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Low-Temperature Geothermal Play Fairway Analysis for the Appalachian Basin

Teresa JORDAN[1], Erin R. CAMP[1], Jared SMITH[1], Calvin WHEALTON[1], Franklin G. HOROWITZ[1], Jery R. STEDINGER[1], Jefferson W. TESTER[1], Maria RICHARDS[2], Zachary FRONE[2], Rahmi BOLAT[2], Matthew HORNBACH[2], Cathy CHICKERING PACE[2], Beatrice MAGNANI[2], Brian ANDERSON[3], Xiaoning HE[3], Kelydra WELCKER[3]

[1]Cornell University, [2]Southern Methodist University, [3]West Virginia University

teresa.jordan@cornell.edu

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ABSTRACT

This Department of Energy funded effort applied the Play Fairway Analysis approach to low-temperature geothermal exploration and potential development of direct-use geothermal plays in the Appalachian Basin portions of New York, Pennsylvania, and West Virginia. The four "Play Fairway" risk factors analyzed in this study are 1) thermal resource quality, 2) natural reservoir quality, 3) induced seismicity, and 4) utilization opportunities. This project considered several methodologies for combining the risk factors into a single index that communicates the estimated overall favorability of geothermal development. Uncertainty analyses considered the estimated precision in the geologic risk factors (1-3) and estimated the uncertainty in the combined index. The assumed use scenario investigated on a basin-wide scale was that of district heating systems. The quantitative analysis was based on pre-existing data from sources inclusive of: previous national and state research efforts; the National Geothermal Data System; the Midwest Regional Carbon Sequestration Partnership; New York, Pennsylvania and West Virginia State geologic, oil and gas well data provided by the State Geological Surveys and by their oil and gas regulatory bodies; NOAA Climate data; NEIC and EarthScope (TA) seismicity data; a regional-scale magnetic grid; regional-scale gravity data; the World Stress Map; US Census Bureau population data; and Energy Information Agency power consumption data. Based on these data and metrics, several geothermal plays in the Appalachian Basin were identified as potentially viable for direct-use-heat applications. Major uncertainties remaining at the end of this analysis are especially large regarding characterization of reservoirs to flow hot water, and regarding the three-dimensional spatial distribution of reservoirs because the data are biased by the hydrocarbon industry source of data. In addition, although the general spatial patterns of the heat resource variations appear to be robust, the accuracy of the temperature-depth profiles at given locations of interest could be improved significantly if new equilibrium temperature and thermal conductivity data were acquired. As a follow-up step, the subsurface costs for a set of case study scenarios should be analyzed as well as the surface infrastructure costs, to facilitate Levelized Cost of Heat discussions with potential user groups at favorable locations. The methodologies developed in this project may be applied in other sedimentary basins as a foundation for low temperature (50-150 °C) direct use geothermal resource, risk, and uncertainty assessment.

DISCLAIMER

NOTE

This document is a slightly augmented and updated version of the Executive Summary from Jordan et al. (2015). Please consult that document after its public release for more details.

1. INTRODUCTION

Geothermal energy is an attractive sustainable energy source. Project developers need confirmation of the resource base to warrant their time and financial resources. The hydrocarbon industry has addressed exploration and development complexities through use of a technique referred to as Play Fairway Analysis (PFA). The PFA technique assigns risk metrics that communicate the favorability of potential hydrocarbon bearing reservoirs in order to enable prudent allocation of exploration and development resources.

The purpose of this Department of Energy funded effort is to apply the PFA approach to geothermal exploration and development, thus providing a technique for Geothermal Play Fairway Analysis (GPFA). This project focuses on four risk factors of concern for direct-use geothermal plays in the Appalachian Basin (AB) portions of New York, Pennsylvania, and West Virginia (Figure 1). These risk factors are 1) thermal resource quality, 2) natural reservoir quality, 3) induced seismicity, and 4) utilization opportunities (Figure 2). This research expands upon and updates methodologies used in previous assessments of the potential for geothermal fields and utilization in the Appalachian Basin, and also introduces novel approaches and metrics for quantification of geothermal reservoir productivity in sedimentary basins. Unique to this project are several methodologies for combining the risk factors into a single commensurate objective that communicates the estimated overall favorability of geothermal development. Uncertainty in the risk estimation is also quantified. Based on these metrics, geothermal plays in the Appalachian Basin were identified as potentially viable for a variety of direct-use-heat applications. The methodologies developed in this project may be applied in other sedimentary basins as a foundation for low temperature (50-150 °C), direct use geothermal resource, risk, and uncertainty assessment. Through our identification of play fairways, this project reveals the potential for widespread assessment of low-temperature geothermal energy from sedimentary basins as an alternative to current heating sources that are unsustainable.

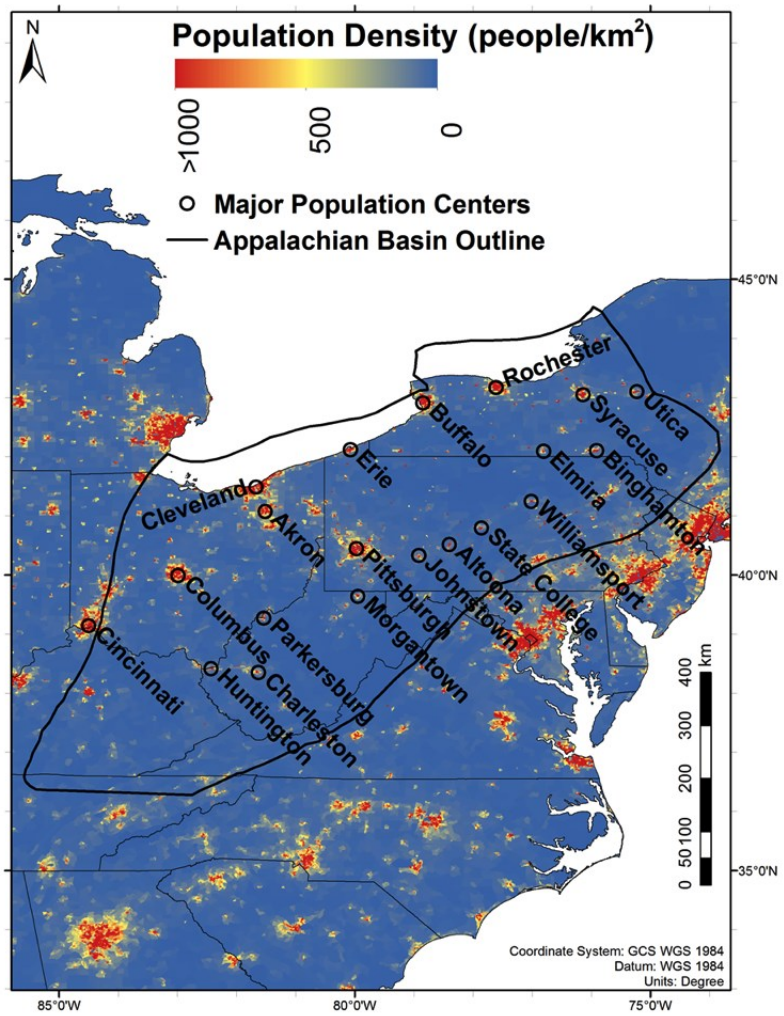

Figure 1: Population density (U.S. Census Bureau, 2010) within the Appalachian Basin region (Shumaker, 1996) highlighting the larger cities. The high-density regions are potential users of geothermal district heating.

There is an important distinction in this Geothermal Play Fairway Analysis project as compared to hydrothermal projects: this Appalachian Basin analysis is focused on the direct use of the heat, rather than on electrical production. Lindal (1973) illuminated numerous industrial and other low-temperature applications of geothermal energy for which this analysis can be useful. The major relationship to electricity is that direct-use applications reduce the electricity requirements for a region. Even though all of the geothermal resources in the Appalachian Basin are low grade, the high population and high heating demand across New York, Pennsylvania, and West Virginia translate into economic advantages if geothermal direct-use heating replaces electricity-based heating. The advantage is derived from the high efficiency of extracting heat from geothermal fluids rather than converting the fluids to electricity (Tester et al., 2015).

The Geothermal Play Fairway Analysis of the Appalachian Basin is valuable for several reasons:

1. The Appalachian Basin is a sedimentary basin with a history of substantial hydrocarbon drilling activity, thereby increasing our ability to access existing knowledge about the subsurface thermal field and reservoirs. GPFA techniques developed here could be applied in other sedimentary basins with ample publicly available hydrocarbon drilling records around the U.S., such as the Williston Basin, Sacramento Basin, San Joaquin Basin, Gulf Coast Basin, Black Warrior Basin, Denver Basin, Anadarko Basin, Illinois Basin, Michigan Basin and others.

2. The Appalachian Basin, like most of the U.S. east of the Rocky Mountains, is considered a 'low temperature' geothermal area. Some low temperature geothermal areas are suitable for direct-use applications (e.g., district heating, greenhouses, aquaculture, and industrial processes, such as pasteurization) or coproduction, but not for electricity generation alone. Because low-temperature geothermal resources are more common than high grade in the U.S., this project is important beyond its regional footprint for the development of direct use low-temperature geothermal projects across the U.S.

3. Several major population centers located within the Appalachian Basin concentrate the demand for heat in small areas. These include Pittsburgh, PA; Williamsport, PA; State College, PA; Morgantown, WV; Charleston, WV; Buffalo, NY; Syracuse, NY; and Rochester, NY (Figure 1).

4. Space heating and cooling of homes is the #1 use of the residential consumption of produced electrical energy in the U.S. (U.S. Energy Information Administration, 2015). This project explores the possibility that communities in the Appalachian Basin may be able to employ geothermal district heating to relieve the growing stress on the electric power grid.

2. DATA SOURCES AND PROJECT FLOW

The team began by characterizing the constraints to developing a geothermal project that must be managed in an integrated fashion. These constraints were treated as four categories of risk: 1) Thermal Resource Quality, 2) Natural Reservoir Quality, 3) Risk of Seismic Activity, and 4) Utilization Viability. Each risk was quantified, as was the uncertainty associated with the resultant risk value. These four risk factors were then combined (Figure 2) into a single metric that was used to determine the most favorable fairways within the Appalachian Basin.

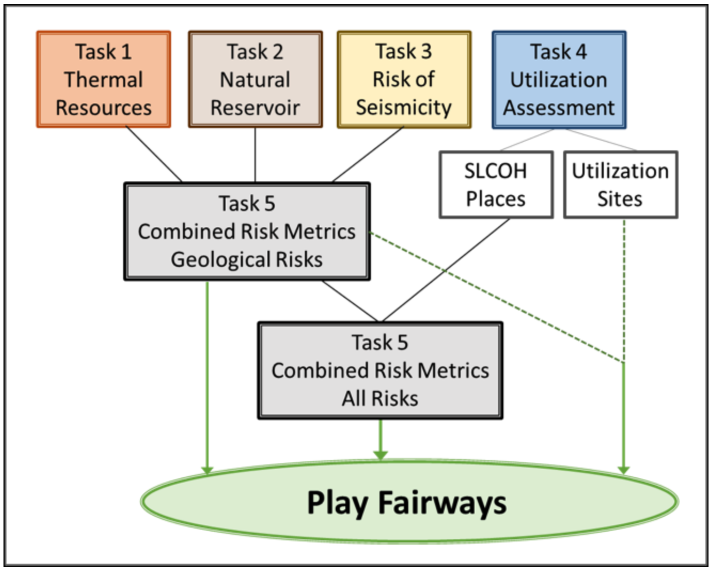

Figure 2: Appalachian Basin Geothermal Play Fairway Analysis Process. Each of four key risk factors studied in the context of favorability and uncertainty were combined using Play Fairway Metrics (PFM) to create final Play maps and overall basin risk.

To conduct a quantitative analysis, we utilized data collected as part of previous national and state research efforts, as well as data from the National Geothermal Data System; the Midwest Regional Carbon Sequestration Partnership; New York, Pennsylvania and West Virginia State geologic, oil and gas well data provided by the State Geological Surveys and by their oil and gas regulatory bodies; NOAA Climate data; NEIC and EarthScope (TA) seismicity data; regional-scale magnetic map; regional-scale gravity map; US Census Bureau population data; and Energy Information Agency power consumption data.

3. THERMAL RESOURCE QUALITY

Appalachian Basin temperature data from oil and gas bottom-hole temperatures (BHTs) are abundant (Figure 3), but of low quality. This project updates the analyses published by Shope et al. (2012) and Stutz et al. (2015), and generated a new set of BHT corrections appropriate for this basin. At the location of each well, the corrected BHT was combined with generalized thermal conductivity stratigraphy to estimate the local geotherm using a 1-D heat conduction model. Analyses of local spatial outliers were performed on the geotherms, followed by a spatially stratified ordinary Kriging regression that predicted properties of the thermal field and its lateral variations. A sensitivity analysis on the input variables to the heat conduction model revealed that BHTs are the most critical input variable for quantifying properties of the thermal field. Overall, these methods resulted in higher quality results and a more robust evaluation of the uncertainty than previous studies. The final Thermal Risk Factor map is shown in Figure 4, with details of its construction found in Jordan et al. (2015).

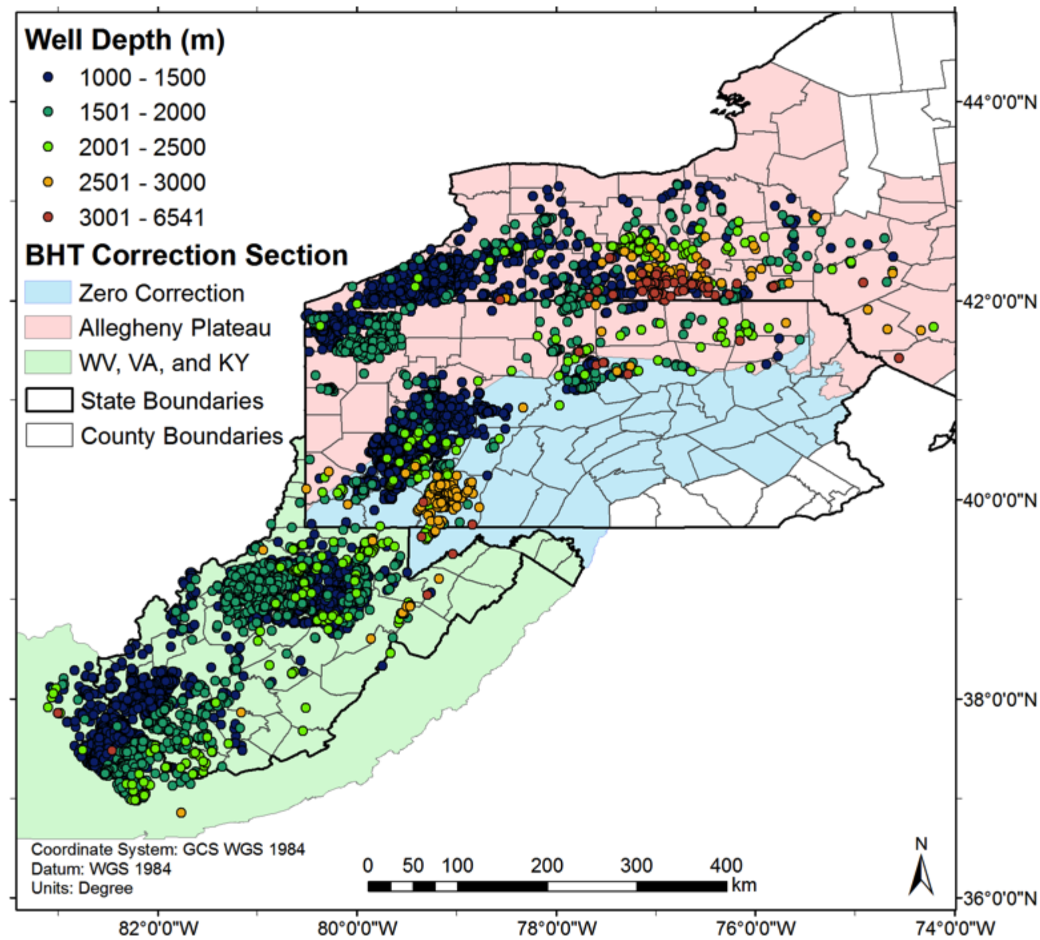

Figure 3: Well locations colored by depth of the BHT measurement, and BHT correction regions used in this project. County and state outlines are shown. For quality reasons, only those BHT measurements at depths greater than 1000 m were retained for analysis.

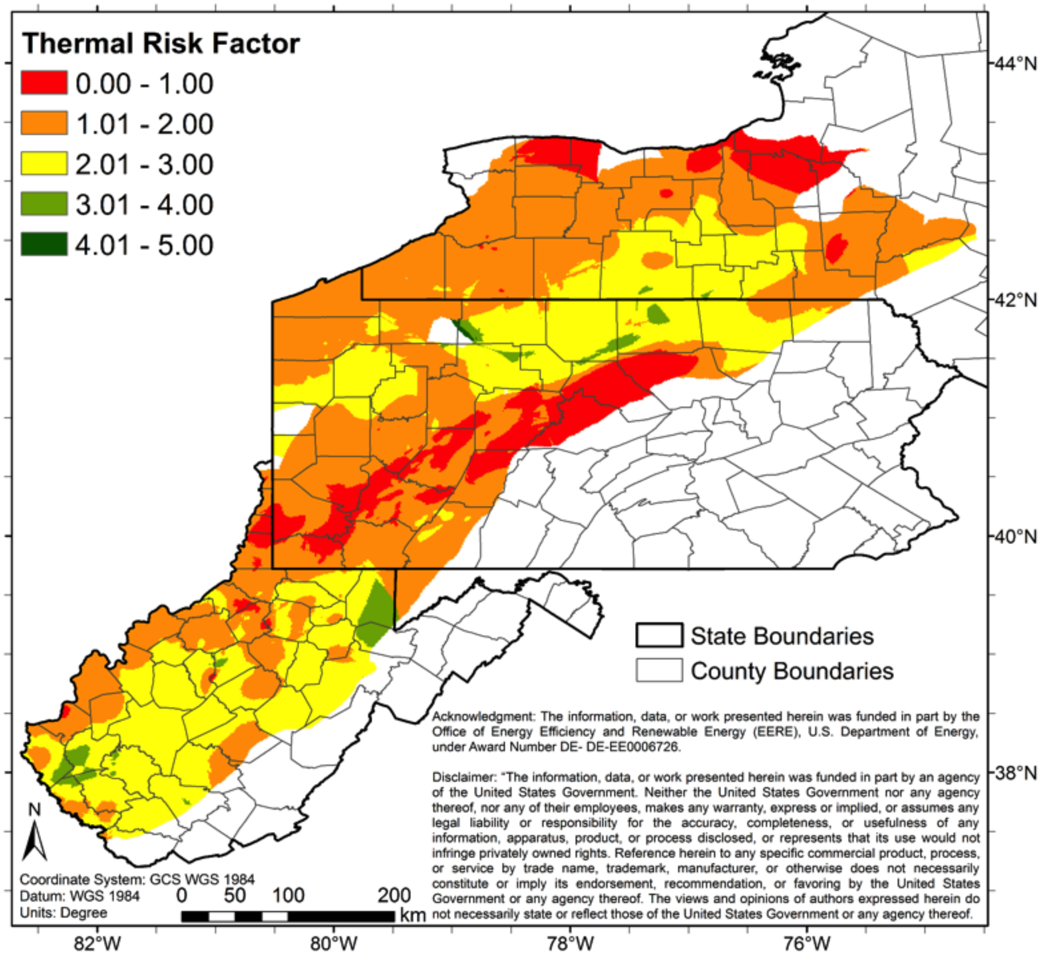

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Figure 4: Play Fairway Metric risk segment map for the thermal resource with a five color scheme. Green-Favorable, Red-Unfavorable.

4. NATURAL RESERVOIR QUALITY

The Appalachian Basin's conventional hydrocarbon fields and its unconventional shale reservoirs have been extensively studied (Engelder, Lash, & Uzcátegui, 2009; Nelson, 2009). In the second task, Natural Reservoir Quality analysis, we examined the suitability of rocks to function as natural reservoirs, which necessitate sufficient water flow rates between injection wells and production wells to harvest heat within the reservoir. This procedure included additional independent methods to predict permeability using information from carbon sequestration studies and porosity data, both overlapped with oil and gas exploration and production datasets. Some of the most vital data are very scarce in public records: permeability values, pressure data, and production data. The oil and gas reservoir property records are spatially biased toward those locations with profitable amounts of hydrocarbons in the rock pore spaces. This bias ought *not* be shared by this project's search for *water* in pore spaces, although the existing data cause persistence of this bias. The spatial bias and the lack of permeability and/or flow data impose a severe limit on the completeness of the reservoir assessment that was possible. The locations of the natural reservoirs and lateral variations in reservoir properties reported here must be considered with the understanding that there exist potential errors that are not quantified due to lack of data and because our data base focused on oil/gas rather than on formations with water. Indeed, more data could identify additional reservoirs. Figure 5 shows the final Reservoir Risk Factor PFM, with full details available from Jordan et al. (2015).

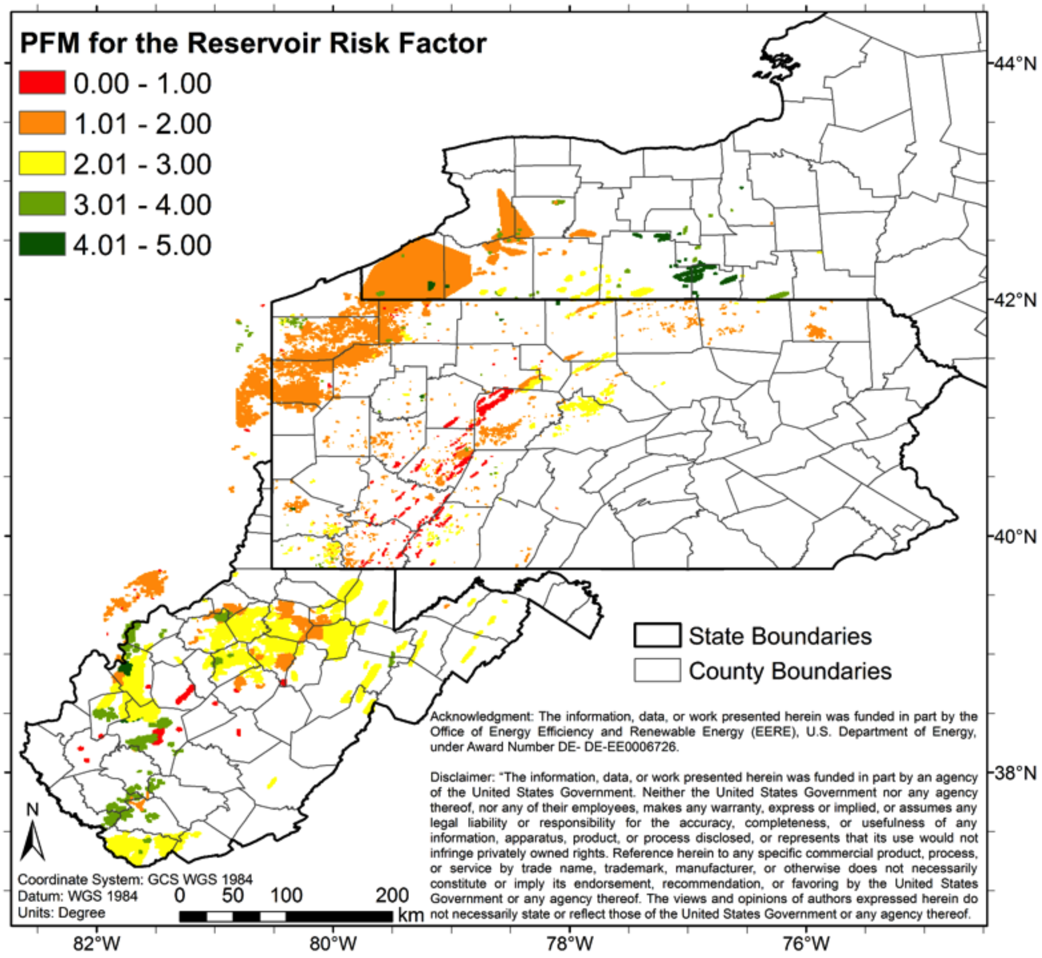

Figure 5: Play Fairway Metric risk segment map for the reservoir resource with a five color scheme. Green-Favorable, Red-Unfavorable.

5. SEISMICITY

With the extent of ongoing induced earthquake activity in several states (Oklahoma, Texas, Kansas, Ohio) and the potential for similar activity in portions of the Appalachian Basin, it is expected that the public will require an informed risk assessment in advance of undertaking a new type of energy extraction work in the subsurface. To anticipate this concern, we examined the options for a regional analysis to identify sub-regions that may be more or less at risk for slip along planes of weakness in the rocks. Acknowledging that data for such a task are insufficient, we utilized what was available: records of seismic activity, regional estimates of the orientations of principal stress directions, and locations and orientations of zones identified on gravity and magnetic data as sites of lateral change in rock properties at depths down to several kilometers below Earth's surface. Analysis of those data sets highlight areas within the basement that have higher or lower sensitivities to fluid pressure changes. With these data, we created a first approximation of spatially variable risks for induced earthquakes. Figure 6 shows the final PFM for an Average of Earthquake Proximity and Stress Orientation Based Risk, with details available both in Jordan et al. (2015) and Horowitz et al. (2016; this volume).

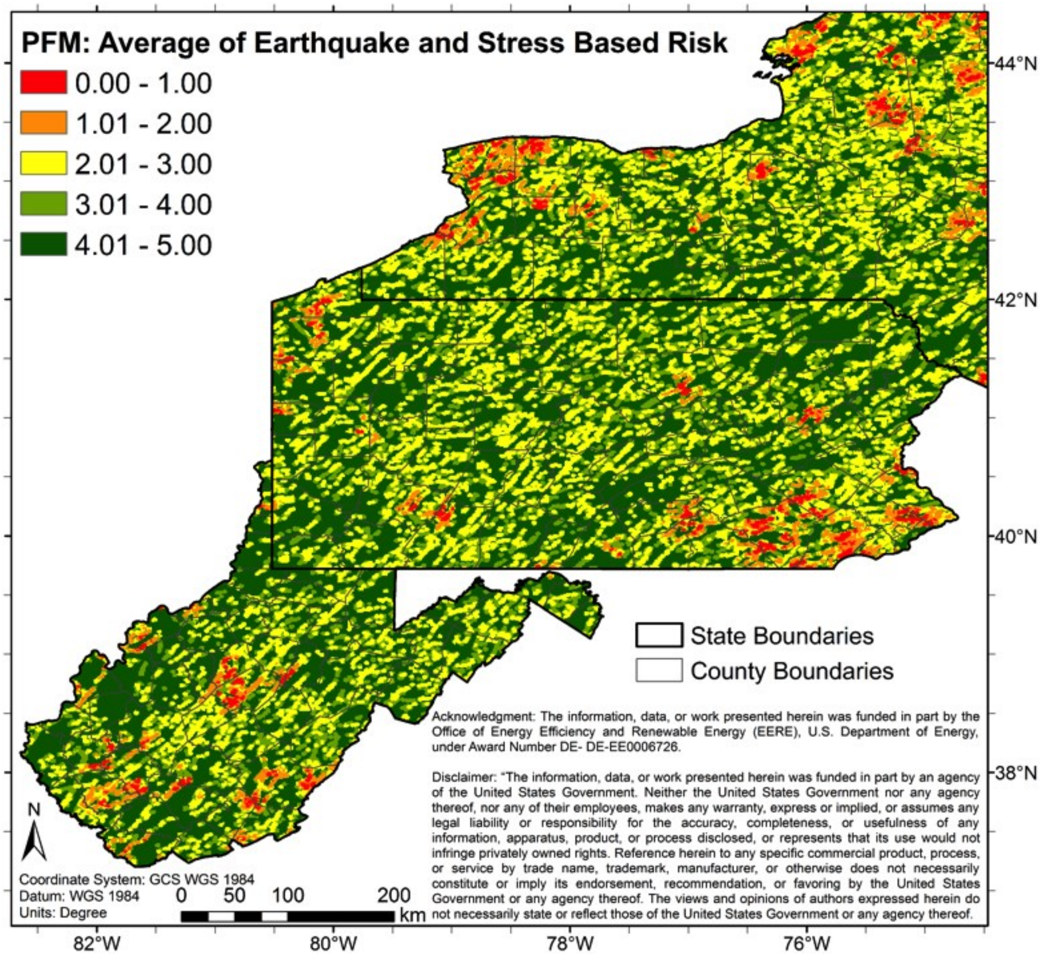

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Figure 6: Play Fairway Metric risk segment map for the seismic resource with a five color scheme. Green-Favorable, Red-Unfavorable.

6. UTILIZATION OPPORTUNITIES

Economically viable projects for low-temperature direct-use geothermal heat must be located near the field where the hot water is extracted to limit thermal losses and excessive pumping costs. Therefore, for the Utilization risk factor we worked principally with population density as a regionally known variable. For this economic analysis, we employed a previously developed model by Beckers et al. (2014), GEOPHIRES (GEOthermal energy for Production of Heat and Electricity [“IR”] Economically Simulated), with variations to capture the surface costs associated with delivering heat from a wellhead to final consumers through a district heating system. The Utilization maps do not include the costs of producing the hot water at the well head, because the below-ground costs are directly coupled to the spatial variability of the heat resource and the reservoir properties, which are factors treated under the Thermal Resource risk and Natural Reservoir risks. The result of the district heating analysis is provided as a surface levelized cost of heat (SLCOH). Because we have now identified potential play fairways, the cost of heat delivery for individual locations within the fairways, including all of the components needed to compute a true levelized cost of heat, should be calculated during a follow-up study. In addition to district heating, we located institutions and businesses that utilize large amounts of thermal energy at low temperatures across the three-state study area. These represent additional utilization opportunities for the region that should be investigated in more detail in future studies. Figure 7 displays the final PFM Utilization Risk Factor map, with full details available in Jordan et al. (2015).

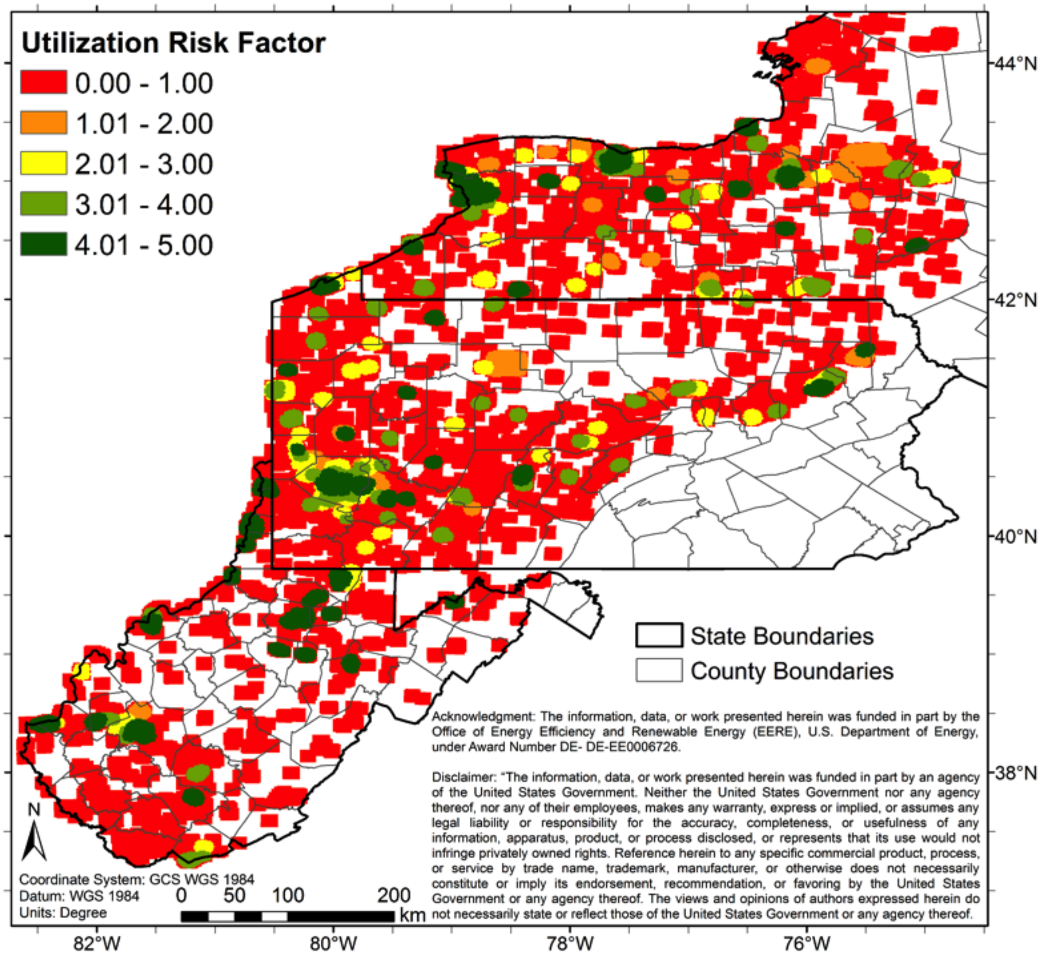

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Figure 7: Play Fairway Metric risk segment map for the utilization of resource with a five color scheme. Green-Favorable, Red-Unfavorable. The utilization locations are buffered by 5 km and then the maximum is selected, which reflects a willingness to move the water small distances.

7. COMBINED RISK METRIC

The final task developed and assigned a Combined Risk solution to incorporate each of the four project risk factors using a set of Play Fairway Metrics (PFMs). This task identified the most favorable locations within the study area to examine with additional scrutiny. The four individual risk factors were assigned favorability ratings from 0 – 5, with 0 unfavorable (red), 3 moderately favorable (yellow) and 5 favorable (green). Several techniques were used to compute the combined risk metric at each location using a grid resolution of 1 km^2. These methods included using the sum of individual risk factor favorability ratings, the product of individual favorability ratings, or the minimum (least favorable) value of the four risk favorability ratings (Figure 8). There is value in considering the outcomes of each of these methods:

1. The summation approach highlights areas that appear favorable overall, but does not inform a decision maker if any given risk factor is unfavorable at a location.

2. The minimum value approach highlights the most unfavorable rating of the four risk factors, but does not inform a decision maker of how much more favorable are other risk factors.

3. The product approach highlights those few areas that are favorable in all four risk factors, but highly down-weights those areas that are even slightly less favorable.

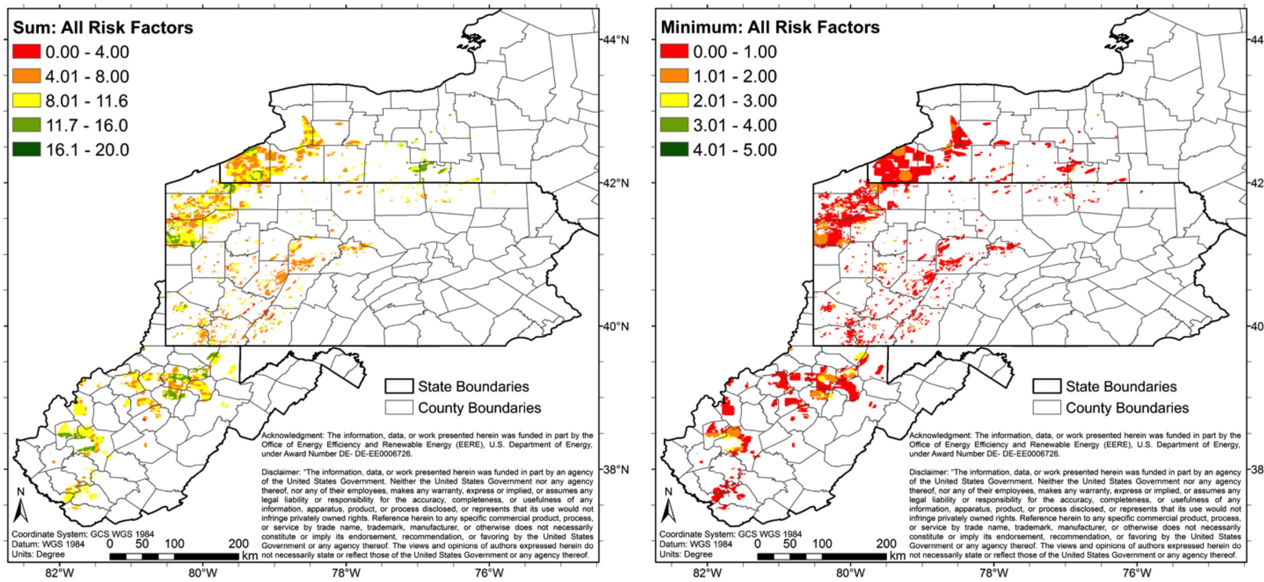

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Figure 8: Combined Risk Maps. Left: Sum of the individual risk maps for Thermal, Reservoir, Seismic and Utilization; Right, Minimum of the individual risk maps for Thermal, Reservoir, Seismic and Utilization

Overall the summation approach rapidly identifies areas for which additional study to reduce risk related to any one of the risk factors is most warranted. The minimum value approach highlights the fact that there is no place where the existing results warrant immediate investment in commercialization.

While it is almost impossible for analysts to say which method is best, the information conveyed by these methods is useful for the decision maker to consider in assessing their site, or when comparing sites for development. Where all three PFM methods are favorable, these sites are most robust as potential plays; however, uncertainty in each metric should also be considered while making a decision. Each individual risk is accompanied by a map of the uncertainty, which was then included as part of the final PFM.

The set of PFMs that combine all four risk factors highlight the spatial lay-out of existing population centers. Areas of low population density are matched by low favorability ratings, irrespective of their geological resources

The geologic risk factors (thermal, reservoir, and seismic), when combined into a set of PFMs, emphasize the fixed natural-system properties that must be accommodated by engineering designs for well fields and for utilization scenarios. The advantage of the 3-factor geology-only PFMs is that they identify areas that a stakeholder group would find suitable for creation of a new industrial, commercial, or residential activity that utilizes the geothermal heat. These geology-only-PFMs express the fact that the Geothermal Play Fairway team cannot anticipate all possible thermal utilization scenarios that may interest a particular future user group. This natural resource information can be combined in future studies with not only direct costs but also indirect benefits, such as reduced use of fossil fuels, regulatory considerations, or tax incentives, to develop more comprehensive descriptions of the spatial variation of costs and benefits.

There are five Play Fairways that we recommend be of highest priority for further investigation (Figure 9). The Corning-Ithaca Play Fairway (mostly in New York) includes locations with especially favorable overall scores and small degrees of uncertainty, and warrants investigation to better determine the full costs of heat delivery as well as to determine the spatial extent of the high quality reservoirs. The Morgantown-Clarksburg Play Fairway (West Virginia), the Meadville–Jamestown Play Fairway (mostly in Pennsylvania) and the Charleston Play Fairway (West Virginia) also have favorable scores for most of the four risk factors, and deserve more in-depth analysis than was within the scope of this Phase 1 project. The Pittsburgh Play Fairway is a region of very few deep wells and therefore scant data for the subsurface depths at which the temperature exceeds 50 °C. Given the large utilization potential near the city of Pittsburgh, we recommend a more focused study of the deepest wells in order to better evaluate the potential for deep natural reservoirs.

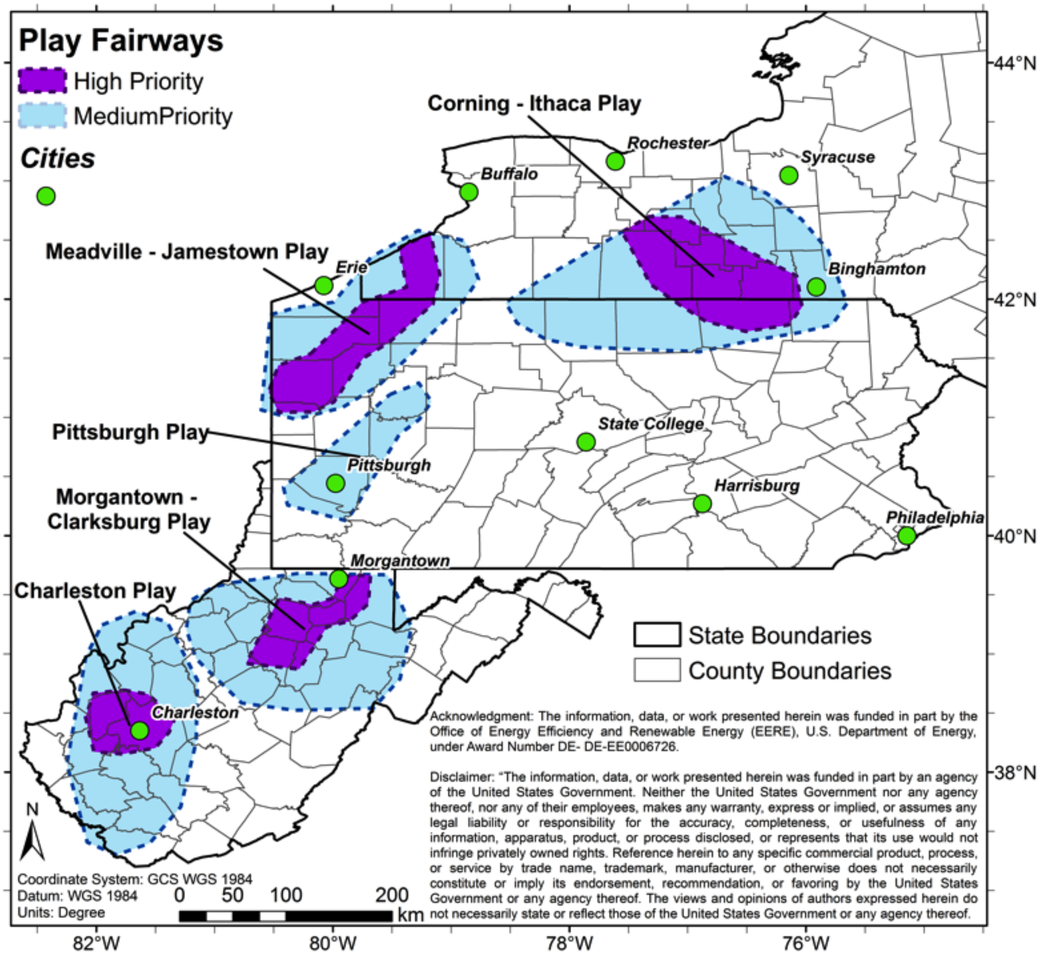

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Figure 9: The most favorable Play Fairways within the Appalachian Basin based on this project synthesis of all Risk Factors as of Phase 1. Play fairways are named for one or more population centers within them. All but the Pittsburgh Play Fairway are subdivided into an inner fairway (high priority) and outer fairway (medium priority) regions, based on the combined risk analysis.

8. CONCLUSIONS

Here we summarize the main conclusions from Jordan et al. (2015):

- The thermal resource maps created as intermediate products of this project improve upon some previously published Appalachian Basin thermal resource maps, including, but not limited to Blackwell & Richards (2004), Frone & Blackwell (2010), Shope et al. (2012), Aguirre (2014) and Stutz et al. (2015). Results of the Phase 1 thermal analyses show that geothermal resources in the Appalachian Basin are indeed almost exclusively low temperature, which is in agreement with previous analyses.

- A new methodology and metric were developed to quantify the favorability of known hydrocarbon reservoirs to perform as low-temperature geothermal reservoirs. Either directly or indirectly, this productivity metric takes into account the depth, reservoir thickness, and permeability. A weakness of the method is that it uses an estimation of matrix permeability flow for all cases, including reservoirs dominated by fracture permeability.

- Throughout the Appalachian Basin study region, based upon analysis of historical earthquake activity, of the locations of rock-property discontinuities that may be faults, and of the regional stress field, we highlighted areas at increased risk of induced seismicity (Figure 6). Earthquake activity over the last 50 years occurred sparsely across the three states of interest, and no seismic events of magnitude exceeding approximately ML 4.7 occurred. Within the Appalachian Basin in New York, the natural faults with a known slip history are almost entirely limited to the northern half of the Basin region, where the insulating sedimentary basin rocks are thin and therefore the geothermal heat opportunities are not favorable. In Pennsylvania, most of the sparse natural earthquakes occurred in the northwestern extreme of the state, where the largest recorded event is of ML 4.5. This cluster of seismic events occurs in general proximity to good natural reservoirs but only modest quality thermal resources. In West Virginia, natural earthquakes are more widespread in the southwestern half of the state, including the ML 4.7 event in the southernmost county (McDowell), but no natural earthquake activity has been recorded in the northeastern half of the state in the last 50 years. Although the thermally favorable areas of southwestern West Virginia are in relatively close proximity to clusters of natural earthquakes, the thermally favorable areas of the north-central part of the state are distant from known earthquakes.

- The four individual analyses were combined into final favorability maps using several techniques (sum, product, minimum values). The various techniques emphasize differing properties of the choices that an institution might make, and thus for now all are retained. Using all 4 criteria, the summation method indicates the most favorable counties within the study area are the West Virginia counties of Monongalia, Taylor, Harrison, Preston and Lewis (dubbed the Morgantown–Clarksburg play), Putnam, Kanawha and Lincoln (Charleston play), the Pennsylvania counties of Mercer, Venango, Crawford, Erie, and Warren, and adjacent Chautauqua county in New York (together, the Meadville–Jamestown play), and New York counties of, Chemung, Steuben, Schuyler, Yates, Tioga and Tompkins, plus adjacent Bradford county in Pennsylvania (Corning–Ithaca play).

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