To: Appalachian Basin Geothermal Play Fairway Analysis Group

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Subject: Selection of Thresholds for Thermal Resource and Thermal Risk Factor Maps

Applicability: The methods described here were used to develop the thermal resource and risk maps for the 3rd quarter and for final products. This memo discusses the steps to create thermal risk factor maps for the project. More broadly, this memo describes a method for objective selection of threshold values for any risk factor considered.

Definitions

Resource Map – Map representing a resource in the Appalachian basin. For example, these include depth-to-temperature maps, temperature-at-depth maps, reservoir productivity maps, etc. These may have continuous or discrete color scales.

Risk Factor Map – A discrete color map submitted as a representation of the risk for the end user considered. A risk factor map reflects actual acceptability (favorability) of the resource. The most general risk factor map would be a single color scheme for all end uses considered in the project. An example of a more specific map would be a single color scheme for all end uses between 50 °C and 80 °C. Separate thresholds would be defined for each of these maps.

Introduction

Thresholds must be assigned for visualizing the resource maps and risk factor maps in a play-fairway color scheme. A distinction must be made between thresholds for visualizing the thermal resource maps (e.g. temperature at depth and depth to temperature), and thresholds for visualizing the thermal risk factor maps. The resource maps may be viewed on any color scale desired that adequately displays the variability in the resource throughout the basin: the resource maps represent favorability relative to the predicted values of the resource in the assessed locations of the basin. The risk factor map must be placed on a color scale that represents the actual acceptability of developing the thermal field in an assessed location of the basin: the risk factor map represents favorability relative to the project(s) considered. For the thermal risk factor, the risk map represents the favorability of drilling to a depth and reaching a sufficient temperature for the project(s) considered. Therefore, the risk factor map thresholds should change based on the project considered. More detailed descriptions of Resource Maps versus Risk Factor Maps are provided in their respective sections.

To distinguish between resource maps and risk factor maps, the colors used to represent resource maps should not be exactly the same as colors used on risk factor maps (green/yellow/red) within reason. For example, it would be odd for temperature at depth to be on a purple/blue/pink color scale, so using green/yellow/red would be acceptable. Another distinction between resource maps and risk factor maps is that the resource map may be placed on a continuous color scale; whereas the risk factor must be on a discrete play-fairway color scale.

Selection of Maximum, Minimum, and Threshold Values

For a resource map the minimum and maximum values have little influence on the resulting map, other than bounding the color scale. On a risk factor map the minimum and maximum values define 0.0 and 3.0 or 0.0 and 5.0, and therefore are of great importance when calculating the commensurate risk statistic. For example, if the maximum value on a resource map is 100 and 100 is advantageous, but threshold 2 (2.0) is a value of 1, and the maximum (3.0 on 3-color scale) is assigned (arbitrarily) a value of 1000, then 100 would be scaled to a value of 2.1 for the commensurate statistic calculation. Thus, the minimum and maximum values on a risk factor map must be selected with care, and represent what is truly a minimum acceptable and maximum acceptable value, within reason.

One way to assign the maximum and minimum risk factor values is to treat them as thresholds, for which any value below the selected minimum would be assigned a value of 0.0, and any value above the selected maximum would be assigned a 3.0 or 5.0 depending on the color scheme. This formulation allows for an objective selection by asking "what is a value above which we could do any project?" and "what is a value below which we could accomplish nothing?" This formulation is more flexible than assigning a single value to 0.0 and 3.0 or 5.0.

The threshold values determine the color divisions on all maps. The thresholds should be selected objectively, at least to a point of being defensible. As such, resource map thresholds could be determined based on the expected cost of drilling and completing a geothermal well (for depth-to-temperature maps) and potential end use temperatures (for temperature-at-depth maps). Risk factor map thresholds are to be defined based on the expected cost of drilling to depths for the project(s) considered. The most general risk factor map would consider all possible projects. An example of a more specific risk factor map would be a single color scheme for all end uses between 50 °C and 80 °C. Separate thresholds would be defined for each risk factor map. The thresholds used for the final risk factor maps are provided in the final section of this memo.

Threshold Selection for Resource Maps

In determining the threshold values for the resource maps, some consideration was given to how much of the map area appeared a certain color. The main concern is that the resource map must display a variety of colors to maximize its utility. For example (using green/yellow/red) this does not mean that areas that are green are favorable to develop, and areas that are red are unfavorable: it only means that green areas are better than red areas.

For resource maps, no consideration was given to the use of different thresholds for different end uses. For example, one may be interested in a district heating project, and therefore sites would require temperatures above 80 °C to be considered. These end-use specifications are potentially important for risk factor maps (below), but are not reflected in the resource maps.

The following discusses how thresholds could be assigned to resource maps using a single threshold set. This approach was not adopted for final products, but could be useful for other projects, or future phases of this project.

To ensure that visual comparison is simple between potentially many maps, only one set of thresholds could be used per resource, no matter the selected depth or temperature. For instance, the temperature at 1 km could use the same color scheme as the temperature at 4 km. Likewise, the Depth to 80 °C could use the same color scheme as Depth to 100 °C.

Depth to Temperature Maps

Threshold values for depth to temperature maps are selected based on the current state of knowledge about the average cost of drilling and completing geothermal wells (Beckers et al., 2014). The main consideration was that the rate of change in the cost for drilling and completing a well is less for shallow depths. For instance, drilling a well 2 km instead of 4 km causes the average cost to increase by about $7 million; whereas drilling a well 4 km instead of 6 km, or 6 km instead of 8 km causes an average cost increase of about $10 million.

Other factors affecting the economics of geothermal operations including the price of competing heating fluids (e.g. natural gas), the natural permeability of the reservoirs at depth, the expected fluid production rate, and the expected temperature of the produced fluid were not taken into account to determine the threshold values; however each factor may aid in an economics-based objective selection of threshold values.

Minimum and Maximum Depth

The minimum depth is 500 m, which is approximately the minimum depth to a corrected BHT of 50 °C in the region – the minimum useful temperature. This hot spot is located in Gilmer and Calhoun counties in West Virginia. Additionally, 500 m is the depth of the shallowest reservoir identified in this study. The maximum depth is 8750 m, which is the maximum predicted mean depth to 80 °C in the region considered, plus two times the standard error of the predicted mean. Again, these values may be adjusted with little effect on the resource maps, other than shifting the color scale values.

Thresholds for 5-color Scheme for All Temperatures

Threshold 1 is set at an average cost of approximately $12 million to drill and complete each well. This corresponds to a depth of 4500 m. Clearly drilling to a depth of 4500 m would be too costly for low temperatures, and only in the very few hottest areas would it be beneficial to drill to deeper depths.

Thresholds 2 through 4 were all selected in approximately $2 million increments, starting with threshold 2 at $8.2 million and 3500 m, to threshold 3 at $6.0 million and 2900 m, and finally threshold 4 at $3.9 million and 2200 m. To place the 2200 m threshold into a thermal perspective, the 50 °C minimum temperature considered in this project would correspond to an average gradient of about 18 °C/km. Therefore, even at the coolest temperature considered there would be a distinction between green, yellow-green, yellow, orange, and red areas on the map (though most of the area would appear green).

Thresholds for 3-color Scheme for All Temperatures

Threshold 2 on the 3-color scale is located between thresholds 3 and 4 on the 5-color scale. Threshold 1 on the 3-color scale is a $5 million increment from threshold 2.

Temperature at Depth Maps

Temperature at depth thresholds are selected based on the end-use temperatures considered in this project. The minimum temperature is 15 °C, which is the average annual ground temperature throughout the region (Gass, 1982), rounded up to the nearest multiple of 5. The maximum temperature is 250 °C, which is the maximum calculated temperature at 4 km depth for wells in the database, rounded up to the nearest multiple of 10. A depth of 4 km was selected because maps for temperature at depth were created up to 4 km depth.

Thresholds for 5-color Scheme for All Depths

Threshold 1 is 50 °C, which is the minimum useful temperature considered in this project.

Threshold 2 is 75 °C, which is desirable to meet the legal minimum temperature of 72 °C needed for Grade A milk pasteurization by the High Temperature Short Time (HTST) method (USHHS, 2011). HTST is typically used for high volume production of milk because of the short 15 second heating time. Lower temperatures of 63 °C are acceptable for pasteurization if milk is heated for 30 minutes (USHHS, 2011), but this is more typical for at-home projects than large scale production. Other processes related to large scale milk pasteurization are possible at temperatures between 60 °C and 70 °C.

Threshold 3 is 90 °C, which is a desirable temperature for direct-use of hot water for district heating.

Threshold 4 is 150 °C, which is considered a minimum temperature for electricity generation in an Organic Rankine Cycle (ORC) geothermal power plant.

Thresholds for 3-color Scheme for All Depths

Threshold 1 is 50 °C, which is the minimum useful temperature considered in this project. Again, threshold 2 on the 3-color scale is located between threshold 3 and 4 on the 5-color scale.

Table 1a: Thresholds for 3-color scheme for depth-to-temperature thermal resource maps.

3 – Color Scale Divisions	Depth to Temperature Maps (m)
Minimum	8750 (too costly)
Bad, unacceptable [8750, 4000)	
Threshold 1	4000 (~$10.1 Million/well)
Okay, acceptable [4000, 2500)	
Threshold 2	2500 (~$4.8 Million/well)
Great, advantageous [2500, 500]	
Maximum	500 (shallowest reservoir)

Table 1b: Thresholds for 3-color scheme for temperature-at-depth thermal resource maps.

3 – Color Scale Divisions	Temperature at Depth Maps (°C)
Minimum	15 (no need to drill)
Bad, unacceptable [15, 50)	
Threshold 1	50 (min useful temperature)
Okay, acceptable [50, 120)	
Threshold 2	120
Great, advantageous [120, 250]	
Maximum	250

Table 1c: Thresholds for 5-color scheme for depth-to-temperature thermal resource maps.

5 – Color Scale Divisions	Depth to Temperature Maps (m)
Minimum	8750 (too costly)
Bad, unacceptable [8750, 4500)	
Threshold 1	4500 (~$12.2 Million/well)
Marginally acceptable [4500, 3500)	
Threshold 2	3500 (~$8.2 Million/well)
Okay, acceptable [3500, 2900)	
Threshold 3	2900 (~$6.0 Million/well)
Favorable [2900, 2200)	
Threshold 4	2200 (~$3.9 Million/well)
Advantageous [2200, 500]	
Maximum	500 (shallowest reservoir)

Table 1d: Thresholds for 5-color scheme for temperature-at-depth thermal resource maps.

5 – Color Scale Divisions	**Temperature at Depth Maps** (°C)
Minimum	15 (no need to drill)
Bad, unacceptable [15, 50)	
Threshold 1	50 (min useful temperature)
Marginally acceptable [50, 75)	
Threshold 2	75 (milk pasteurization)
Okay, acceptable [75, 90)	
Threshold 3	90 (district heating)
Favorable [90, 150)	
Threshold 4	150 (ORC power plant)
Advantageous [150, 250]	
Maximum	250

Thresholds for Risk Factor Maps

The risk factor maps must combine temperature and depth in a meaningful way. These risk factor maps may be defined based on the overall risk of developing any project, or be more specific to selected end uses, such as technologies that require temperatures from 50 °C to 80 °C.

The thresholds selected for risk factor maps give no consideration to the percentage of map area assigned to each color because the thresholds are objectively defined for acceptability. It is therefore possible for a risk factor map to omit some of the colors because that level of acceptability is not reached in the assessed area.

Definition of risk factor thresholds can be determined from two methods (M1 or M2) by asking:

M1) "What temperatures are being considered for this use map?" Thresholds for a thermal risk map would be assigned based on unfavorable, okay, and advantageous depths to reach those temperatures considered.

M2) "At what depth are the interesting reservoirs that are being considered for this map area?" Thresholds describing thermal risk would be based on unfavorable, okay, and advantageous temperatures to be reached at those reservoir depths.

Examples of thresholds for the thermal risk factor using each of these methods (M1 and M2) are provided in Table 2. Thresholds selected for use in the project are provided in the following section. In Table 2, the thermal gradient is used as a simple method of assigning thresholds, but using the thermal gradient does not account for complexities in thermal conductivity or heat generation with depth, or any economic factors that may want to be considered.

Alternatively to M1) and M2), a map depicting overall thermal risk may be made from the combination of maps created at depth intervals. For example, taking the average of the 3-point or 5-point scaled values for depths ranging from 1.5 km to 3.5 km in 1.0 km increments. The threshold values would be defined in temperature units and would be different for each depth considered because of a change in favorability of a temperature with depth. For example, 80 °C at 1000 m is great, but 80 °C at 5000 m is awful. These thermal maps could be combined with the reservoirs, which are defined on 0.5 km intervals, to create combined thermal and reservoir risk maps. This is an option for further communicating risk in Phase 2.

Table 2a: Example thresholds for 3-color scheme and point scale for thermal risk factor maps in Method 1 (above). M1 considers a single map for end use temperatures from 60 °C – 80 °C.

3 – Color Scale Divisions and Point Value (0 = Worst, 3 = Best)	**M1) Depth to End Use Temperatures from 60 – 80 °C** (m)
All Values Above 0.0: Unacceptable	4000 (~15 °C/km for 70 °C)
Bad, unacceptable [0.0, 1.0)	
Threshold 1 1.0	3000
Okay, acceptable [1.0, 2.0)	
Threshold 2 2.0	2000
Great, advantageous [2.0, 3.0]	
All Values Below 3.0: Very favorable	1000

Table 2b: Example thresholds for 3-color scheme and point scale for thermal risk factor maps in Method 2 (above). M2 considers a single map for reservoirs between 2000 m and 3000 m.

3 – Color Scale Divisions and Point Value (0 = Worst, 3 = Best)	**M2) Temperature at Reservoirs Depths from 2000 m– 3000 m** (°C)
All Values Below 0.0: Unacceptable	50 (~15 °C/km for 2.5 km)
Bad, unacceptable [0.0, 1.0)	
Threshold 1 1.0	80 (~28 °C/km for 2.5 km)
Okay, acceptable [1.0, 2.0)	
Threshold 2 2.0	120 (~45 °C/km for 2.5 km)
Great, advantageous [2.0, 3.0]	
All Values Above 3.0: Very favorable	180 (~68 °C/km for 2.5 km)

Table 2c: Example thresholds for 5-color scheme and point scale for thermal risk factor maps in Method 1 (above). M1 considers a single map for end use temperatures from 60 °C – 80 °C.

5 – Color Scale Divisions and Point Value (0 = Worst, 5 = Best)	**M1) Depth to End Use Temperatures from 60 – 80 °C** (m)
All Values Above 0.0: Unacceptable	4000
Bad, unacceptable [0.0, 1.0)	
Threshold 1 1.0	3500
Marginally acceptable [1.0, 2.0)	
Threshold 2 2.0	3000
Okay, acceptable [2.0, 3.0)	
Threshold 3 3.0	2500
Favorable [3.0, 4.0)	
Threshold 4 4.0	2000
Advantageous [4.0, 5.0)	
All Values Below 5.0: Very favorable	1000

Table 2d: Example thresholds for 5-color scheme and point scale for thermal risk factor maps in Method 2 (above). M2 considers a single map for reservoirs between 2000 m and 3000 m.

5 – Color Scale Divisions and Point Value (0 = Worst, 5 = Best)	**M2) Temperature at Reservoir Depths from 2000 m– 3000 m** (°C)
All Values Below 0.0: Unacceptable	50 (minimum useful temp.)
Bad, unacceptable [0.0, 1.0)	
Threshold 1 1.0	70 (~25 °C/km at 2.5 km)
Marginally acceptable [1.0, 2.0)	
Threshold 2 2.0	100 (~35 °C/km at 2.5 km)
Okay, acceptable [2.0, 3.0)	
Threshold 3 3.0	130 (~48 °C/km at 2.5 km)
Favorable [3.0, 4.0)	
Threshold 4 4.0	150 (~56 °C/km at 2.5 km)
Advantageous [4.0, 5.0)	
All Values Above 5.0: Very favorable	180

Thresholds Used for Final Thermal Resource and Risk Factor Maps

The resource maps made as products for this project did not use the method of resource threshold assignment described in this memo. Instead, resource maps were made by simply stretching the colorbar from the minimum to the maximum value recorded for the resource in the basin.

Risk factor maps did follow the procedure outlined here for assignment of favorability thresholds. Lists of thresholds for each thermal risk factor map in 3 and 5 color scheme are provided below. Thresholds for the 3-color scheme are all located between thresholds in the 5-color scheme. The risk factor maps for this project included Depth to 80 °C, Depth to 100 °C, Temperature at 1.5 km, Temperature at 2.5 km, and Temperature at 3.5 km. The Play Fairway Metrics that combined thermal, reservoir, seismic, and utilization risk factors were created using only the Depth to 80 °C risk factor map, as stated in the SOPO. Other Play Fairway Metric maps could be created using the other thermal risk factors, but time did not permit to perform these calculations in Phase 1. With additional time, Play Fairway Metrics could be computed using all of these thermal risk factors, and the most robust areas would be favorable in all renditions of the Play Fairway Metric. Heat flow is not considered to be a risk factor because heat flow alone is not of great value to those interested in drilling a geothermal well.

Dollar values for depth to temperature thresholds are from Beckers et al. (2014) and represent the average cost in 2012 US dollars needed to drill a single geothermal well. Dollar values are rounded. A value of $15 million/well is used as the worst value, corresponding to a depth of 5000 m. Approximate $2 million/well increments are used to select thresholds 1 through 4 on a 5-color scheme. Temperature thresholds for temperature at depth maps are selected based on typical utilization temperatures, or favorability of thermal gradients from the temperature-at-depth to the annual average ground surface temperature of 15 °C, as discussed above. All values greater than the maximum are assigned a value of 3 or 5, and all values less than the minimum are assigned a value of 0.

Depth to 80 °C

5-color scheme
0: 8750 m (>$15M/well)
1: 4000 m ($10M/well)
2: 3000 m ($6.5M/well)
3: 2300 m ($4.2M/well)
4: 1500 m ($2.2M/well)
5: 500 m (< $2M/well)

3-color scheme
0: 8750 m (>$15M/well)
1: 3000 m ($8.2M/well)
2: 2000 m ($3.3M/well)
3: 500 m (< $2M/well)

Depth to 100 °C

5-color scheme

0: 5000 m ($15M/well)
1: 4200 m ($11M/well)
2: 3700 m ($9M/well)
3: 3200 m ($7M/well)
4: 2600 m ($5M/well)
5: 1900 m ($3M/well)

3-color scheme

0: 5000 m ($15M/well)
1: 4000 m ($10M/well)
2: 3000 m ($6.5M/well)
3: 1900 m ($3M/well)

Temperature at 1.5 km

5-color scheme

0: 30 °C (~10 °C/km)
1: 50 °C (Minimum useful temperature)
2: 60 °C (~30 °C/km)
3: 70 °C (~37 °C/km)
4: 80 °C (~43 °C/km)
5: 90 °C (~50 °C/km)

3-color scheme

0: 30 °C (~10 °C/km)
1: 50 °C (Minimum useful temperature
2: 75 °C (~40 °C/km)
3: 90 °C (~50 °C/km)

Temperature at 2.5 km

5-color scheme

0: 40 °C (~10 °C/km)
1: 60 °C (~18 °C/km)
2: 75 °C (~25 °C/km)
3: 90 °C (~30 °C/km)
4: 100 °C (~35 °C/km)
5: 110 °C (~40 °C/km)

3-color scheme

0: 40 °C (~10 °C/km)
1: 70 °C (~22 °C/km)
2: 95 °C (~32 °C/km)
3: 110 °C (~40 °C/km)

Temperature at 3.5 km
5-color scheme
0: 50 °C (Minimum Useful Temperature)
1: 75 °C (Milk Pasteurization)
2: 90 °C (Small-Scale District Heating)
3: 100 °C (25 °C/km)
4: 120 °C (Large-Scale District Heating)
5: 150 °C (ORC Power Generation)

3-color scheme
0: 50 °C (Minimum useful temperature)
1: 80 °C (~19 °C/km)
2: 110 °C (~28 °C/km)
3: 150 °C (ORC Power Generation)

References

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