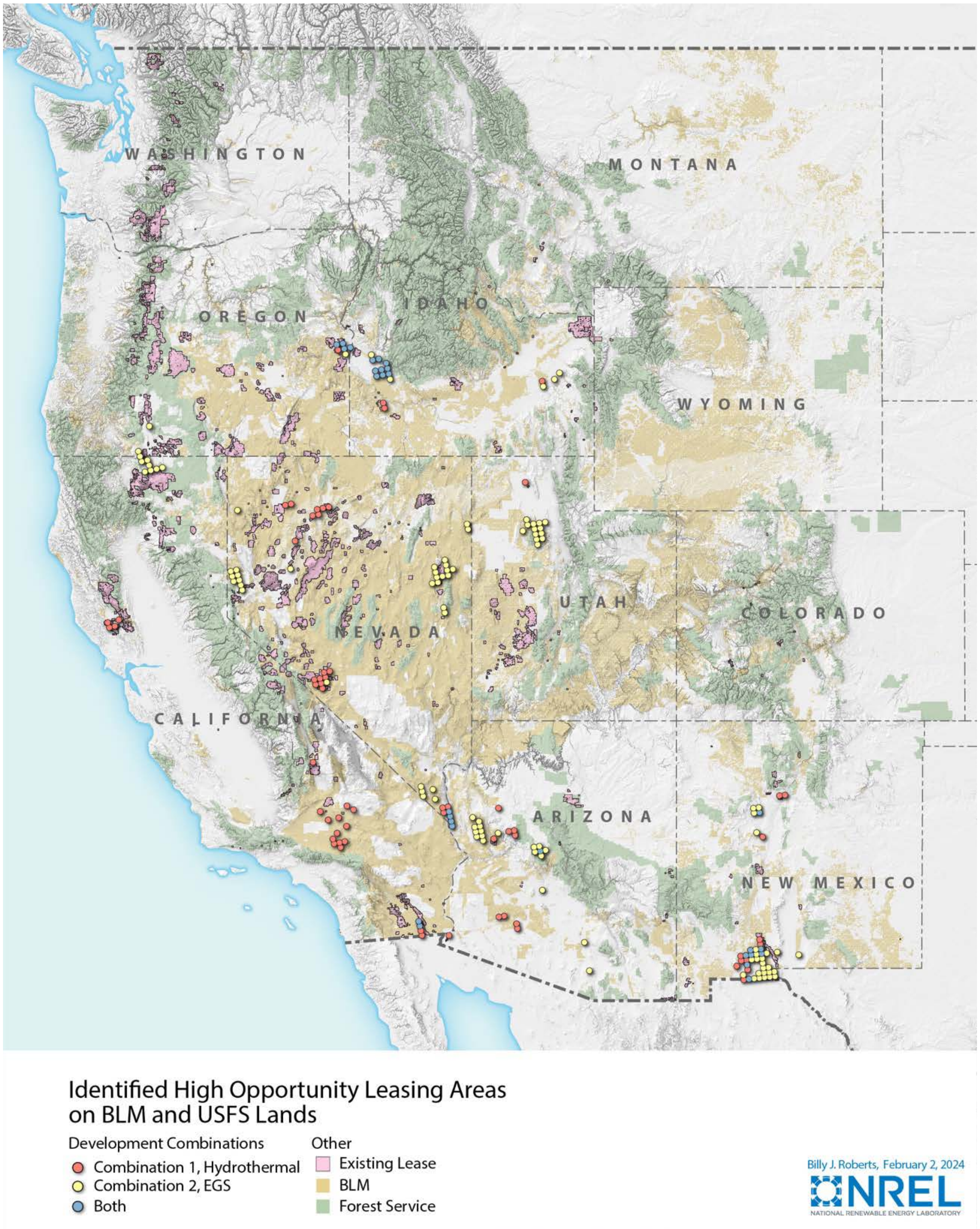

Figure ES-2. Identified high opportunity leasing areas on BLM and USFS lands

Figure ES-2 illustrates the combination of output from the modeling exercises for Geothermal Resource Depth and Technology Combinations 1 and 2.

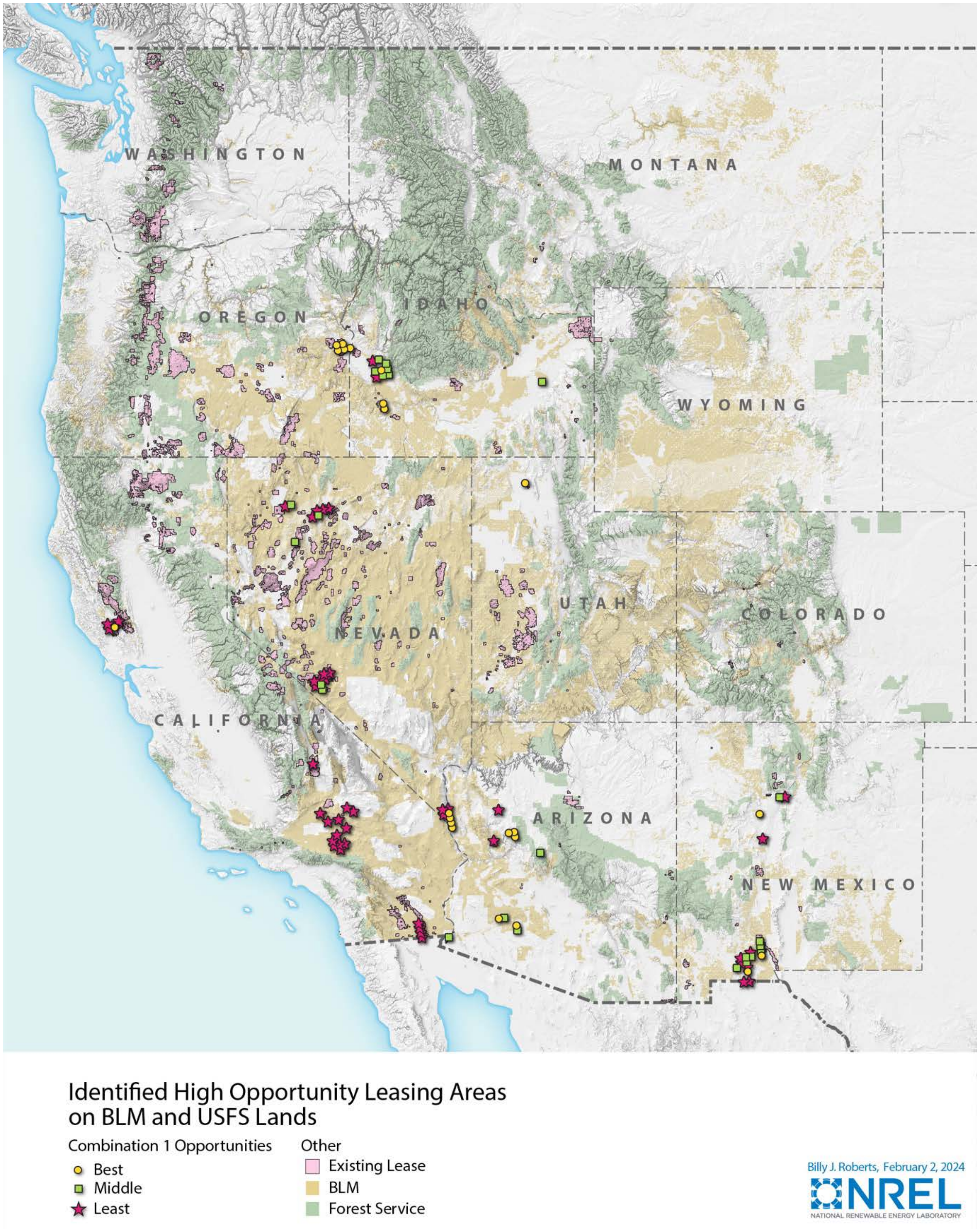

Figure ES-3. Identified high opportunity leasing areas on BLM and USFS lands for Geothermal Resource Depth and Technology Combination 1: Hydrothermal binary at 3.5-km depth

Figure ES-3 illustrates the output from the modeling exercises for Geothermal Resource Depth and Technology Combination 1 broken down by the *Best, Middle,* and *Least* Deployment categories.

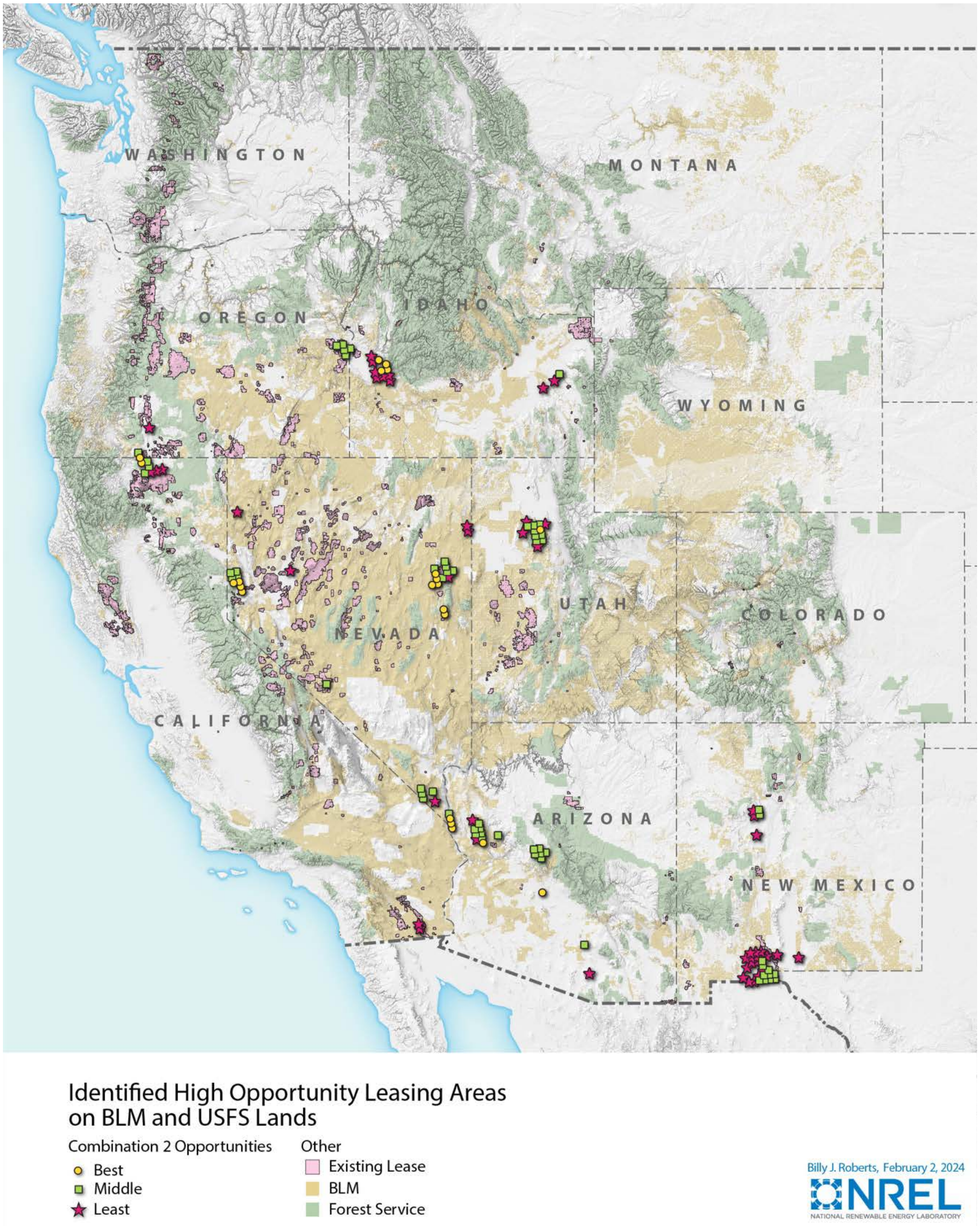

Figure ES-4. Identified high opportunity leasing areas on BLM and USFS lands for Combination 2: EGS binary at 4.5-km depth

Figure ES-4 illustrates the output from the modeling exercises for Geothermal Resource Depth and Technology Combination 2 broken down by the *Best, Middle,* and *Least* Deployment categories.

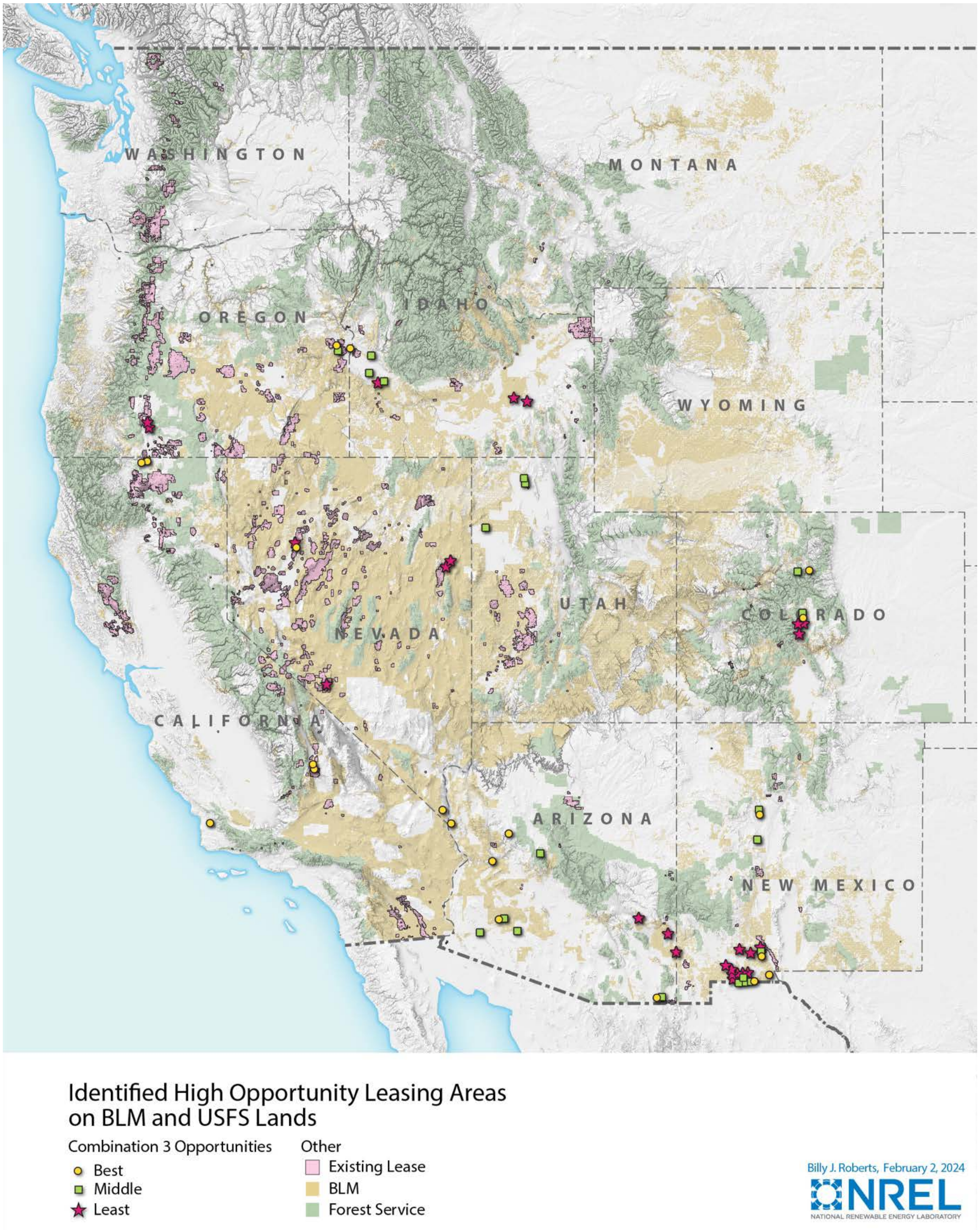

Figure ES-5. Identified high opportunity leasing areas on BLM and USFS lands for Combination 3: EGS flash at 6.5-km depth

Figure ES-5 illustrates the output from the modeling exercises for Geothermal Resource Depth and Technology Combination 3 broken down by the *Best, Middle,* and *Least* Deployment categories.

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1 Introduction

The Biden administration has set a goal for the United States to have a clean electricity sector by 2035 and a net-zero emissions economy by 2050 (United States Department of State and the United States Executive Office of the President, 2021). In addition, the Energy Act of 2020[2] set specific renewable energy deployment targets on federal land, seeking to permit more than 25 gigawatts (GW) of utility-scale wind, solar, and geothermal energy no later than 2025. Geothermal energy can play a significant role in reaching both the clean electricity sector and Energy Act of 2020's goals. This analysis focuses on the role that geothermal electricity can play for Bureau of Land Management (BLM) administered subsurface mineral estates, which includes United State Forest Service (USFS) managed lands, hereafter referred to as federal land.

This analysis, conducted by the National Renewable Energy Laboratory (NREL) with support from the U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO), models potential geothermal deployment on BLM and USFS land for the years 2025, 2030, 2035, and 2050 under various scenarios using the Renewable Energy Potential (reV) model and the Regional Energy Deployment System (ReEDS) model. This report identifies potential future high opportunity geothermal leasing areas (i.e., *Best, Middle, and Least* identified opportunities) based on available data for geothermal resource potential, natural resource conflicts, and transmission access. In addition, this analysis considers the impacts of the Energy Policy Act of 2005's (EPAct 2005's) default competitive leasing provisions, specifically the impact this may have had on geothermal resource discovery outside of known geothermal resource areas.

This report provides an overview of the methodology for both the reV and ReEDS modeling exercises, their integration process, and the results of these exercises, which identifies potential locations for high opportunity geothermal leasing areas. Included in the methodology section is an overview of the recent reV upgrades to include geothermal energy. A sample of these results is illustrated via maps in Section 4; the supply curves produced from this analysis will be available on DOE's Geothermal Data Repository (GDR).[3]

This analysis provides data identifying future potential high opportunity geothermal leasing areas and does not discuss technical barriers associated with geothermal energy development on federal lands. However, this analysis builds on and uses data collected for previous work from the *GeoVision* report and the associated *GeoVision Analysis Supporting Task Force Report: Barriers* (DOE 2019; Young et al. 2019).

This report builds on analysis completed in the *GeoVision* report—including deployment potential for multiple scenarios and nontechnical barriers associated with geothermal development related to the leasing process as well as the *GeoVision Analysis Supporting Task Force Report: Barriers*. Since the publication of the *GeoVision* report and associated reports, multiple NREL modeling capabilities have been updated to provide more parity between renewable energy resources including geothermal energy. The reV model has specifically been

[2] The Energy Act of 2020 is the short title of Division Z – Energy Act of 2020 of the Consolidated Appropriations Act, 2021.
[3] https://gdr.openei.org/home.

updated to incorporate geothermal energy to be comparable to wind and solar resources when estimating technical potential and levelized cost of energy (LCOE) (Pinchuk et al. 2023).

2 Background

Prior to 2005, the Geothermal Steam Act of 1970 (GSA) provided the first leasing procedures for geothermal resources located on public lands (30 U.S.C. §§ 1001 Et seq.; Tannen 2014; Nedd 2022; BLM 2008). The GSA established federal lands known to have geothermal resource potential as "Known Geothermal Resource Areas" (KGRAs) and put in place a two-tier leasing program: 1) competitive leasing in the KGRAs; and 2) noncompetitive leasing for lands outside of the KGRAs (Nedd 2022; Tannen 2014; BLM 2008). In 2005, Congress passed EPAct 2005, which amended the GSA and removed the divided approach to leasing processes within and outside of KGRAs—requiring that all electricity generating geothermal resources be offered through a competitive leasing process (P.L. 109-58, 42 U.S.C. § 15801; 72 FR 24358; 43 C.F.R. § 3200.6). Accordingly, prior to 2005, applicants could nominate parcels and receive a noncompetitive lease if the parcel were outside of a KGRA (Nedd 2022; Tannen 2014; BLM 2008). However, since the passage of EPAct 2005, all parcels available for geothermal leasing and nominated for geothermal electricity production must first be offered competitively to the highest qualified bidder (43 C.F.R. § 3203.5; BLM 2008). Nominated parcels that do not receive a bid are available noncompetitively for two years following the competitive lease sale (42 C.F.R. § 3204.5; BLM 2008).

Previous DOE and national laboratory reports have focused on both nontechnical and technical barriers to geothermal deployment. Nontechnical barriers associated with development include the leasing process, addressing potential natural and cultural resource conflicts, the permitting and environmental review processes, transmission siting, and existing and potential future market conditions (e.g., power purchase agreements). This analysis focuses on identifying future high opportunity geothermal leasing areas based on the available spatial resolution and data output modeled using reV and ReEDS analysis.

DOE's *GeoVision*, released in 2019, was a multiyear study led by DOE's Geothermal Technologies Office and supported by the national laboratories. *GeoVision* and the associated *GeoVision Analysis Supporting Task Force Report: Barriers* identified nontechnical barriers associated with geothermal development including land access or leasing, permitting, and environmental review processes (DOE 2019; Young et al. 2019). *GeoVision* specifically identified six areas that significantly contributed to the ability to access land: cultural and Tribal resources, environmentally sensitive areas, biological resources, land ownership, federal and state lease queues, and proximity to military installations (Young et al. 2019).

The *GeoVision* analysis also included an estimate on the potential future deployment of geothermal energy using multiple analysis tools, including NREL's Geothermal Electricity Technology Evaluation Model (GETEM), ReEDS, and the Jobs and Economic Development Impact (JEDI) model. *GeoVision's* analysis using these models incorporated data for cost, techno-economic assessment, resource assessment, demand, transmission, and construction timelines. Figure 1 illustrates the *GeoVision* market deployment analyses, which include the following outputs: techno-economic assessment, supply curves, deployment curves, and potential impacts assessments as described in *GeoVision Analysis Supporting Task Force Report: Barriers*. The *GeoVision* analysis illustrates deployment potential for multiple scenarios considering different technology types, market conditions, and potential barriers. In addition, the

NREL report team considered the impacts of EPAct 2005's default competitive leasing process by identifying priorities for leasing broken down into three tranches as discussed further below.

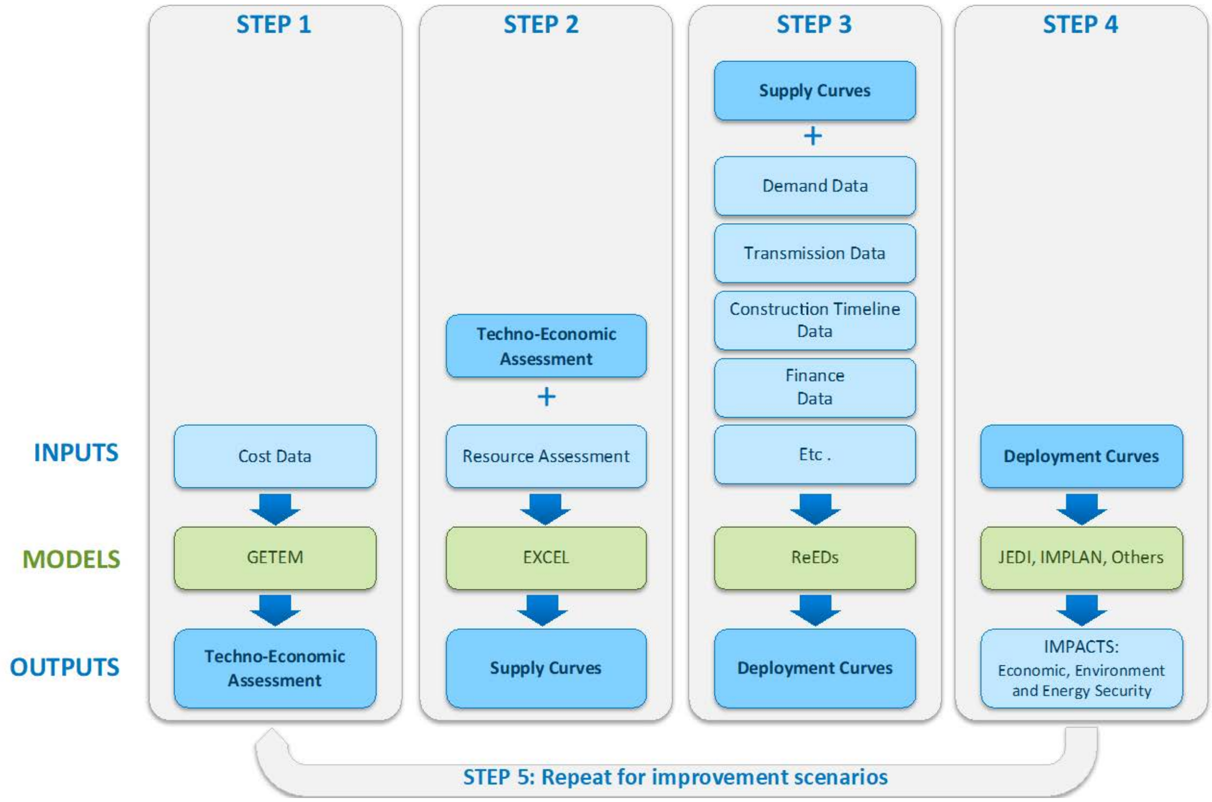

Figure 1. GeoVision analysis' market deployment analyses steps

This figure describes the market deployment analyses steps as illustrated in the *GeoVision Analysis Supporting Task Force Report: Barriers*. For context, EXCEL refers to Microsoft Excel. JEDI uses data from IMPLAN[4] Professional state data files.

As previously discussed, EPAct 2005 created a default competitive leasing process for geothermal resources harnessed for electricity generation on federal land. Ownership of geothermal resources on federally managed public lands is generally included within the federal mineral reservation, where the BLM oversees the leasing and regulation of the geothermal resources. Through review of literature as well as interviews with BLM geothermal staff and developers, anecdotal evidence suggests the EPAct 2005 default competitive leasing process may impact the exploration of unleased lands.

During the rulemaking process revising the BLM's leasing regulations to implement EPAct 2005, the BLM noted industry representatives had expressed concern that the default competitive leasing process could limit future exploration and development on federal lands (72 FR 24358). Specifically, industry raised the possibility that the default competitive leasing process may reduce incentives for exploring unleased lands because a company that was not involved with the

[4] IMPLAN is a cloud software tool used for economic impact analysis (https://implan.com).

initial expense of conducting research could then win the site by placing a higher bid at auction (Tannen 2014; 72 FR 24358). As such, industry has previously noted concerns that the implementation of the EPAct 2005 default competitive leasing process may limit future exploration and development on federal lands and decrease competition within the industry (72 FR 24358). Notably, although little publicly available quantitative data are available,[5] interviews with BLM geothermal program staff as well as industry suggest the volume of exploration permits (Notices of Intent [NOI]) issued on unleased lands has decreased since the passage of EPAct 2005 (Nichols 2024).

The results of this modeling exercise could provide interested parties with initial information to consider when identifying areas to competitively pursue for federal geothermal leasing, exploration, and development.

[5] To gather more information, NREL reviewed publicly available BLM data sets and databases to analyze whether the volume of exploration permits issued for unleased lands changed post-EPAct 2005. Though the data reviewed provided the volume of competitive versus noncompetitive leases issued pre- and post-EPAct 2005, publicly available information was too limited to provide context explaining why NOIs issued were on unleased lands (e.g., whether a post-EPAct 2005 NOI on unleased lands had been nominated or issued following a competitive lease sale).

3 Methodology

NREL's power system models can be used to inform the deployment pathways for renewable energy technologies. This section provides an overview of the models used in this analysis. As such, this section begins with an overview of the updates to the Renewable Energy Potential (reV) model and then discusses the coordination between the reV and the ReEDS models—the results of which provide the physical locations of high opportunity geothermal leasing on BLM and USFS land.

3.1 Renewable Energy Potential (reV) Model Updates

The reV model was developed by NREL to estimate the renewable energy technical potential for generation and capacity, system costs, and supply curves[6] of various renewable energy technologies. Starting in 2022, reV was updated to include new capabilities that include the ability to model enhanced geothermal systems (EGS) and hydrothermal geothermal systems (Pinchuk et al., 2023). The model allows the user to include any desired spatial representations of both the built and natural environment in the generation and cost estimates that are computed (Maclaurin et al. 2019).

3.2 Renewable Energy Potential Model Analysis

reV estimates the geothermal supply curves by ingesting geothermal resource assessments, data layers that represent potential development constraints and costs associated with development of different geothermal plant technologies. These three components are covered in more detail in the following section. reV couples with NREL's System Advisor Model (SAM), which allows the batching of simulations of power production and costs for various renewable energies, including geothermal. reV outputs can further be used with the ReEDS model. Figure 2 highlights an example of the reV workflow, from resource collection (data sets) to the outputs. reV provides large-scale analysis of renewable technologies, through the geospatial intersection with grid infrastructure and land use characteristics, allowing the modeling of generation, LCOE, and spatial exclusions on allowable developable land.

[6] Supply curves refer to the characteristics, location, developable generation capacity, and cost (e.g., plant capital costs and costs to connect to the grid) of a technology specific resource type (e.g., solar, wind, and geothermal).

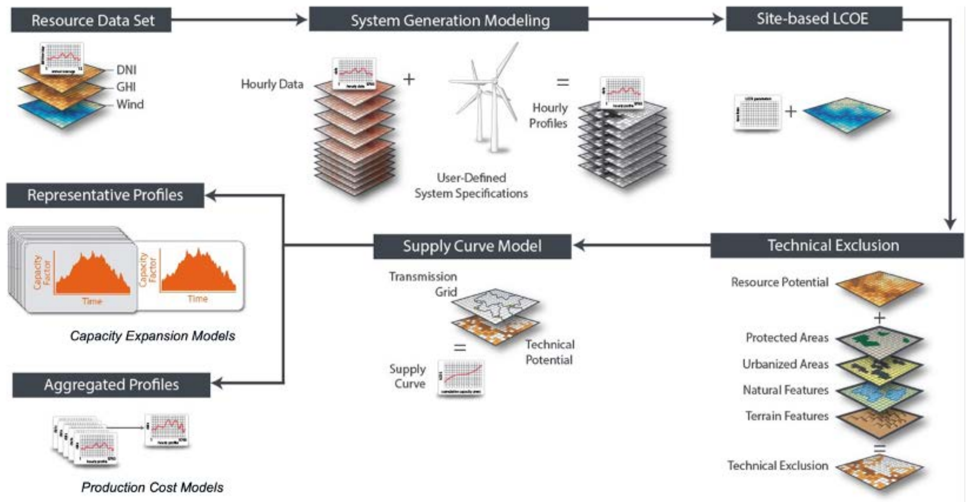

Figure 2. reV workstreams

The first workstream uses resource data to calculate generation and LCOE; the second applies technical exclusions according to different land type and ecological features. Within the figure, DNI stands for Direct Normal Irradiation and GHI stands for Global Horizontal Irradiation, both of which are used for solar data resource sets.

3.2.1 reV Model Inputs

3.2.1.1 Geothermal Resource Data

The Southern Methodist University (SMU) temperature at depths data set was selected because it provides the most comprehensive nationwide representation of geothermal data, both spatially and in the depth dimension (Blackwell et al. 2011). Table 1 highlights the SMU data source and various information including spatial extent and depth resolution. Though Pinchuk et al. (2023) also examined this using the updated 2022 United States Geological Survey (USGS) heat flow data set, it was excluded for this analysis because it covers only the larger Greater Basin area—and this analysis includes all BLM and USFS land (DeAngelo et al. 2022). In addition, the spatial interpolation process (e.g. estimating heat flow away from sparse well locations) that was used removed any convective heat sources and therefore provides a very low estimate of heat flow that greatly limits hydrothermal resource estimations. It is not ideal that only temperature interpolations and extrapolations are used to estimate the hydrothermal potential, as a hydrothermal resource requires naturally flowing fluids, and therefore a consideration of the natural permeability. However, no proxy data set at the same scale or scope as the SMU temperature exists. Therefore, hydrothermal potential estimates can be considered optimistic.

Table 1. SMU Data Source

Data Source	Spatial Extent	Count/Aerial Resolution	Depth Resolution	Units	Reference
SMU Temperatures	Conterminous United States (CONUS)	2.5 km x 2.5 km = 6.25 km^2	3.5- to 10-km depth increments of 1 km	°C	Blackwell et al. 2011

3.2.1.2 Geothermal Depths & Technologies modeled with reV

Three geothermal depth and technology combinations were included for this analysis, outlined in Table 2. They encompass both geothermal resources (hydrothermal and EGS) and technologies (binary and flash) as well as different depths (3.5 km, 4.5 km, and 6.5 km [Pinchuk et al. 2023]). EGS resources in this analysis can be considered additive and representing distinct resources (i.e., Combination 2 and Combination 3 from Table 2).

Table 2. Different Geothermal Resource Depths and Technologies modeled using reV

Combination #	***Geothermal Technology***	***Resource Depth***	***Geothermal Technology***	***Well Costs***[7]	***Total* Number of Generation Points Across CONUS**
1	Hydrothermal Binary SMU exponential ATB + depth cost	SMU temp at depth (3.5 km)	Hydrothermal (binary/3.5 km)	Advanced (Ideal) GETEM depth cost curve	319,907
2	EGS Binary ATB	SMU temp at depth (4.5 km)	EGS (4.5 km)	Advanced (Ideal) GETEM depth cost curve	520,216
3	EGS Flash ATB	SMU temp at depth (6.5 km)	EGS (6.5 km)	Advanced (Ideal) GETEM depth cost curve	520,216

3.2.1.3 Adjusted Geothermal Project Development Costs

NREL's Annual Technology Baseline (ATB) is a data set that provides an outlook for the cost and performance characteristics of renewable technologies (NREL 2023). Geothermal-specific costs were adjusted based on the 2023 ATB cost assumptions (NREL 2023). The ATB provides transparent information for the basis of research and development advancements that inform improvements to cost and performance as well as available assumptions for construction timelines and financing. These costs are specific to the reV analysis and are considered separately from the use of ATB 2023 costs in the ReEDS simulation. Table 3 highlights the financial options modeled for both the hydrothermal binary and EGS binary cost assumptions used for the scenarios. These cost assumptions use a 2030 projection of the ATB 2023 Capital Costs, inclusive of drilling costs.

[7] The project team opted to use the Advanced (Ideal) GETEM depth cost curves due to recent (i.e., February 2024) industry announcements that drilling costs reductions already meet the Advanced (Ideal).

Table 3. ATB 2030 Projected Financial Options Used as Input for Two Geothermal Technologies (GETEM inputs)

Scenario	Depth (km)	Mean Temperature; Median Temperature (°C)	ATB Capital Cost* ($/kW)	Adjusted Capital Cost ($/kW)	Fixed Operating Cost ($/kW)	Variable Operating Cost ($/kW)	Fixed Charge Rate (%)
Hydrothermal Binary	3.5	194.38; 189.91	4,828	4,521.92	129	0	6.348
EGS Binary	4.5	188.73; 185.98	5,791	5,417.59	254	0	6.348
EGS Flash	6.5	214.45; 210.88	3,511	3,136.25	254	0	6.348

*This analysis uses a 2030 projection of the 2023 ATB Capital Costs, which includes drilling costs.

We also accounted for depth-dependent drilling costs by calculating the drilling costs associated with a sample plant (assumed by the 2023 ATB using GETEM cost curves). We assumed the ideal drilling cost curves derived from the *GeoVision* analysis with a vertical open hole well type and large well diameter for well characteristics. The resulting drilling costs were subtracted from the base ATB capital costs. reV then uses this value to calculate the depth-dependent drilling costs. A summary of these drilling costs for the projected year of 2030 inclusive of the vertical wells is shown in Table 4. Horizontal well costs were not included in this summary as the greater expense would be for the larger diameter vertical wells, but they are included in the EGS drilling costs.

Table 4. Adjusted Drilling Costs Projected for the Year 2030

Depth (km)	Drilling Cost per Well ($)
2.5	2,391,703
3.5	3,130,258
4.5	3,864,018
5.5	4,592,983
6.5	5,317,153

3.2.1.4 Siting Exclusions and Characterization Layers

reV allows for both the characterization and exclusion of land. Characterization within reV categorizes the land manager or permit owner for the resource while exclusion identifies the land that cannot be built on or developed due to existing infrastructure, conflicts with sensitive species, legal challenges, or administratively restricted lands. Table 5 outlines the layers used in this analysis. One criteria example excludes areas that represent critical habitat for species of concern. This includes the Dixie Valley Toad and Tiehm's Buckwheat (Carnell 2023; Gibbens

2022), two species that have recently been listed as endangered and fall in areas for potential geothermal energy development. In addition, exclusion layers from the *GeoVision* report were used in this analysis and updated as data allowed (DOE 2019). The Greater Prairie Chicken and the Lesser Prairie Chicken were listed as vulnerable species during the *GeoVision* analysis; however, they are now included on lists of species with habitat threatened—as such, they were considered an exclusion in this analysis.

Table 5. GeoVision and Project Exclusions and Characterization Layers

Layer	Exclusion/ Characterization	In *GeoVision* Analysis?	Description	Area in BLM land (km^2)	Area Percentage in BLM (%)*[8]	Total Area in Square Kilometers (km^2)
Dixie Valley Toad	Exclusion	No	Species of concern	-	-	2.3⁺
Tiehm's Buckwheat	Exclusion	No	Species of concern	-	-	0.052⁺
Desert Tortoise	Exclusion	Yes	Species of concern	45,622.3914	7.43	189,760
Greater Prairie Chicken	Exclusion	No	Species of concern	272.88	0.044	376,850
Lesser Prairie Chicken	Exclusion	No	Species of concern	128.34	0.021	107,555
Sage Grouse PHMA	Exclusion		Species of Concern	127,703.23	20.79	614,116.91
CONUS Protected Areas	Exclusion	Yes	Protected Area Database of the United States (PAD-US)	77,264.28	12.58	610,122
BLM National MLRS Geothermal Leases	Exclusion	No	Existing geothermal leases	37,028.61	6.02	42,005

* CONUS being 8,080,464.3 km^2.

⁺ These areas are too small to calculate a percentage of CONUS.

[8] This is specific for CONUS, however, roughly 28% of the U.S. is federally managed.

Following the reV analysis, the results are fed into the ReEDS model for further analysis.

3.3 Regional Energy Deployment System Model

ReEDS is an open-source electric sector long-term capacity expansion tool developed at NREL. ReEDS reports the evolution of the electric power system using a least cost optimization method to select investments in generation, storage, and transmission through 2050. Investment decisions and operations are regionally specific and consider transmission topology, regional load growth, and lifetime and economic retirements of power system assets. ReEDS uses resource supply curves generated by reV to inform the geographic distribution, cost, and grid integration cost of renewable technologies, including geothermal, wind, and utility-scale photovoltaics. Outputs of ReEDS include capacity and operations for generation, storage, transmission, retirements, total costs, and CO_2 emissions.

3.3.1 Integrating reV Resource Data

Using ReEDS modeling, we identified the locations of high opportunity areas for geothermal leasing, based on competitive economic deployment in select analysis scenarios. Specific to this analysis, we use the reV-ReEDS linkage capability to add geothermal resource from the three reV combinations of resources and depths described in Section 3.2.1.2 to the model. Each of these reV geothermal resource scenarios is modeled independently, and there is no direct competition for new capacity between resource representations in the scenarios or previously used in ReEDS. Resource capacity representing different geothermal technology types, geo-hydrothermal, and EGS reV combinations can be considered additive and representing distinct resources. In contrast to comparisons across geothermal technology types, within EGS reV combinations, which include multiple resource depths, this resource should not be considered additive. We presume that for a given location it is not possible to simultaneously develop EGS at multiple resource depths. When multiple depths are considered simultaneously in ReEDS, the optimal depths are preselected prior to simulation in ReEDS to avoid unrealistic interpretation of resource data.

When integrating reV resource data, we map plant capital cost trajectories from the ATB, based on resource quality, which is based on the reservoir temperature for a given site. Site-specific resource integration costs generated by reV, which include spur-line transmission and grid reinforcement costs, are binned using k-means clustering to preserve the differentiation between similar geothermal resources with varying ease of access for grid integration.

To determine if the modeled geothermal investments from ReEDS could be located on federal land, the results were disaggregated and mapped back to the original site-specific resolution in reV. The range for federal land deployment is assessed by mapping ReEDS geothermal capacity investments back to the original site-specific reV combination. ReEDS aggregates the reV site-specific sites based on geothermal technology, geothermal resource class, and spur line transmission costs. The aggregated bins in ReEDS represent one or more reV sites with similar characteristics. The range of estimated deployment on BLM and USFS land depends on what fraction of selected bins are federal land.

3.3.2 ReEDS Model Scenarios

For each of the reV geothermal resource scenarios, we modeled four ReEDS model scenarios. This modeling varies the inputs, impacting the economic favorability of new geothermal capacity investments. The scenarios are organized across two dimensions: geothermal plant cost improvement and a carbon cap scenario where nascent technologies including hydrogen, carbon capture, and nuclear SMR are not available, where renewable energy deployment increases and there is a significant need for carbon-free technologies that can satisfy resource adequacy requirements.

Table 6. ReEDS Model Scenario Assumptions

Scenario	**Geo Capital Costs**	**National CO_2 Cap**	**Technology Restriction**
Reference	ATB 2023 Moderate		
Low-Cost Geothermal	ATB 2023 Advanced		
Decarbonization	ATB 2023 Moderate	100% Decarb by 2035	No nascent tech
Decarbonization with Low-Cost Geothermal	ATB 2023 Advanced	100% Decarb by 2035	No nascent tech

We used ATB 2023 to inform all renewable cost and performance assumptions in ReEDS. In reV the ATB is used to provide a snapshot of costs for a specific analysis year, in contrast ReEDS uses ATB cost trajectories to represent technology cost improvement in future model years. Within the ATB, all electricity generating technologies provide a forward-looking range of cost assumptions based on the aggressiveness of advancement for a range of technology-specific improvements, categorized under Conservative, Moderate, or Advanced case scenarios. The ATB Moderate case is used as the default in our scenarios with the Geothermal ATB Advanced case used in the two Low-Cost Geothermal ReEDS Model scenarios. ATB geothermal plant costs drilling costs are based upon geothermal resource class average depths and supply curve specific depths were not considered in the ReEDS simulation.

Constraining the least cost optimization of the power system to achieve net-zero CO_2 emissions in the electric sector by 2035 drives a significant need for carbon free power sources and technologies that can meet resource adequacy requirements. In scenarios with 100% decarbonization, ReEDS is required to fully decarbonize the electric power sector by 2035 through a CO_2 cap analogous to the trajectory used in the *100% Clean Electricity by 2035 Study* (Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022). Under 100% decarbonization, the need for non, low, or negative emitting technology solutions that can provide capacity to meet resource adequacy requirements significantly increases, which can be addressed by several technology solutions including geothermal, nuclear small modular reactor, carbon capture[9], and hydrogen storage. Many of these technologies are in the process of commercialization, and there are significant uncertainties about future costs and availability. We restricted the availability of

[9] Carbon capture includes generation technology coupled solutions including coal and natural gas with CCS which have low emissions, biomass with CCS with negative emissions, and direct air capture which is not a generation technology but offset emissions from other generation technologies (e.g. natural gas combined cycle).

nongeothermal nascent technologies to incentivize deployment. The combination of aggressive decarbonization, limited technology availability, and low-cost geothermal represents an optimal scenario for deployment and provides a bounding scenario for development.

4 Results

4.1 Identifying Favorable Geothermal on Federal Land

A ReEDS solution contains information about the timing, location, and type of economic generation capacity investments. Though ReEDS aggregates aspects of the site-specific geothermal reV resource representation, we can map a given capacity expansion solution back to the original reV sites. Using this information, we evaluate from the economic ReEDS investment which sites are developed and estimate the maximum and minimum amounts of BLM and USFS lands required to satisfy the selected economic investments in ReEDS.

We solved ReEDS for the Western Interconnection for each of the three reV combinations with each ReEDS model scenarios. The economic favorability of geothermal changes with scenario, with the Reference scenario being least favorable and the Decarbonization with Low-Cost Geothermal scenario being most favorable. Using this method, we can identify the types of conditions as well as the bounds of resource deployment for geothermal on BLM and USFS land relative to other sources of supply. These results are discussed by scenario next, including high-level maps illustrating locations for potential high opportunity leasing areas.

4.1.1 reV Combination 1: Hydrothermal Binary at 3.5-km Depth

In the first reV Combination modeling Hydrothermal Binary at 3.5 km (Figure 3), no geothermal deployment occurs in the scenarios without decarbonization. Under decarbonization, both the case with moderate geothermal costs and the advanced case see economic deployment in ReEDS with 42 GW and 84 GW, respectively, of overall installed national capacity in 2050. The ATB 2030 projected overnight capital costs of hydrothermal binary technologies is 80% of the 2022 overnight capital costs of hydrothermal binary technologies. Of the total installed capacity in decarbonization scenarios, 10-25 GW is sited on BLM and USFS land.[10] The range between the maximum and minimum use of BLM and USFS land is relatively small, varying by 1.8 GW in the Decarbonization scenario and 1.6 GW in the Decarbonization with Low-Cost Geothermal scenario.

[10] The hydrothermal resource in reV using SMU is distinct from the 2008 USGS resource assessment, which included location-specific identified hydrothermal sites as well as probabilistic state-level estimates. The reV methodology does not include a distinction between identified and undiscovered resources.

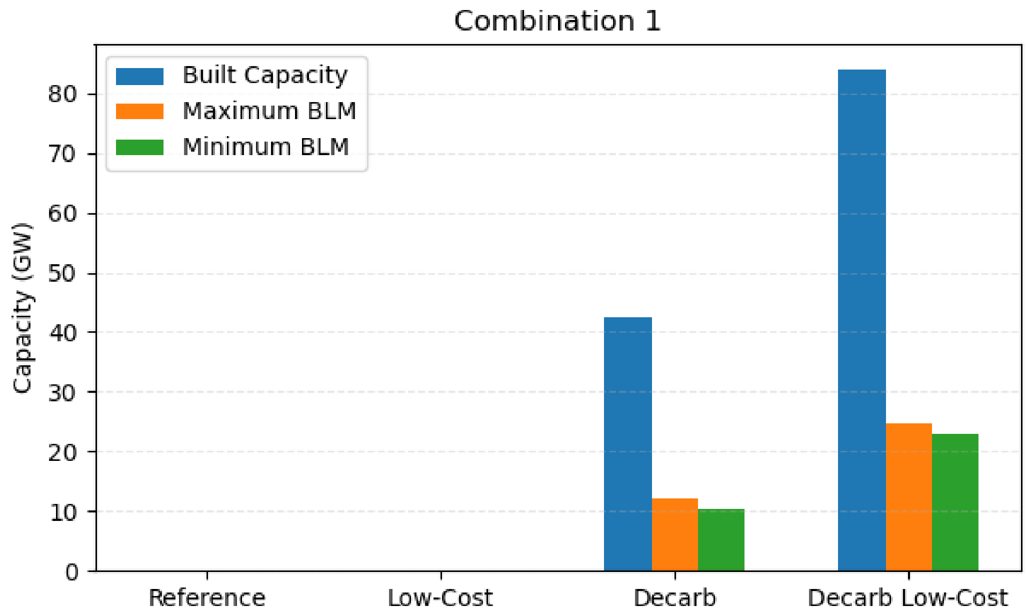

Figure 3. reV Combination 1: Hydrothermal Binary at 3.5-km reV results for total installed capacity in 2050 for the Western Interconnection

4.1.2 reV Combination 2: EGS Binary ATB at 4.5-km Depth

The second reV combination, EGS Binary ATB at 4.5 km (Figure 4), deploys only in the cases with both decarbonization and significant improvements in geothermal costs. EGS, though seeing promising early developments, has yet to achieve the commercialization of hydrothermal development and depends more on the cost improvements in the ATB Advanced case to achieve deployment relative to the results in reV Combination 1. The ATB 2030 projected overnight capital costs of EGS binary technologies is 20% of the 2022 overnight capital costs of EGS binary technologies. This projection is a larger decrease in cost when compared to the hydrothermal cost reduction within the ATB 2030 projected overnight capital costs for hydrothermal binary largely due to 2022 overnight capital costs of EGS being much higher than hydrothermal costs while benefiting from the same drilling cost improvements. In the Decarbonization with Low-Cost Geothermal case, with EGS resources, modeling resulted in 96 GW of deployment, which is greater than the highest hydrothermal deployment ReEDS scenario. This is in part a consequence of increased total resource availability with EGS, which offsets the higher development costs for a hydrothermal resource with a similar reservoir temperature. Combination 2 had much lower use of federal land, representing 8.6 - 14 GW of the total installation based on ReEDS-selected investments. There was a wider band of variation—5.7 GW—between the maximum and minimum use of BLM and USFS land, indicating among selected investment bins a greater intermix of federally and non-BLM and USFS lands.

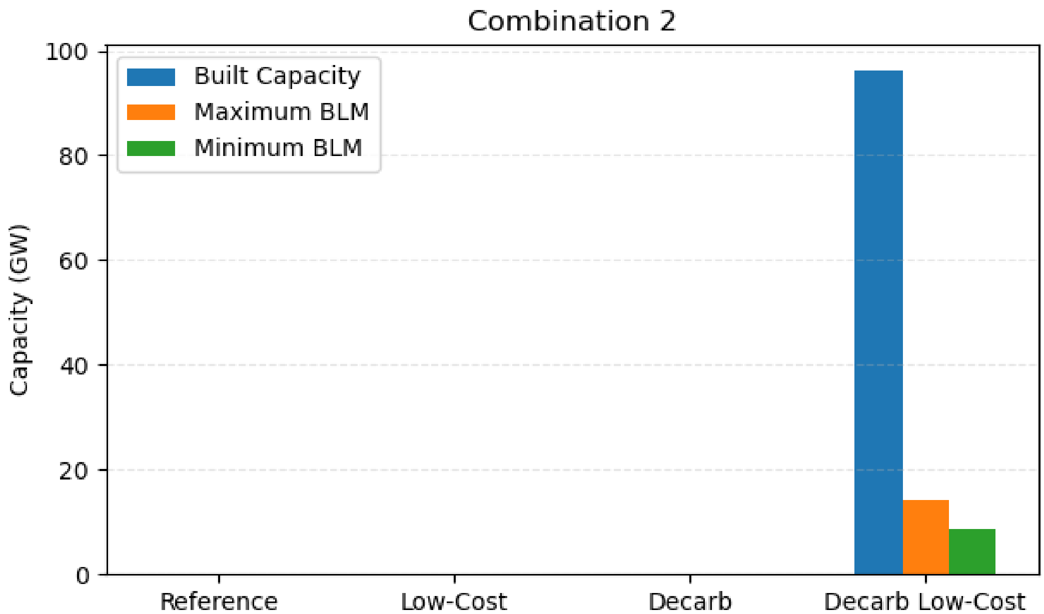

Figure 4. reV Combination 2: EGS Binary ATB at 4.5-km reV results for total installed capacity in 2050 for the Western Interconnection

4.1.3 reV Combination 3: EGS Flash ATB at 6.5-km Depth

The third combination, EGS Flash ATB at 6.5 km (Figure 5), improves the available geothermal resource quality by including access to higher-temperature geothermal resources. The costs associated with the increased depth are offset by the higher resource quality, and we observe higher levels of adoption and across more scenarios than in the second reV combination. The ATB 2030 projected overnight capital costs of EGS flash technologies is 0.3 of the 2022 overnight capital costs of EGS flash technologies. This projection is a larger decrease in cost when compared to the hydrothermal cost reduction within the ATB 2030 projected overnight capital costs for hydrothermal binary.

Deployment is observed in ReEDS model scenarios that include low geothermal costs (16 GW) or decarbonization policies (12 GW). The combination of those scenario assumptions deploys 136 GW of geothermal capacity. The use of BLM and USFS lands is higher, with the Low-Cost Geothermal and Decarbonization scenarios depending heavily—100% and 90%, respectively—on federal land. The specific developed geothermal classes and binned resources in the utilized portion of the resource supply curve were almost entirely BLM and USFS lands resulting in the high utilization and narrow utilization range. In the Decarbonization case, deployment occurs in a wider geographic area, requiring between 83-100 GW of its capacity to use BLM and USFS land, which results in the total installed capacity varying by 16 GW.

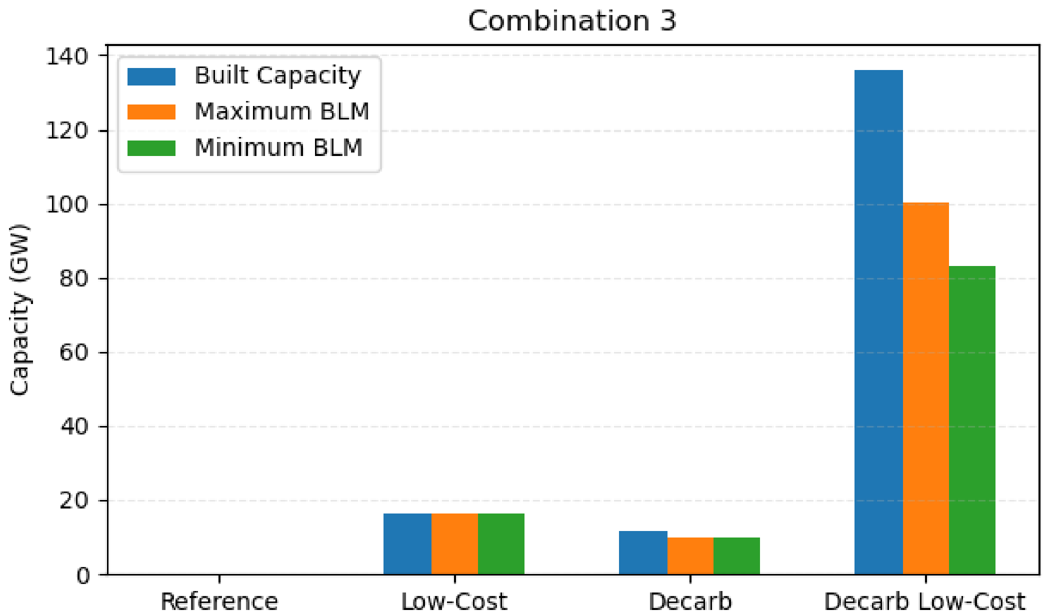

Figure 5. reV Combination 3: EGS Flash ATB at 6.5-km results for total installed capacity in 2050 for the Western Interconnection

The depth range for reV Combinations 1 and 2 represents a similar range of resource, which includes a combination of the ranges of deployed capacity on BLM and USFS land for the different technologies and depths (Figure 6). This increase impacts only the Decarbonization with Low-Cost Geothermal scenario. It is important to note that the capacity expansion analysis that informs these results was run independently. The deployment in an economic scenario would likely be less than a purely additive total if the reV hydrothermal and EGS resource supply curves had been competed directly against one another.

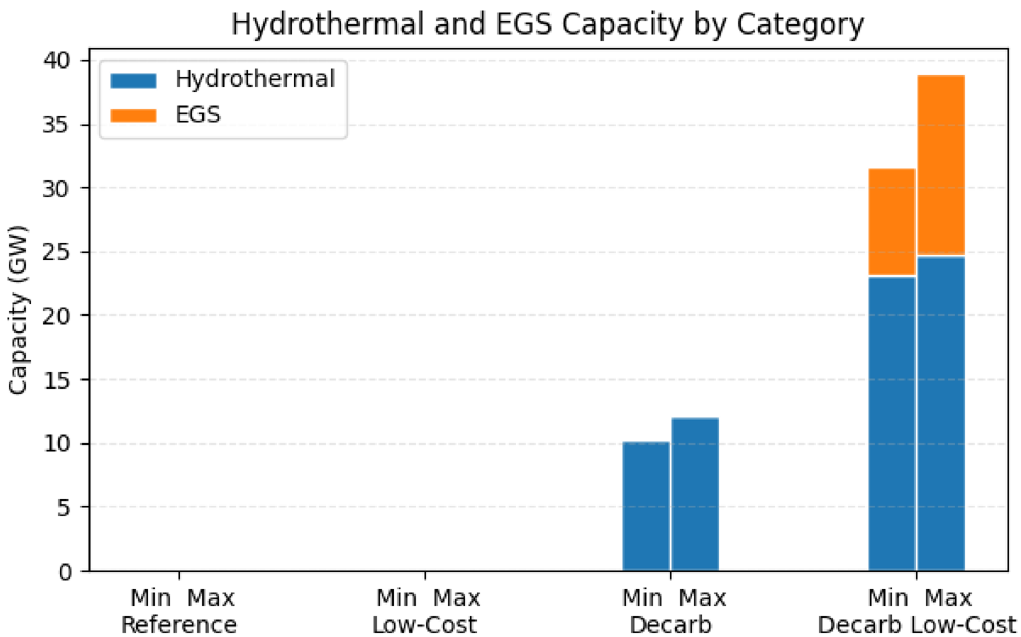

Figure 6. reV Combinations 1 and 2 deployed capacity ranges on BLM and USFS land in 2050 for the Western Interconnection

Geothermal Data Repository

Geothermal supply curves for this analysis can be found on the DOE's Geothermal Data Repository https://gdr.openei.org/. The GDR is the repository for data generated by projects funded by the DOE GTO. The GDR is publicly available, providing access to geothermal data sets.

5 Conclusions

In Section 4, we presented the potential range of economically developed capacity across a range of possible futures for the power system. From this, we identified specific geothermal sites from the reV combinations that see development in one or more of the ReEDS analysis scenarios. Though this identifies the potential capacity of prioritizable geothermal leases, it does not indicate which among these sites have greater favorability. In each reV combination the highest geothermal deployment occurred in the Decarbonization with Low Cost Geothermal Costs case. This is illustrated in Table 7, which defines the maximum target capacity in GW for each reV combination. We added an additional constraint to ReEDS requiring total geothermal capacity match specified target capacities in 2050. Using least the favorable analysis scenario (Reference scenario), we apply the geothermal capacity constraint and identify which reV sites are built for a specific target.

Table 7. Geothermal Capacity Targets in 2050 (GW)

Capacity Breakpoints	reV Combination 1 Hydrothermal Binary Deployment Capacity (GW) at 3.5 km	reV Combination 2 EGS Binary Deployment Capacity (GW) at 4.5 km	reV Combination 3 EGS Flash Deployment Capacity (GW) at 6.5 km
Best	29	41	46
Middle	58	82	93
Least	88	123	139

We applied this target in increments of thirds as shown in Table 7, allowing us to identify which sites fall into three different tranches of favorability, using *Best, Middle, and Least* to label these. To identify these three categories, the maximum deployment in Combinations 1–3 was considered alongside the combinations' economic deployment trajectories. Though, using the geothermal capacity constraint, we mandate that ReEDS must build sufficient capacity to satisfy the target, the model still considers economic competitiveness of available sites, building those that offer the best combination of value of grid services and development costs.

- *Best* economical geothermal sites: The best third of the deployed resource at each depth and technology combination scenario represents the portion of the selected resource most favorable for development. These geothermal sites are built when building to the Best capacity target as illustrated in Table 7.

- *Middle* third economical geothermal sites: The middle third of the deployed resource at each depth and technology combination scenario, represents the second group of geothermal resources. These geothermal sites were built with the Middle geothermal capacity target but not using the lower *Best* geothermal capacity target as illustrated in Table 7.

- *Least* economical geothermal sites: The final third of the deployed resource in a geothermal resource depth and technology scenario, and represents the last group of geothermal resources to see deployment, geothermal sites not built under either *the Best* or *Middle* geothermal capacity targets as illustrated in Table 7.

These are the near-term locations identified in Figure 9, 10, and 11, broken down by each scenario. A key advantage of this approach is it allows us to more economically model competitive sites on BLM and USFS land, considering not just the geothermal resource costs but also the value of the services delivered by a power plant considered as part of ReEDS modeling.

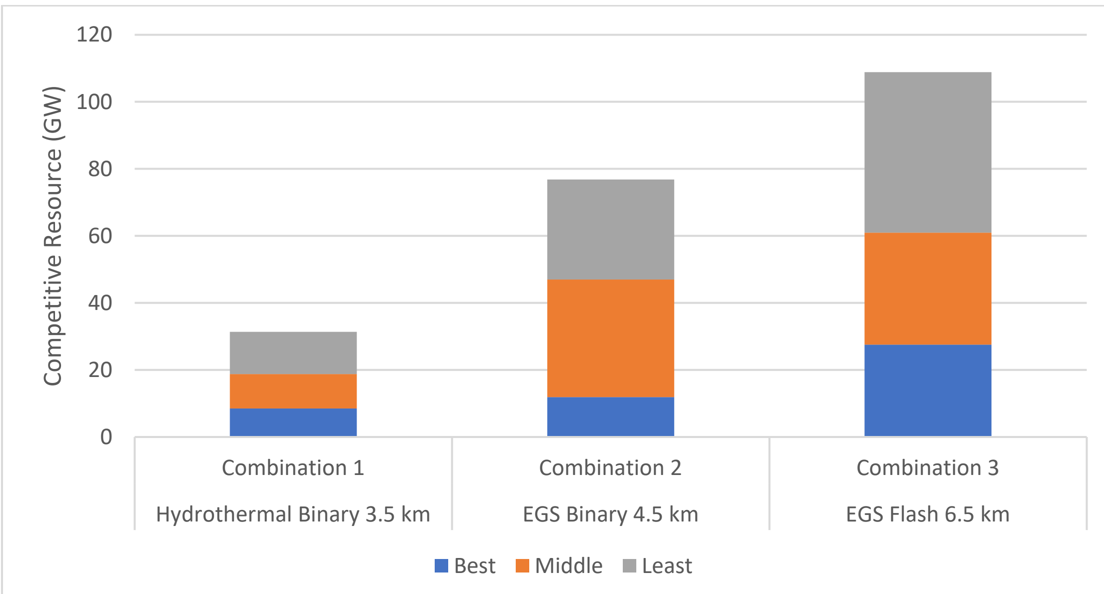

Figure 8. Competitive geothermal available resources on BLM and USFS land

Figure 8 shows the available resource capacity on BLM and USFS land by tranche for the three reV combinations. A key difference from results shown in Section 4, which calculated ranges of installed capacity in 2050, is the results here show the total available resource for selected sites even if only a portion of it was developed in ReEDS. Scenarios 1 and 3 have a similar overall distribution by tranche with the *Best* category representing between 25% and 27% of the prioritizable resource of federally managed public land, in contrast to Scenario 2 with 15% belonging to the *Best* tranche. Moving from Scenario 1 to 3, the total leasable BLM and USFS land fraction consistently increases, including the total resource capacity in the *Best* tranche.

Under all modeled scenarios, geothermal has the potential to provide a substantial contribution to the Biden administration's goal to have a clean electricity sector by 2035 and a net-zero emissions economy by 2050 in addition to the Energy Act of 2020's[11] renewable energy deployment target of more than 25 GW permitted on BLM and USFS land (United States Department of State and the United States Executive Office of the President 2021). The results of

[11] The Energy Act of 2020 is the short title of Division Z – Energy Act of 2020 of the Consolidated Appropriations Act, 2021.

this analysis illustrate that on BLM and USFS land, 8.5 GW of hydrothermal resources and between 12-28 GW of EGS resources of modeled deployment exists within the *Best* tranche for the reV Combinations. Deployed capacity on federally managed land for each tranche and in total for each reV Combination in GW are shown in Table 8.

Table 8. ReEDS Model Scenario Assumptions (GW)

Tranche	reV Combination 1 Hydrothermal Binary 3.5 km	reV Combination 2 EGS Binary 4.5 km	reV Combination 3 EGS Flash 6.5 km
Best	8.5	12	28
Middle	10	35	33
Least	13	30	48
Total	**31**	**77**	**109**

reV Combinations State-by-State Results

State-by-state breakdowns of the prioritization tranches for the reV analysis scenarios are illustrated next. The maps shown in Figures 9 through 12 illustrate the locations of the prioritization tranches for the reV analysis scenarios.

Combination 1 Mapping Results

The following map illustrates the results of Combination 1, the analysis of Hydrothermal Binary at 3.5-km depth.

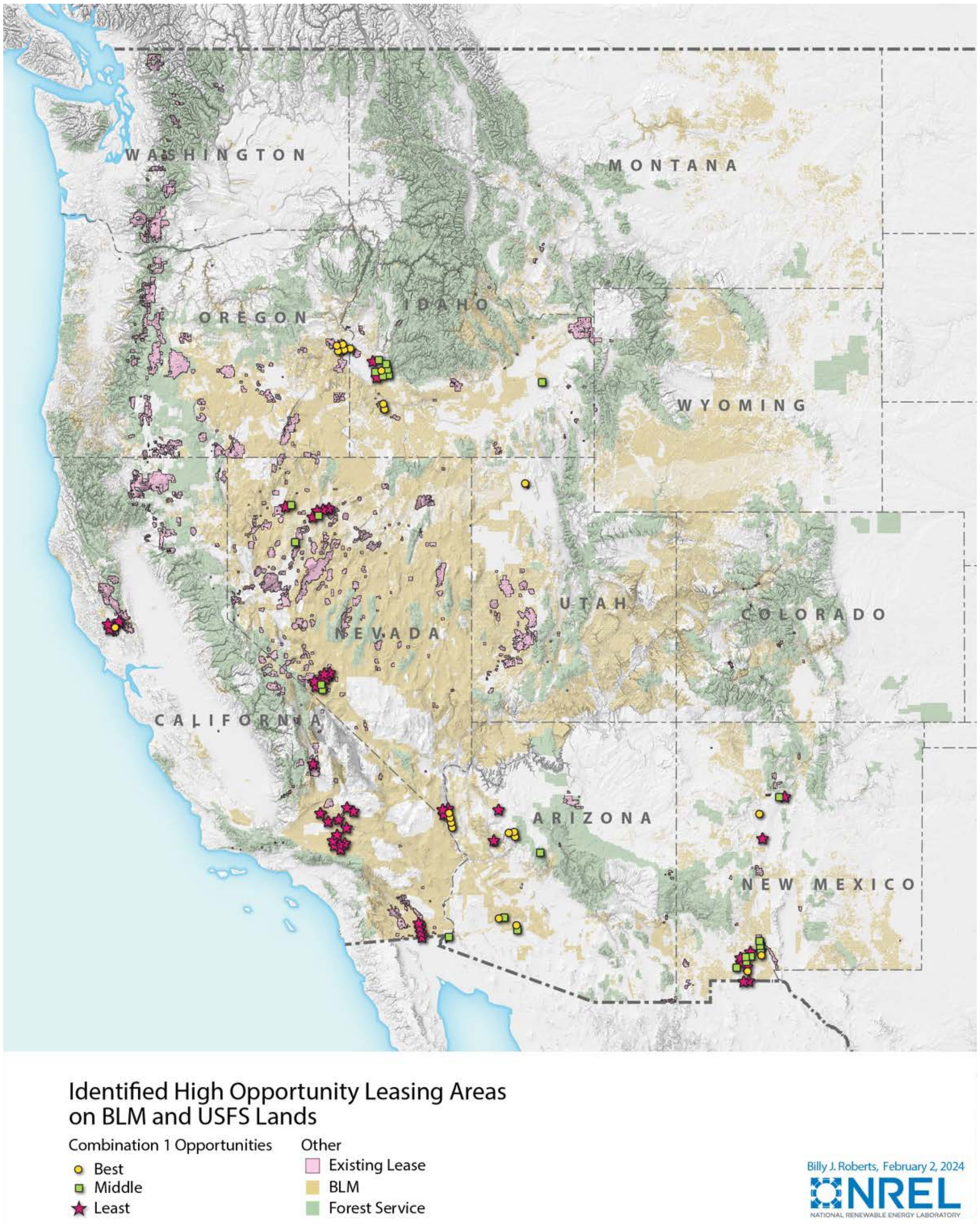

Figure 9. Scenario 1 opportunities

Figure 9. Identified high opportunity leasing areas on BLM and USFS lands for Geothermal Resource Depth and Technology Combination 1: Hydrothermal binary at 3.5-km depth

Figure 9 illustrates output from the modeling exercises for Geothermal Resource Depth and Technology Combination 1 broken down by the *Best, Middle,* and *Least* terms. Identified areas could be pursued for leasing according to these terms.

Combination 2 Mapping Results

The following map illustrates the results of Combination 2, the analysis of EGS Binary ATB at 4.5-km depth.

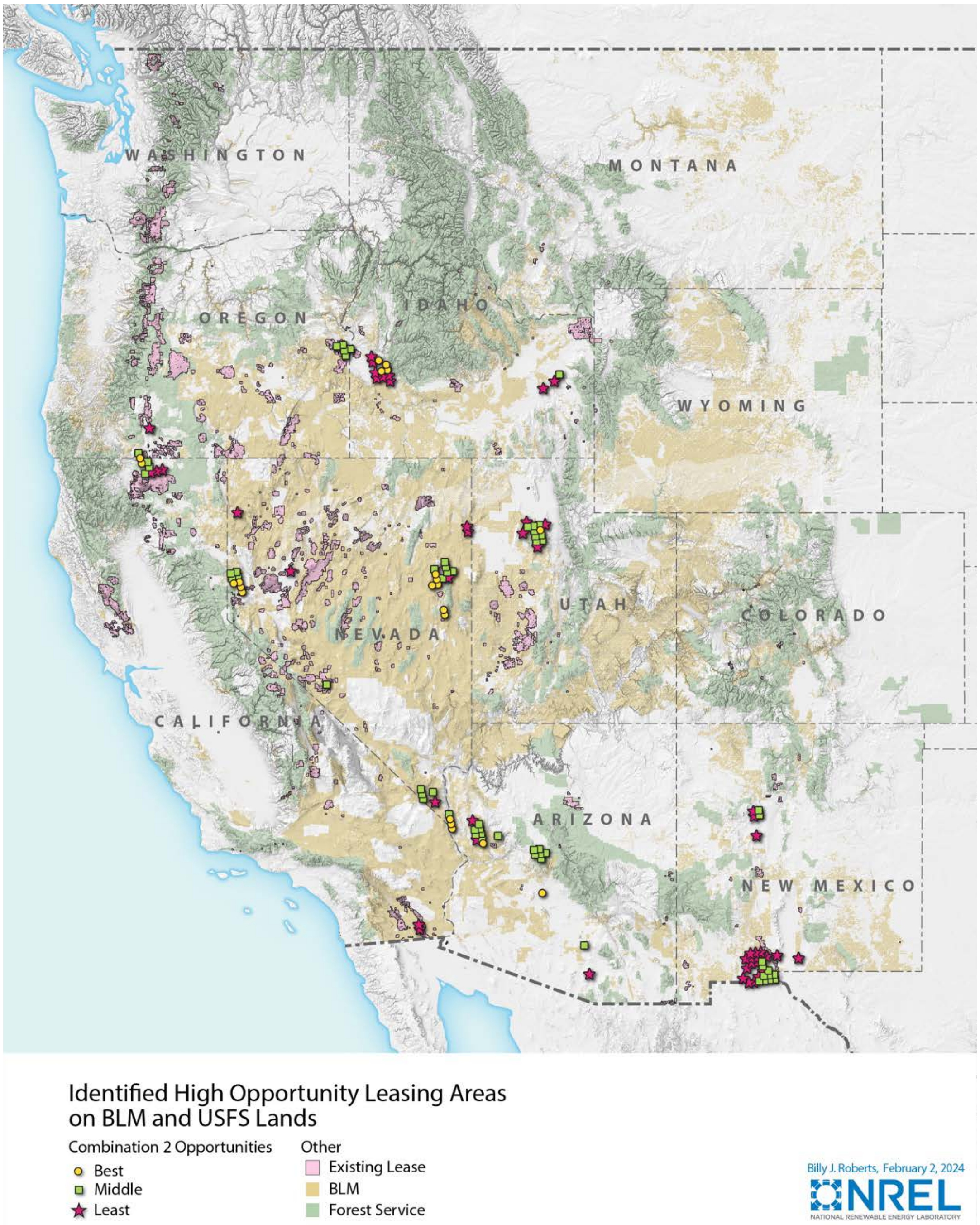

Figure 10. Identified high opportunity leasing areas on BLM and USFS lands for Combination 2: EGS Binary ATB at 4.5-km depth.

Figure 10 illustrates the output from the modeling exercises for Geothermal Resource Depth and Technology Combination 2 broken down by the *Best, Middle,* and *Least* terms. Identified areas could be pursued for leasing according to these terms.

Combination 3 Mapping Results

The following map illustrates the results of Combination 3, the analysis of EGS Flash ATB at 6.5-km depth.

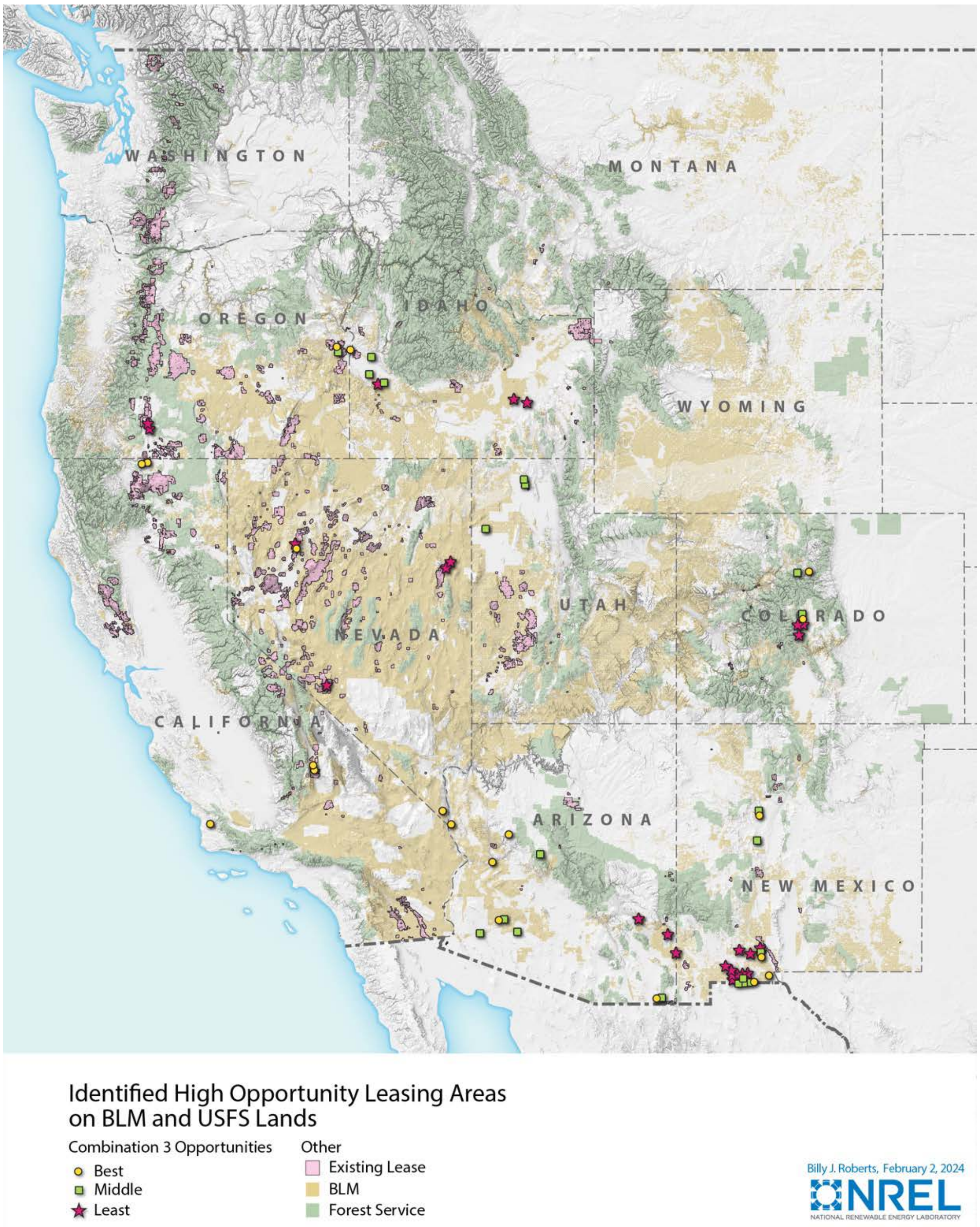

Figure 11. Identified high opportunity leasing areas on BLM and USFS lands for Combination 3: EGS flash at 6.5-km depth

Figure 11 illustrates the output from the modeling exercises for Geothermal Resource Depth and Technology Combination 3 broken down by the *Best, Middle,* and *Least terms.* Identified areas could be pursued for leasing according to these terms.

Combined Output of Geothermal Resource Depth and Technology Combinations 1 and 2

The following map illustrates the combination of output from the modeling exercises for Combinations 1 and 2, the analysis of Hydrothermal and EGS Flash at 3.5-km and 6.5-km depth, respectively.

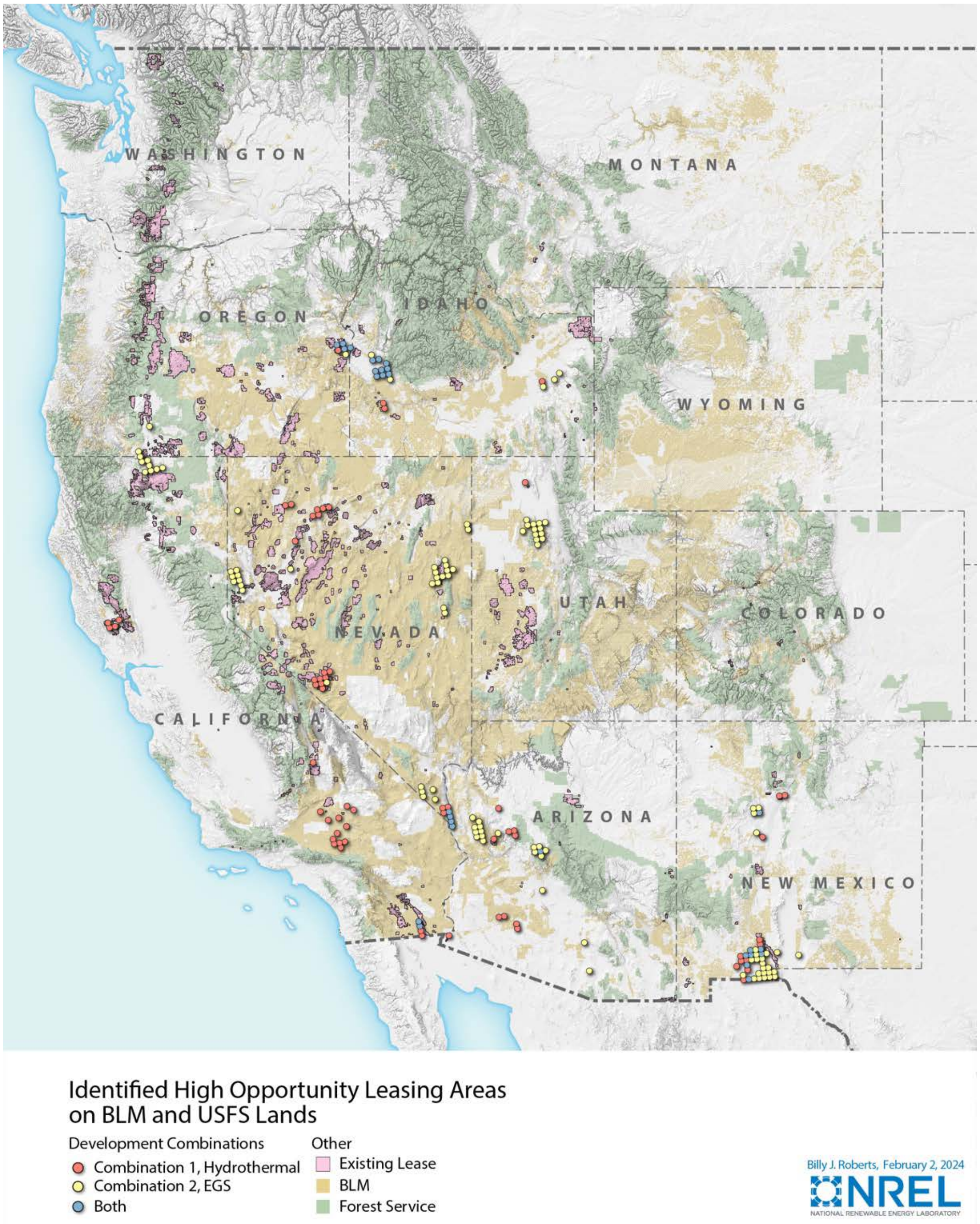

Figure 12. Identified high opportunity leasing areas on BLM and USFS lands

Figure 12 illustrates the combination of output from the modeling exercises for Geothermal Resource Depth and Technology Combinations 1 and 2.

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